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COMPARISON OF PRISM COUPLING AND ELLIPSOMETRY FOR THIN FILM AND BULK MATERIAL CHARACTERIZATION (4/18)

Although the prism coupler and the ellipsometer can both be used to measure the index of bulk materials and to simultaneously measure film thickness and refractive index, there are major differences in the underlying measurement techniques and in the accuracy and the application range of the two instruments. As a result, ellipsometry and prism coupling can be viewed as complementary techniques, with the strengths of one supplementing the weaknesses of the other, and vice versa.

In ellipsometers, the intensity and polarization state of monochromatic light reflected from the film or bulk sample yields the measured parameters. Prism coupling measurements are based on techniques developed in the field of integrated optics, treating the thin film to be measured as an optical waveguide. The prism coupling technique works by measuring the angles at which the thin film waveguide will propagate light, and then calculating film thickness and refractive index from the observed mode angles.

Since ellipsometry can measure thinner films than the prism coupling technique, the film thickness range to be measured is the single most important factor determining whether ellipsometry or prism coupling is the preferred technique. But for measuring single or dual layers of moderate-to-thick films with thickness ranging from a few hundred nm to tens or hundreds of microns, as well as for measuring bulk materials, prism coupler measurements are typically more accurate and straightforward.

Comparison to single wavelength ellipsometers: The earliest ellipsometers typically employed a single wavelength and had a number of severe limitations compared to the prism coupling technique:

- periodicity problems: ellipsometer data is periodic with film thickness with typical period 150-250 nm. Consequently, if total film thickness is desired, film thickness must be known a priori or pre-measured using some other technique to an accuracy of ±75 nm to ±125 nm.
- periodic thickness ranges where measurements are impossible: ellipsometer measurements lose accuracy and resolution for some part of each cycle thickness. For example, for a film with index 2.0 and period 150 nm, measurements are impossible for films with thickness around 0, 150, 300, 450 nm…
- sensitivity to optical absorption: Single wavelength ellipsometers are first-order sensitive to optical absorption in measured films, and if the usual thickness-index measurement is desired, inaccuracies in measured index (and thus cycle thickness) will result if the film has even a small amount of optical absorption. This problem is compounded with thicker films, since total absorption across the full film thickness increases and the corresponding measured thickness and index inaccuracies also increase.
- thickness measuring range: Because of the periodicity of ellipsometer data and sensitivity to optical absorption, single wavelength measurements become extremely difficult for films thicker than one micron.

For all these reasons, the single wavelength ellipsometer has now been largely replaced by the spectroscopic ellipsometer (SE) which overcome most of the above disadvantages by using a continuous spectrum of wavelengths.

Advantages of spectroscopic ellipsometry over the prism coupling technique include:

Spot size: Many SE's offer small spot capabilities allowing the measurement of structures on the order of 10-20 microns. Minimum spot size for Metricon's 2010/M is ~0.5 mm, making measurement of smaller features impossible.

Contact vs non-contact measurements: The prism coupling technique requires that the sample to be measured be brought into close physical contact with the measuring prism. SE measurements are fully non-contact.

Multilayer structures: For multilayer structures, the prism coupling technique can measure at most the top two layers (and only for the case where the layer at the sample surface has index higher than the layer directly below it). The SE can measure more than two layers although the analysis is highly complex and significant advance modeling (a priori knowledge about the structure) is required for reliable solutions.

Ability to measure k: In addition to measuring n, SE's can also measure k, the imaginary part of the refractive index (which determines optical absorption) while the basic prism coupling technique only provides n, the real part of the index. On the other hand, for optical waveguide structures (i.e., films on lower index substrates), the prism coupling technique can measure waveguide loss which is sensitive to both absorption (k) and scattering losses in the film. In some cases, the waveguide loss measurement can be used to place an upper limit on the k value for the film.

Advantages of the prism coupling technique over spectroscopic ellipsometry include:

Refractive index resolution/accuracy: For both thin films and bulk materials, the Model 2010/M offers a routine refractive index resolution of ±0.0003 and an absolute accuracy of ±.0005. For samples of reasonable optical quality, if the user is willing to perform a one-time calibration procedure with each prism, absolute index accuracy of □±0.0001-0.0002 and resolution of ±0.00005 is achievable. This level of index accuracy and resolution is not attainable by any other film measurement technique.

Simplicity of data analysis: In the prism coupling technique, while the equations which extract thickness and index from the measured optical propagation modes are not simple, these equations have a unique solution and they can be solved by a typical PC in less than a second. SE data analysis, on the other hand, is quite complex and the fitting procedures which extract the optical parameters from the raw SE data often take minutes (or tens of minutes). In addition, many users report that to achieve reliable results with their SE's they must start with refractive index data for one or two wavelengths (which they often measure with their Metricon system) and then the SE will "lock on" to the correct solution.

No advance knowledge required: In the prism coupling technique, no advance knowledge is required about the film or underlying layer (substrate or thin film). SE measurements require significant advance knowledge (modeling) about the film and are quite sensitive to the optical properties of the substrate or underlying layers.

Tolerance of poor sample quality: For both thin films and bulk materials, the prism coupling technique is extremely tolerant of sample quality problems including haze, poor surface polish/roughness, flatness, and rapid thickness variation.

Insensitivity to optical properties of substrates: SE measurements are sensitive to the real and imaginary parts of the substrate refractive index. If these parameters are not known, or modeled accurately, or if they vary due to roughness or other surface conditions, appreciable errors can result. The prism coupling technique is only weakly sensitive to the real part of the substrate index and insensitive to the imaginary part. For the case of a low index film over a higher index substrate it is only important for the Model 2010/M to know that the index is higher -- the exact index is unimportant. For the case of a film over a lower index substrate, thickness and index as measured by prism coupling are weakly dependent on the real part of the substrate index only, but if substrate index is not known in advance, it can be determined during the measurement of the film.

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Wide tolerance of substrate types, imperfections, and shapes: Prism coupling measurements are easily made on metal, dielectric, crystalline, semiconductor, or polymer substrates. Films on transparent substrates (which can cause troublesome back-reflections for SE's) are easily measured. The prism coupling technique is also much more tolerant of substrate imperfection/roughness – for example, prism coupling measurements have been made on films over printed circuit board composites, ceramics, brushed metal surfaces, and smooth paper. Measurements can also be made on concave surfaces (e.g., lenses) and on flexible polymer materials.

Advantages for characterizing waveguides: For optical waveguiding work, the prism coupling technique provides much greater insight into the waveguiding properties of films because it uses waveguiding techniques (i.e., it measures films by exciting their optical propagation modes). For example, the prism coupling technique can be used to determine the number of optical propagation modes a film possesses, how close the modes are to cutoff, how much light can be coupled into the mode, and the mode propagation loss (in db/cm). In addition, it is also possible to gain considerable insight about the waveguide properties just by looking at the shape of the mode spectrum. For graded index guides (for example, lithium niobate or ion exchanged glass guides), the Model 2010/M can even calculate the profile of index vs depth.

"Spectroscopic" results from index measurement at a few discrete wavelengths: Because the Model 2010/M measures index at only one or a few discrete wavelengths, it would seem at first that SE's, which provide a continuous index vs wavelength curve, offer a significant advantage for measuring dispersion. However, Metricon has recently developed innovative fitting software which can create extremely accurate continuous curves of index vs wavelength from measurements at only a few (3-5) wavelengths. Specifically, for both thin films and bulk materials with index 2.0 or below, the new fits have a maximum error of □±0.00005, an order of magnitude lower than the error provided by conventional fits (the accuracy of these new fitting techniques have been tested with the entire Schott and Ohara glass catalogs and with several crystalline materials). As a result, the total index error for any point on the index vs wavelength curve will not exceed the index error at the measured wavelengths (□±.0002) plus the fitting error (±0.00005), for a total error of ±0.00025. This means that index values at any intermediate wavelength on the curve will have nearly the same accuracy as if a laser had been used to measure the index at that wavelength. Specific three-laser Model 2010/M configurations are available to cover the 400-700 nm visible wavelength range as well as the 633-1550 nm range. A four-laser system covers the 400-1000 nm range and a five laser system covers the full visible to near-IR range (400-1550 nm). Each of these systems will provide index accuracy of ±0.00025 over the full wavelength range for materials with index up to 2.0. For higher index materials, please consult Metricon for specifications.

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