Novel Near-Field Optical Probe for 100-nm Critical Dimension Measurements

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ABSTRACT

Although the theoretical resolution for a conventional optical microscope is about 300 nm, it is normally difficult to obtain satisfactory critical dimension (CD) measurements below about 600 nm. E-beam technology has been popular for sub-500 nm metrology but also has well known limitations. Scanning probe and near-field optical methods have high spatial resolution. Yet they are ill-suited for routine CD metrology of high aspect ratio features because of a combination of short working distances (< 10 nm) and large tips. In this paper we present the concept and initial modeling results for a novel near-field optical probe that has the potential of overcoming these limitations. The idea is to observe resonance shifts in a waveguide cavity that arise from the coupling of the evanescent field of the waveguide to perturbations beneath the waveguide plane. The change in resonance frequency is detected as a change in the transmission of a monochromatic probe beam through the waveguide. The transmitted intensity, together with the appropriate signal processing, gives the topography of the perturbation. Our model predicts that this probe is capable of determining the width of photoresist lines as small as 100 nm. The working distance is much more practical than other probe techniques at about 100 to 250 nm.

KEYWORDS: IC metrology, near-field optics, waveguide resonator

1. INTRODUCTION

For routine critical dimension (CD) metrology on process wafers, there are at least four possible approaches: (1) far-field optics, (2) scanning electron microscopy (SEM), (3) scanning probe microscopies (SPM) such as near-field scanning optical microscopy (NSOM), and (4) scatterometry.

Each of these techniques have their advantages, as well as their limitations. Optical microscopy is non-invasive, robust, and inexpensive. However, the resolution of a far field optical instrument is Rayleigh limited.[1] At optical wavelengths, sub-micrometer measurements are difficult due to the present computational intractability of the inverse problem. After a slow start in the early 1980's the SEM is now the workhorse of the semiconductor industry for wafer CD metrology. It promises to provide reliable linewidth measurements down to about 250 nm. However, the SEM is an invasive method and requires the inconvenient step of taking the wafer to high vacuum. SPM techniques are conceptually simple and essentially non-invasive.[2,3] However, the tip convolution problem may prove impossible to overcome. For example, the NSOM tip is typically 250 nm wide (including the aluminum cladding) and must be brought to within about 10 nm of the sample.[4] Therefore, NSOM cannot readily determine linewidths of high aspect ratio structures. Scatterometry appears to have considerable promise at the 250 nm feature size.[5] However, it requires a rather large grating test structure in the scribe-grid and cannot be applied to isolated features.

In this paper we present the concept and simple modeling results for a novel near-field optical probe that has the potential of overcoming these limitations. The idea is to observe resonance shifts in a

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waveguide cavity that arise from the coupling of the evanescent field of the waveguide to perturbations beneath the waveguide plane. The change in resonance frequency is detected as a change in the transmission of a monochromatic probe beam through the waveguide. The transmitted intensity, together with the appropriate signal processing, gives the topography of the perturbation. Our model predicts that this probe is capable of determining the width of photoresist lines as small as 100 nm. The working distance of 100 to 250 nm is much more practical than other probe techniques.

2. THE WAVEGUIDE RESONATOR PROBE

The novel probe that we propose is an optical waveguide resonator. The resonator is formed by two Bragg reflectors that are shifted by a quarter-wave to form a half-wave cavity.[6,7] A sketch is shown in Fig. 1. The first step in fabricating the resonator is to grow a thin-film waveguide. For our studies, we have chosen the SiN/SiO$_2$ system since it is transmissive at 1550 nm and can be readily fabricated at Sandia. Next, patterning and etching are used to form the rib waveguide and finally the Bragg grating structure. The specific waveguide structure in Fig. 1 is only for illustration. Different types of waveguides and Bragg reflectors are being investigated to identify the design that maximizes the finesse of the resonator for this application.[8]

The lowest resonant mode of the resonator has an electric field distribution that is confined principally in the cavity region and is exponentially evanescent in the direction perpendicular to the cavity (see Fig. 2). This evanescent tail probes the region in the immediate vicinity of the cavity. The presence of dielectric disturbances in the region neighboring the cavity alters the resonant frequency of the cavity. Also, the resonant frequency changes as the perturbation is translated along the axis of the waveguide relative to the center of the cavity. This change in the resonant frequency results in a corresponding change in the transmission of monochromatic light through the waveguide resonator.

Figure 3 is a schematic drawing indicating a possible mode of operation of the probe. Shown in the figure is a scheme using second-order grating couplers (couplers with 30-40% coupling efficiencies are relatively easy to fabricate); however, other methods such as prism coupling can also be used. The structure to be interrogated is placed beneath the resonator at a distance of ~100 -250 nm and translated along the length of the Bragg structure. The light transmitted through the waveguide resonator is the signal from which the topography of the structure is ascertained. The laser is tuned so that maximal transmission occurs when the perturbing structure is centered beneath the cavity.

3. INTERPRETING THE SIGNAL

The principal reason why this technique can provide high resolution is that the deconvolution or inverse problem has a straightforward solution, whereas in other measurement techniques, the deconvolution is difficult, if not impossible, to perform. Any measurement process (be it optical, SPM, SEM etc.) can be summarized as

$$S(\xi) = H(\xi) \otimes t(\xi)$$

where the measured signal $S(\xi)$ is a convolution of the actual topography $t(\xi)$ with the instrument response, $H(\xi)$. If $H(\xi)$ were known, then $t(\xi)$ could be readily ascertained. For example, the National Institute of Standards and Technology's (NIST) photomask standard (SRM 473) is established by calculating $H(\xi)$ theoretically by a numerical solution of the vector diffraction problem (i.e. solving Maxwell's equation). Unfortunately, the approach undertaken by NIST to establish a photomask

standard is not so reliable when applied to wafer metrology. The influence of poorly defined underlying layers breaks the connection between the theoretical results and their practical application. Variations in film thicknesses that are perfectly acceptable from the standpoint of electrical device function may seriously interfere with the precision and accuracy of CD measurements. Also, for microscopies relying on scanning mechanical tips the inverse problem is virtually intractable owing to a lack of precise information on the shape of tip and the microscopic interactions between the tip and sample.

However, with the resonator probe described here, this deconvolution is quite straightforward because the guided modes in waveguides are relatively easy to describe theoretically. In fact, simple analytical models can describe accurately (within a few percent) the changes in the resonance frequency. For example, the transmission near the resonance frequency, w_0, for a high-Q resonator is well described by a Lorentzian:[6,7]

$$T = \frac{\Gamma^2}{(\omega - \omega_0 - \beta\,(\xi))^2 + \Gamma^2},$$

where $\beta(\xi)$ is the shift in resonance frequency and Γ (=1/2Q) is the linewidth. Therefore, from a measurement of transmission (which is merely proportional to the detected power), one obtains the resonance shift. For modeling and design the Lorentzian approximation is acceptable. In actual practice, one could readily determine the lineshape function empirically and use this empirical function independent of the application.

The shift in resonance frequency, $\beta(\xi)$, can in turn be related to the topography. This is most easily understood from cavity perturbation theory[6,7] where

$$\beta(\xi) = \frac{\Delta E_{stored}(\xi)}{E_{stored}} + higher\_order\_terms,$$

and $\Delta E_{stored}(\xi)/E_{stored}$ is the fraction change in the stored energy in the resonator due to the perturbation.

The stored energy change can be shown to be expressible in the form shown:

$$\Delta E_{stored}(\xi) = H_{probe}(\xi) \otimes t(\xi)$$

where $H(\xi)$ is now the transfer function of the probe. A reasonably accurate transfer function can be obtained by perturbation theory; however, a more exact and rigorous function can be obtained by numerical (such as the beam propagation computer codes developed at Sandia) and empirical methods. It should be noted that the perturbation model is routinely used in the literature pertinent to microwave cavities and circuits and provides estimates that are accurate to within a few percent.

To summarize the steps in the modeling exercise, the stylus is moved across a surface with the feature of interest. The simulated transmitted signal is calculated at equispaced positions relative to the center of the cavity (the resolution of the instrument is inversely proportional to the distance scanned). Laser and detector noise contributions to the signal are included in the simulation, and ultimately limit the resolution. Using the Lorentzian model, the frequency shift is calculated and, from its Fourier transform, the response of the resonator is deconvolved. In order to suppress aliasing and other related effects, the signal is filtered using well known techniques in signal processing (e.g. Hanning filter). Finally, the inverse Fourier transform, to complete the deconvolution, yields the topography.

4. NUMERICAL RESULTS

With the model briefly described above we simulated the performance of the waveguide resonator probe. Figures 4 and 5, present representative results from these simulations. We assume a 1 mW 1550 nm diode laser coupled to a 70 μm long Bragg resonator with 10% coupling efficiency. We assume room-temperature operation (e.g. InGaAs detectors) and have include effects of laser and detector noise. We use a simple deconvolution and filtering method in order to get rough performance estimates. Simulations that include more sophisticated data processing may predict even higher effective resolution.

In Fig. 4, we plot the reconstructed topography for four photoresist lines on poly-Si, with spaces of varying widths. In the simulation, the sample was translated in 20 nm increments for a total of 2000 calculations of transmitted intensity. After the appropriate data processing the resulting trace faithfully reproduces the topography. This modeling result indicates that the new method can effectively measure CDs as small as 100 nm. The noise in the trace is a result of our having included both laser and detector noise in the model. We have been conservative in this regard. State-of-the-art detection methods (e.g. homodyne), may produce lower noise than modeled in Fig. 4 and hence a higher effective resolution.

In Fig. 5 we present the simulated result of a CD measurement on a phase-shift mask. The effective resolution is considerably lower than for the resist on poly-Si in Fig. 4. Interestingly, the probe responds to each of the important transition regions. Metallic features, owing to their absorption, require a more careful treatment of the lineshape than for dielectrics. With further theoretical work, perhaps a better reconstruction (and hence a higher effective resolution) will be possible.

5. INSTRUMENT DESIGN

Figure 6 shows the concept for a proposed instrument. A conventional microscope is used to locate the line to be measured. The probe, which is at a known offset from the microscope's cross-hairs, is automatically brought over the line to be measured. The scan in a single direction is repeated the desired number of times to improve signal to noise. The deconvolution is performed and the linescan (as in Fig. 4) is displayed along with the linewidth measurement result.

It should be noted that producing a complete two-dimensional image of a portion of a wafer requires a two-dimensional resonator and a two-dimensional scan. At present we are suggesting only the one-dimensional version of the probe. However, we are presently studying designs for two dimensional probes based on circular planar resonators and work is progressing to develop the appropriate theoretical model. Alternatively, a two-dimensional image may be acquired using a one-dimensional probe by taking two sets of scans rotated by 90 degrees.

Another interesting variant for utilizing the proposed instrument is to perform scans at several heights above the wafer. Preliminary studies show that it may be possible to reconstruct from these top-down measurements the physical sidewall profile of a line or space in photoresist. While other methods can also do this in principle, they have failed in practice. The simplicity of the inverse problem for this new type of probe is the key to our hope that this may now be possible.

6. SUMMARY

The leading edge products in the semiconductor industry will switch to a 0.25 μm process in 1998 and to a 0.18 μm process in 2001.[9] The need for robust metrology tools with sufficient precision as well as accuracy at these dimensions is therefore clear. The principal features of the concept described here are: (1) it is a high resolution technique, (2) it is non-invasive, and (3) it operates under ambient

conditions. These features give it the potential for displacing the SEM for routine CD measurements on wafers. Unlike NSOM, which also is a high resolution technique, the working distance of the new probe is convenient at about 100 to 250 nm. Furthermore, the evanescent field does not probe too deeply into the wafer surface. Unlike conventional optics (and presumably NSOM) the proposed instrument is essentially immune to poor CD precision caused by variations in underlying layers. Another unique feature of this probe, relative to conventional optics, is that there is no hard theoretical limit for the resolution. Ultimately, the signal-to-noise-ratio limits the resolution. We feel that our simulations are conservative in predicting an effective 100 nm resolution for wafer metrology.

Finally, we are considering the application of this probe to optical data storage. The best commercial technology operates at a density of about 1 Gbits/inch^2. Even with advances in shorter wavelength blue-green semiconductor diode lasers, raw storage densities beyond 3- 5 Gbits/inch^2 do not appear feasible. This new probe could potentially increase this density 5-10 fold.

ACKNOWLEDGMENTS

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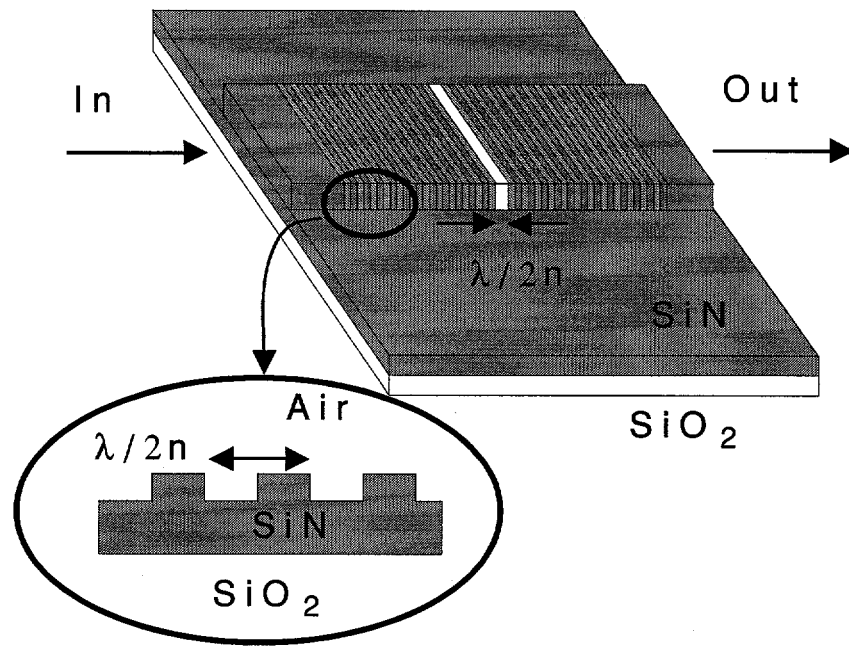
Figure 1. Schematic of one possible waveguide resonator probe. The cavity in the rib waveguide is formed by two Bragg reflectors.
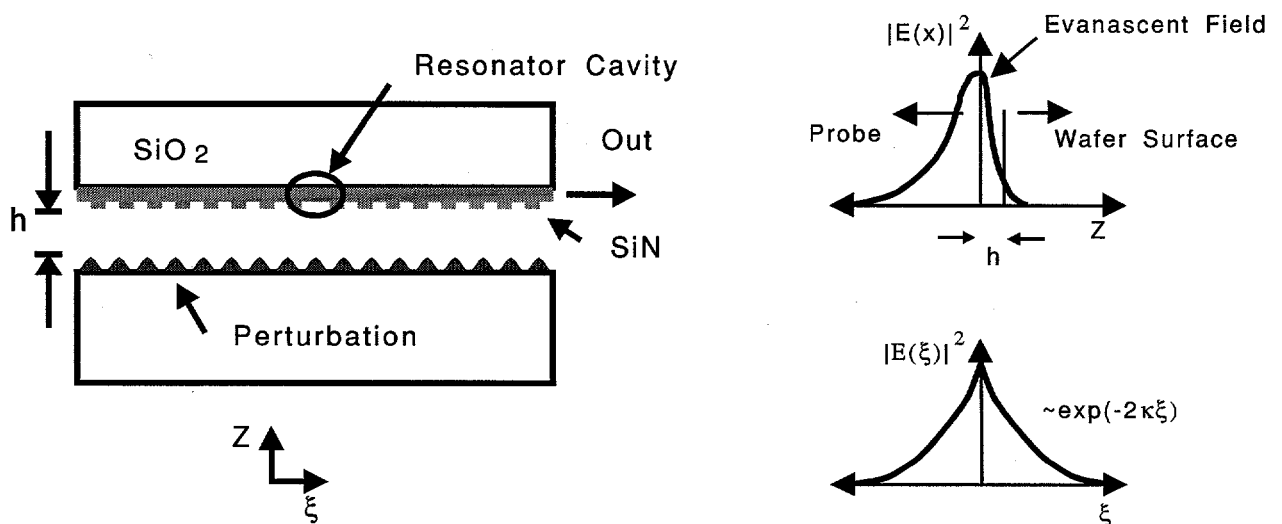

Figure 2. Physics of the resonator probe. For the E-field in the ξ direction only the low frequency envelop is shown. The evanescent tail in the z direction probes beneath the resonator. The presence of dielectric disturbances alters the resonant frequency of the cavity. Hence, the transmission of monochromatic light varies as the perturbation is translated in the ξ direction.
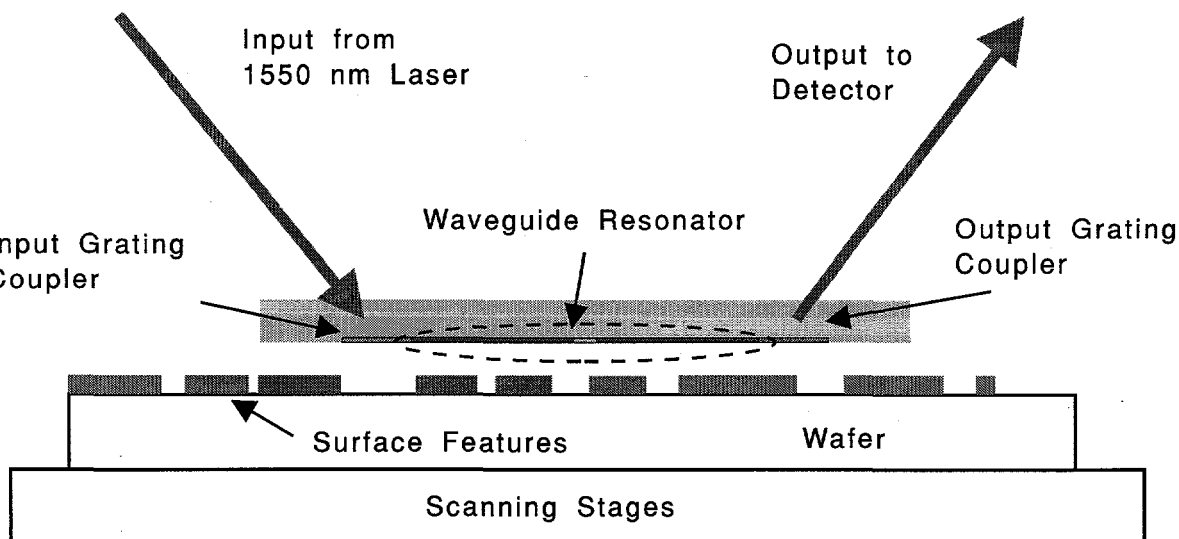
Figure 3. Possible mode of operation for the waveguide resonator probe. The probe is brought to a
height of about 100 to 250 nm above the wafer surface. Light is coupled in and out with a second
order grating coupler. Other schemes are possible. The scanning stage produces the motion while
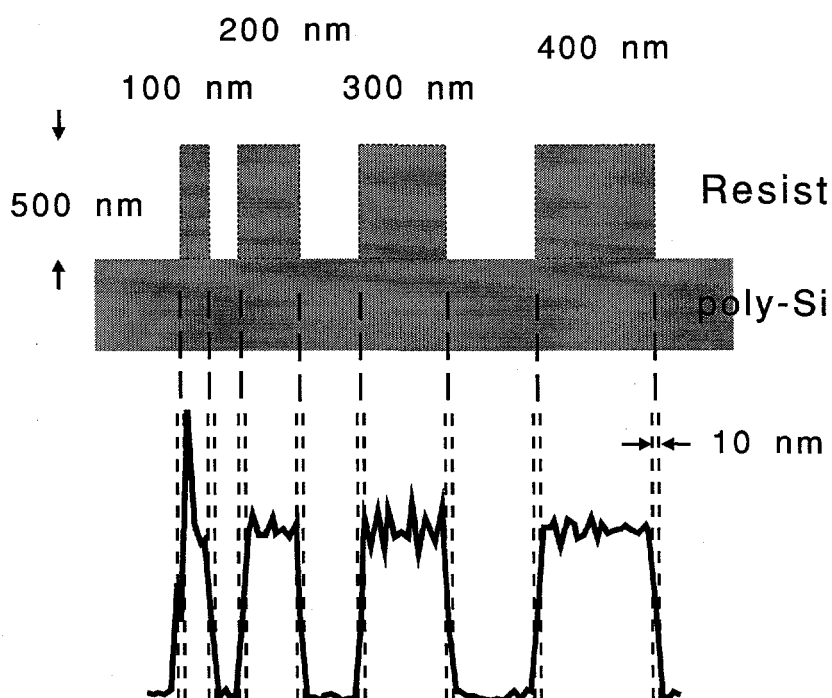the probe remains stationary.

Figure 4. Computed profile for photoresist lines on poly-Si. A linewidth of 100 nm is readily resolved.
The slope of the line scan at the edges of the feature indicates that a precision of about 20% may be
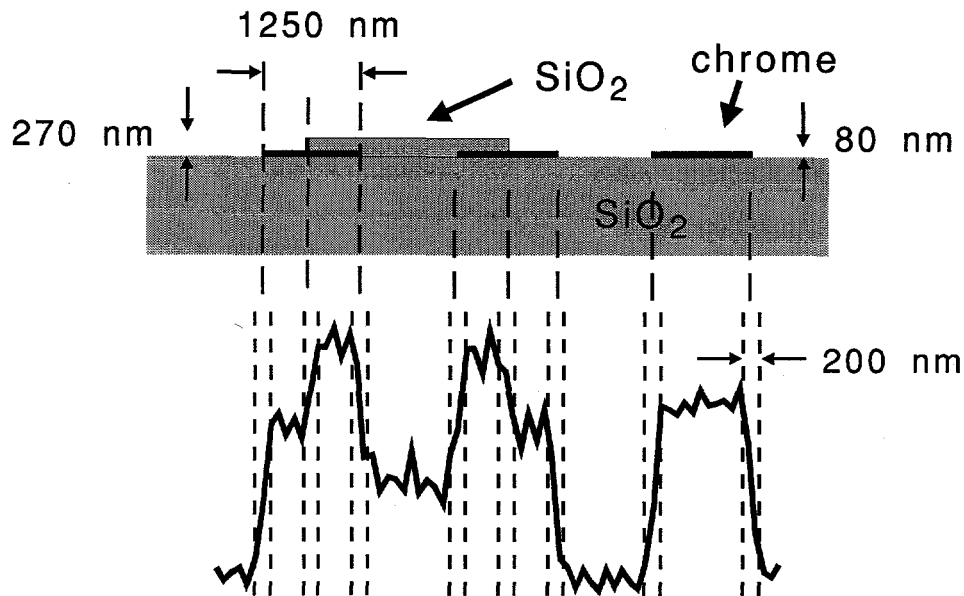possible for the 100 nm lines.

Figure 5. Computed profile for a 5x phase shift mask. Details of both layers are discernible. Yet the resolution is inferior to the case in Fig. 4 of resist on poly-Si.
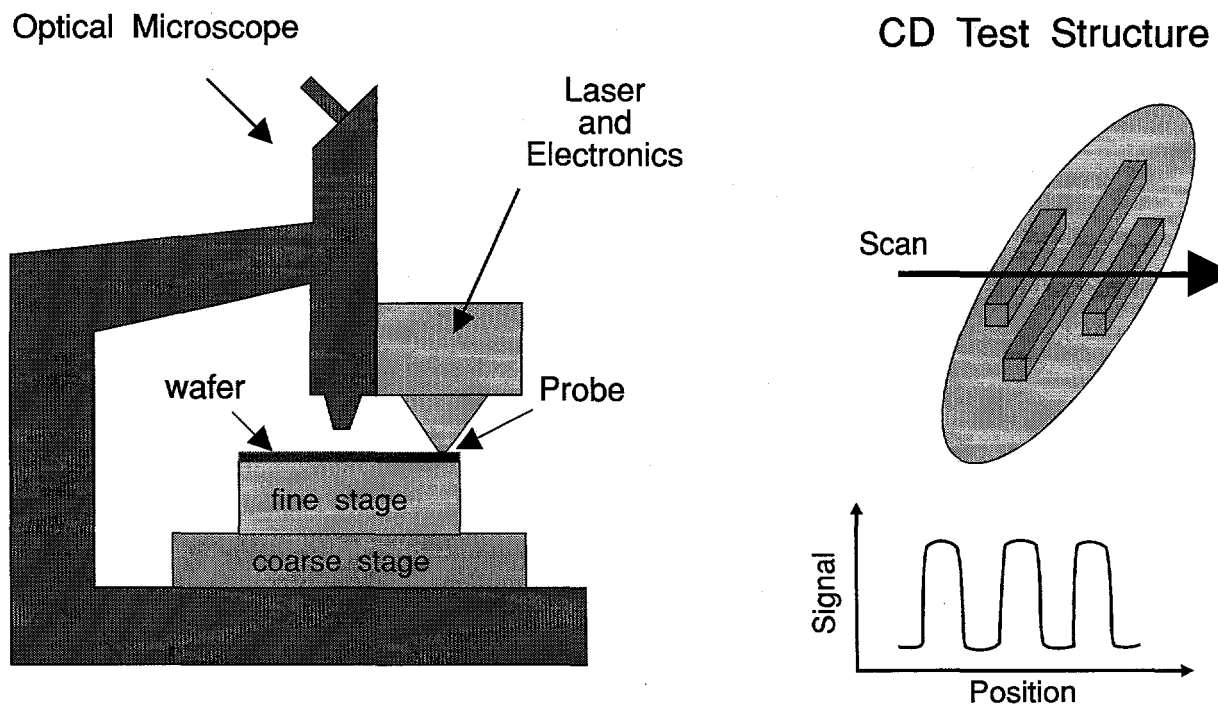

Figure 6. Schematic diagram of the proposed metrology instrument. The measurement position is located through the optical microscope. The stage moves the features of interest under the probe. A one-dimensional scan plus data processing yields the CD.