Measurement of the thickness profile of a transparent thin film deposited upon a pattern structure with an acousto-optic tunable filter

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A simultaneous volumetric thickness-profile measurement method based on an acousto-optic tunable filter for transparent film deposited upon pattern structures is described. The nondestructive thickness profilometer prevents the destruction of samples such as one encounters in using a scanning-electron microscope and provides good accuracy. The information on the volumetric thickness profile is obtained through least-squares fitting with a phase model, \( \phi_{\text{model}}(k) = 2\pi h + \phi(k, d) + \text{offset} \), which has three unknowns: surface profile \( h \), thickness \( d \), and an indeterminate initial phase offset. Accurate phase information in the spectral domain can be obtained by introduction of the concept of spectral carrier frequency. Experimental results for a metal patterned sample show that the volumetric thickness profile can be determined within an error range of \( \pm 10 \) nm. © 2002 Optical Society of America

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It has been difficult to measure film thickness profiles accurately by nondestructive methods such as the optical method whereby thin films are deposited upon patterned opaque structures. Instead, the available and common instruments used for such measurements, such as scanning electron microscopes (SEMs) and mechanical stylus profilometers, have been destructive. Although such destructive approaches can produce accurate measurements, they are undesirable because they destroy samples. A highly accurate nondestructive optical thin-film thickness profile measurement method described in this Letter overcomes such shortcomings.

In white-light scanning interferometry the reference mirror is scanned until a constructive interference signal is achieved. Because of the short white-light coherence length of 3–4 \( \mu \)m, interference is obtained only in the vicinity of zero path difference.\(^1\) Alternatively, spectral scanning can be used to determine the absolute path difference between the two arms, i.e., the reference mirror plane and the measured target.\(^2\)–\(^4\) However, when a thin film is deposited upon a patterned opaque structure it induces a multireflected wave that affects the phase of the interferogram. The effect of phase change must be taken into account to produce accurate surface profile information.\(^5\) In particular, when the deposited film is thinner than the white-light coherence length, the conventional approach that uses a white-light scanning interferometer can no longer be applied because of the overlap of the white-light interference signal. Recently an attempt was made to use a white-light scanning interferometer to measure the thickness profile of a thin film deposited upon a patterned sample.\(^6\) However, there is still room for improvement in stability and accuracy.

Here we suggest using a simultaneous volumetric thickness profile measurement method, especially for films that are thinner than the white-light coherence length and are deposited upon pattern structures, that is based on acousto-optic tunable filter (AOTF) spectral scanning interferometry. Although the AOTF has the shortcoming of a slight image shift that depends on the scanning wavelength, the AOTF-based system has the benefit of stable and reproducible two-dimensional real-time spectral imaging capability because it has no moving parts.

Figure 1 shows the proposed system, which consists of an AOTF for spectral scanning ranging from 400 to 650 nm, which inversely corresponds to a rf signal from 180 to 120 MHz, a two-dimensional CCD sensor, and a Michelson interferometer with an objective lens that has a numerical aperture of 0.13 at 5\( \times \) magnification. The AOTF has a resolution of 1–5 nm, depending on the diffracted wavelengths, and a tuning speed of 20 \( \mu \)s. The thickness and the surface profile, both functions of spatial measurement points \( x \) and \( y \), are hereafter labeled \( d(x, y) \) and \( h(x, y) \), respectively. \( h(x, y) \) indicates the directional distance from an imaginary reference plane to the upper surface of the thin film, as in Fig. 1. The following equation describes how the interference intensity is affected by the existence of a thin film on a measurement sample:
where \( \Gamma \) represents the complex refractive index of a de-
posited thin film. Total phase function \( \phi(k) \) from measured intensity information \( I(k) \) can be obtained without ambiguity through the following procedures, provided that the greatest gradient of phase \( \phi(k) \) is less than spectral carrier frequency \( \nu_0 \) and that \( \nu_0 \) is less than half of spectral sampling frequency \( \nu_{i+1} - \nu_i \). This method is based on the spatial carrier frequency concept used in spatial domain interference analysis. Simple conversion of the amplitude terms \( a(k) \) and \( b(k) \) in Eq. (1) to \( c(k) \) and \( d(k) \), respectively, and induction of an addi-
tional spectral carrier frequency \( h_0 \) to the slowly varying function \( \phi(k) \) give the following equation:

\[
I(k) = a(k) + b(k)\exp\{\phi(k) + 2h_0k\}
\]

\[
= a(k) + c(k)\exp(2h_0j) + d(k)\exp(-2h_0j),
\]

where

\[
c(k) = \frac{1}{2} b(k)\exp\{\phi(k)j\}.
\] (5)

Spectral carrier frequency \( h_0 \) can be induced by appro-
priate positioning of the reference mirror away from the sample to generate a high-frequency intensity distribution.

First, the intensity function is transformed by a fast
Fourier transform (FFT), which leads to

\[
I(f_k) = A(f_k) + C(f_k - h_0) + C^*(f_k + h_0),
\] (6)

where \( A(f_k) \) and \( f_k \) indicate the dc term and the spectral frequency, respectively, and \( C(f_k) \) is the Fourier-transformed function of \( c(k) \). Spectral car-
rier frequency \( h_0 \) is induced such that \( C(f_k - h_0) \) is entirely separated from \( A(f_k) \). To obtain phase function \( \phi(k) \) requires that \( C(f_k - h_0) \) be filtered with a rectangular function and be centered as close as possible to \( C(f_k) \) to produce more-accurate phase fitting results.

Second, this approximately centered \( C(f_k - h_r) \) is
inversely Fourier transformed to \( c_r(k) = \frac{1}{2} b(k)\exp\{\phi(k) + 2h_r + \text{offset}\} \). Here, subscript \( r \) means remainder. Finally, the phase term \( c_r(k) \) must be unwrapped to produce a continuous phase function

\[
\phi_{\text{measured}}(k) = 2k(h + h_r) + \psi(k, d) + \text{offset}.
\]

Although the generation of an uncertain \( h_r \) is inevitable, \( h_r \) does not affect the calculation of \( h(x, y) \) because it is a constant for all \((x, y). \) The FFT–inverse FFT
signal processing procedure above inherently induces the offset term in the spectral phase.

We used the phase model \( \phi_{\text{model}}(k, h, d, \text{offset}) = 2kh + \psi(k, d) + \text{offset} \) to obtain three unknowns, i.e.,
film thickness \( d \), surface profile \( h \), and an indeterminate initial phase offset. This minimizes the following error function:

\[
\eta(h, d, \text{offset}) = \sum_{i=1}^{n} \left[ \phi_{\text{model}}(k_i, h, d, \text{offset}) \right] - \left[ \phi_{\text{measured}}(k_i) \right]^2.
\] (7)

![Fig. 1. Schematic diagram of the proposed AOTF-based volumetric thin-film thickness profile measurement system, showing \( d(x, y) \) and \( h(x, y) \). SMF, single-mode fiber.](image1)

![Fig. 2. Photo of the aluminum patterned sample and a view along points A and A with a SEM.](image2)
To apply spectral carrier frequency $h_0$ we positioned the measured sample surface such that the distance between the two arms was $\sim 1.5 \mu m$. With this initial setup, spectral scanning with rf signal scanning steps of 0.277 MHz from 120 to 180 MHz was carried out to produce spectral intensity $I(k)$. Then a spectral frequency domain signal processing algorithm, FFT–filtering and centering–inverse FFT, was performed for all measurement points. The filtering in the spectral frequency domain involved a rectangular function; the filtered signal was then centered approximately such that $h_0$ became near zero. Figure 3 shows the measured phase distribution $\phi_{\text{measured}}(k)$ and an estimated phase $\phi_{\text{model}}(k, h, d, \text{offset})$ for a specific point. Finally, the result of a volumetric thickness profile measurement of the metal patterned SiO$_2$ thin-film sample was obtained as in Fig. 4.

The measurement accuracy of the proposed system was examined through comparisons with stylus profilometer measurements of the surface profile, ellipsometer measurements of the film thickness, and SEM measurements of both. Experimental results showed that the thin film's thickness and surface profile measurement error range was $\sim 10$ nm. Note that, because of practical limitations, an exact point-by-point comparison was not made. Instead, average film thickness and surface profile height difference were compared, as listed in Table 1. White noise, caused mainly by the inherent dark signal of the CCD and the light source, was eliminated by averaging. Some possible systematic error sources are an imperfect calibration of the AOTF image shift owing to the presence of discrete CCD pixels, and a deviation from a normal incident wave.

In conclusion, an AOTF-based method for measuring the volumetric thickness profile of a transparent thin film deposited upon a pattern structure has been proposed. An analysis that used the spectral carrier frequency concept was conducted in the spectral frequency domain to produce the phase information required for finding a thickness profile by use of phase model fitting. We expect that the current approach should be easily applicable for volumetric thickness profiling of various transparent materials on metal patterned structures, such as dielectric materials in semiconductor fields.

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### References

8. The Levenberg–Marquardt algorithm is available as the lsqnonlin function by a commercial S/W MATLAB.

![Fig. 3. Measured phase function $\phi_{\text{measured}}(k)$ and result of phase model fitting.](image)

![Fig. 4. Results of volumetric thickness profile measurement of the aluminum pattern sample.](image)

### Table 1. Results of Thin-Film Thickness Profile Measurements

<table>
<thead>
<tr>
<th>Property Measured</th>
<th>Results (nm) from Conventional Measurement Method</th>
<th>Results (nm) from the Proposed Measurement Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness $(d_1, d_2)$</td>
<td>2250 and 2850 from a SEM; 2245 and 2862 (ellipsometer)</td>
<td>2235 and 2858</td>
</tr>
<tr>
<td>Profile difference $(h_1 - h_2)$</td>
<td>0 from a SEM; 8 nm from a stylus profilometer</td>
<td>14</td>
</tr>
</tbody>
</table>

Also, as phase change $\psi(k, d)$ is highly nonlinear, the Levenberg–Marquardt algorithm was used in this investigation for its fast convergence capability.