Simultaneous Reflection and Transmission Measurements of Scandium Oxide Thin Films in the Extreme Ultraviolet

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Introduction

Materials science at the nanoscale has been an active facet of physics research in recent years as consumers drive the electronics industry to deliver smaller, faster devices. To satisfy demand, industry has had to respond with advances in lithographic techniques that would allow for the fabrication of increasingly smaller features in their semiconductors. This is achieved by employing slightly more energetic light with each new generation of lithographic processes. In order to be able to use shorter wavelengths of light, researchers are asked to reveal the mysteries of how materials behave optically in the Extreme Ultraviolet (EUV). However, the EUV is a complicated regime, as all materials readily absorb photons of these energies. Also, the wavelengths of photons in the EUV are of the same order as nanoscopic physical features which sometimes appear in thin films (diffusion between materials, surface roughness, and grain sizes), such that consideration must be given to their presence for a complete description of the photon/material interaction to be developed.

Interest in EUV optics is not limited to the semiconductor industry, though. Any task that involves detecting or imaging EUV light would be greatly aided by having highly reflective optical coatings for the photon manipulation. These areas include x-ray astrophysics, development and use of EUV lasers, plasma imaging, and attosecond metrology.

In 1998, Russian researchers led by Y. Uspenskii theorized the use of scandium in multilayer mirrors could provide a reflectivity of 72% of 42 nm light. Since then, several researchers have become active in studying scandium thin films in the EUV, to the degree that at the 2004 International Society for Optical Engineering Annual Meeting, an entire session of the Optical Constants of Materials for UV to X-Ray Wavelengths talks was dedicated to discussing scandium thin films. The experimental research done with scandium to produce highly reflective coatings, however, has yet to realize the theoretical predictions, since the highest measured reflectivity is 47%.

Despite all the interest in scandium thin films, no published work exists describing the performance of scandium oxide thin films in the EUV. This is truly odd given that scandium metal immediately oxidizes upon exposure to the atmosphere, such that it is expected that any lone, exposed scandium thin film is only accurately described when the presence of the oxide is acknowledged. Also, the properties which make scandium a choice material for use in optical coatings may also be present in scandium oxide, and study of this unknown material in the EUV is worthwhile in the sense that it may also be a material worth considering for use in multilayer coatings.

This project intends to study thin films of scandium oxide in the extreme ultraviolet. The goal is to experimentally determine the EUV optical constants for scandium oxide thin films, so that the optical performance of these films can be accurately described. These constants are necessary to supplement the analysis of the performance of scandium thin films, and will also provide insight into the potential use of scandium oxide thin films in future coating schemes.

Experiment

Reactive sputtering was used to deposit the thin films for this project on a variety of substrates. By preparing samples in this way, the atoms of scandium used to form the coating pass through an oxygen-rich environment as they move towards the substrate, so that the material deposited is scandium oxide. Sputtering is done in a high vacuum chamber, which is pumped to $4\cdot10^{-6}$ torr before the process is begun to ensure a clean growth environment.

Preliminary work to establish the growth rate of scandium oxide thin films involved the deposition of scandium oxide on silicon substrates, which were analyzed using variable angle spectroscopic ellipsometry. Optical grade quartz was also coated with thin films of scandium oxide, allowing for ellipsometry to be done using transmission data, also. Later samples involved the deposition of the thin films directly upon the face of silicon photodiodes. Using the sputter rates determined through the ellipsometric studies, the thicknesses of these films were calculated. The coated photodiodes are dedicated for study at the Advanced Light Source (ALS), Beamline 6.3.2, where EUV measurements of the films are made. At the ALS, data is collected using the simultaneous reflection and transmission data collection technique, recently developed by the BYU thin films research team. Figure 1 illustrates this method.

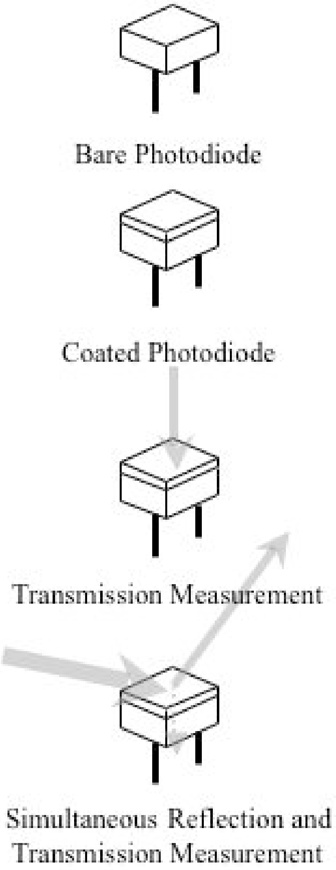

Figure 1

The detection face of a photodiode is coated with a thin film to be studied. In doing so, the signal reported by the photodiode corresponds to photons that have traveled through the thin film. When the incoming light is at a non-normal angle, some of the light will be reflected from the surface. With the use of a second, auxiliary detector, the light reflected by the thin film can be measured, in addition to the measurement made of the light transmitted by the thin film. At the bottom of the figure, the distribution of the photons is illustrated: the energy from the incident beam will be found in either 1. the transmitted signal, 2. the reflected signal, or 3. absorbed by the thin film and not present in either photodiode signal (represented by the dashed line through the coating).

Analysis

Collected data is modeled by making calculations that simulate the interaction of specific energy light with a thin film having certain qualities, and then comparing the measured data with the data generated. The parameters of the model (such as the film thickness, surface roughness, interface quality, and optical constants) are varied in the model using a least squares fitting technique until the set of parameters which best describes the film is found.

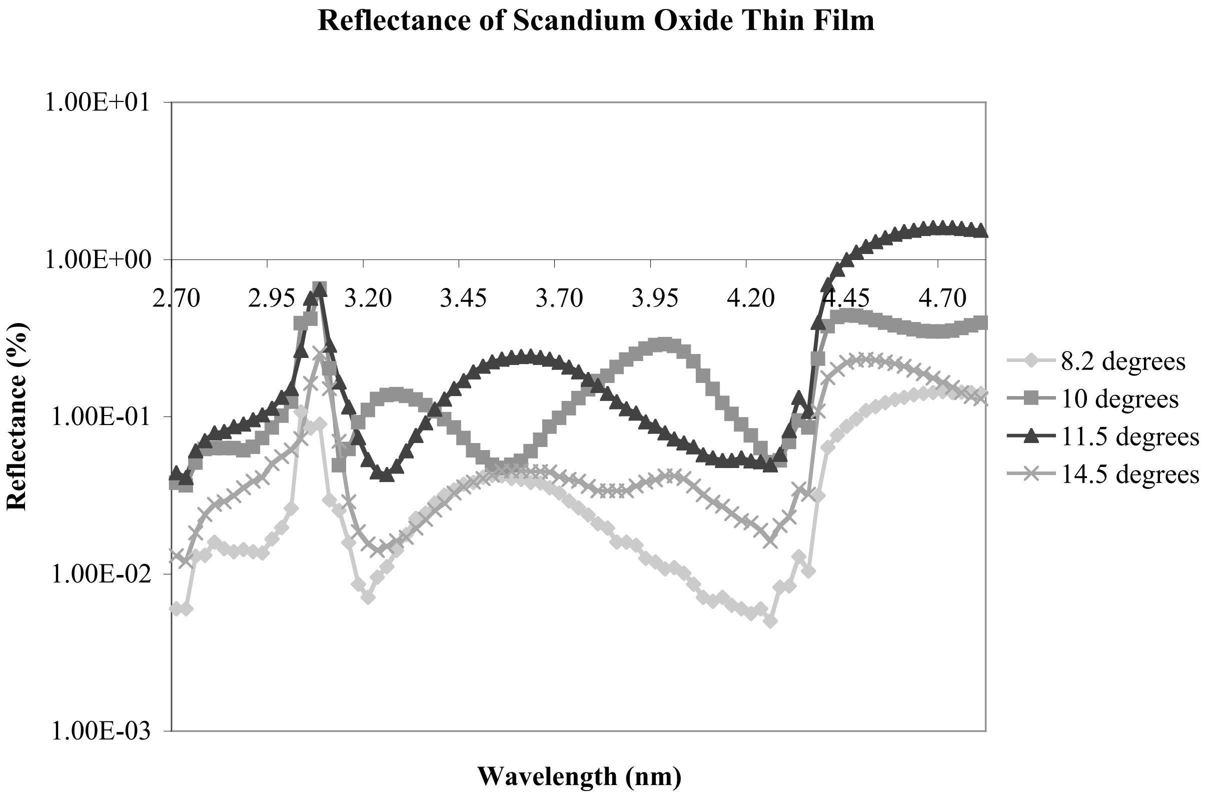

Figure 2

Reflectance data collected at several angles from a single, scandium oxide coated detector. In each graph, the features at 3.07 nm and 4.32 nm are attributed to electronic transitions. The other more gently changing features of the graphs are interference fringes which can be analyzed to find film thickness.

Inspection of the measured reflectance data revealed the presence of interference fringes in the wavelength range of 3.2 - 4.2 nm, as shown in Figure 2. These are identified by the graphs slowly rolling between gentle minima and maxima, in contrast to the features resembling spikes which are telltale of electronic transitions. Interference fringes occur when conditions are met between light reflected off the top and bottom of the thin film to either constructively or destructively interfere, resulting in local maxima and minima, respectively. Noticing that two of the graphs coincidentally have both constructive and destructive interference structures occurring at the same wavelength (both 10° and 11.5° at both 3.26 nm and at 3.57 nm), it is possible to generate a thickness for the sample using the equations which describe the requirements for such interference. In the case of this sample of scandium oxide, the thickness was found to be 247 angstroms, which is in agreement with what was expected from the sputter rate established by the ellipsometric studies.

Following the determination of the thickness of the film on the diode, the transmission data can then be analyzed to find the absorption coefficient. Analysis is carried out first in a region where the sample is seen to have it's greatest transmisivity. In this area, the transmission coefficient β will dominate the film performance such that the absorption coefficient δ can essentially be ignored.

Having determined the thickness of the film and the optical constant β (over a portion of the EUV spectrum), analysis can now be expanded to include both the transmission and reflection data sets. With such strong correlation between the data sets, and a reduced number of fit parameters, the final analysis to produce both δ and β over the entire spectral range is relatively straightforward. This last portion of the analysis is still underway, as it took considerable time to resolve several issues with the data collected.

Conclusions

These experiments are, to the best of our knowledge, the first to explore the behavior of scandium oxide thin films in the EUV. Earlier work with scandium thin films neglected to acknowledge the presence of scandium oxide in the samples previously studied. Film thickness of the samples used in these experiments were gauged by the sputter rates and confirmed by analysis of interference fringes in the reflectance data at low angles (which, to our knowledge, is a new approach for finding film thickness from reflectance data of this sort). Transmission data was analyzed in regions where the value of δ was not expected to vary much, producing reasonable values for β.