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An Ellipsometry System for High Accuracy Metrology of Thin Films*

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Abstract

A computer-controlled spectroscopic ellipsometer of high accuracy has been designed and constructed. A theta-two-theta goniometer unit and optical rail system allows various ellipsometric methods to be used to measure the parameters Δ and ψ. Three important methods under study for accuracy, precision, and speed of measurement are the conventional null method, the rotating analyzer method, and the principal angle method. All the goniometer angles, including the angle of incidence, can be measured to an accuracy of 0.001 deg. The present light sources are two lasers with fixed wavelengths, 632.8 nm and 441.6 nm, in addition to a monochromator that can be used to scan the wavelength range from 190 to 2600 nm. A unique sample alignment system which utilizes two quadrant detectors has been developed and a simple but very effective nulling scheme is used. This instrument is primarily used for the metrology of semiconductor materials and for the calibration of reference standards for thin film thickness and refractive index.

I. Introduction

To study problems important to VLSI semiconductor technology,[1] we have designed and built a fully automated spectroscopic ellipsometer of high accuracy. The results of detailed error analyses[2-4] and the performance characteristics of other spectroscopic ellipsometers[5-9] were considered in the design and construction of our ellipsometer. The instrument is built around a massive theta-two-theta goniometer unit and optical rail system that permit the use of various ellipsometric methods to obtain Δ and ψ. Three important methods under study for accuracy, precision, and speed of measurement are conventional null ellipsometry (CNE), rotating analyzer ellipsometry (RAE), and principal angle-rotating analyzer null ellipsometry (PA-RAE). Two photographs of the ellipsometry system are shown in figure 1 and a schematic diagram is given in figure 2. The RAE and PA-RAE methods use identical optical configurations, whereas the CNE method employs a quarter-wave plate in the polarizer arm and a stepper-motor-controlled analyzer in place of a continuously rotating analyzer. The three methods of obtaining Δ and ψ and a summary of the light intensity equations near null[10] are shown in figure 3. The RAE and PA-RAE methods are well suited for spectroscopic studies.

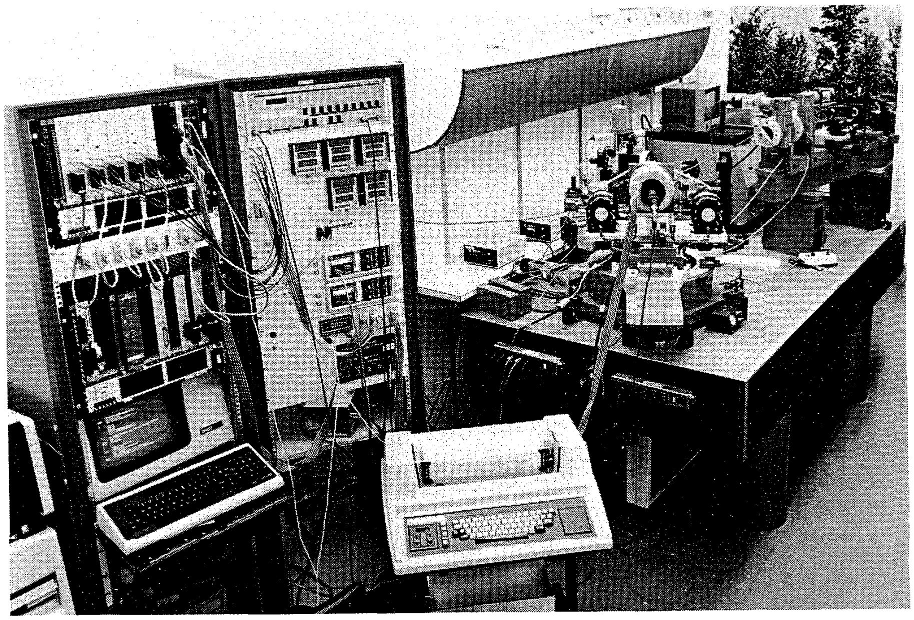
In this paper we describe the mechanical, optical, and electronic parts of the ellipsometer and provide a description of the computer control methods, the calibration techniques, and the alignment procedure. The methods of nulling in both the CNE and PA-RAE are also explained.

II. Mechanical

1. Optical Bench, Goniometers, and Rail System

The instrument is supported by a 1.2 m × 2.4 m air-suspended honeycomb-type table which is flat to ±0.1 mm (figure 1). The table top and the ellipsometer components are kept dust free with a HEPA air filter system. The massive theta-two-theta goniometer unit, which weighs 180 kg and which can support over 1300 kg, an optical rail, and the light sources are securely fastened to the table. A heavy optical rail is fastened to the table top for the polarizer arm components and another is attached to the arm of the two-theta goniometer for the analyzer-detector components. The optical rails are straight to within ±0.01 mm per meter. The analyzer, polarizer, and quarter-wave plate goniometers are fastened to sturdy right-angle plates which are bolted to optical rail carriages that are fastened to the optical rails. This sturdy mechanical arrangement makes it possible to exchange the components in a convenient yet reproducible manner.

The theta-two-theta goniometer unit is a single assembly which supports the sample stage on the theta goniometer and the analyzer-detector on the two-theta goniometer. The geometric centers of rotation of the two goniometers are aligned to within ±0.01 mm and the surfaces of the goniometers are parallel to within ±0.003 mm.



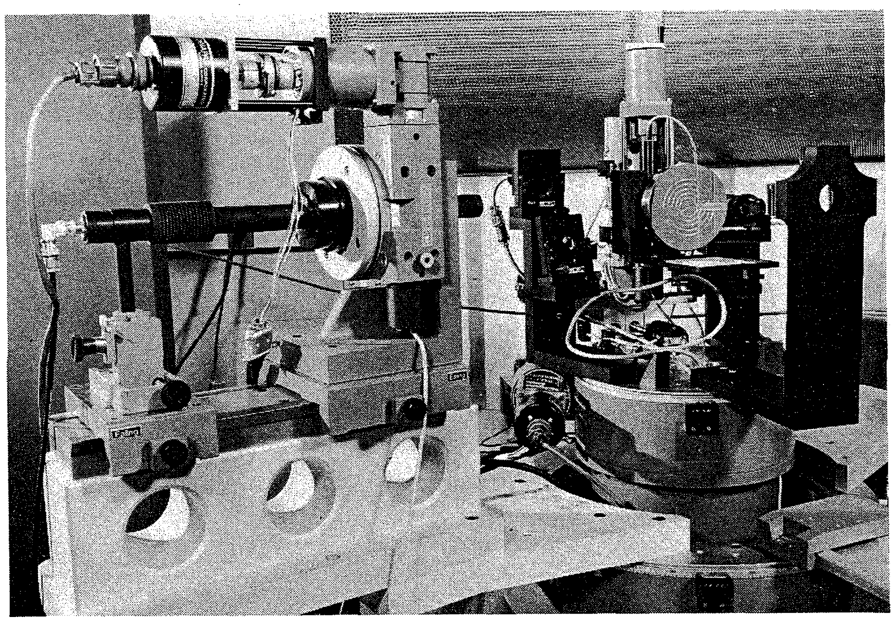


Figure 1. Photographs of the ellipsometric system showing the general layout and the theta-two-theta goniometer unit, the sample chuck, and the analyzer and detector.

Three smaller goniometers are used for rotating the analyzer, the polarizer, and the quarter-wave plate. All goniometers are controlled by stepper motors such that one step of the motor turns the goniometer 1 mdeg. The goniometers have less than ±0.02 mdeg of backlash, which makes it possible to use optical encoders that are attached directly to the shafts of the stepper motors to provide angular position information for all the goniometers to the computer. All of goniometers have been calibrated and the calibration data have been fitted by polynomial equations which are stored in the computer.

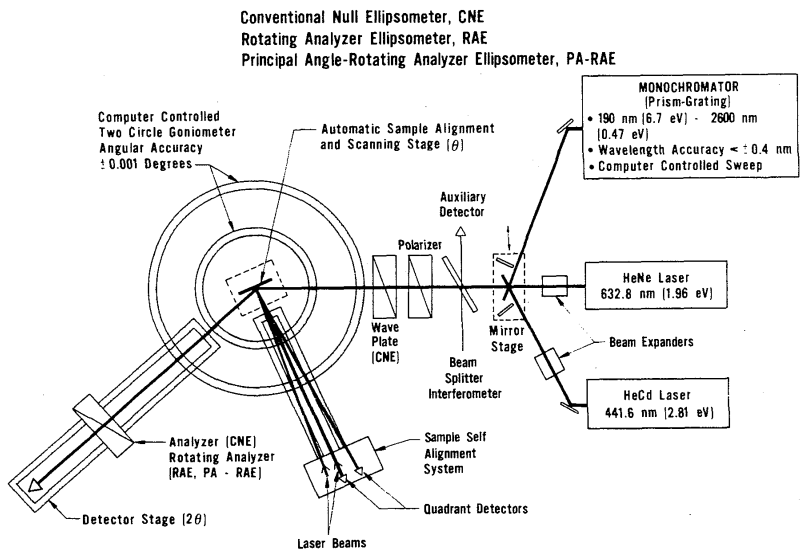
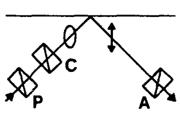


Figure 2. Schematic of the ellipsometer.

CONVENTIONAL NULL CNE



$$I\,(CNE) = I_0(|R_P|^2+|R_S|^2)\times$$
$$\left[1-\cos 2\psi \cos 2A - \sin 2\psi \sin(\Delta-2P)\sin 2A\right]/4$$

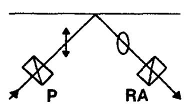
Null, P and A for C = $+\pi/4$

$$\Delta = 2P + \pi/2$$
$$\psi = +A$$

NEAR NULL

$$I\,(CNE) = \frac{I_0}{2}(|R_P|^2+|R_S|^2)\times$$
$$\left[(\delta A)^2+(\delta P)^2\sin^2 2\psi\right]$$

ROTATING ANALYZER RAE



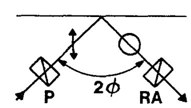
$$I\,(RAE) = I_0(|R_S|^2\sin^2 P + |R_P|^2\cos^2 P)\times$$
$$\left[1+\alpha\cos 2A + \beta \sin 2A\right]/2$$

$$\alpha = \frac{\tan^2\psi\cot^2 P - 1}{\tan^2\psi\cot^2 P + 1}$$

$$\beta = \frac{4\tan\psi\cot P\cos\Delta}{\tan^2\psi\cot^2 P+1}$$

$$RA \rightarrow \alpha,\beta \rightarrow \Delta,\psi$$

PRINCIPAL ANGLE - ROTATING ANALYZER PA-RAE



$$I\,(PA\text{-}RAE) = I\,(RAE)$$

with $\alpha = \beta = 0$

Null, P and AI

$$\Delta = \pm\,\pi/2$$
$$\psi = \pm P$$

NEAR NULL

$$I\,(PARAE) = I_0(|R_S|^2\sin^2 P+|R_P|^2\cos^2 P)\times$$
$$\left[1-\frac{2\delta P}{\sin(\pm 2P)}\cos 2A \pm 4\delta\Delta\sin 2A\right]$$

Figure 3. Ellipsometric methods to obtain Δ and ψ. The general and near null light intensity equations are shown.

2. Sample Stage

A stainless steel variable-vacuum chuck shown in figure 1 was designed and constructed to hold flat samples such as semiconductor wafers without distortion. The front surface of the chuck is ground and polished to a flatness of 1/10 wavelength at 632.8 nm. A commercial vacuum chuck can also be used. This alternative chuck minimizes the problem of wafer distortion caused by the trapping of dust between the chuck and the wafer because only two percent of the wafer makes physical contact with the chuck.

The chuck is mounted on a stage that can be moved in three orthogonal translation and two tilt directions. Vertical tilt affects the sample azimuth angle, and horizontal tilt, the incident angle. The x- and y-motions which are in the plane of the chuck are controlled by stepper motors and are used to position the sample's surface with respect to the incident light beam. The z-motion which is perpendicular to the plane of the chuck and the two tilt motions of the chuck are controlled by dc motors. The z-motion is required to keep the sample surface at the center of rotation of the theta-two-theta goniometer unit to ensure that the light beam remains at the same position on the sample as the incident angle is varied. The two tilt motions are essential for correcting the incident and azimuth angles. The procedures used for sample alignment are described in the optical section below.

3. Rotating Analyzer

The rotating analyzer incorporates a high quality incremental optical encoder. The encoder generates both a zero angle pulse and 4096 counts per revolution. The encoder has a hollow shaft on which the analyzer and a pulley are mounted and balanced. The encoder is belt-driven by one of two balanced hysteresis synchronous motors. Smooth, thin 1.27-cm wide belts made of plasticized fabric are used. By changing the belts, either a 3600 rpm motor or a 1200 rpm motor can be used, and pulley size ratios were chosen so that the analyzer rotates at either 33 Hz or 5 Hz, respectively, when the motors are driven by a 60-Hz source. The motors are designed for minimum vibration and electrical noise and they provide absolutely constant speed. Power to the motors is supplied by a power amplifier whose input signal is an NBS standard signal of extremely stable frequency. The two motors and the encoder are mounted on a heavy right-angle cast iron plate which is fastened to a large optical rail carriage base, visible in figure 1.

III. Optical

1. Light Sources

Two laser sources are presently being used. The wavelength of the HeCd laser is 441.6 nm, and that of the HeNe laser is 632.8 nm. The laser beams are expanded and collimated to a 1-cm diameter beam to minimize beam divergence and hence error in the angle of incidence. This collimation also enables the beam to be used interferometrically for sample alignment at zero incident angle. For spectroscopic ellipsometry, a prism-grating monochromator is used. The light sources for the monochromator are a 75 watt xenon arc lamp and a 150 watt mercury arc lamp. The output wavelength of the monochromator can be scanned over the range of 190 nm to 2600 nm with the aid of a computer-controlled scanning motor.

2. Light Detectors

A silicon photodiode is used as the main light detector. The detector output is amplified by a computer-controlled amplifier whose gain can be adjusted over a range of nine orders of magnitude. All the reflected light is collected by a lens/detector system so that the position of the detector is not critical. By using a beam splitter and an auxiliary detector (figure 2), the effect of variations in the light intensity can be normalized during the time it takes to obtain a null. This normalizing procedure is described in the nulling methods section below.

3. Polarizer, Analyzer, Wave Plates, and Mirrors

The polarizer, quarter-wave plate, and analyzer are placed at the centers of their respective goniometers in mounts which have adjustments for two tilts and the center of rotation. The polarizer and analyzer are Glan-Thompson calcite prisms and have an extinction coefficient of 10^{-6}. They were selected for minimum wavefront distortion and beam deviation. The variable quarter-wave plate is a Babinet-Soleil compensator; its wave-plate constants were determined at various wavelengths by ellipsometry using metal samples.[10,11] Various other lenses, mirrors, beam splitters, etc. are of the necessary quality to ensure the desired accuracy.

4. Interferometer to Test for Normal Incidence

The incident angle is one of the most important parameters in all modes of ellipsometry and must be determined to an accuracy at least as good as the accuracy of the Δ and ψ goniometers.[3] We used the following interferometric technique to ensure that the incident angle can be determined to the accuracy of the main goniometer. An interferometric pattern is obtained from the front surface of the sample when it is rotated into a position normal to the collimated incident light beam. This ensures that the incident beam is normal to the sample's surface at zero angle of incidence. The interferometer consists of a pellicle beam splitter which introduces virtually no beam distortion or displacement and a corner cube prism accurate to better than 1 second of arc. This interferometer can be easily moved in and out of the beam as needed.

5. Sample Self-Alignment System (SSAS)

After the sample has been set at normal incidence using the interferometer, the SSAS maintains the section of the sample surface that is being measured in alignment when repositioning or scanning the sample's surface or when samples are changed. This system is necessary because the x- and y-scanning mechanisms supporting the chuck may not be perfectly orthogonal and because the surface of the sample may not be completely flat. By using two auxiliary HeNe laser beams, four mirrors, and two quadrant light detectors fixed to the sample stage, the sample surface can be kept in position in the z-direction (the direction normal to the sample surface) and in position relative to the vertical and horizontal tilt directions.

The sample chuck is mounted on a stage that has two dc-motor-controlled tilt motions called Ⓥ and Ⓗ and one dc-motor-controlled linear motion called Ⓩ, shown in figure 4. One of the quadrant light detectors intercepts the vertically reflected beam and the other intercepts the horizontally reflected beam. A vertical rotation of the chuck causes a vertical movement of the beam on both detectors and a horizontal sample rotation causes a horizontal movement of the beam on both detectors. However, a movement of the chuck in the z-direction causes a vertical light beam movement on the vertical detector and a corresponding horizontal light beam movement on the horizontal detector. The beam movements across the detectors, labeled [H], [V], and [Z] in the figure, cause an amplified output from the quadrant detector to drive the dc motors and correct the sample position. The face of the sample chuck has been carefully positioned on the axis of rotation of the theta-two-theta goniometer unit so that the measuring beam is always in the same position on the chuck surface when the incident angle is varied. This z-position can be accurately set by means of a vernier scale arrangement. Initially, the two quadrant detectors are zeroed when the chuck is at normal incidence using the interferometer; the Z, the vertical, and the horizontal beams are then kept in the proper position on the detectors to keep the chuck in alignment. When a sample is placed on the chuck, the SSAS automatically aligns on the sample surface. From our measurements we determined that the SSAS keeps the two tilt motions within one second of arc (0.3 mdeg) and holds the z-direction motion to within ±0.25 mm.

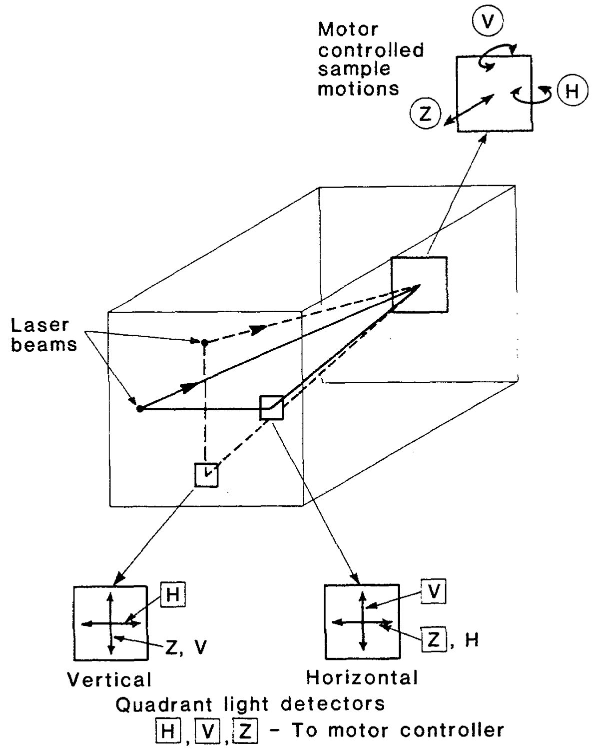


Figure 4. Schematic of the sample self-alignment system (see text for details).

IV. Computer Control and Data Acquisition

1. Computer Hardware and Software

A minicomputer interfaced with two CAMAC crates is used to automate the ellipsometer and to perform the ellipsometric calculations (figure 5). Various CAMAC modules are used to control each part of the instrument. Five stepper motor controllers are used for the theta-two-theta stage, polarizer, analyzer, and quarter-wave plate rotations, and two controllers are used for the wafer translation stages. Optical encoder inputs are used to determine the angular positions of the goniometers. A dual analog-to-digital converter monitors the light signals from the main and auxiliary detectors. A fast data logger is

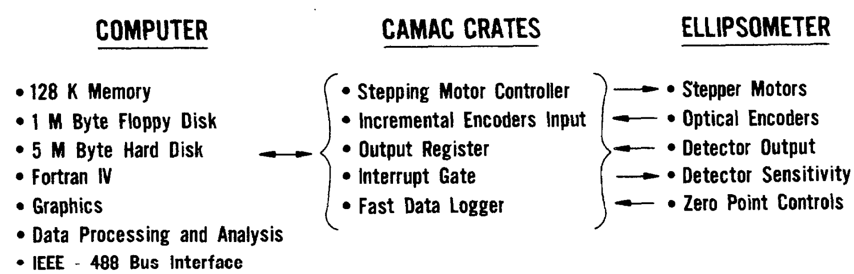


Figure 5. Schematic of the computer system network.

used to process the light intensity signals when using the rotating analyzer. Output registers and interrupt gates are used to process the signals associated with the resetting of the instrument. This includes such processes as zeroing all the goniometers along with their angular readouts and changing the gain setting of the light detector amplifiers. All computer programs are written in FORTRAN. There are programs to calibrate the instrument, to take data on a wafer by any of the three ellipsometric methods, to perform the ellipsometric calculations on that data,[12] or to perform simulation studies.

2. Nulling Procedures

The practice used for nulling in the CNE method is straightforward and simple, yet works extremely well. The analyzer and polarizer are alternately stepped through their respective minima. Light intensity data are taken 82 times at each angular position during one complete 60-Hz period. An average of these 82 points cancels out the variations in detector output caused by stray room light that may fall on the detector. Thus data can be taken with the laboratory lights on without loss in accuracy. Just before and just after the 82 points are collected, a light intensity reading of the incident beam is taken by the auxiliary detector. The averaged data points are normalized to the auxiliary detector output for each 50 mdeg of analyzer or polarizer angle in a ±2 deg interval about the minimum and a least squares fit to a parabola is calculated. By this procedure, any change in the light intensity while the null is being taken will not influence the fit to the light intensity parabola. The best fit parabola, the null point, and the data points are then plotted. Figure 6 is a plot of a typical nulling curve. This method yields null points that are reproducible to better than 1 mdeg, are independent of scan direction, and have excellent fits to a parabola. This nulling procedure also provides a very easy and accurate way to obtain alignment and calibration data for the instrument. All optical alignment corrections and goniometer calibration curves are automatically taken into consideration when the computer program processes the null data.

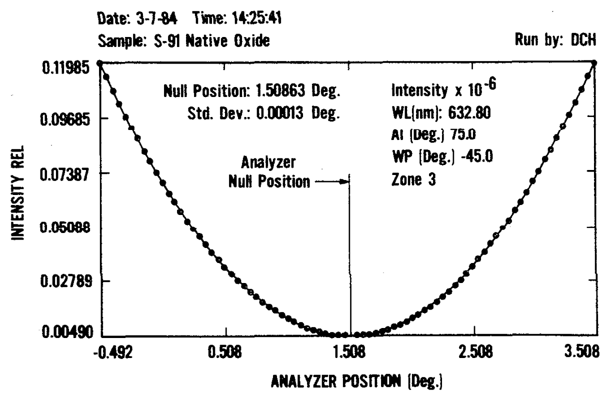


Figure 6. CNE method nulling plot. The parabolic light intensity equation which holds near null is shown in figure 3.

In the PA-RAE method, the data are taken in a similar manner except that the detector output is treated as an ac signal and is processed by a two-phase lock-in amplifier. The amplifier is locked to the RA zero-point encoder signal, and the resultant dc output of the lock-in amplifier is fed into an analog-to-digital converter. Using this arrangement, the polarizer and the angle of incidence are scanned near null. For the PA-RAE method the light intensity varies linearly, as described in figure 3, for small deviations of the incident angle or the polarizer angle from the null. A typical null plot is shown in figure 7.

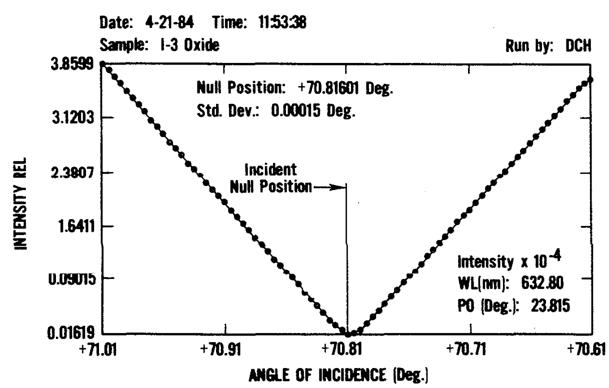


Figure 7. PA-RAE method nulling plot. The linear light intensity equation which holds near null is shown in figure 3.

The RAE method has been perfected by Aspnes et al.[5,6] Our procedures are very similar to theirs. The time required to collect data using the RAE method is much less than that required using the other two ellipsometry methods.

V. Initial Objectives

We have made measurements of film thickness and of optical constants of materials and are presently assessing the absolute accuracy of these measurements. The absolute accuracy of the instrument will become known only after extensive study; there are no suitable comparison standards and the interpretation of measurements on actual thin film materials depends on knowledge of the properties of the films. Much of the accuracy determination involves error analysis studies, as a function of angle of incidence and wavelength, on sets of selected samples.

We have designed and are fabricating a standard reference material (SRM) in the form of a patterned silicon wafer, which will have oxide films of different thicknesses that can be measured by ellipsometry, by stylus profilometry, and by interferometry, shown in figure 8. The optical constants of the inconel metal overlayer can also be measured by ellipsometry. This SRM can be used to calibrate the angle of incidence of an ellipsometer by using the refractive index of the metal overlayer, and to calibrate other film-thickness measuring instruments using the oxide films of known thickness and refractive index.

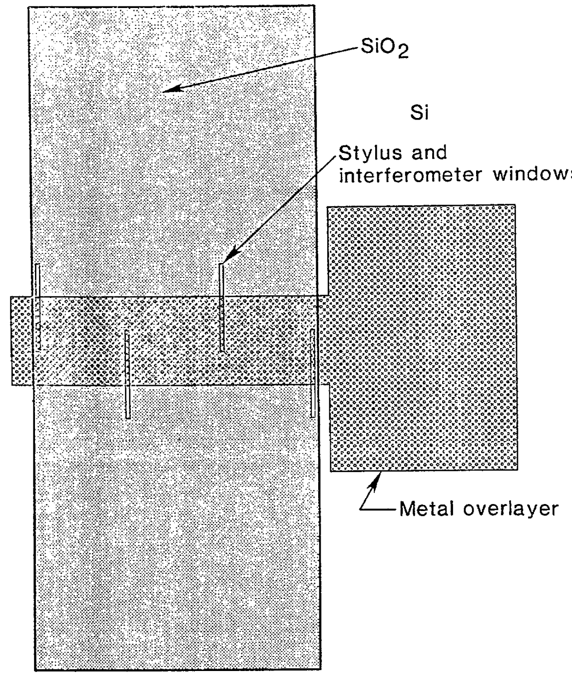


Figure 8. Schematic of the film thickness, refractive index, and step height SRM. This pattern, with various thicknesses of SiO_2, will be fabricated on a 3-in. silicon wafer.

Acknowledgments

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