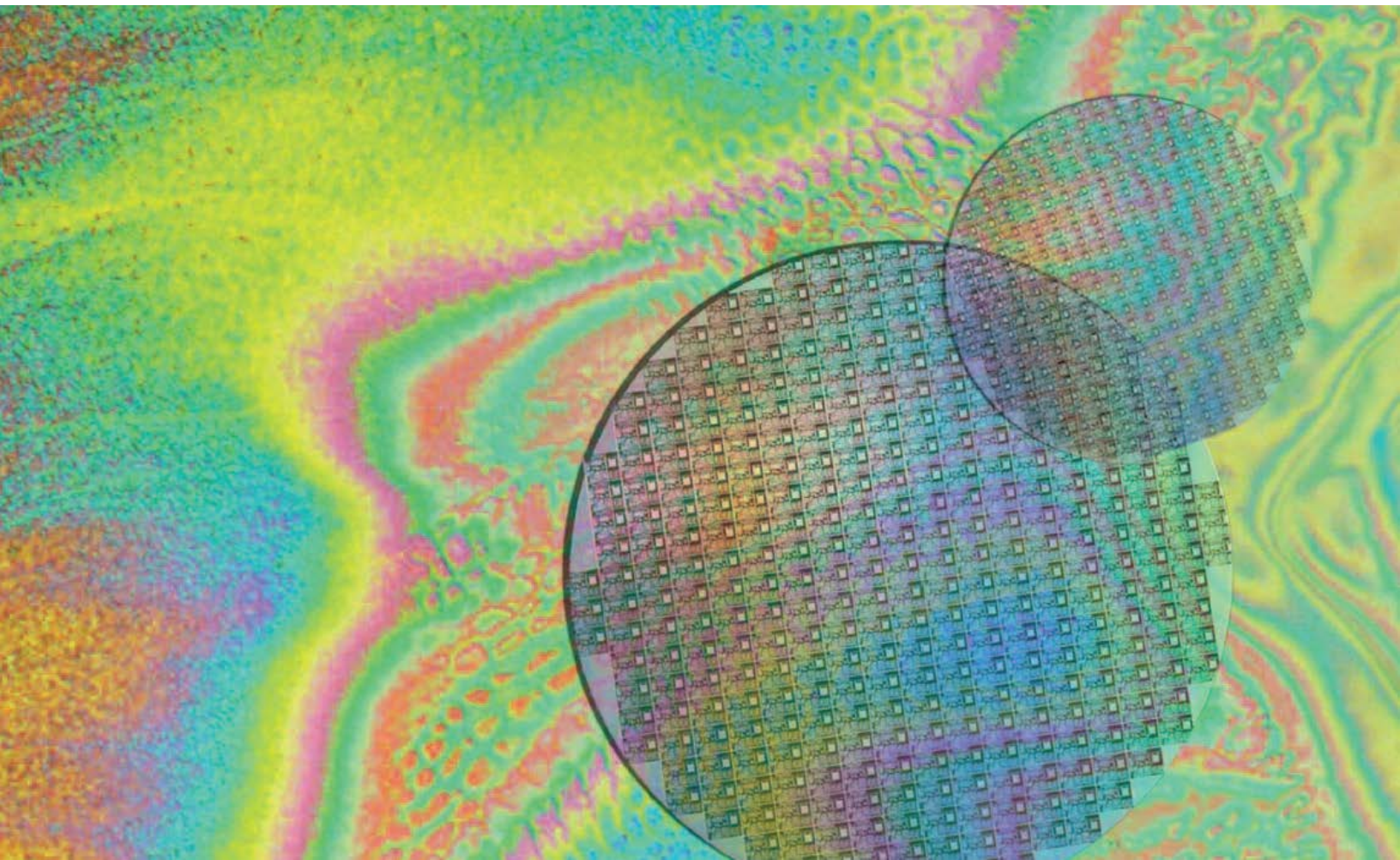
KLA INSTRUMENTS

Taking the Mystery Out of Thin-Film Measurement

Filmetrics® Advanced Thin-Film Measurement Systems



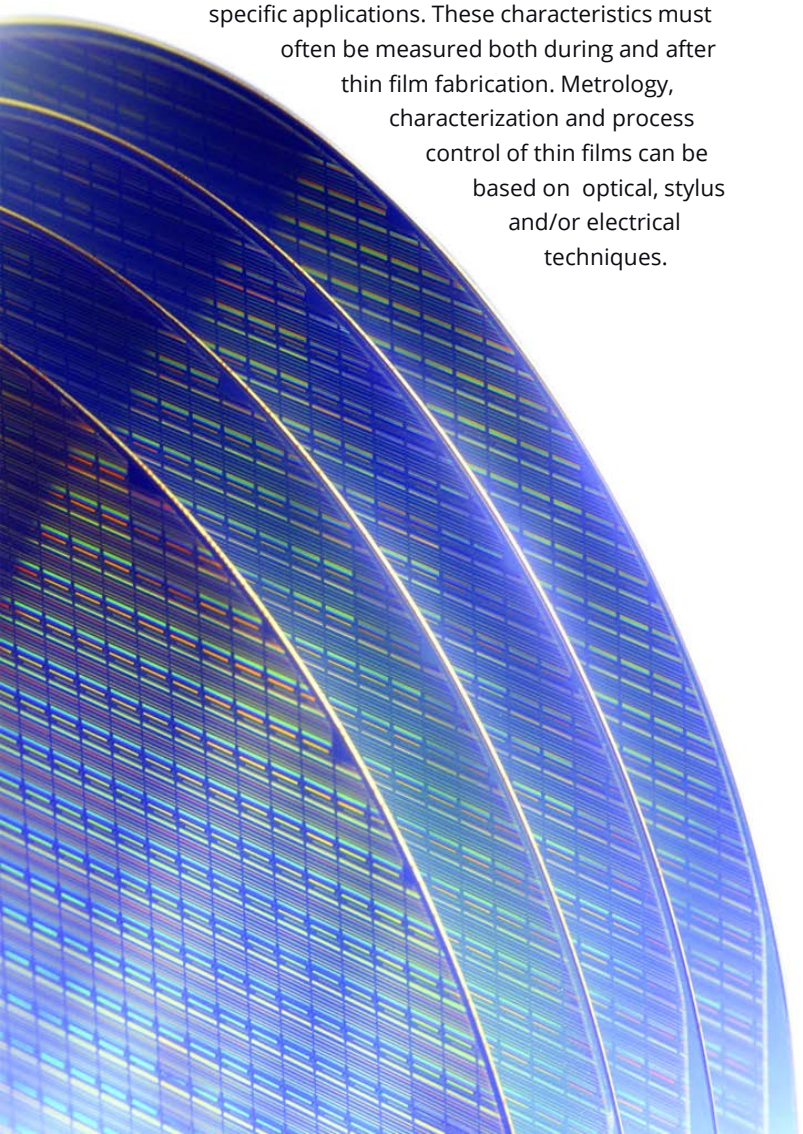
Thin-Film Measurement

Introduction to Thin Films

Thin layers of material that are deposited on the surface of another material (thin films) are extremely important to many technology-based industries. Thin films are widely used, for example, to provide passivation, insulating layers between conductors, diffusion barriers and hardness coatings for scratch and wear resistance. The fabrication of integrated circuits consists primarily of the deposition, device formation and selective removal of different types of thin films.

Films typically used in thin-film applications range from a few atoms (< 1nm or 0.001µm) to 100µm thick. They can be formed by many different processes, including spin coating, vacuum evaporation, sputtering, epitaxial growth, vapor deposition and other techniques.

To perform the functions for which they were designed, thin films must have the proper thickness, composition, roughness and other characteristics important to specific applications. These characteristics must often be measured both during and after thin film fabrication. Metrology, characterization and process control of thin films can be based on optical, stylus and/or electrical techniques.



Stylus measurements measure thickness and roughness by monitoring the deflections of a fine-tipped stylus as it moves along the surface of the film. Stylus measurements are often the preferred method when measuring opaque films, such as metals.

Optical techniques determine thin-film characteristics by measuring how the films interact with light. Optical techniques can measure the thickness, roughness and optical constants of a film. Optical constants describe how light propagates through and reflects from a material. Once known, optical constants may be related to other material parameters, such as composition and band gap.

Optical techniques are usually the preferred method for measuring thin films because they are accurate, nondestructive, and require little or no sample preparation. The two most common optical measurement types are spectral reflectance and ellipsometry. Spectral reflectance measures the amount of light reflected from a thin film over a range of wavelengths, with the incident light normal (perpendicular) to the sample surface. Ellipsometry is similar, except that it measures reflectance at non-normal incidence and at multiple polarizations. In general, spectral reflectance is much faster, simpler and less expensive than ellipsometry, but it is restricted to measuring less complicated structures.

n and *k* Definitions

Optical constants (*n* and *k*) describe how light propagates through a film. In other words, the electromagnetic field that describes light traveling through a material at a fixed time is given by:

$$A \cdot \cos\left(n\frac{2\pi}{\lambda}x\right) \cdot \exp\left(-k\frac{2\pi}{\lambda}x\right)$$

where ***x*** is distance, ***λ*** is the wavelength of light, and ***n*** and ***k*** are the film's refractive index and extinction coefficient, respectively. The refractive index is defined as the ratio of the speed of light in a vacuum to the speed of light in the material. The extinction coefficient is a measure of how much light is absorbed in the material.

Spectral Reflectance Basics

Single Interface

Reflection occurs whenever light crosses the interface between different materials. The fraction of light that is reflected by an interface is determined by the discontinuity in ***n*** and ***k***. For light reflected off a material in air,

$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2} = \left|\frac{(n-1)}{(n+1)}\right|^2$$

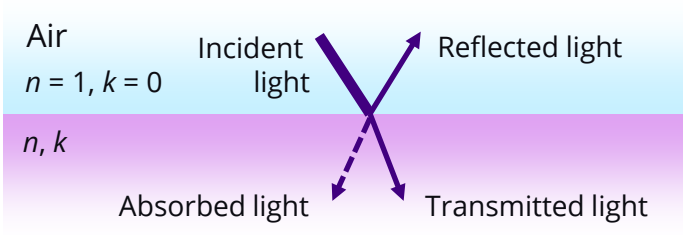


Figure 1. Light schematic.

To see how spectral reflectance can be used to measure optical constants, consider the simple case of light reflected by a single non-absorbing material (***k*** = 0)**.**

Clearly, ***n*** of the material can be determined from a measurement of ***R***. In real materials, ***n*** varies with wavelength (i.e., real materials exhibit dispersion), but since the reflectance is known at many wavelengths, ***n*** at each of these wavelengths is also known, as illustrated below.

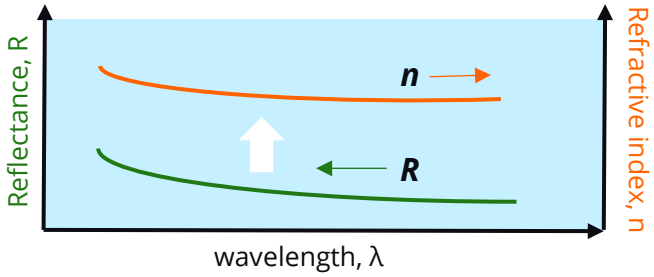


Figure 2. Reflectance, R, and index of refraction, n, vary with wavelength.

Multiple Interfaces

Consider now a thin film on top of another material. In this case, both the top and bottom surfaces of the film reflect light. The total amount of reflected light is the sum of these two individual reflections.

Because of the wavelength nature of light, the reflections from the two interfaces may add together either constructively (intensities add) or destructively (intensities subtract), depending upon their phase relationship. The phase relationship is determined by the difference in optical path lengths of the two reflections, which in turn is determined by the thickness of the film, its optical constants and the wavelength of the light. Reflections are in-phase and therefore add constructively when the light path is equal to one integral multiple of the wavelength of light. For light perpendicularly incident on a transparent film, this occurs when 2***nd*** = ***iλ***, where ***d*** is the thickness of the film and ***i*** is an integer (the factor of two is due to the light passing through the film twice). Conversely, reflections are out of phase and add destructively when the light path is a half-wavelength different from the in-phase condition, or when 2***nd*** = (***I*** + ½)/***λ***. The qualitative aspects of these reflections may be combined into the single equation:

$$R = A + B \cdot \cos(4\pi n\, d/\lambda)$$

From this equation, we can see that the reflectance of a thin film will vary periodically with 1/wavelength, which is illustrated below. Also, thicker films will exhibit a greater number of oscillations over a given wavelength range, while thinner films will exhibit fewer oscillations (often only part of an oscillation) over the same range.

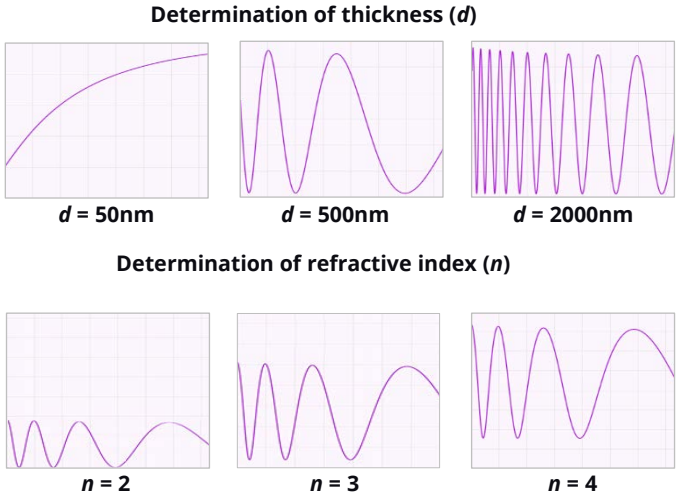


Figure 3. (top) Reflectance, R, as a function of wavelength, for film thickness values of 50nm, 500nm and 2,000nm; (bottom) refractive index, n, as a function of wavelength, for materials with nominal values of n = 2, n = 3, and n = 4.

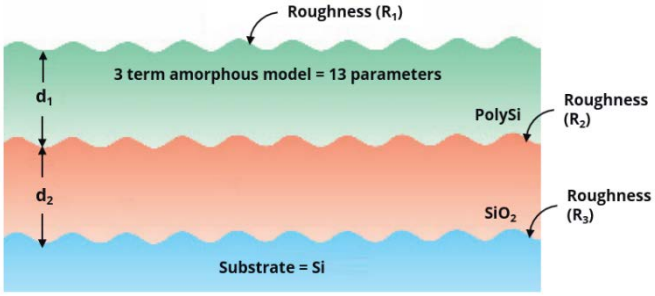
Determining Film Properties from Spectral Reflectance

The amplitude and periodicity of the reflectance of a thin film are determined by the film's thickness, optical constants and other properties such as interface roughness. In cases where there is more than one interface, it is not possible to solve for film properties in closed form, nor is it possible to solve for ***n*** and ***k*** at each wavelength individually. In practice, mathematical models are used that describe ***n*** and ***k*** over a range of wavelengths using only a few adjustable parameters. A film's properties are determined by calculating reflectance spectra based on trial values of thickness and the ***n*** and ***k*** model parameters and then adjusting these values until the calculated reflectance matches the measured reflectance.

Models for *n* and *k*

There are many models for describing ***n*** and ***k*** as a function of wavelength. When choosing a model for a particular film, it is important that the model be able to accurately describe ***n*** and ***k*** over the wavelength range of interest using as few parameters as possible. In general, the optical constants of different classes of materials (e.g., dielectrics, semiconductors,

metals, amorphous materials) vary quite differently with wavelength and require different models to describe them (see below). Models for dielectrics (***k***= 0) generally have three parameters, while non-dielectrics generally have five or more parameters. As an example, to model the two-layer structure shown below, a total of 18 adjustable parameters must be considered in the solution.



$n(\lambda) = A + B/(\lambda^2) + C/(\lambda^4)$

$k(\lambda) = 0$

Figure 4. Model for a two-layer structure with roughness at each surface.

Mathematical Models for *n* and *k*

Cauchy: Fitting parameters: A, B, C (total of 3)

$$\varepsilon_2(E) = 2nk = \sum_{i=1}^{j=1,2 \text{ or } 3} \frac{A_i C_i E_{0i} (E-E_{gi})^2}{(E^2-E_{0i}^2)^2+C_i^2E^2} \bullet \frac{1}{E} \quad \text{if } E > E_g, \text{ or } = 0 \text{ if } E < E_g$$

$$\varepsilon_1(E) = n^2 - k^2 = \varepsilon_1(\infty) + \frac{2P}{\pi} \int_0^\infty \frac{s\varepsilon_2(s)}{s^2-E^2} ds \quad \text{(Kramers-Kronig)}$$

Amorphous Semiconductor: Fitting parameters: $\varepsilon_1(\infty)$, A_1, B_1, E_{g1}, E_{01}, ... (total of 5, 9 or 13)

$$\varepsilon_2(E) = 2nk = \sum_{i=1}^{j=1,2 \text{ or } 3} \frac{A_i}{B_i+(E-E_{0i})^2}$$

$$\varepsilon_1(E) = n^2 - k^2 = \varepsilon_1(\infty) + \frac{2P}{\pi} \int_0^\infty \frac{s\varepsilon_2(s)}{s^2-E^2} ds \quad \text{(Kramers-Kronig)}$$

Crystalline Semiconductor: Fitting parameters: $\varepsilon_1(\infty)$, A_1, B_1, E_{01}, ... (total of 4, 7 or 10)

Number of Variables, Limitations of Spectral Reflectance

Spectral reflectance can measure the thickness, roughness and optical constants of a broad range of thin films. However, if there is fewer than one reflectance oscillation (i.e., the film is very thin), there is less information available to determine the adjustable model parameters. Therefore, the number of film properties that may be determined decreases for very thin films. If one attempts to solve for too many parameters, a unique solution cannot be found; more than one possible combination of parameter values may result in a calculated reflectance that matches the measured reflectance.

An example of the reflectance from a very thin film, 5nm of SiO_2 on silicon is shown below, where it is compared to the reflectance from a bare silicon substrate. In this case, measuring the thickness, roughness and *n* of the SiO_2 requires five parameters to be determined. Clearly, the change in the spectra caused by adding 5nm SiO_2 does not require five parameters to describe, and a unique solution can only be found ifthin some additional assumptions are made.

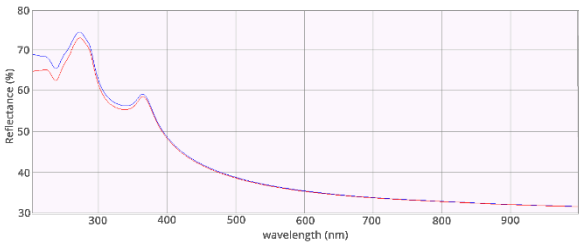


Figure 5. Modeled reflectance of 5nm SiO_2 on silicon (red) vs. bare silicon (blue).

Depending upon the film and the wavelength range of the measurement, the minimum single-film thickness that can be measured using spectral reflectance is in the 1-30nm range. If one is trying to also measure optical constants, the minimum thickness increases to 10-200nm, unless minimal parameterization models can be used. When solving for the optical properties of more than one film, the minimum thicknesses are increased even further.

Spectral Reflectance vs. Ellipsometry

Given the restrictions listed above, spectral reflectance can be used to measure a large percentage of technologically important films. However, when films are too thin, too numerous or too complicated to be measured with spectral reflectance, they can often be measured with the generally more powerful technique of spectroscopic ellipsometry. By measuring reflectance at non-normal incidence (typically ~ 75° from normal), ellipsometry is more sensitive to very thin layers and the two different polarization measurements provide twice as much information for analysis. To carry the idea even further, variable-angle ellipsometry can be used to take reflectance measurements at many different incidence angles, thereby increasing the amount of information available for analysis.

The following sections of this brochure describe Filmetrics® spectral reflectance systems available from KLA Instruments™. If you are uncertain whether spectral reflectance or ellipsometry is appropriate for your film measurements, please call us at +1 (858) 573-9300 to discuss your application. If spectral reflectance cannot satisfy your needs, we will be happy to refer you to a reputable source for ellipsometry.

Thin-Film Measurements on Your Benchtop

Thickness, refractive index and extinction coefficients are measured quickly and easily with Filmetrics advanced spectrometry systems. Simply plug the Filmetrics system into your computer's USB port and start making measurements. The entire system sets up in minutes and measurements can be made requiring little more than basic computer skills. The simple hardware and intuitive software provide knowledge to a whole new group of users.

From Near-Infrared to Ultraviolet

Systems are available with wavelengths from 190–1700nm, enabling thickness measurements of films 1nm – 3mm. The Filmetrics systems measure transparent thin films made from all common materials.

Easy to Use Software

The user-friendly interface of the Filmetrics FILMeasure® software is quickly mastered, and film thickness measurements take about one second. Measured data, along with measurement details, are easily saved and exported to standard file formats. Plus, a public .NET Assembly allows for easy integration with other programs.

Complex Measurements Made Simple

Both the measured (blue) and calculated (red) reflectance spectra are displayed so that the integrity of the measurement may easily be judged. The measured *n* and *k* curves may also be plotted.

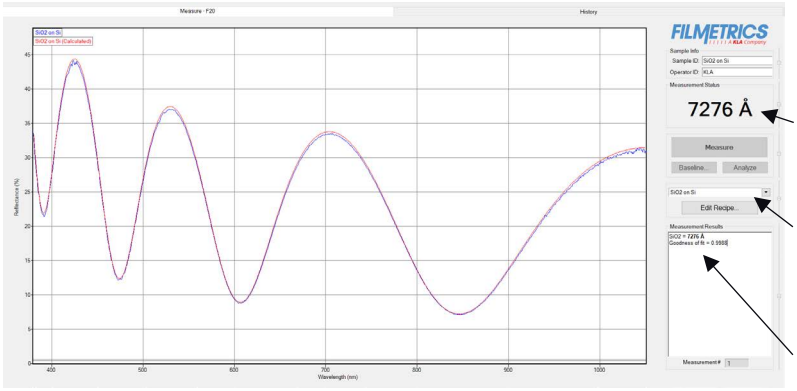


Figure 5. Measured and calculated spectra are displayed for SiO_2 on silicon. A wide range of reflectance wavelengths are available, from 190 – 1700nm.

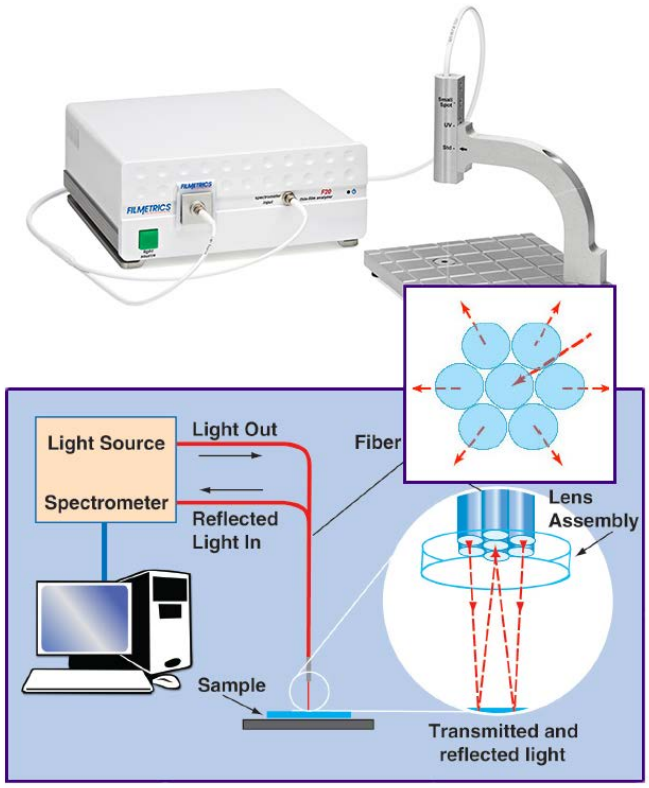


Figure 6. Spectral reflectance schematic.

Award-Winning Products

R&D 100 Award

The Filmetrics in situ system, Model F30, was selected as one of the 100 most technologically significant new products by R&D magazine.

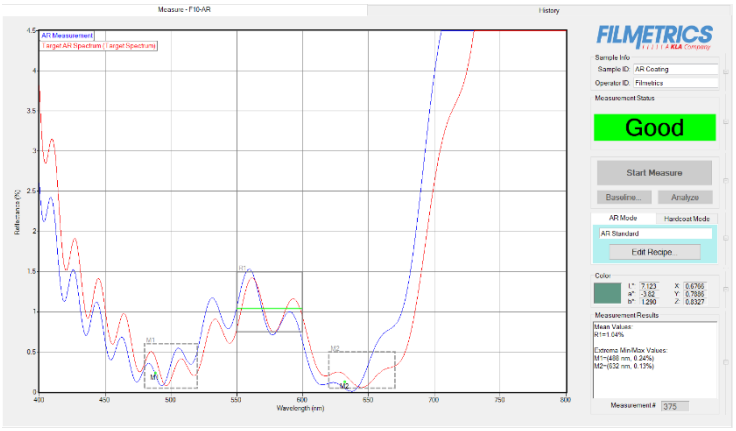
Photonics Spectra Circle of Excellence

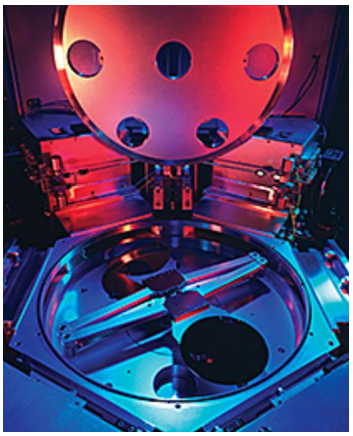
The Filmetrics F20 was chosen as one of the 25 most significant new products by Photonics Spectra magazine.

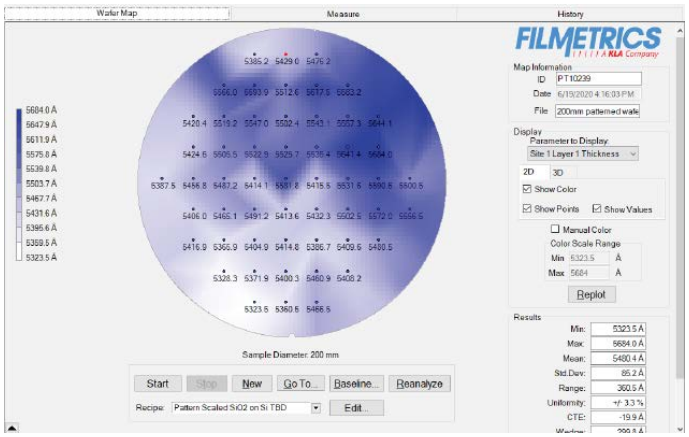
Real World Applications

Semiconductor Process Films

Filmetrics measurement systems are routinely used to measure the thickness, roughness and optical constants of oxides, Si_xN_y, photoresist and other semiconductor process films. In addition to these single layer applications, many two- and three-layer film measurements are also possible. An example is polysilicon/SiO_2 on silicon, which is used in silicon-on-insulator (SOI) applications.







In Situ Measurements

The flexible optical probe assembly makes inline and in situ thickness measurements possible. All that is required is optical access for normal incidence reflectance measurements. Call us at +1 (858) 573-9300 or contact us through our website for more details about interfacing with your production equipment.

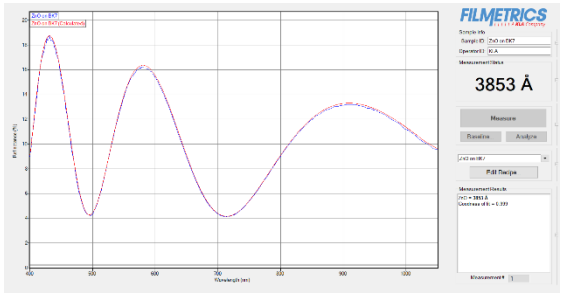
Optical Coatings

Thin films are used for scratch resistance and/or anti-reflection coatings in many industries. Automotive plastics, eyeglass lenses and many plastics packaging applications use thin films. For hardcoats, a primer layer is often applied first for improved film adhesion. Filmetrics systems are capable of measuring the thickness of these layers individually or as a full stack, regardless of the presence of coatings on the backside of the sample.



Display Films

The thickness and uniformity of display films such as polyimide, photoresist, indium tin oxide (ITO) and transparent conducting oxide (TCO), are critical to yield in mobile and display device manufacturing. Besides measuring these materials, Filmetrics systems can also measure cell gap spacing for both empty and filled cells.



Filmetrics F20 Thin-Film Analyzer



Thin-Film Measurements in Seconds

Benchtop measurements of thickness, optical constants (n and k) and transmittance are made quickly and easily by the Filmetrics F20. This versatile hardware can be configured to measure transparent or translucent films that are 1nm to 450µm in thickness. Typical accuracy is within a few angstroms. Spot size is adjustable over a wide range. Setup takes mere minutes by a USB connection, and measurements take under a second.

Accessories

A wide range of stages, chucks and specialized measurement heads are available to accommodate most sample geometries.

Cost-Effective Metrology

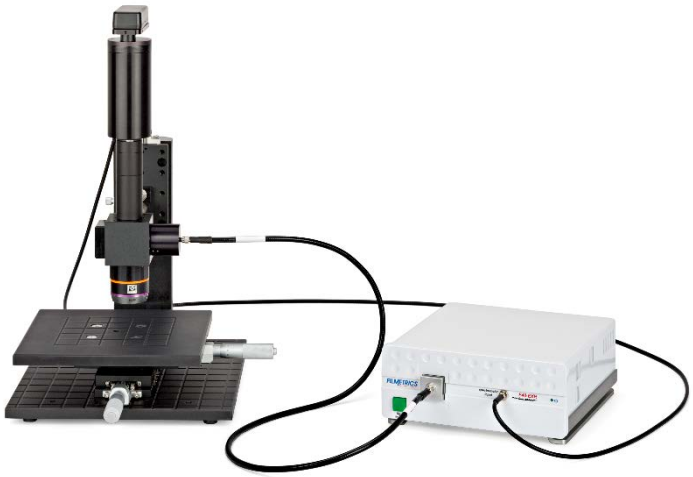
The formerly difficult and expensive task of thin-film measurement is now simple and inexpensive using the F20.

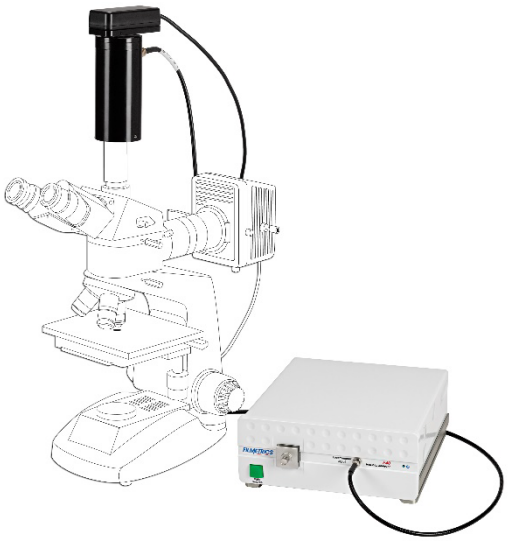
Filmetrics F40 Thin-Film Analyzer

Turns Your Microscope into a Film Thickness Measurement Tool

For measurements on patterned surfaces and other applications that require a small spot size (as small as 1µm with optional hardware), the F40 is available as an add-on to your existing microscope. Step-through calibration for each objective lens provides precise absolute reflectance across the spectrum, resulting in optimum thickness accuracy and enabling the measurement of the refractive index. For common microscopes, the F40 is a simple bolt-on attachment, complete with a C-mount and camera. Integrated video provides an on-screen display of the sample as well as the measurement location.

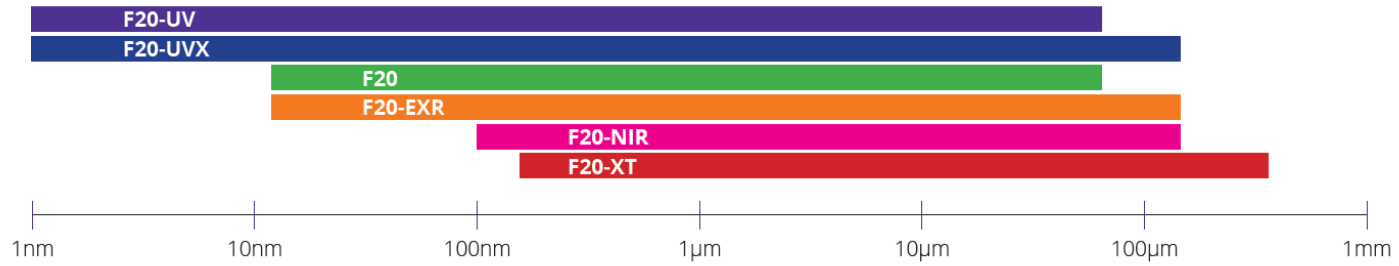
Thickness and optical constants are measured quickly and easily with Filmetrics advanced spectrometry systems. Spectral analysis of reflectance from the top and bottom of the thin film provides results in seconds.





Filmetrics F20 Specifications

Thickness Measurement Range



General Specifications	F20-UV	F20-UVX	F20	F20-EXR	F20-NIR	F20-XT
Spectrometer Wavelength Range	190-1100nm	190-1700nm	380-1050nm	380-1700nm	950-1700nm	1440-1690nm
Light Source	External, D2 + Halogen		Internal, Halogen			

Measurement Specifications	F20-UV	F20-UVX	F20	F20-EXR	F20-NIR	F20-XT
Thickness Measurement Range*	1nm – 40µm	1nm – 250µm	15nm – 70µm	15nm – 250µm	100nm – 250µm	0.2µm – 450µm
Min. Thickness to Measure n&k*	50nm	50nm	100nm	100nm	500nm	2µm
Accuracy*: the greater of	1nm or 0.2%	1nm or 0.2%	2nm or 0.2%	2nm or 0.2%	3nm or 0.4%	5nm or 0.4%
Precision[1]	0.02nm	0.02nm	0.02nm	0.02nm	0.1nm	1nm
Stability[2]	0.05nm	0.05nm	0.05nm	0.05nm	0.12nm	1nm
Spot Size	Standard 1.5mm, Optional down to 20µm					600µm
Sample Size	From 1mm to 300mm diameter and up					

General Requirements	
Power	100-240VAC, 50 - 60Hz, 0.3 - 0.1A
Computer Interface	USB 2.0
Certifications	CE EMC and Safety Directives

Operating System	
PC	Windows 10 – Latest Windows (64-bit)
MAC	macOS Catalina – Latest macOS running Parallels

*Material dependent.

[1] 1σ of 100 measurements of 500nm SiO_2-on-Si. Average of 1σ over 20 successive days.

[2] 2σ of daily average of 100 measurements of 500nm SiO_2-on-Si over 20 successive days.

Filmetrics F50 Thin-Film Mapping Analyzer



Automated Thin-Film Thickness Mapping System

Thin-film thickness of samples up to 450mm in diameter are mapped quickly and easily with the F50 advanced spectral reflectance system. The motorized r-theta stage moves automatically to selected measurement points and provides thickness measurements as fast as two points per second. The F50 stage delivers high precision and high reliability.

Choose one of dozens of predefined polar, rectangular, or linear map patterns, or create your own with no limit on the number of measurement points. The entire desktop system is set up in minutes and includes easy-to-use, intuitive software.

Filmetrics F54-XY



Automated Thin-Film Thickness Mapping for Patterned Samples

Building on Filmetrics industry-leading thin-film metrology expertise, the compact benchtop F54-XY systems bring precision measurement positioning to production applications. Optional pattern recognition enables measurement automation and minimizes time-to-results.

The F54-XY is available in the F54-XY-200 or F54-XYT-300 configurations to support wafers up to 200mm and 300mm diameters, respectively. The wavelength range is configurable to accommodate a variety of film thickness ranges. Samples are easily mapped with an advanced spectral reflectance system and Filmetrics industry-leading solving algorithms.

Choose from dozens of predefined polar, rectangular, and linear map patterns or import your own with no limit on the number of measurement points. The desktop system is plug-and-play with an easy guided recipe setup that enables wafer mapping in minutes.

Optical Profiler Solutions from KLA Instruments

Filmetrics Profilm3D® and Zeta™ Optical Profiling Systems

The Profilm3D and Profilm3D-200 are affordable, state-of-the-art optical profilers. The Profilm3D family of profilers uses white light interferometry (WLI), phase shifting interferometry (PSI) and Enhanced Roughness Mode to produce high quality 3D surface measurements, profiles, and True-Color images. The latest Profilm3D platform is designed to measure from the smoothest of surfaces to highly rough and steeply-sloped samples. The tool's flexibility enables measurements from polished optics to microfluidics channels, circuit boards, biological samples, biomedical devices, solar cells, and micromachining.

The Zeta-20 optical profiler is a non-contact, 3D surface topography benchtop measurement system in a compact, robust package. The system is powered by ZDot™ technology and Multi-Mode optics, enabling measurement of a variety of samples: transparent and opaque, low to high reflectance, smooth to rough texture, and step heights from sub-nanometer to millimeters. The Zeta-20 supports both R&D and production environments by providing comprehensive step height, roughness and film thickness measurements, plus defect inspection capability. The Zeta-Solar is a dedicated optical profiler specifically designed for the unique requirements of advanced metallization finger and busbar solar process metrology, as well as next generation development.

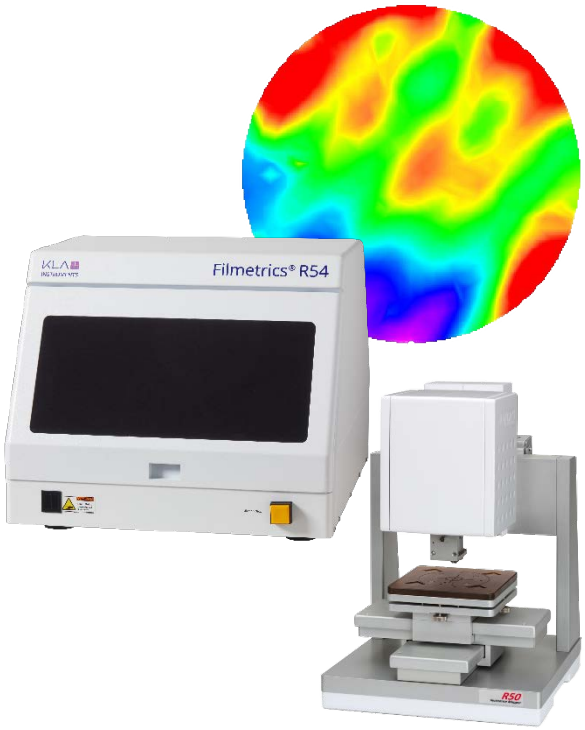


R Series Sheet Resistance Mapping Systems

Automated Thin-Film Thickness Mapping for Metal Films

Sheet resistance monitoring is critical to any industry that utilizes conductive films, from semiconductor manufacturing to the flexible electronics required to enable wearable technology. Since the introduction of our first resistivity gauge in 1975, the KLA family of companies has revolutionized the measurement of both sheet resistance and thickness for conductive layers.

The Filmetrics R Series represents a culmination of over 45 years of sheet resistance technology leadership. The R50 provides automated mapping for samples up to 200mm in diameter and 60mm in height. The R54 design includes a light-tight enclosure and supports samples up to 300mm in diameter and up to 15mm in height. The R Series capabilities are optimized for metal film uniformity mapping, ion implant doping and anneal characterization, film thickness and resistivity mapping, and non-contact film thickness measurement with eddy current detection.



The KLA Instruments™ Family

The KLA Instruments™ group within the KLA Corporation includes our Labs and Fabs metrology suite. Lab tools are primarily benchtop systems and include the Alpha-Step® D-Series and Tencor® P-Series stylus profilers, the Zeta™-20, Zeta-Solar and Zeta-300 optical profilers, the Nano Indenter® product group, and the Filmetrics suite of measurement equipment, which includes the thin-film measurement systems, the R50-Series and R54-Series sheet resistance mappers, and the Profilm3D® optical profiler. Fab tools are designed for automation and production environments and include the HRP®-260 and Tencor P-170 stylus profilers, the Zeta-388 optical profiler and the Filmetrics F60-c film thickness mapper.

Labs

Optical Profilers



Profilm3D®



Zeta™

Stylus Profilers



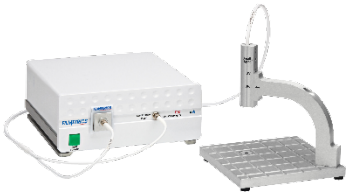
Tencor® P-Series



Alpha-Step®

Thin-Film Metrology





Filmetrics® F-Series

Nano Indenter®



G200X, iNano®, iMicro

Resistivity



R50, R54-Series

Fabs

Automated Metrology





Stylus Profilometry



Optical Profilometry



Film Thickness

HRP®, Tencor®, Zeta™, Filmetrics®



KLA SERVICES
From tool installation and system optimization to productivity enhancements and global supply chain management, KLA Services is a trusted partner to customer around the world – delivering an unrivaled experience focused on maximizing tool performance and availability.

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KLA Instruments
10655 Roselle Street
San Diego, CA 92121
www.kla-instruments.com
www.kla-instruments.cn
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