Linnik microscope imaging of integrated circuit structures

D. M. Gale, M. I. Pether, and J. C. Dainty

Experimental one-dimensional intensity and phase images of thick (>200 nm) oxide lines on silicon are presented together with profiles predicted from the waveguide model. Experimental results were obtained with a purpose-built Linnik interference microscope that makes use of phase-shifting interferometry for interferogram analysis. Profiles have been obtained for both TE and TM polarizations for a wide range of focal positions and in both bright-field and confocal modes of microscope operation. The results show extremely good agreement despite several simplifying assumptions incorporated into the theoretical model to reduce computing times.

Key words: Interference microscopy, waveguide imaging theory, integrated circuit metrology, profilometry. © 1996 Optical Society of America

1. Introduction

The optical measurement of submicrometer features has, in the past, been extremely difficult because of the lack of a suitable imaging theory for thick structures (>200 nm) and the absence of instruments capable of gathering the appropriate data. In particular this has presented problems for measurement and inspection in the semiconductor industry, in which one commonly encounters features whose height and width are in the 0.1–1-µm range.

Conventional scalar imaging theory has been used successfully to provide measurements of linewidths on photomasks and thin wafers [±200 nm]. An important part of this process is the use of a primary linewidth-measurement system to allow measurements to be made on real samples under well-characterized conditions consistent with those implied by the theory. Such systems have been developed at both the National Institute of Science and Technology in the U.S.A.1,2 and at the National Physical Laboratory in the U.K.3 With sufficient agreement between theory and experimental results, these primary measurement systems can be used to calibrate linewidth standards, which in turn calibrate commercial measuring instruments throughout the semiconductor industry.

For thicker objects it becomes increasingly difficult to match experimental image profiles with those produced by scalar theory; for objects >200 nm, a new theoretical approach is required. To this end, the rigorous waveguide model has been discussed in the literature and has shown promising initial results. To investigate further the validity of the waveguide model, a primary measurement system has been constructed at Imperial College. The system provides phase as well as intensity images, as we are dealing with three-dimensional objects for which the phase image may aid interpretation. In view of the considerable present interest in confocal microscopy it was decided to incorporate both confocal and nonconfocal scanned imaging modes. Principal design considerations needed to secure an appropriate primary measuring system were

- Operation in reflection for study of opaque objects.
- Polarization state variable between transverse electric (TE) and transverse magnetic (TM).
- Operation at high-imaging N.A. (numerical aperture) for optimum resolution.
- Monochromatic illumination for accurate phase information and high contrast.
- Köhler system for optimum bright-field illumination.
- Variable illuminating N.A. for control of coherence.

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Lasersourceforhigh-intensitymonochromatic
images.

- An effective scanning slit at the sample, which
  is smaller than the impulse response width of the
  system.

- Near-diffraction-limitedoptics.

- Axialimagingtoeliminateway-axisaberrations.

- Automatizedcomputerizeddatacollectionand
  processing.

We describe in detail the primary measurement
system and the phase and intensity images obtained
for a thick silicon oxide on silicon wafer sample. These results are compared with theoretical predic-
tions of the waveguide model.

2. Waveguide Imaging Model for Thick Objects
An imaging model based on a waveguide description
of thick objects was described by Nyyssonen4 for
vertically edged one-dimensional (1-D) structures
and later applied to nonvertical edges by Nyyssonen
and Kirk.5 Both models were restricted to TE polar-
ization, that is, with an incident electric field oscillat-
ing parallel to the wafer structure. More recently
Yuan and Strojwas6 have extended the model to
include TM or any arbitrary state of polarization and
have reported good agreement with measured differ-
ential Nomarski images of shallow objects (150 nm).

In summary, the two-dimensional (2-D) waveguide
model assumes that a line object of width \( W \) and
depth \( d \) forms part of a periodic grating, as shown in
Fig. 1. For the TE case, an incident electric field
polarized in the \( y \) direction oscillating parallel to the
grating, as shown in the figure, gives rise to a
scattered field that is also polarized in the \( y \) direction.

For TM illumination, the incident and the scattered
electric fields are polarized in the plane of incidence,
having components in the \( x \) and the \( z \) directions.

TE and TM polarizations are treated quite indepen-
dently; the total transmitted or reflected field for any
situation is given by a linear combination of the TE
and the TM solutions.

The plane wave illuminating the object of Fig. 1
gives rise to a reflected field propagating back into
free space (region 1) and a transmitted field propagat-
ing through the grating (region 2) into the area
occupied by the substrate (region 3). In each of the
three regions the electromagnetic field is expanded
in a series of orthogonal solutions or eigenfunctions,
each satisfying the TE or the TM wave equation
within that region. In addition, the eigenfunctions
of region 2 also satisfy the boundary conditions
defined by the periodic form of the object. We find
the expansion coefficients for each region by invok-
ing the boundary conditions at the interface between
regions 1 and 2 and between regions 2 and 3, namely,
that the tangential components of the electric and
the magnetic fields are continuous across any discon-
 tinuity in relative permittivity. The resulting equa-
tions may then be solved numerically with matrix-
inversion techniques. The complex amplitude of
the scattered field in region 1 is used in the conven-
tional scalar imaging formulation to calculate the
final image.

Most real objects have dimensions that vary with \( z \)
bars with sloping or rounded edges for example].

Such objects are modeled by slicing region 2 into
several layers5 whose values of \( d \), \( W \), and \( \Lambda \) are
constant over a finite interval in \( z \). The extent of
each slice will depend on the slope and the width of
the object at any given \( z \) position. The waveguide
modes are solved for each layer and then equated
with adjacent layers, so that the fields at \( z = 0 \) and
\( z = d \) may be linked by a series of matrix operations.

3. Linnik Interference Microscope
A. Optical Layout

The primary measurement system constructed to
provide experimental images is a computer-con-
trolled phase-stepping Linnik interference micro-
scope, shown schematically in Fig. 2. Bright-field
illumination is provided by either a 100-W tungsten–

halogen lamp or a 3-mW helium–neon laser. For the latter, a fast-spinning ground-glass diffuser averages out speckle noise. Lenses L1–L3 ensure Köhler illumination so that the variable aperture stop is imaged at the back focal plane of the objectives. To facilitate confocal operation, a second helium–neon laser can be switched into the system by a dichroic mirror. The dichroic mirror allows the confocal spot and the full field to be viewed simultaneously in the eyepiece during setup. A spatial filter emulates a point source, the light from which is collimated by lens L3. Because the objective lenses are infinity corrected, the point source is focused at the sample.

The incident illumination is divided at a glass beam-splitting cube into reference and sample arms. A three-position stop allows either arm to be viewed independently or with both arms together for interference. Matched objective lenses are located in each arm, mounted on dovetail slides to permit rapid change of magnification with accurate realignment. For the research presented here, 0.9 N.A. 100× objectives were used throughout. These lenses were tested on a Twyman–Green interferometer and found to have less than $\lambda/8$ aberration across the pupil. The reference arm terminates at a $\lambda/20$ mirror with strips of differing reflectance, one of which is selected to match the object reflectivity and to maintain good fringe contrast. Tilted parallel glass plates in each arm may be rotated manually to adjust the interference fringe spacing and direction. Coarse or fine pairs of opposing glass wedges facilitate manually controlled or computer-controlled path-length adjustment, respectively.

Beyond the interferometer, a tube lens brings the collimated imaging rays to an intermediate focus, which may be relayed to one of several bright-field detectors by a projection eyepiece or directed onto an aperture in front of a photomultiplier tube for scanning modes of operation. A rotatable polarizer and analyzer are positioned in front of and behind the interferometer section, respectively. They are used in conjunction with a $\lambda/2$ wave plate to select either TE or TM polarization with respect to the sample.

B. Mechanical Construction

The majority of the system is secured to a horizontal aluminum plate, forming an optical table. This is firmly secured to the top of a large box angle plate measuring approximately 23 cm $\times$ 46 cm $\times$ 30 cm deep [Fig. 3]. Attached to one side is a second L-shaped plate (shown cut away in the figure) from which the sample stage is suspended. Both of these sections are made from cast iron and form a massive frame around which the rest of the microscope hangs. The sources are situated to one side of the box angle plate and are shielded from it by a reflective aluminium baffle (not shown). The confocal laser source is secured vertically, and the beam is turned into the system before the spatial filter assembly. Bright-field illumination is directed onto the optical table by way of a periscope that incorporates the filter holder, aperture stop, and source-selecting mirror. Both bright-field sources are attached to the periscope column and do not contact any other part of the instrument.

All the reference and sample arm components lie on the optical table, with the exception of the sample objective, which is located vertically above the stage. The sample arm is reflected down through a hole in the overhanging L plate by a 90° turning prism. An identical prism in the reference arm folds the optical path while keeping it on the table. The bright-field detector arm is turned upward so that the viewing eyepiece can be located at a convenient working height.

The large box angle plate and periscope column are firmly bolted to a 3 ft $\times$ 3 ft (91.44 cm $\times$ 91.44 cm) lapped surface table of cast iron with 3-in. (7.62-cm) ribbing on the underside. The table sits on inflated tire inner tubes sandwiched between sheets of blockboard. This gives a reasonable degree of vibration isolation from the building in which the instrument is housed. The optical table is enclosed beneath an aluminum cover that contains various access hatches. The vertical detector head and illumination periscope are enclosed in tubing throughout. The instrument is thus shielded from external light, dust, and air turbulence.

C. Sample-Stage Assembly

The hanging sample-stage assembly replaces an earlier arrangement in which individual positioning stages were stacked one above the other on the surface table. Such an arrangement was found to introduce unacceptable path-length drifts into the sample arm. The complete stage assembly is illustrated in Fig. 4, as viewed from the front of the microscope. Three steel pillars hold a triangular support table at its apices approximately 150 mm
below the angle plate. The pillars, shown cutaway for clarity in the figure, can be extended with matching spacers to accommodate deeper samples. Three micrometers push against a second triangular plate to provide a tilt stage for leveling and coarse focusing of the sample. Tension springs between the plates complete the kinematic arrangement.

A 1-D object-scanning stage uses strip hinges arranged as parallelograms to provide accurate, frictionless movement of the sample (perpendicular to the plane of the figure) while minimizing movement in the z direction. The stage is piezoelectrically driven under computer control and incorporates position feedback to minimize hysteresis. The sample is positioned on a circular vacuum chuck secured to the stage. A series of concentric grooves may be evacuated to pull the sample down, making the task of locating features easier (this is done by moving the sample by hand) and ensuring interferometric stability. The stage assembly is enclosed by a transparent Perspex cover between the surface table and the overhanging angle plate.

D. Computer Control and Operation
Phase-shifting interferometry \[\text{PSI}\] permits rapid retrieval of phase and intensity images in the microscope. We use Carré’s method of recording four interferograms with a phase step of approximately 90° between each image.11 A piezoelectrically driven variable-thickness glass block in the sample arm introduces the phase steps, and interferograms are recorded with fluffed fringes. The glass block consists of two opposing wedges with a wedge angle of 0.5°. Fine control of focus is effected by moving the sample objective along the optic axis. A piezoelectric translator mounted in a strip-hinge assembly drives the objective and ensures smooth repeatable focusing.

A personal computer (PC) controls the piezoelectric devices in the microscope and collects and processes the 1-D intensity data. The control and processing system is shown in Fig. 5. Bright-field images are recorded by a 384 × 491 pixel CCD camera and stored on an 8-bit video digitizer board. For scanned images, a photomultiplier tube is read out by an analog–digital converter. The object-sampling interval is determined by the ratio of image-sampling rate to stage scan speed; sampling intervals of between 12 and 50 pixels per micrometer are available, with corresponding scan lengths of between 40 and 10 µm. Each scanned profile consists of 500 12-bit intensity values.

Data input and control output are handled by commercial software subroutines. Custom assembly language subroutines handle all data processing operations, including phase calculation, phase unwrapping, and display. An 800-line BASIC program manages the subroutines and provides user interface (for setting the sampling interval, scan averaging parameters, etc.). 1-D phase and intensity profiles derived from 100 averaged video lines can be acquired, processed, and displayed in 6 s. Photomultiplier images are slower because of a scan rate of ~1 Hz (a value chosen arbitrarily). The acquisition, processing, and display time for intensity and phase profiles derived from nine averaged scans per phase step is ~70 s.

4. Microscope Performance Characterization
Microscope performance is summarized in Table 1. Individual performance characteristics are considered below.

A. Sampling Interval and Focus
Lateral magnification was calibrated by the measurement of distances between similar image features on a photomask linewidth standard. In the scanning mode, measurements were taken at different regions of the scan to check the linearity of the driving piezo under load. With position feedback, the stage showed a linear response to within the accuracy of measurement. The fine-focus mechanism was calibrated in situ against a portable length-measuring interferometer. The mechanism was found to show
Table 1. Microscope Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>632.8-nm monochromatic</td>
</tr>
<tr>
<td>Objective lenses</td>
<td>100%, 0.9 N.A. achromats</td>
</tr>
<tr>
<td>Coherence</td>
<td>Continuously variable: 0.1 &lt; S &lt; 1.0</td>
</tr>
<tr>
<td>Object sampling</td>
<td>Mode</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bright-field</td>
</tr>
<tr>
<td></td>
<td>Scan low res.</td>
</tr>
<tr>
<td></td>
<td>Scan high res.</td>
</tr>
<tr>
<td>Fine focus</td>
<td>Range 10.7 µm in steps of 10 nm</td>
</tr>
<tr>
<td>Optical resolution</td>
<td>0.45 µm (type 1a) scanning</td>
</tr>
<tr>
<td>Phase profiling</td>
<td>Carré PSI technique: four steps of 90°</td>
</tr>
<tr>
<td>Phase resolution</td>
<td>1°, limited by PSI algorithm lookup table</td>
</tr>
<tr>
<td>Accuracy</td>
<td>±0.47°/λ/760 (scanning mode)</td>
</tr>
<tr>
<td>Repeatability</td>
<td>±0.48°/λ/750 (scanning mode)</td>
</tr>
<tr>
<td>Processing speed</td>
<td>~6 s (bright-field mode)</td>
</tr>
<tr>
<td></td>
<td>~115 s (scanning mode)</td>
</tr>
</tbody>
</table>

*See Section 4 for details.
1Averaging 16 stage scans per phase step.
2Averaging 100 video lines per phase step.

a nonlinearity of ~1% that was due to piezohysteresis.

B. Optical Resolution

A chromium line object of width below the resolution limit of the microscope was used to determine the line-spread function for each scanning mode of operation. Following the definitions used in Ref. 7, these are (i) bright-field scanning type 1a (an extended source provides Köhler illumination at the object, which is scanned beneath a point detector), (ii) scanning probe type 1b (a point source illuminates the object, which is scanned beneath a large-area detector), and (iii) confocal scanning type 2 (a point source illuminates the object, which is scanned beneath a point detector).

The measured responses are shown in Fig. 6 after the removal of the dc background and centering–normalizing by the fitting of Gaussians to each response. The dc background was produced by the glass substrate supporting the line object and obscures any detail beyond the central maximum. The dc asymmetry in the images results from asymmetry in the object, whereas the small peak occurring at ~0.6 µm indicates on-axis aberrations, which most likely arise from assembly errors in the objective. This is verified by conducting similar scans with the object reversed. The confocal half-width shows an improvement of ~10% over that of type 1b. Although in theory type 1a and type 1b systems are equivalent, their responses differ because of the finite source and detector apertures used. Measurements of the full width at half-maximum were used to calculate the experimental resolution of the microscope (see Table 1), assuming the conventional form of the line-spread function $I(x) = \sin(x)/x^2$ in each case.

C. Numerical-Aperture Factors

It is well known that the measurement of phase in a high-N.A. interference microscope is subject to a correction factor because of the difference between effective and nominal N.A.’s. The bright-field illuminating aperture in our microscope was adjustable by means of the aperture-stop iris diaphragm (Fig. 2); hence the variable effective N.A. required calibrating at each stop setting. Phase-correction factors were calculated at each stop position by the measurement of the height of a known step height standard. The values obtained were too small, being less than unity for low apertures (N.A. factors are always >1 in reflection microscopes). The coherence parameter $S$ at each setting was calculated from the ratio of source diameter in the objective back focal plane to objective pupil diameter. Values of $S$ were then used to calculate the effective N.A. according to

$$S = \frac{\text{N.A.\,effective}}{\text{N.A.\,imaging}},$$

where N.A.\,imaging is the nominal N.A. of the objective. Plotting N.A. factor versus effective N.A. for each stop setting and comparing the results with theory at low apertures (see Ref. 12) enabled corrections to the N.A. factors to be made. Values of the coherence parameter were used in the waveguide-modeling process.

D. Accuracy of Phase Measurements

Careful consideration was given to the elimination or the reduction of sources of error in the calculated phase returned by the microscope. Simulations of phase-shifting errors showed a mean error in the calculated phase of ±0.32° resulting from ±1°
accuracy in the setting of the phase steps. The
system wave front was investigated by profiling a
\(\lambda/20\) aluminized flat placed on the sample stage.
The most notable feature of the system phase profile
was a repeatable position-dependent error of \(\pm 2.5^\circ\)
introduced by the scanning stage over the central 10
\(\mu m\) of displacement. This scan length corresponds
to the smallest sampling interval, used for the
results presented here, and indicates a stage displace-
ment of \(\pm 2.2\ nm\) parallel to the optic axis. The
system profile was stored in a lookup table and
subtracted from measured profiles. The effect of
signal noise on the calculated phase was simulated,
and results were obtained for typical measured
values of rms intensity. The error was reduced to
\(\pm 0.15^\circ\) by the averaging of 16 scans at each phase
step. Simulations of quantization noise that was
due to analog–digital conversion showed errors of
\(\pm 0.14^\circ\) for the CCD detector and less than \(\pm 0.01^\circ\) for
the photomultiplier. The use of a lookup table in
the PSI algorithm to convert arctangent values led to
a more serious phase-quantization error of \(\pm 0.29^\circ\).
Random errors introduced by vibration, air tur-
bulence, and thermal drift were minimized by the
recording of data during quiet periods on weekends
or overnight. In summary, it was found that, when
16 scanned intensity profiles were averaged per
phase step, the total error in the calculated phase
could be kept to within \(\pm 0.47^\circ\).

E. Repeatability of Phase Measurements
Measurement repeatability may be investigated by
taking many phase measurements for a given sample
and determining the standard deviation at each
pixel. Approximately 70 phase profiles were re-
corded with the CCD camera in \(~11\ min, during
which time the measured phase drift that due to
temperature variations was less than 1\(^\circ\). Bright-
field repeatability (averaging 100 video lines per
phase step) was \(\pm 0.52^\circ\). For scanning operation the
longer data collection time leads to unacceptably
large phase drifts. Assuming that a Gaussian error
source determines repeatability, we note that the
standard deviation of the measured phase at a single
pixel, taken over many measurements, is equal to
the standard deviation of the phase difference be-
tween two data sets, taken over all pixels.\(^5\) Thus
the measurement repeatability for the scanning
mode is obtained by calculating the rms phase
difference between two consecutive phase profiles.
The mean of 10 such measurements gave a repe-
atability for the scanning mode (each phase step aver-
aging 16 scans) of \(\pm 0.48^\circ\).

5. Profiles of a Thick Wafer Object
A. Wafer Object
The test sample is a silicon wafer overcoated with an
oxide layer of 666-nm nominal thickness. Sets of
parallel grooves etched into the oxide layer reveal
the silicon substrate beneath. The grooves form
test sites of approximately 250 \(\mu m\) \(\times\) 250 \(\mu m\) (Fig. 7),
repeated across the surface of the wafer. The widths
of the grooves vary nominally from 0.4 to 2.5 \(\mu m\) in
0.1-\(\mu m\) intervals, although in practice grooves below
0.7 \(\mu m\) are of poor quality or nonexistent. Optical
measurements were made across the center of the
widest set of grooves in the extreme top right-hand
corner of a single test site. The quantities under
investigation are the phase of the interferogram in
the Linnik microscope and the square of the product
of the moduli of the complex amplitudes of the two
beams, as returned by the PSI algorithm. These
quantities are referred to below and in the figures as
phase and intensity.

B. Experimental Profiles
Experimental profiles were recorded by using two
modes of microscope operation, both employing ob-
ject scanning. For bright-field (type 1[a]) scanning,
Köhler illumination was effected at the sample, and

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a slit of width 6.7 µm was placed in front of the photomultiplier detector. The slit was oriented parallel to the wafer grooves and gave a 67-nm-wide footprint at the object. The length of the slit was set by the field stop at ~5 µm in the object plane. The bright-field coherence parameter $S$ was 0.3, giving an effective N.A. of 0.27 (±2%). The N.A. correction factor at this stop setting was 1.02. For confocal scanning, an 8.5-µm-diameter source pinhole was imaged at the sample and a 10-µm-diameter detector pinhole was placed in front of the photomultiplier; projected footprints at the object plane were 0.13 and 0.1 µm, respectively. Both scanning modes used laser light sources at $\lambda = 632.8$ nm.

The highest sampling interval of $19.5 \pm 0.3$ nm was used for both operating modes, giving a scan length of 9.75 µm with 500 data points. Sixteen intensity scans were averaged for each phase step in the PSI routine; typical PSI output is shown in Fig. 8. Sets of phase and intensity profiles were calculated for a 1.5-µm range of focal positions, taken at $0.05 \pm 0.01$-µm intervals of defocus. Separate sets were recorded for TE and TM polarization in each operating mode.

Profile sets were transferred from PC hard disk to a Sun workstation for processing. It can be seen from Fig. 8 that each profile includes just under two complete periods of the bar/groove structure. Preparation of these raw profiles was as follows:

1. Removal of a small lateral displacement of ~5 nm between consecutive profiles (presumably caused by residual piezocreep).
2. Equal shift of all profiles in $x$ so that the origin lies at the center of a chosen bar.
3. Windowing of profiles to display a single sample period; $-2.5 \mu m \leq x \leq +2.5 \mu m$.
4. Centroiding of each phase profile to give a mean phase of 0° across the window.

C. Theoretical Profiles

Object parameters available for use in the waveguide model are shown in Fig. 9. Electron micrographs of the wafer edge cleaved along the widest grooves suggest slopes of ~70°, resulting in a bar-to-

![Fig. 9. Physical parameters and refractive indices available for modeling the wafer sample.](image)

![Fig. 10. Bright-field intensity and phase profiles of a centered 1-D bar object (silicon oxide on silicon) with vertical edges. Nominal bar height: (a), (b) 151 nm; (c), (d) 640 nm. Comparison of scalar and waveguide images: ——scalar, ----- -waveguide TE, ––––waveguide TM. All profiles are focused at the top of the bar.](image)
Fig. 11(a). Bright-field intensity and phase profiles of a centered 1-D bar object (silicon oxide on silicon). Measured bar height 640 nm, ——experimental profile, ———theoretical profile. Profiles are at four focal positions [a]–[d] measured from the top of the bar; TE polarization throughout. This sequence is continued in Fig. 11(c).
Fig. 11(b). Confocal intensity and phase profiles of a centered 1-D bar object (silicon oxide on silicon): measured bar height 640 nm, —— experimental profile, ----- theoretical profile. Profiles are at four focal positions (a–d) measured from the top of the bar; TE polarization throughout. This sequence is continued in Fig. 11(d).
Fig. 11(c). Bright-field intensity and phase profiles of a centered 1-D bar object (silicon oxide on silicon): measured bar height 640 nm, —— experimental profile, ----- theoretical profile. Profiles are at four focal positions (e)–(h) measured from the top of the bar; TE polarization throughout. This sequence is continued in Fig. 11(e).
Fig. 11(d). Confocal intensity and phase profiles of a centered 1-D bar object (silicon oxide on silicon): measured bar height 640 nm, experimental profile, theoretical profile. Profiles are at four focal positions (e)–(h) measured from the top of the bar; TE polarization throughout. This sequence is continued in Fig. 11(f).
Fig. 11(e). Bright-field intensity and phase profiles of a centered 1-D bar object (silicon oxide on silicon): measured bar height 640 nm, —— experimental profile, ----- theoretical profile. Profiles are at four focal positions (i)–(l) measured from the top of the bar; TE polarization throughout.
Fig. 11(f). Confocal intensity and phase profiles of a centered 1-D bar object (silicon oxide on silicon): measured bar height 640 nm, —— experimental profile, ----- theoretical profile. Profiles are at four focal positions (i)–(l) measured from the top of the bar; TE polarization throughout.
space ratio of approximately 1:1.3 at midheight. Measurements of the groove height and period were made with a Talystep stylus profilometer and the Linnik microscope, respectively. Repeated Talystep measurements gave a step height of 640 ± 4 nm. Microscope parameters used for modeling included illumination at 632.8 nm, an N.A. correction factor of 1.02, and an imaging N.A. of 0.9. These values were also used for the theoretical simulations of Figs. 10, 12, and 13 below. Sets of theoretical profiles were computed at 0.1-μm intervals of defocus (twice the experimental interval) with programs running on a Sun workstation. Because of constraints of program computing time, the object was modeled with vertical edges instead of the apparent 70° slope. This removed the need to calculate a set of waveguide equations corresponding to discrete vertical slices of the object. Bright-field images were computed assuming a line source in the back focal plane of the microscope, as a means of further reducing program complexity and computing time. This 2-D approximation was considered to be less valid at higher illuminating N.A.'s, so the confocal images were computed with a more accurate 3-D approximation, requiring the calculation of images for all points on a circular source. These program simplifications are discussed further in Section 6.

D. Modeling the Object: Scalar versus Waveguide Theory

Before experimental and theoretical profiles are compared, it is informative to model our wafer object by using both the waveguide and the scalar imaging theories. The latter uses the Fresnel equations to calculate the phase and the amplitude of the reflected field at the substrate and the thin-film reflection formulas for the field at the bar. Because the model uses scalar waves, the polarization state of the incident and the reflected light is not taken into account. Figure 10 compares bright-field phase and intensity profiles calculated with both models, for thin (151-nm) and thick (640-nm) vertically edged silicon oxide bars on silicon. Focus is at the top of the bar, and the intensity is normalized to unity for an object that consists of a perfectly conducting bar, which are not always consistent with the experimental images. The phase change is given by

$$\phi = \frac{2\pi}{\lambda} 2t.$$  

This gives a phase difference of 172° and 758° for thin and thick steps, respectively, ignoring any N.A. factor. Equation (2) is typically used by optical interferometric surface profiling microscopes to measure object height.

E. Results

Experimental and theoretical profiles are plotted together in Fig. 11. To reduce the quantity of data, only TE images are shown. Figures 11(a) and 11(b) show bright-field and confocal images, respectively, beginning at a focal position 0.2 μm above the oxide bar (the four top images) and thence focusing down into the object. The focal sequence is continued in Figs. 11(c) and 11(d), and ends with Figs. 11(e) and (f), displaying a total of 12 focal positions for each mode. We paired experimental and theoretical profiles by sliding the experimental sets through focus to obtain a best match by eye with the theoretical data. Hence only odd- or even-numbered experimental profiles are displayed, depending on which set gave the better match. Each set of experimental intensity profiles was normalized with the maximum theoretically calculated intensity at the substrate. Experimental phase profiles were individually shifted by a dc term where appropriate. Note that the Strehl limit of defocus gives ±0.14 μm, which roughly corresponds to the focal range (b)–(j) in the figures, given the extent of the object.

It is seen that agreement between experimental and theoretical profiles is in general extremely good for intensity and phase images in both operating modes. For bright-field intensity and phase, the theory shows tight oscillations at the center of the bar, which are not always consistent with the experimental images. The same inconsistency is evident at the center of the groove (+2.5 μm) in some of the intensity profiles. Conversely, many of the subtle changes between adjacent focused images have been clearly picked up by both the microscope and the waveguide model (for example, the bright-field intensity lobes at ±1 μm, focal positions (b)–(k) and the confocal phase ripples at the bar center, focal positions (e)–(h)). The confocal images show less ringing for all profiles, and the intensity images grow and diminish rapidly because of the optical sectioning property of the confocal microscope. Here the main discrepancy lies in the contrast of intensity images. It was found impossible to match the contrast at more than two or three focal positions, with the best compromise achieved by normalizing to the maximum intensity at the substrate. The phase ears in the vicinity of the bar edge are narrower for the confocal profiles, indicating an improvement in resolution, as expected. The brief unwrapping of the confocal phase in Fig. 11(b), focal positions (b)–(d),

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occurs because the extra resolution in the confocal mode allows the phase to resolve the $2\pi$ ambiguity at the bar edge.

**6. Choosing and Adjusting the Modeling Parameters**

The good agreement shown in Fig. 11 was reached after several adjustments to the input parameters of the waveguide model. Measurements of the period $\Lambda$ and height $D$ of the bar were considered to be reliable, and refractive indices of bar and substrate material were taken from standard tables. These parameters were thus fixed before modeling. Edge slope and bar-to-space ratio were less well defined and were considered legitimate variables in the modeling process.

The wafer was initially modeled with vertical edges to check program performance and to obtain some trial through-focus image sequences. Phase and intensity profiles for a thin (<200-nm) bar are almost invariant to a change in edge slope from 70° to 90° but the effect is significant for a 640-nm bar, as shown in Fig. 12. The influence of the sloping edge is best seen in the ears of the phase profiles, which occur in the region of the bar edge. As expected, the transition from vertical to sloping edges gives the phase profile more time (more resolution) to follow the physical step, resulting in more pronounced ears. We found that the vertical edge approximation gave good agreement between experiment and theory, with the phase ears matching well over a large focal range. This suggests that the appearance of sloping edges in the electron micrographs may be somewhat exaggerated. Following a decision to use vertical edges for all modeled sets of profiles, the bar-to-space ratio was adjusted by trial and error to produce the best agreement with experimental profiles across a wide focal range. The optimum value of bar width was $1.975 \pm 0.025 \mu m$.

A second simplification in the modeling process was to use the 2-D source approximation for bright-field images. Figure 13 compares 2-D and 3-D models for a thin [Figs. 13(a) and 13(b)] and a thick [Figs. 13(c) and 13(d)] bar object for which the experimental illumination parameters outlined in Section 5 were used. Both models are virtually identical for the thin wafer, but show subtle differences for the thick profiles. Comparisons were made between bright-field experimental profiles and the waveguide model by incorporating the 3-D source, but no improvements in the matching of profiles was obtained.

**7. Polarization State**

Figure 11 shows profiles for TE polarization only. Similar results for TM polarization indicate equally good agreement, but are not reproduced here because of lack of space. In general the TE profiles exhibit more ringing in both intensity and phase and for both imaging modes, but the differences are subtle. This difference becomes more evident on viewing how the profiles change with focal position. Figure 14 shows sequences of overlaid bright-field profiles calculated at multiple focal positions. Profiles in a sequence are separated by 0.1 µm of defocus that covers a range of 0.5 µm, 0.6–1.0 µm below the
Fig. 13. Bright-field TE intensity and phase profiles produced by the waveguide imaging theory. Centered 1-D bar object (silicon oxide on silicon) with vertical edges. Nominal bar height: (a), (b) 151 nm; (c), (d) 640 nm; ——2-D model, ------3-D model. All profiles are focused at the top of the bar.

Fig. 14. Bright-field intensity and phase profiles produced by the 2-D waveguide imaging theory. Centered 1-D bar object (silicon oxide on silicon) with vertical edges, height 640 nm. Each graph shows an overlay of profiles for focal positions 0.6–1.0 µm below the top of the bar, in 0.1-µm intervals. (a), (b) TE polarization; (c), (d) TM polarization.
The sequences of Figs. 14(a) and 14(b) are for TE polarization, and the sequences of Figs. 14(c) and 14(d) are for TM polarization. The chosen focal range corresponds to the region of greatest stability in the phase image, which is also the region in which the intensity image changes most rapidly (Figs. 14(a) and 14(c)). Note that this region of defocus corresponds to a focal plane that is largely located within the substrate.

The experimental versions of the sequences shown in Fig. 14 are reproduced for comparison in Fig. 15. The rapidly changing intensity profiles show instantly to which polarization state each set of images belong. The nodes that occur at ±0.9 µm from image center are clearly reproduced in the microscope profiles. The TE sequences are generally better matched than those for TM polarization. In the latter, the spreading of the lobes in the x direction, which gives rise to the thickness of the multiple intensity and phase plots (Figs. 14(c) and 14(d)), is not reproduced experimentally. This is somewhat surprising, as the model assumed vertical bar edges; one might expect the theoretical profiles to be tighter in x as a result.

8. Summary and Conclusions

Results have been presented for a simple object consisting of a silicon oxide bar on silicon, and good agreement with the waveguide theory has been obtained for both Type 1(a) bright-field and confocal images. TE- and TM-polarized illuminations give similar profiles but with subtle differences, which have been picked up by both the microscope and the theory.

Further research is required for improving agreement between theory and practical images. In particular correct modeling of the microscope requires additional investigation. Attempts to include the effect of aberrations by incorporating a measured value of the pupil function into the imaging theory modified the finer details in the ringing but failed to give any improvement in the matching of data. The general trend toward increased ringing in the theoretical bright-field profiles suggests incorrect calibration of the illuminating N.A. in the microscope. Repeating the experimental or theoretical data sets for different N.A. settings would thus be a useful exercise. It has been mentioned that implementing the 3-D source model for a bright-field mode failed to show any improvement in the matching of profiles. Nevertheless, the subsequent modification of theoretical images shown in Figs. 13(c) and 13(d) should clearly be taken into account in further studies.

The stability of the bright-field phase ears over a defocus range of 0.5 µm enabled the edges of the bar to be located to an accuracy of 25 nm, assuming a vertically edged structure. This region of stability and the nodes in the accompanying intensity pro-

Fig. 15. Bright-field intensity and phase profiles from the Linnik microscope. Centered 1-D bar object (silicon oxide on silicon); measured height 640 nm. Each graph shows an overlay of profiles for focal positions 0.6–1.0 µm below the top of the bar, in 0.1 ± 0.01-µm intervals. (a), (b) TE polarization; (c), (d) TM polarization.
files, Figs. 14(a) and 14(c)] may be of use for dimensional measurement of thick structures, although it is not known within what limits of object width this level of accuracy can be applied.

We have presented results for an optically thick symmetrical object with relatively large lateral dimensions. Thus we have been able to study the performance of the waveguide model on relatively isolated object features while taking advantage of the anticipated image symmetry to facilitate the matching of experimental and theoretical profiles. The real interest lies in the ability to profile structures with submicrometer dimensions accurately, and it is hoped that, with further improvements in the validation of modeling and experimental techniques, we can begin to study such objects with confidence.

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References and Notes


8. Objective lenses were NPL achromats purchased as matched pairs from E. Leitz Ltd., London.


