SCANNING DIFFERENTIAL CONTRAST MICROSCOPY

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INTRODUCTION

We have been carrying out research on two types of scanning optical microscopes with the aim of measuring not only the width of surface features, but also the thickness of thin films and surface profiles.

There are two possible ways to directly measure film thickness with a microscope. One is to determine when the beam is focused on a reflecting surface and look for the maximum reflected amplitude. As the microscope lens is moved up and down, maxima in the reflected amplitude will be observed at the top and low surfaces of a transparent reflecting film. This technique works most easily when the film thickness is considerably larger than the depth of focus of the microscope.

A second technique is to measure phase directly and to determine the thickness from the phase shift of the reflected beam through the film. Such a technique is at its best when the film thickness is less than an optical wavelength, i.e., well within the depth of focus. It is particularly simple to apply when the films themselves are opaque and the technique is used to measure surface profiles or the thickness of opaque films on transparent or opaque substrates. An additional advantage of being able to make measurements of optical amplitude and phase directly is that the resultant data obtained can be inverse filtered to improve the transverse definition or to obtain more accurate information on the width of surface features.

THE MECHANICALLY SCANNED SCANNING OPTICAL MICROSCOPE

The basic type II microscope system with which we are working is shown in Fig. 1. The microscope objective lens is illuminated by a collimated laser beam, producing a diffraction-limited spot on the surface of the object to be examined. The beam reflected from the surface of the object passes back through the microscope objective lens to a beam splitter and through a second lens. This lens focuses the beam onto a pinhole through which it passes to a detector. A Bragg cell is used to modulate the beam.
The object itself can be moved in the transverse and range directions by piezoelectric pushers. Sometimes the object is mounted on an additional piezoelectric transducer which can vibrate the sample in and out periodically. At other times, the scanning stage itself is used to vibrate the object at a relatively low frequency of the order of 100 Hz. We have shown [1,2] that the amplitude of the signal reaching the detector is of the form

\[ V(z) = \frac{\theta}{\int_0^{\theta_0} P^2(\theta) \Gamma(\theta) e^{-2jkz \cos \theta \sin \theta} \sin \theta \, d\theta} \]

(1)

where \( z \) is the distance of the focus from the reflecting object; \( z \) is positive when the vertical focus is within the object, \( \theta_0 \) is the aperture angle of the lens, \( \Gamma(\theta) \) is the reflection coefficient as a function of angle, and it is assumed that the illumination of the pupil has an amplitude which varies as \( P(\theta) \). For simplicity, we normally assume that \( P(\theta) = 1 \) with \( \theta < \theta_0 \). In general, however, the pupil function \( P(\theta) \) can be used to account for both amplitude weighting and phase aberrations.

When \( \Gamma(\theta) \) is constant and \( P(\theta) = 1 \), Eq. (1) can be integrated to yield the result

\[ V(z) = e^{-jkz(1+\cos \theta_0)} \frac{\sin [kz(1 - \cos \theta_0)]}{kz (1 - \cos \theta_0)} \]

(2)

The amplitude of the reflected wave is maximum at the focal point \( z = 0 \). Furthermore, the phase of the reflected wave, which is of importance for phase measurements, is

\[ \phi = kz(1 + \cos \theta_0) \]

(3)
The range definition for a planar reflecting object is given by the relation

\[ \Delta z(3 \text{ dB}) = \frac{45\lambda}{1 - \cos \theta_0} \]  (4)

where \( \Delta z(3 \text{ dB}) \) is the distance between the 3 dB points [1]. A result taken with this system is shown in Fig. 2. It will be observed that there is good agreement between theory and experiment, and that the 3 dB range resolution for a 0.9 aperture lens using a He-Ne laser is about 0.6 \( \mu m \). It will be noted that the sidelobes are not at the same level or as symmetric as the simple theory indicates. A more sophisticated theory, which takes phase aberrations and amplitude weighting of the lens into account, explains the discrepancy in the sidelobe behavior [2].

Results taken on photoresist films of the order of 1.8 \( \mu m \) and 4.1 \( \mu m \) thick are shown by the solid line in Fig. 3 and the dotted line in Fig. 4. Two peaks are obtained corresponding to the focus at the top and bottom surfaces of the film. It is relatively easy to change the theory to take account of the change in the refractive index of the film and the two reflecting surfaces a distance \( h \) apart. We replace the term \( \Gamma(\theta) \exp(-2jkz \cos \theta) \) in Eq. (1) by \( S(\theta) \), where

\[ S(\theta) = \Gamma_0 e^{-2j\theta_0} \cos \theta_0 + \Gamma_1 e^{-2j\theta_1} \cos \theta_1 \]  (5)

where the subscripts 0 and 1 refer to the media outside and inside the film, respectively, and \( \Gamma_0 \) and \( \Gamma_1 \) are the reflection coefficients from the top and bottom surfaces of the film, respectively. However, for thinner films, where the two peaks overlap, the results obtained tend
to be accurate as a measure of the film thickness to only the order of a half wavelength (~2500 Å). This uncertainty is primarily due to the unknown phase difference between the reflection from the top and bottom surfaces of the film. Use of phase measurements, as described below, can eliminate the difficulties. Direct comparison on calibrated samples can also eliminate this problem. For thicker films, where the peaks do not overlap, no corrections are necessary and film thickness may be easily and accurately measured.

It is apparent that it would be useful to be able to measure the position of the maximum of the reflectivity function with as high an accuracy as possible. To do this, we have adopted a simple stratagem. We vibrate the sample at a frequency \( \Omega \) using a vibration amplitude comparable to or less than the depth of focus of the beam. In this case, we obtain an output from the photodetector at a frequency \( \Omega \) which passes through zero when the average value of \( |V(z)|^2 \) at the detector passes through a maximum. Thus, by looking for the zero or the minimum at a frequency \( \Omega \), we can determine the position of the focal point with very good accuracy. The result, taken on a 4.86 \( \mu \)m thick photoresist film, is shown by the solid line in Fig. 4. When the depth of focus is of the order of 1 \( \mu \)m, we can determine the position of the maximum, and hence the film thickness, to within a few Angstroms.

PHASE MEASUREMENTS

A second technique with which we have been working for some time is shown in Fig. 5. An acousto-optic Bragg cell is used to deflect an optical beam. This technique has the advantages of great speed, repeatability, and random access. Part of the beam travels straight through the Bragg cell, but part is deflected. The deflection angle varies linearly with the driving frequency \( \omega_B \) of the Bragg cell. The Bragg cell is positioned at the pupil plane of an optical microscope. The beams from the Bragg cell are focused onto the object being examined and produce two focused spots. One spot is fixed and the other scans as the frequency \( \omega_B \) of the Bragg cell is varied. The beams are reflected from the sample, retrace their paths through the Bragg cell, and interfere

![Graph](image-url)
Fig. 4. $|V(z)|^2 V'(z)V(z)$ curves of 4.86 μm photoresist on silicon.

on a photodiode, as shown. A Fabry lens images the center of the Bragg cell on the photodiode so that the spot does not wander off the detector as the beam is scanned.

The beam reaching the photodiode from the scanned spot is upshifted by a frequency $\omega_B$, and the one from the fixed spot is downshifted by the same frequency $\omega_B$. When the beams interfere on the photodiode (a square-law device), we obtain an output product term at frequency $2\omega_B$ whose phase is the optical phase difference between the fixed reference spot and the scanned spot. Since the amplitude of the fixed spot is constant, the amplitude of the output signal varies linearly with the amplitude of the scanned spot.

We are using a modified Leitz microscope, kindly supplied to us and modified by the E. Leitz Company, with an Inrad (Matsushita) Bragg cell. The Bragg cell has a frequency range of approximately 50-100MHz and is capable of providing about 340 resolvable spots (equivalent to 680 after our post-processing).

We measure the amplitude and phase of the rf signal (100-200 MHz) by mixing down to a 60 MHz IF, as shown in Fig. 6, and then using the digital detectors shown in Fig. 7. These circuits are capable of making amplitude and phase measurements at a rate of about 50,000 points per second, with an accuracy of a few tenths of a degree in phase, and about a tenth of a percent in amplitude.

On this basis, we expect to measure heights with sensitivities on the order of a thousandth of a wavelength or better, i.e., a few Angstroms. Early results taken with this type of system by R. L. Jungerman in our laboratory are shown in Figs. 8a and b. For identical 900 Å thick aluminum films on glass and on aluminum, the phase changes are the same. The amplitude changes as the beam is scanned over the edge of the film show the reflection coefficient change between the films and the substrates. When the spot is partly on the film and partly on the substrate, the two parts do not add in phase at the detector. This results in amplitude dips at the edges of the film.

The device has the same illumination pattern as more standard scanning optical microscopes, but because the detector has the same spatial
selectivity as the illuminator, we get an effective point spread function \( V(r) \), which is the illumination function squared; thus

\[
cV(r) = \left| \frac{2J_1(kr \sin \theta)^2}{kr \sin \theta} \right|
\]

(6)

where \( \sin \theta \) is the numerical aperture. This function has much lower sidelobe levels, resulting in very little ringing when imaging steps. The amplitude response is exactly the intensity response of a standard microscope. The 3 dB definition of this microscope, without post-processing, is approximately 1.4 times better than a standard microscope's.

As the point spread function is squared, the spatial frequency bandwidth is twice that of a standard type 1 microscope. The transfer functions fo the type 1 and type 2 microscopes are shown in Fig. 9, plotted in normalized spatial frequency. These correspond to the spatial frequency transforms of the linespread function of the microscope. Since we have both amplitude and phase information available, and twice the bandwidth, we can use linear deconvolution to improve the resolution to twice that of a type 1 microscope at the expense of introducing sidelobes.
This is done by digital filtering in a personal computer (it typically takes 20 seconds for 1024 points), so we can change the filter very easily. The curve marked $F(s)$ in Fig. 9 is the approximate transfer function we have obtained after processing. The roll-off at the high end reduces the noise sensitivity of the filter. By choosing various filters, one can trade off lateral resolution against ringing or sidelobe response.

Figure 10 shows this trade-off clearly [3]. The original data (diamonds) are plotted with the theoretical curve (solid) and two deconvolved experimental curves. The raw data show a 10-90% rise interval of 0.23 μm. Deconvolution I used a relatively gentle filter to achieve 0.13 μm edge response (10-90%) with little added ringing. Deconvolution II used a different filter to achieve 0.10 μm edge response (10-90%) but with extra ringing added.

The results shown in Fig. 11 are for a gold film on silicon, 1000 Å thick and 0.61 μm wide, taken using laser illumination of 0.51 μm wavelength. By carrying out the same inverse filtering process, we can sharpen up the phase response of the film a great deal and get a good measure of the width and thickness of the film. The measured width is 0.64 μm (our scanning steps are .04 μm apart), which agrees very well with the high-voltage SEM value of 0.61 μm. The very sharp edges in the phase curve permit unambiguous measurements of width.

RELATED TECHNIQUES

We have described here two basic techniques for measuring height and width. We have shown that deconvolution techniques can improve the resolution of the microscope, and by vibrating the sample, we
Fig. 8. Early results (very low numerical aperture). (a) Step response 900 Å aluminum on glass. (b) Step response 900 Å aluminum on aluminum.
Fig. 9. Comparison of the theoretical transfer function of a type 1 microscope with that of the electronically-scanned type 2, before, after, and post-processing.

Fig. 10. Data from a single scan of a 900 Å step of aluminum on aluminum taken with the electronically-scanned microscope. The experimental results are compared with theory, along with improved scan data made by using two different inverse filters.

can obtain a very sensitive measure of the position of the focal point. We have recently begun to work with other techniques for moving the focal position back and forth. One is a modified Zernike phase contrast microscope, illustrated in Fig. 12. An rf voltage of frequency $\Omega$ is applied to a transparent center electrode deposited on an electro-optic cell of PLZT. The electro-optic cell is placed in the back focal plane of the lens. It may be shown that an ac output at the frequency $\Omega$ is obtained from the detector as the phase through the central region of the beam is varied. However, when the beam is focused on the surface of a reflecting object, the rf signal amplitude passes through zero. This zero occurs because small phase variations do not affect the amplitude of the $V(z)$ curve when it is at its maximum. When the beam is defocused,
there is a static phase shift between the rays at the center of the beam and those at the outside, resulting in an ac output. Hence, it is very easy to determine when the beam is defocused. Furthermore, the phase of the rf output from the detector reverses in sign as the focus moves past the reflector. A simple result of this kind is shown in fig. 13. A similar system, which operates with a reflecting mirror in the optical path, employs a flexible spherical mirror made of a piezoelectric cantilever material. We prefer the transmission system because it is simpler.
CONCLUSION

We conclude that it is possible to modify the standard microscope, turn it into a scanning system, and obtain better resolution and more quantitative information than has been available with optical microscopy techniques in the past.
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REFERENCES