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Impact of Roughness of Reflective Films on the Application of Multiple Beam Interferometry

JOHN M. LEVINS AND T. KYLE VANDERLICK[1]

University of Pennsylvania, Department of Chemical Engineering, 220 South 33rd Street, Philadelphia, Pennsylvania 19104-6393

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Multiple beam interferometry can be used to measure accurately changes in the separation between two opposed surfaces. In this paper, we assess the impact of surface roughness on the application of multiple beam interferometry. In particular, we use classical electromagnetic theory to predict the fringes of equal chromatic order (FECO) that are generated when white light is passed through an interferometer comprised of a rough silver film separated from a smooth mica sheet. We find that as roughness is increased, the observed FECO broaden and shift to longer wavelengths. Furthermore, for a given change in surface separation, the resultant change in FECO wavelengths depends on the degree and geometry of surface roughness. We perform a quantitative case study to show how the two phenomena of broadening and shifting reduce the precision and accuracy of measurements of surface separation.

INTRODUCTION

Multiple beam interferometry can be used to obtain highly accurate measurements of the optical thicknesses of thin films (1, 2). Recently, multiple beam interferometry has been exploited to its full potential in conjunction with the surface forces apparatus (SFA), a device which is used to measure the force acting between two opposed surfaces as a function of their separation (3). The mechanical features of the SFA allow the separation between two surfaces to be controlled to within angstroms. Multiple beam interferometry is used to measure the separation between the surfaces and to provide a quantitative description of the relative geometry of the two surfaces.

Multiple beam interferometry is applied by constructing an interferometer consisting of two highly reflective metallic films separated by a layer, or layers, of dielectric material with an overall thickness greater than the wavelength of light in the visible spectrum. White light is directed through the interferometer, and undergoes multiple reflections between the two metallic films. Only certain wavelengths of the transmitted light have appreciable intensity; all others are nearly zero. The transmitted light can be dispersed and viewed as a series of fringes of equal chromatic order (FECO). The wavelengths of the FECO can be predicted by the multilayer matrix method, an application of classical electromagnetic theory, which takes into account the thickness and refractive index of each layer in the interferometer (4, 5).

Nearly all SFA experiments to date have employed an interferometer composed of two mica sheets coated on one side only with a highly reflective silver film; the sheets are arranged so that the bare mica surfaces are facing each other and separated by a fluid medium. Mica serves as an ideal substrate for the SFA because it can be cleaved molecularly smooth and is transparent. Although this particular interferometer has been exploited to study a variety of surface forces (see, for example, Israelachvili and McGuiggan (6)), it is desirable to extend the SFA technique to surfaces other than mica so that a wider range of interactions can be investigated.

Recently, a few other surfaces have been employed in the SFA—such as silica (7), poly(ethylene terepthalate) (8), sapphire single crystals (9), and platinum films (10); and we, along with others, have used the SFA to study interactions between a silver surface and a mica surface (11–13). With the exception of sapphire single crystals, these materials are not molecularly smooth. It is therefore necessary to understand the impact of surface roughness on the application of multiple beam interferometry in a SFA experiment; we address this herein in the context of the experiments we are currently pursuing. Specifically, in this paper we show how the FECO are affected when one of the two opposed surfaces is rough silver and the other is smooth mica. The roughness of the silver film is modeled using a sinusoidal topography. We use the multilayer matrix method to predict how the FECO change as the degree of roughness is varied and how this influences the measurement of surface separation in a SFA experiment.

INFLUENCE OF ROUGHNESS ON FECO: A QUALITATIVE DESCRIPTION

The purpose of this section is twofold. The first objective is to describe the optical system used to generate and view

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[1] To whom correspondence should be addressed.

FECO in a SFA experiment. Knowledge of this practical information is essential to meeting the second objective, which is to put forward a qualitative description of how the FECO are affected when one of the layers in the interferometer has a rough surface.

As a basis for this discussion, consider two model interferometers, as shown in Fig. 1. Both interferometers are composed of the same sequence of layered materials: silver–mica–silver. In one interferometer—referred to as the "smooth interferometer"—all the layers have smooth surfaces. In the "rough interferometer," one of the silver films is rough; its surface, which faces the mica surface, is modeled as a sine wave with prescribed amplitude and frequency. The medium that fills the space between the smooth mica and the troughs of the rough silver is air. Furthermore, when the amplitude of the roughness is zero, the two interferometers are identical.

In the practical application of multiple beam interferometry, white light is beamed normal to the interferometer; the transmitted light is collected and magnified by a microscope objective and then directed to the entrance slit of a spectrometer (shown in Fig. 1). In the spectrometer, the light strikes a dispersion grating which reflects it at an angle which depends on the wavelength of the light. The dispersion grating acts to separate, in space, light of different wavelengths; the spatial separation is proportional to the wavelength difference. The dispersion of the gratings typically used in SFA experiments is approximately 30 Å wavelength/mm. The dispersed light is then directed to an exit port, approximately 15 mm wide, which serves as a window where the experimenter can view light (i.e., FECO) over a span of wavelengths.

To best understand the impact of surface roughness on FECO, it is useful to first understand the generation of FECO from the smooth interferometer. To start, consider the light passing through a single point located within the smooth interferometer, depicted in Fig. 1 as a filled dot. The intensity of light transmitted through this point varies with wavelength; upon being dispersed it would appear as sketched in Fig. 1. This spectrum consists of a series of intensity peaks, the so-called FECO, of which only two are shown. The exact intensity versus wavelength spectrum can be predicted using the multilayer matrix method, described in the appendix.

As stated previously, the intensity versus wavelength spectrum is a function of the thickness and refractive index of each layer in the interferometer. For the particular materials considered here, the following can be demonstrated. If the thickness of the mica layer trapped between the silver layers is made larger (or if an air layer is inserted between the mica and the silver), the FECO shift to longer wavelengths. On the other hand, if the thickness of either silver layer is made larger, the FECO shift to shorter wavelengths. Moreover, the magnitude of the shift for a given change in mica (or air) thickness is much larger than that for an equivalent change in the silver thickness.

It is important to appreciate that the finite width of the

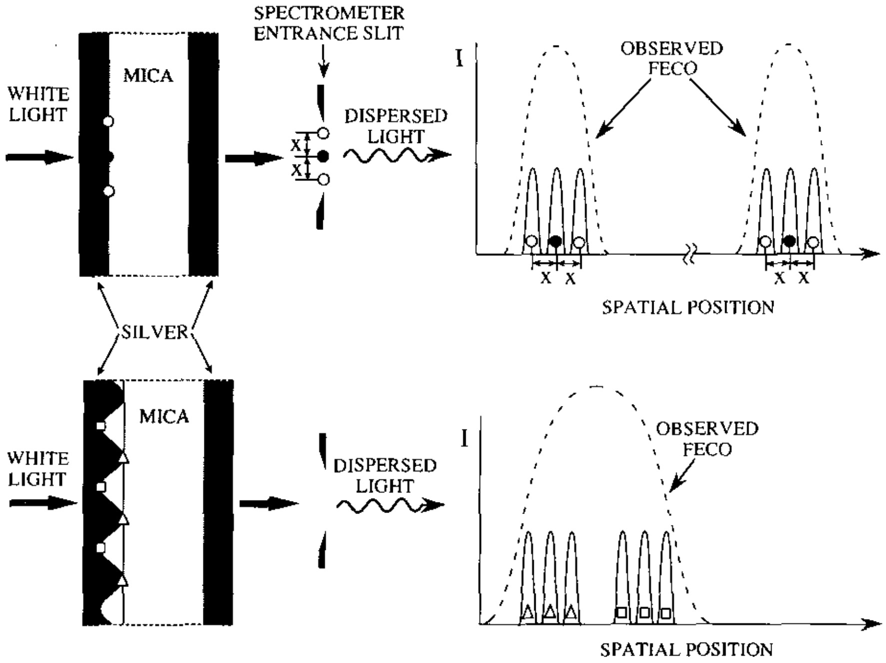

FIG. 1. Schematic representation of the optical system used to generate and view FECO. Two types of interferometers are sketched. The first is composed of three layers, silver–mica–silver, all of which are smooth; the second consists of the same three layers, except one of the silver layers has a rough surface. The FECO generated from each interferometer, as they appear at the exit of a spectrometer, are also sketched. Note that light of longer wavelengths appears spatially to the right.

entrance slit impacts the appearance of the FECO at the exit port. To best illustrate this, we consider now the light directed through two additional points within the smooth interferometer, represented by open dots in Fig. 1. The light transmitted through all three points consists of an identical intensity versus wavelength spectrum. However, because the three dots are separated in space, three spatially separated points of light are incident on the entrance slit. If x represents the distance between these adjacent points of light, then the three intensity versus wavelength spectra, as viewed at the exit port of the spectrometer, will be slightly shifted from one another by an amount equal to x (shown in Fig. 1). This spatial shift—which could be interpreted as an apparent wavelength shift—is due solely to the finite width of the entrance slit and we henceforth refer to this as the "slit effect." In actuality, the FECO observed at the exit port amount to the summation of all the intensity profiles corresponding to those points of light which are incident on the entrance slit. Thus, widening the entrance slit both broadens and brightens the observed FECO.

To describe the impact of roughness on the appearance of the FECO, we consider now the light transmitted through six points within the rough interferometer, represented in Fig. 1 by squares and triangles. Each of the three squares is at a trough of the silver surface, whereas the three triangles are located at peaks. Comparing the light transmitted through the triangles with that through the squares, the intensity maxima of the latter occur at longer wavelengths (as shown in Fig. 1). Taking into account now all the spots along the rough surface, the resulting FECO image represents the summation of all the different intensity versus wavelength spectra that are admitted through the entrance slit with proper account taken for the slit effect, as described above. The roughness thus induces a broadening of the observable FECO.

In addition to the broadening, increasing the roughness of the silver causes the center of observed FECO to shift to longer wavelengths. This is most easily understood by noting that (1) the intensity maxima of the light transmitted through the triangles in the rough interferometer occur at nearly the same wavelengths as that of the light transmitted through the dots in the smooth interferometer (this is because changing only the silver thickness causes negligible wavelength shifts) and (2) the intensity maxima of the light transmitted through all other points are shifted to longer wavelengths due to the presence of the air gap.

Finally, it is worth noting that the appearance of roughness on the outside surface of either silver layer (i.e., the surface facing away from the mica) causes an insignificant effect on the observed FECO. This is because roughening the outside silver surface amounts to nothing more than varying the silver thickness. In contrast, roughening the inside silver surface amounts to changing both the thickness of the metal as well as the thickness of the dielectric medium confined between the mica and silver.

INFLUENCE OF ROUGHNESS ON FECO: A QUANTITATIVE CASE STUDY

We base our case study on the interferometer and optical system shown schematically in Fig. 1. Taking values that are typical for real experiments, we set the width of the entrance slit of the spectrometer to 100 μm and the magnification of the transmitted light to 20×. This means that the light projected across the entrance slit corresponds to that transmitted through a 5-μm-wide section of the interferometer. The dispersion of the spectrometer grating is set to 0.033 Å wavelength/μm.

The thicknesses and refractive indices of each layer in the interferometer are set as follows. The mica sheet is 3.0 μm thick, with a refractive index, n_m, as given by Israelachvili and Adams (3)

$$n_m(\lambda) = 1.5820 + \frac{4.76 \times 10^5}{\lambda^2},$$

where λ is the wavelength of light in angstroms. The rough silver thickness z_s, varies along the direction perpendicular to the path of light, x, as

$$z_s(x) = 530 + a \sin(2\pi x/d),$$

where z_s, a, and d are in angstroms (a and d are the amplitude and frequency of the sine wave, respectively). A smooth silver film 530 Å thick lies on the opposite side of the mica sheet. For the refractive index of the silver, $\tilde{n}_s = n_s + ik$, we have used the data from Johnson and Christy (14), where $n_s = 0.05$ and we have fitted their data for k as a function of wavelength, λ, to the quadratic equation

$$k(\lambda) = a + b\lambda + c\lambda^2,$$

where λ is in angstroms, $a = -3.10$, $b = 1.55 \times 10^{-3}$ Å^{-1}, and $c = -6.04 \times 10^{-8}$ Å^{-2}. The refractive index of the dielectric confined between the rough silver and mica is set to 1.0. The refractive index of the medium surrounding the interferometer (referred to as n_0 in the appendix) has negligible effect on the FECO; in the case study presented herein we set this to be 1.0.

Finally, there is a practical detail of SFA experiments that has not yet been addressed: the layers of the interferometer are not stacked in parallel sheets, as shown in Fig. 1. Instead, the opposed surfaces are bent to a cylindrical shape (radius of 1–2 cm) and oriented at right angles, with the axes of curvature perpendicular to one another. The geometry of two crossed cylinders is closely approximated by that of a sphere on a flat surface. Thus, to properly account for curvature in our interferometric analysis, the interferometer should be constructed with the silver-coated mica sheet bent to a radius of 1 cm, with the tip touching the rough silver. We have incorporated this into our calculations and we find

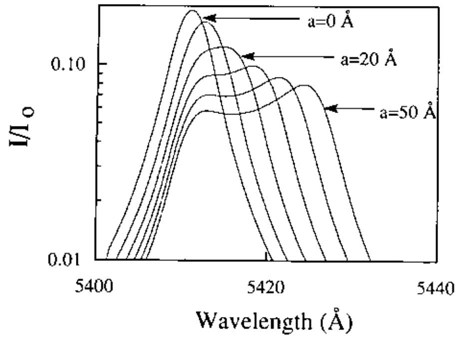

FIG. 2. Intensity of transmitted light (normalized by the intensity of the incident white light) versus wavelength for a particular FECO. Six profiles are shown, each corresponding to a different amplitude of the silver sinusoidal topography, from 0 to 50 Å in 10 Å steps. As the amplitude is increased, the FECO broadens and its center shifts to longer wavelength.

that the curvature is so slight, compared to the width of the spectrometer entrance slit, that it has a negligible effect on the calculated FECO.

The FECO generated from an interferometer containing a rough surface were calculated by approximating the profile of the rough surface as a series of discrete steps. In the calculations reported here, we have approximated the sinusoidal surface as a series of steps 0.005 μm wide. The intensity versus wavelength spectra are determined at each step, using the multilayer matrix method, and summed to yield the observed FECO.

Figure 2 shows the calculated intensity versus wavelength profile of a FECO for various amplitudes of the silver surface, a, from 0 to 50 Å. As a is increased, the FECO broadens and the center of the FECO shifts to longer wavelengths, as described in the previous section. In contrast to the strong dependence of the intensity versus wavelength profile on a, it is virtually insensitive to changes in the peak-to-peak distance, d, of the sinusoidal topography; this is true provided that d/w is much less than one, where w represents the width of the entrance slit. For the calculations shown in Fig. 2, d was taken to be 0.1 μm.

Broadening and shifting of the FECO are general manifestations of silver surface roughness. However, the specific shape of the resulting intensity profile depends on the surface topography. One can show that the profile is most influenced by the light transmitted through those points where the rate of change of the silver thickness is small. Thus, for the sinusoidal model used in this analysis, the intensity profile is dominated by the light transmitted through the peaks and valleys of the silver surface, accounting for the bimodal appearance of the FECO in Fig. 2.

If a fluid medium is inserted between the mica and rough silver surfaces, thereby separating them, the FECO all together change to new wavelengths. At any given surface separation, the same manifestations of surface roughness, i.e., broadening and shifting, occur. However, the amount of broadening and shifting induced by a given roughness varies with surface separation. At any particular separation, the degree of broadening and shifting can be predicted qualitatively by referring to a plot of FECO wavelength (specifically, the wavelength at which the intensity is a maximum) versus separation between a smooth silver surface and a smooth mica surface; we henceforth refer to this plot as a "roughness sensitivity curve." The utility of this curve is based on the result that what is most responsible for the broadening and shifting of the FECO is the variation of thickness—in the direction perpendicular to the path of light—of the dielectric medium which fills the gap between the smooth mica and rough silver surfaces. Essentially, the broadening and shifting due to roughness occurs because the roughness sensitivity curve has a nonzero slope; the higher the slope, the more significant the broadening and shifting. Since in general the slope of the curve varies with separation, the degree of broadening and shifting varies with separation.

In the practical application of multiple beam interferometry, it is the change in surface separation that is determined from the resultant changes in FECO wavelengths; the wavelength of a FECO is typically defined as the wavelength of its center. Because of the phenomenon described in the preceding paragraph, for a given change in surface separation, the change in FECO wavelengths will be slightly different for surfaces of different roughness; this is because the broadening and shifting will generally be more exaggerated at one separation than at the other. For example, Fig. 3 shows for various surface separations from contact the corresponding wavelength changes of the center of a FECO; three different cases of surface roughness (a = 0, 40, 80 Å) are examined. As readily noted, for small changes in separation from contact (less than ca. 50 Å), the corresponding change in the wavelength of the center of a FECO is the same for all three cases of surface roughness.

The results of this quantitative case study can be used to assess the impact of silver roughness on the application of multiple beam interferometry in a SFA experiment. Two key conclusions can be made. First, the broadening of FECO

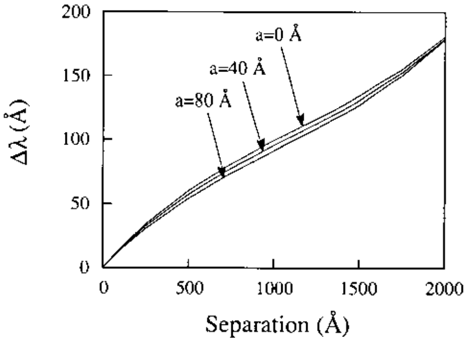

FIG. 3. The resultant change in the wavelength of a FECO versus separation (from contact) between a smooth mica surface and a rough silver surface. Three different amplitudes of the silver topography are examined, 0, 40, and 80 Å. The FECO that is being tracked is the same one shown in Fig. 2.

induced by surface roughness acts to increase the error associated with measuring the wavelength of the center of FECO. Second, changes in surface separation cannot be determined accurately without knowledge of surface roughness. However, the systematic error introduced by assuming a certain, or negligible, roughness is negligible when the separation is small. The roughness sensitivity curve allows the experimenter to identify the ranges of surface separation over which the systematic error is largest. Of course the amount of the systematic error is dependent on the exact thicknesses of each layer in the interferometer, as well as the topography of the silver surface.

SUMMARY

The purpose of this work was to investigate the impact of roughness of reflective films on the application of multiple beam interferometry. This technique is often employed to deduce changes in the separation between two opposed surfaces; this is accomplished by measuring associated changes in the wavelengths of fringes of equal chromatic order (FECO), which are generated by shining white light through the surfaces. In this paper, we describe how the observed FECO are effected when one of the opposed surfaces is rough silver and the other is smooth mica. We find that the FECO broaden and shift to longer wavelengths as the degree of silver roughness is increased. Furthermore, for a given change in separation between silver and mica, the resultant change in FECO wavelengths depends on the degree and geometry of silver roughness. The impact of these results on the application of multiple beam interferometry are discussed, and can be summarized as follows. Broadening acts to increase the error associated with measuring the centers of FECO; the dependence of changes in FECO wavelength on the topography of the silver surface can introduce a systematic error in the measurement of surface separation.

APPENDIX: DESCRIPTION OF THE MULTILAYER MATRIX METHOD

Consider white light normally incident upon a medium composed of a number of nonmagnetic layers, each with a thickness z_j and a refractive index $\tilde{n}_j$ (in general, $\tilde{n}_j$ is complex where $\tilde{n}_j = n_j + ik_j$). Each layer can be described by a characteristic matrix $\tilde{M}_j$

$$\tilde{M}_j = \begin{pmatrix} \cos q & -(i/\tilde{p}_j)\sin q \\ -i\tilde{p}_j \sin q & \cos q \end{pmatrix},$$

where

$$q = \frac{2\pi \tilde{n}_j z_j}{\lambda}.$$

Here, $\tilde{p}_j = \tilde{n}_j\sqrt{\epsilon_0}$ where ϵ_0 is the permittivity of free space, and λ is the wavelength of light. The characteristic matrix of a multilayer consisting of a succession of layers is simply

$$\tilde{M} = \prod_j \tilde{M}_j.$$

The transmission coefficient of the multilayer is given by

$$t = \frac{2\tilde{p}_0}{(m_{11} + m_{12}\tilde{p}_0)\tilde{p}_0 + m_{21} + m_{22}\tilde{p}_0},$$

where m_{ij} are the elements of $\tilde{M}$, and $\tilde{p}_0 = \tilde{n}_0\sqrt{\epsilon_0}$ where $\tilde{n}_0$ is the refractive index of the semi-infinite medium that surrounds the interferometer. The transmissivity is equal to the product of t and its complex conjugate. Thus, by knowing $\tilde{n}_j$ and z_j for each layer of the interferometer, the intensity of transmitted light can be calculated as a function of wavelength.

ACKNOWLEDGMENTS

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