TECHNOLOGY | by Charles Taylor, Darryl Barlett, Eric Chason, and Jerry Floro

A Laser-Based Thin-Film Growth Monitor

The Multi-beam Optical Sensor (MOS) was developed jointly by k-Space Associates (Ann Arbor, MI) and Sandia National Laboratory to directly measure film stress and thickness in real-time during fabrication (Figure 1). Understanding and controlling stress in thin films are critical for achieving the desired optical, electronic, and mechanical properties. Many of today's high performance devices rely on "built-in" strain within the individual layers for tailoring specific characteristics. Controlling the degree of strain poses a significant challenge. On the other hand, unwanted changes in strain can be introduced at any stage of the fabrication process and may lead to degradation in device performance as well as failure of interconnects and delamination of films.

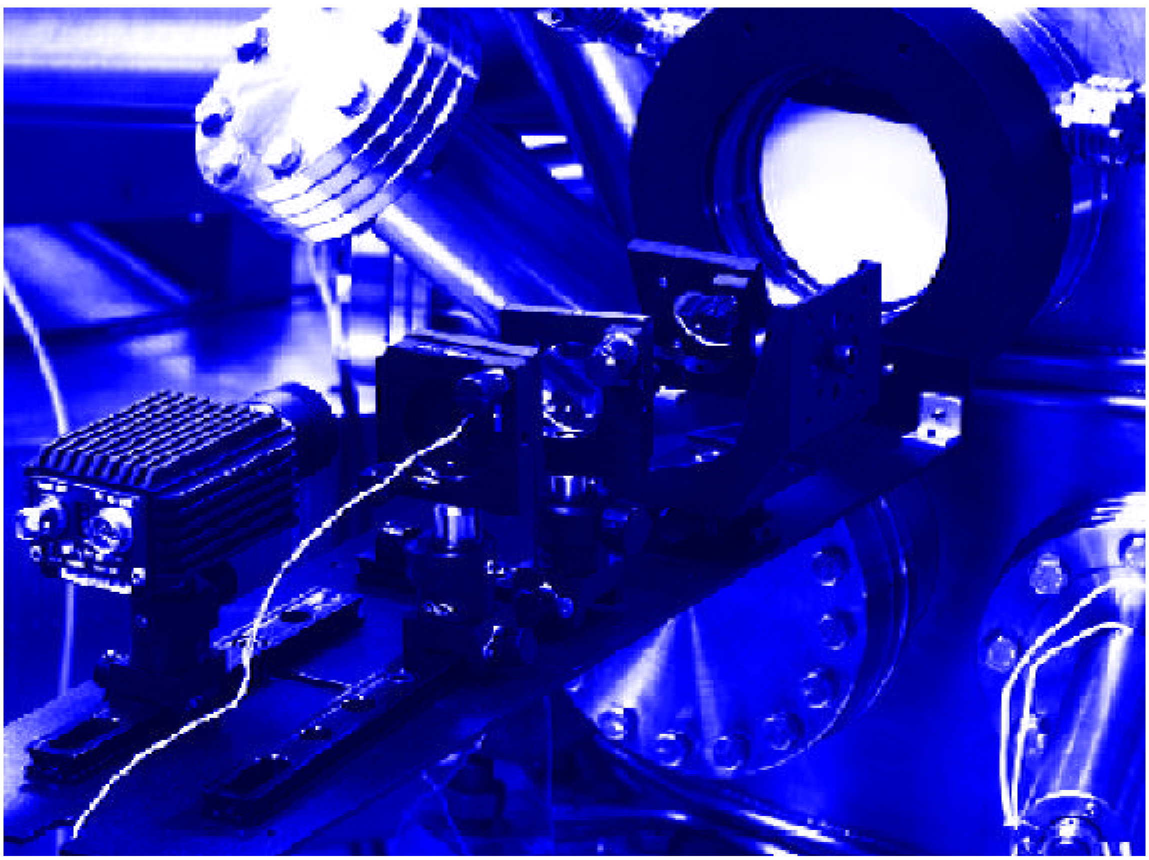

Figure 1- Multi-beam optical sensor mounted on a commercial thin-film deposition system.

BACKGROUND

Deposition of thin film materials for electronic and optoelectronic devices requires precise control of the deposition process. Typically, information is obtained about the thin-film growth from a limited assortment of sensors. These sensors measure process parameters, such as gas flow rate, chamber pressure, and evaporation-source temperature. The parameters are predetermined using empirical results to produce a film with the desired thickness, microstructure, and electronic and optical properties. The actual film properties or device characteristics are usually measured after the deposition is completed.

Improvements in both process sensors and control systems have lead to very stable operation during the time required to fabricate a thin-film device. The problems lie in the variations that occur on a day-to-day or weekly basis. Such variations in the process often lead to unpredictable changes in deposition rate or film composition, which can drastically alter the film properties. Calibration runs, which involve costly downtime, must be performed regularly to ensure and maintain device specifications.

Recent developmental efforts in process control have focused on in situ sensors to directly measure film properties during deposition. Ideally, such sensors would provide complete information about the state of the film and substrate at any instant during fabrication. This information could be used to continuously adjust process parameters to optimize film properties and correct for unexpected variations as they occur. Optical-measurement techniques are the natural choice for such sensors because they are noninvasive, can be mounted outside the deposition chamber, and are typically insensitive to the level of stray electric and magnetic fields associated with thin-film-fabrication equipment. Furthermore, many commercial thin-film-deposition processes involve high-pressure, chemically reactive environments, which make optical techniques the only viable option for in situ sensors.

The principles underlying the MOS technique are simple. Basically, a thin film under stress will induce a curvature $k = 1/R$, in the underlying substrate. Here R is the radius of curvature on the surface of the thin film. The film stress in turn can be calculated from k by a simple equation, originally developed by Stoney in 1909, that requires only knowledge of the film and substrate thickness, as well as the elastic modulus of the substrate.

Thus the challenge of the MOS technique is to accurately detect curvature in the substrate with sufficient resolution to measure the amount of stress typically found in thin films. For very thin films, on the order of tens of angstroms, this resolution may require detecting a radius of curvature as large as 10 to 20 km.

Researchers have devised various experimental approaches to measure the curvature of a surface. We will concentrate on techniques that use deflection of a beam of light from the sample surface. Consider, first, a perfectly flat sample surface. If one moves a laser beam across the surface at a constant angle, then the angle of deflection will be the same everywhere on the surface. With a curved surface, then the amount of deflection will change as the beam is transverses the sample.

In one such technique, a rotating mirror scans a laser across the sample without changing the angle of incidence. A position-sensitive detector (PSD) measures the deflection of the beam during scanning. This technique is currently used in bench-top measurement systems and even on some fabrication lines, but only as a post process diagnostic. The primary drawbacks of this approach lie in the need for precise alignment of the sample with respect to the focusing optics, and the use of a rotating mirror. Precise alignment of the sample is not possible in most deposition systems, and laser scanning is much more sensitive to vibration than a Multi-beam, stationary optic approach. A simple alternative uses a beam splitter to produce two parallel beams whose deflections are measured independently with position-sensitive detectors. Although extremely robust and offering good curvature resolution, this approach is limited to measuring only two positions on a sample.

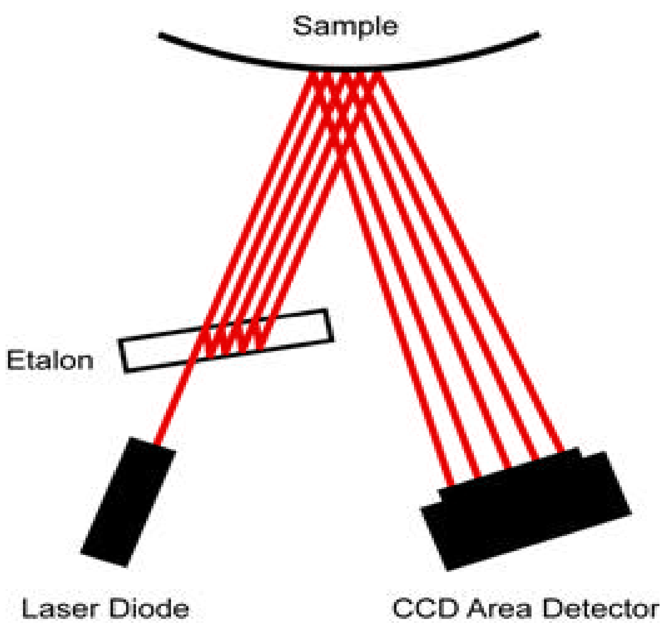

Figure 2 – An etalon placed at an angle to a laser beam generates a linear array of parallel beams. These beams reflect off the sample surface and are directly imaged by a CCD area detector.

MULTI-BEAM OPTICAL SENSOR

The Multi-beam Optical Sensor uses a variation of this technique as well as other features that simplify its use for in situ diagnostics (Figure 2). An etalon, with highly reflective dielectric coatings on each side, is placed at an angle to a laser beam. The incidence angle of the laser leads to multiple internal reflections within the etalon, which generates a linear array of parallel beams. These beams then pass through a second rotated etalon to produce a 2-dimensional array of beams. The number and spacing of these beams can be controlled by the rotation angle of each etalon. The low power (uW) array of parallel beams is then reflected from the sample surface and directly imaged with a charge-coupled device (CCD) camera.

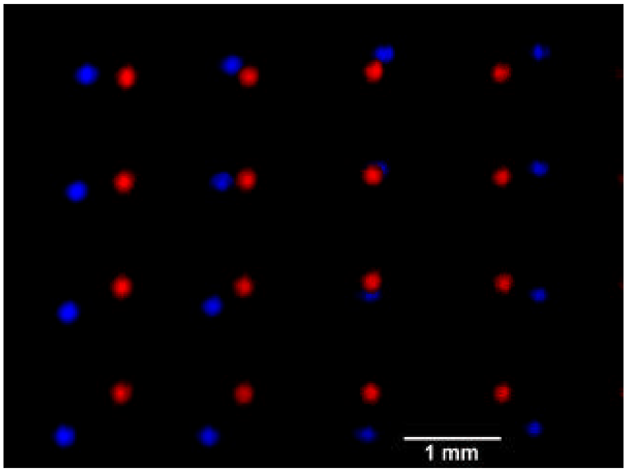

Figure 3. Superposition of a laser spot array imaged from a silicon surface before (red) and after (blue) the wafer has been stressed; maximum deflection of the surface is 5 um.

Figure 3 shows an example of the laser-array image measured by the CCD detector. The array was first reflected from an unstressed 2-in.-diameter silicon wafer. Then a force applied to the back of the wafer stressed it non-uniformly. The induced curvature caused the individual beams to reflect to slightly different positions on the detector. The relative change in spacing of all the spots was measured simultaneously by the CCD detector, and the data was then converted to represent the surface displacement or radius of curvature (Figure 4).

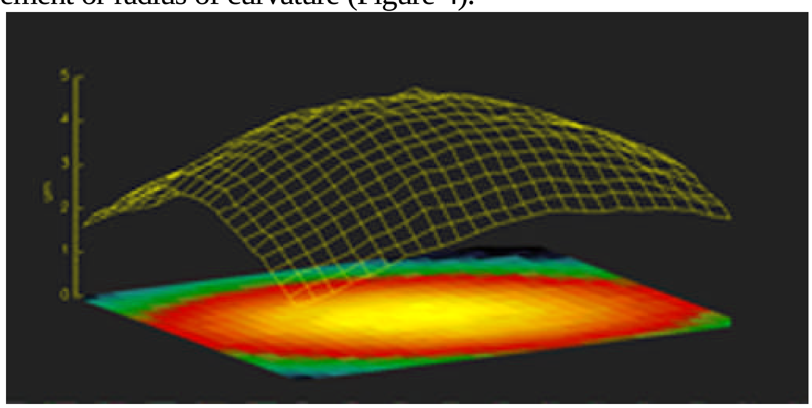

Figure 4. Surface displacement of a silicon wafer calculated from the changes in the laser spot array shown in Figure 3.

The use of a laser-beam array and CCD detector provides several benefits for in-situ measurement. The primary advantage is that the optics are simple and stationary, requiring only minimal alignment during initial setup. The ability to directly image and view the entire reflected laser array greatly simplifies use and alignment compared with other position sensitive detectors. Simultaneous detection of the array makes the measurement inherently less sensitive to sample vibration compared with scanning-mirror systems. Since all the laser spots move together at the same frequency, movement or tilt is not detected as a change of curvature. Critical to the measurement is the use of a high- resolution CCD array that enables highly accurate determination of the spot positions. Through the use of simple image processing and data-analysis algorithms, MOS can easily detect micron-size changes in spot position. This translates to a curvature detection of 10 to 20 km in the fabrication environment. Such a level of

sensitivity enables the system to detect single monolayers deposited on the substrate surface. By monitoring the entire
array of beams, two-dimensional, spatially varying curvature and stress profiles can be obtained with enough speed necessary for real-time measurement and process control.

Two major issues needed to be solved before the MOS technique could be applied as a routine diagnostic and control sensor. The first involved making the technique available to industrial deposition chambers, where the sample is continuously rotating to improve material uniformity. By placing an optical shaft encoder on the rotation stage, the CCD detector and image-acquisition electronics are triggered by the encoder to acquire an image at a preset rotation angle(s). In addition, the user can select the speed of the CCD's electronic shutter. Short shutter times (typically 1/5,000 s) yield images that are acquired over a very small rotation angle, eliminating image "blurring." In this matter, extremely stable stress and thickness data are obtained during rotation.

A second issue involves the changing reflectivity of the sample, which is a concern for all optical- based sensors. In many applications, thin films are deposited on substrates, such as silicon or gallium arsenide, which have a very different reflectance from that of the films being deposited. For example, depositing copper on a semiconductor substrate such as silicon will cause the reflectivity of the sample to increase rapidly during the first few seconds of the process. Such a change will increase the intensity of the laser spots and can easily saturate the CCD detector. When this occurs, the accuracy in determining the position of each spot on the CCD is reduced, leading to large errors in the measured stress.

This problem was solved by using a controllable diode laser. Technological advances have enabled the production of robust solid-state diode lasers operating in the visible spectrum. The output power of the laser is stable and adjustable, yielding rapid and accurate feed back control. Through additional image processing, the intensities of each reflected laser spot on the CCD detector are used as feedback control to the laser-diode controller. The intensity of the reflected array is monitored continuously and adjusted to optimize the signal at the detector.

Monitoring the intensity of the reflected laser-array can provide a wealth of additional information about the film. If the films index of refraction differs from that of the underlying substrate, then the reflected laser intensity will oscillate as the film thickness increases. The shape of the oscillations can be fitted very accurately to a model for thin-film interference of coherent monochromatic light. The fitting algorithm used is based on a "virtual interface" model that can easily handle a multilayer-film structure without precise knowledge of the positions of the film interfaces. This algorithm provides a fully automated procedure for extracting the film thickness and high-temperature optical constants, during deposition, with no prior knowledge other than the starting reflectance of the substrate. Although other accurate, in situ methods can measure optical properties and thickness of thin films, such as spectroscopic ellipsometry and spectroscopic reflectance, the intensity information provided by the single-wavelength laser array is sufficient for most applications and is simply serves as an added benefit to the MOS technique.

A number of facilities- including Motorola, Lockheed Martin, and the University of Michigan- are using the new sensor technology to monitor the deposition of compound semiconductors, oxides, nitrides, and diamond like coatings by a variety of methods such as chemical-vapor deposition (CVD), sputtering, and molecular-beam epitaxy. Sandia National Laboratory has several MOS systems in use. One monitors the stress of gallium nitride films grown on gallium arsenide. The sample rotates at 1,200 rpm, and an optical shaft encoder triggers one image acquisition per revolution, yielding near real-time stress measurement. The stress value can be relayed as a voltage signal to the CVD-control system, yielding a feedback mechanism for controlling strain and constituent composition.

B I O G R A P H Y

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