Metrology of optically-unresolved features using interferometric surface profiling and RCWA modeling

Peter de Groot,* Xavier Colonna de Lega, Jan Liesener, and Michael Darwin

Zygo Corporation, Laurel Brook Road, Middlefield, CT 06457
**Corresponding author: peterd@zygo.com*

Abstract: Rigorous coupled wave analysis (RCWA) interprets 3D white-light interference microscopy profiles and reveals the dimensions of optically-unresolved surface features. Measurements of silicon etch depth of a 450-nm pitch grating structure correlate to atomic force microscopy with R^2= 0.995 and a repeatability of 0.11nm. This same technique achieves a <1nm sensitivity to 80-nm lateral widths of 190-nm pitch gratings using a 570-nm mean wavelength.

OCIS codes: (120.3180) Instrumentation, measurement, and metrology: Interferometry; (180.6900) Microscopy: Three-dimensional microscopy

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References and links

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1. Introduction

Semiconductor devices such as microprocessors, DRAM, and FLASH memory require production process control of feature dimension below the resolution limit of visible-wavelength microscopy. Transistor gate widths, for example, are currently on the order of 40nm wide; whereas the Rayleigh criterion limit (0.61 times the mean wavelength divided by the objective NA) for visible-wavelength interference microscopes is typically 450-nm. Under-resolved features of this kind cannot be measured directly as height objects in the usual way by interference microscopy.

Although sub-wavelength features are poorly resolved in interference microscopes, parameter monitoring (e.g. depth and width) is nonetheless still possible if we understand how height variations below optical resolution affect the generation of 3D images. Here we describe a simple technique, illustrated in Fig. 1, which relies on a step-height measurement from an unpatterned reference surface to an etched area, combined with modeling to understand and interpret the results.

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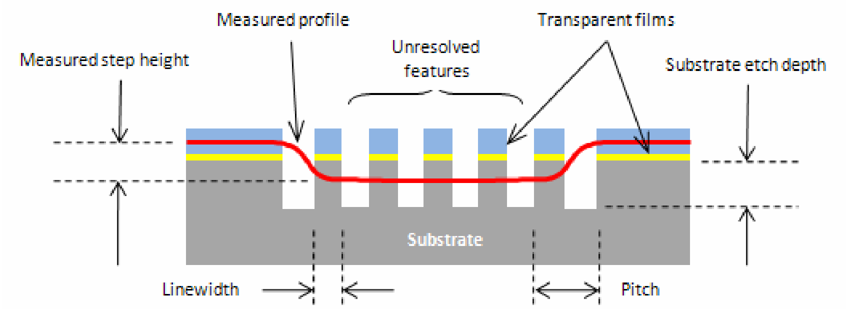

Fig. 1. Optical step-height measurement on a surface structure that includes transparent film layers with optically unresolved features. The measured profile does not resolve the features but is influenced by linewidth and etch depth.

2. Instrument

We employ a visible-wavelength (white-light LED, mean wavelength=570nm) interference microscope with a 0.8 NA objective (Fig. 2). Linearly polarized light increases sensitivity to specific geometrical parameters of the measured grating, such as etch depth. A computer records interference intensity data for every camera pixel as a function of objective scan position. Surface height follows from any one of the known techniques for interpreting white light interference data. Our preferred approach is frequency-domain analysis as described in ref.[1], but other analysis methods would also be suitable for the metrology principle.

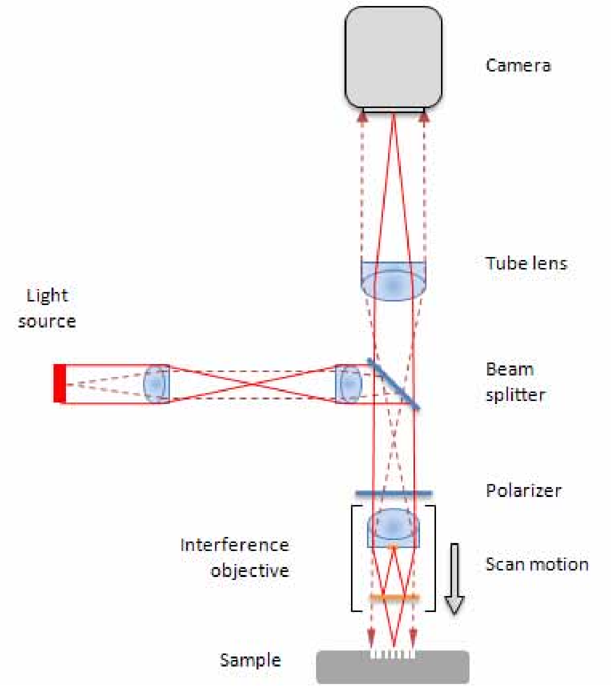

Fig. 2. White light interference surface profiler adapted for parameter metrology of sub-wavelength structures.

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3. Modeling

We use rigorous coupled wave analysis (RCWA) to predict offsets in the measured step height for a range of parameter variations including shape, height, width and the influence of transparent films [2,3]. RCWA is an established calculation method for scatterometry of grating structures in semiconductor wafer process metrology [4] and has been applied to interference microscopy to better understand the imaging properties of these tools [5]. In collaboration with the Institut für Technische Optik at the University of Stuttgart, we employ a version of RCWA adapted to high-NA white light interferometry [6].

Figure 3 (left) illustrates a calculation of the predicted interference response of the instrument when viewing a square grating with a 200-nm pitch. The figure illustrates how the grating structure, although unresolved, nonetheless contributes to a perceived change in surface height in our instrument.

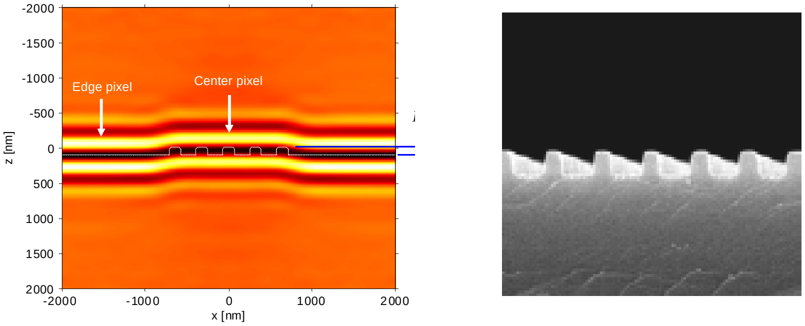

Fig. 3. Left: Example RCWA calculation of a white-light interference signal for a 200-nm pitch, optically-unresolved grating, showing the intensity distribution at each scan position *z* (vertical axis) and at each object-space pixel position *x* (horizontal axis). Right: electron microscope image of a similar structure.

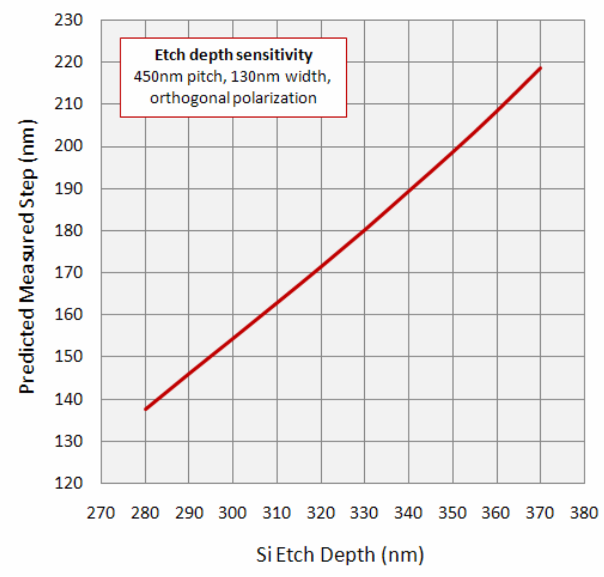

Fig. 4. Predicted measured step according to RCWA modeling as a function of the Si etch depth for the structure shown in Fig. 1 with a 450-nm feature pitch. The illumination polarization in the pupil plane is orthogonal to the grating lines.

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4. Experiment

We measured a sequence of four patterned silicon wafers having the basic structure illustrated in Fig. 1. The two transparent film layers are of fixed thickness and material type while the depth of the gratings was intentionally varied from wafer to wafer. There was an additional range of etch depths within each wafer as a consequence of normal process variability.

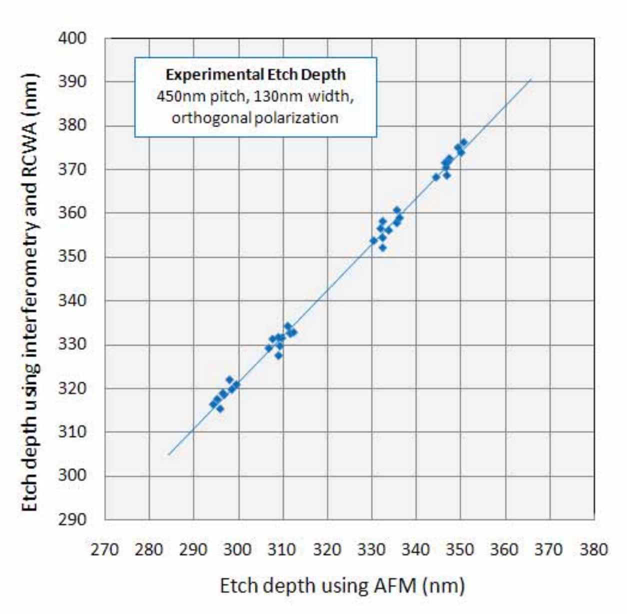

Fig. 5. Silicon etch depth measured using the technique of this paper with the prediction graph of Fig. 4 compared to an independent AFM measurement.

Computer simulation provides the expected interference signal using RCWA for a range of etch depths. Processing these simulated signals for surface height in the same way as the experimental data generates a look-up table of perceived height as a function of feature parameter such as grating depth. The graph in Fig. 4 serves as a translator from measured step height to the true physical dimensions of the unresolved structure. In the case of Fig. 4, the relationship is nearly linear, with a slope of 0.896 and a -114nm offset. The data cluster into groups corresponding to the four wafers in the experiment, while variations across multiple wafer sites distribute data points over a 10-nm range for each wafer.

The experimental results in Fig. 5 compare the proposed method to independent AFM measurements, and show an encouraging 0.995 R^2 slope correlation between the two approaches and a fixed instrument bias of 20nm. Repeatability for individual measurements is 0.11nm rms. Principle sources of error include vibration and part finding reproducibility.

Alternative test structures and adjustments to the optical geometry enable targeted sensitivity to specific process parameters of interest. For example, while the 450-nm structure with orthogonal polarization is a good monitoring strategy for etch depth, a polarization parallel to 190-nm pitch grating lines provides a sensitive measure of linewidth or lateral critical dimension (CD). The sensitivity predictions in Fig. 6 show that measurements of a nominal 80-nm CD are independent of etch depth for this configuration. This approach provided the map of experimental lateral-CD variations shown in Fig. 7. A combination of measurements on 450- and 190-nm structures is one approach to independently monitoring etch depth and CD on the same tool using a simple step-height method.

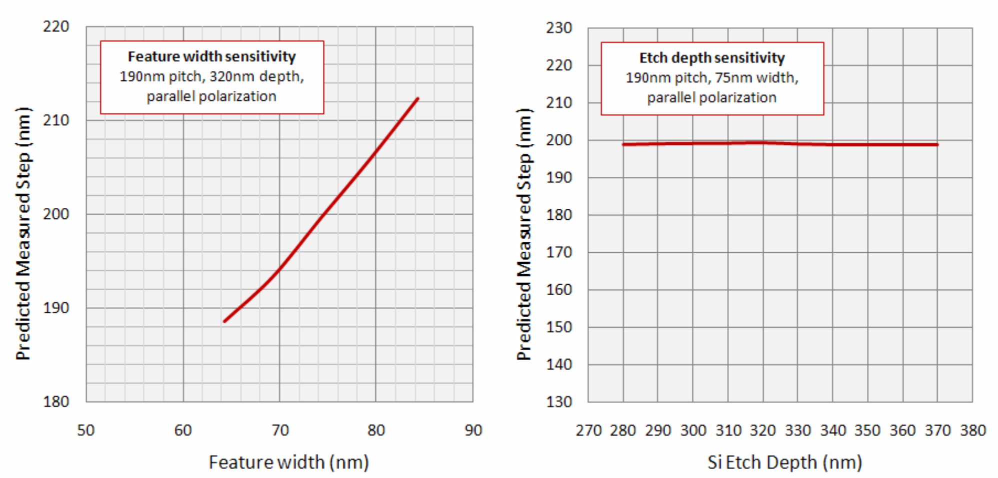

Fig. 6. Predicted step height measurement values for the structure of Fig. 1, assuming a 190-nm pitch and a polarization parallel to the grating lines. This configuration shows high sensitivity to feature width (left-hand graph) and low sensitivity to etch depth (right-hand graph), making this configuration ideal for parameter metrology of grating line widths.

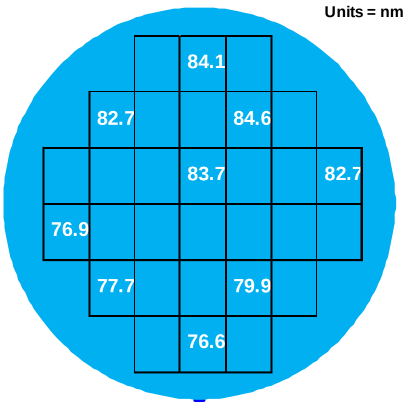

Fig. 7. Wafer map showing the experimentally-measured variation in the nominal 80-nm linewidth for a 190-nm pitch grating printed at different locations on the wafer.

5. Conclusion and further work

In these experiments, the metrology principle relies on modeling the response of a white light interferometer operated in the usual way to generate surface profiles. The measurements in Fig. 5 and Fig. 7 demonstrate the usefulness of this approach for parameter metrology of unresolved structures, using a simple step-height method and RCWA modeling to characterize the response of the instrument. This is a convenient technique in that the translation from measurement to final result involves a simple graph such as the one shown in Fig. 4. The principle weakness in the technique is the inability to solve for multiple parameters simultaneously, such as linewidth, etch depth, film thickness and sidewall angle in one measurement. To solve for all such parameters, we need to define appropriate test targets, polarization and wavelength ranges to maximize sensitivity to the individual parameter of interest, preferably using simple structures such as that of Fig. 1.

As a direction for further work, one can readily imagine a more direct comparison of the modeled interference intensity signals (Fig. 3) with the unprocessed signal data. This approach involves a library of example signals compared in a least-squares sense with the acquired signal data, potentially leading to more detailed information regarding the surface structure [7]. This is a topic of on-going research.

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