SE for Telecom Applications

Part 1: Semiconductor Devices

The telecommunications industry is growing larger than ever mainly due to the demand for faster information transfer. Fiber-optic communication is rapidly becoming the backbone for voice, video, and internet data transfer. As this industry matures, the components for broadband fiber networking undergo continuous research and development. These components include VCSEL and edge-emitting lasers, thin-film DWDM filters and waveguides for multiplexing/demultiplexing, EDFA and Raman amplifiers, photodiode detectors, and more. Thin films are critical to the performance of these devices. Spectroscopic ellipsometry (SE) is uniquely suited to measure both film thickness and refractive index at telecom wavelengths in the infrared. This article surveys both *ex situ* and *in situ* SE applied to the single and multilayer film structures of telecom devices.

Transmitters and Receivers

Optical communication literally begins and ends with a transmitter and receiver. In the transmitter, lasers produce light to travel down the fiber encoded with information. In the end, the receiver converts this light to an electronic signal via a photodiode detector. Thin alloy semiconductor films play an important role in both components.

A. Laser Sources

Semiconductor lasers are designed to operate in the near infrared at 1310 nm or 1550 nm for fiber-optic communication. Another important wavelength is 980 nm used for pump lasers.

Semiconductor lasers create light via optical transitions between energy levels in a direct-bandgap semiconducting film. Ternary and quaternary alloy semiconductors offer the flexibility to tune the desired emission wavelength by changing the composition of the materials, as the bandgap is dependent on the ratio of materials in the alloy. For instance, the quaternary material In$_x$Ga$_{1-x}$As$_y$P$_{1-y}$ can provide laser emission in the $1.1\mu m < \lambda < 1.6\mu m$ range depending on alloy ratio (x and y). Similarly, the ternary material Al$_x$Ga$_{1-x}$As can be varied for use in pump lasers.

B. Photodiode Detectors

The same energy levels that produce laser light will absorb light to excite electrons to an elevated state. Absorption frees electrons from their atoms to create a measurable electric current which is directly related to the intensity of light shining on the detector. The energy levels adjust with alloy concentration, resulting in varying amount of absorption at different wavelengths. This variation in optical properties is described by the material optical constants, commonly known as n and k or ε_1 and ε_2. The optical constant shape corresponds to the material's electronic transitions. Thus, the optical constants become a "fingerprint" for the semiconductor.

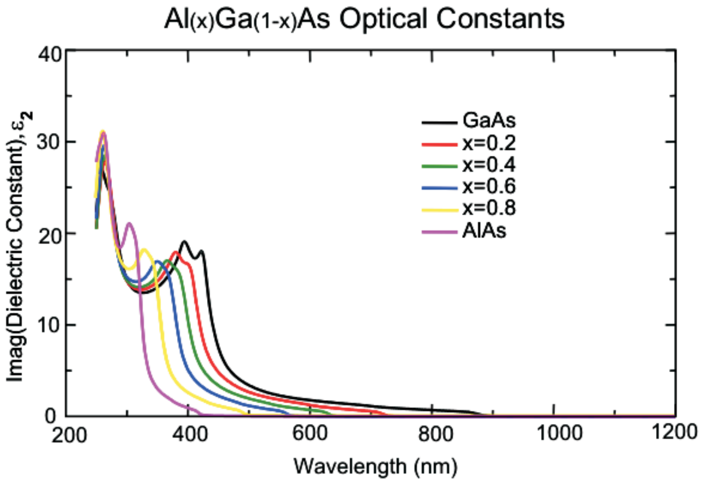

FIGURE 1: Changes in Al$_x$Ga$_{1-x}$As with alloy ratio, x.

For example, in Al$_x$Ga$_{1-x}$As, the direct bandgap shifts toward shorter wavelengths with increasing aluminum concentration, x. This is seen in Figure 1 as an absorption edge shift toward shorter wavelengths, along with similar shifts in each high-energy transition.

Spectroscopic Ellipsometry

Spectroscopic ellipsometry takes advantage of the changing optical constants in a semiconductor to determine alloy ratio. Accurate alloy ratio measurements require a database of the optical constants for different compositions. Fortunately, the energy bands shift systematically with changing composition. Thus, a series of five to ten samples that cover the full range of compositions will provide enough information to setup an ***alloy model***. The alloy model creates the correct optical constants for any specified alloy ratio, x. If an alloy ratio is specified between two of the original database values, an appropriate interpolation is performed. This is enhanced by using the alloy-shifting model developed by Snyder. In practice, the optical constants can be properly described by simply selecting the correct alloy ratio. In Figure 2, we show the ellipsometric measurement from a bi-layer semiconductor stack. Five fit parameters were used to match this data: three layer thicknesses (including the surface oxide) and two alloy compositions.

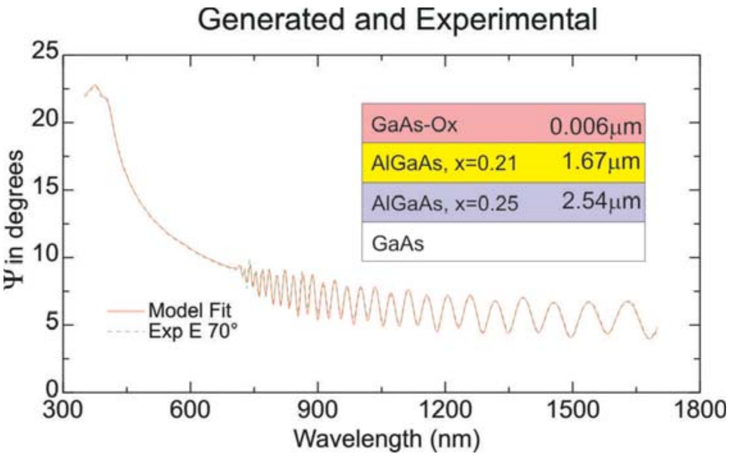

Figure 2: Data and fits for bi-layer compound semiconductor.

The AlGaAs material has a larger bandgap than used for source lasers. However, it is acceptable for pump laser wavelengths. The pump laser is used to supply energy to EDFA and Raman amplifiers. For example, a pump laser at 980nm can excite Erbium to a higher energy state that emits light near 1550nm.

In most cases, a single layer film is used to determine the alloy ratio from a process. However, in situ ellipsometry is used to monitor the alloy ratio during film deposition. In situ ellipsometry has also been used for real-time feedback control of different processes. The typical laser diode structure can be very complex and consist of hundreds of layers. In this case, it can be difficult to monitor each and every layer.

The capabilities of a spectroscopic ellipsometer depend strongly on the measured wavelength range. For this reason, a wide wavelength range is typically preferred. The primary spectral region for telecom applications is the near infrared, as the components will operate using light in this region. It is important to understand the thin film properties at the operation wavelengths. However, there can be valuable information about the materials that is not available in this wavelength region. For instance, doping concentration and alloy composition can both be determined with ellipsomety over specific wavelength regions.

Recent investigations by Schubert have demonstrated the capabilities of mid- to far- infrared ellipsometry for laser diode and LED structures. Although the final structure is very complicated (Figure 3A shows Schubert's model for a laser diode) and can consist of 100's of thin semiconductor layers, infrared ellipsometry has shown sensitivity to carrier concentration and mobility, layer thickness, composition, strain, and crystal quality. In this case, the infrared wavelengths are much larger than the individual layer features, so SE senses the overall effect of the structure without requiring an exact description of each layer.

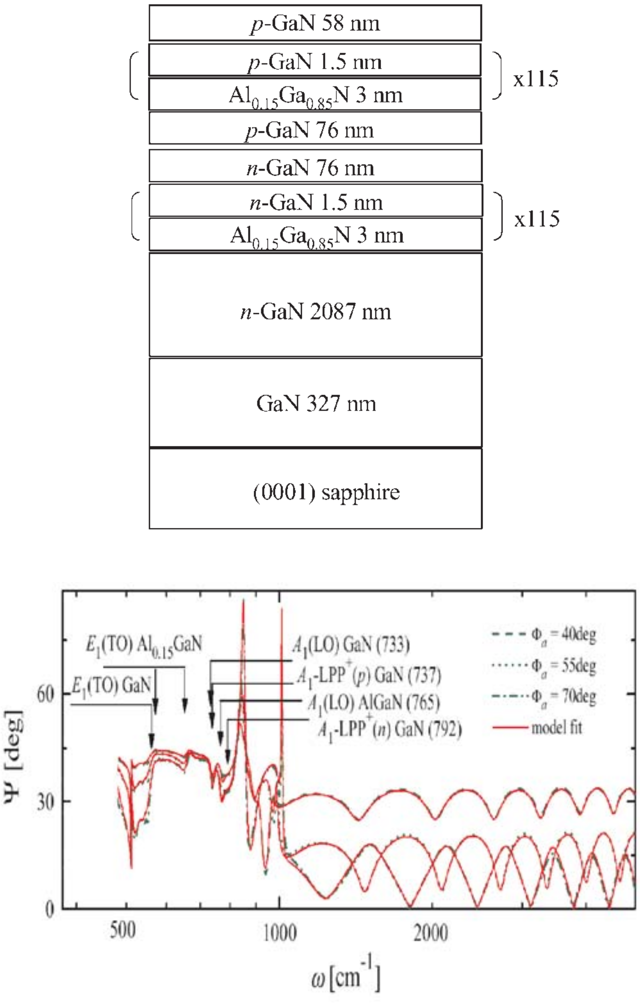

Figure 3 (A) Model and (B) data fit for Laser Diode structure.[8]

Film thickness for a semiconductor layer can also be a critical parameter. Spectroscopic ellipsometry measures the interference pattern created from multiple reflections of the probe-light within the layer. Thus, no thickness information is available from ellipsometry if the film is absorbing. The light must be allowed to reach the bottom of the film and return to the surface to determine thickness. The low-bandgap semiconductors used in infrared detectors will absorb over most conventional ellipsometer wavelengths. For instance, an InGaAs film thickness would not be measurable using commercial ellipsometry out to 1.7μm, as its bandgap is very near the longest wavelength of this instrument. New extended-range detectors are being implemented in SE to overcome this limitation. VASE measurements with a new extended-range detector are shown in Figure 4 from a thick InGaAs film. This fit result provides an accurate thickness for the film that would not be available from conventional ellipsometry out to 1.7μm (shown in yellow).

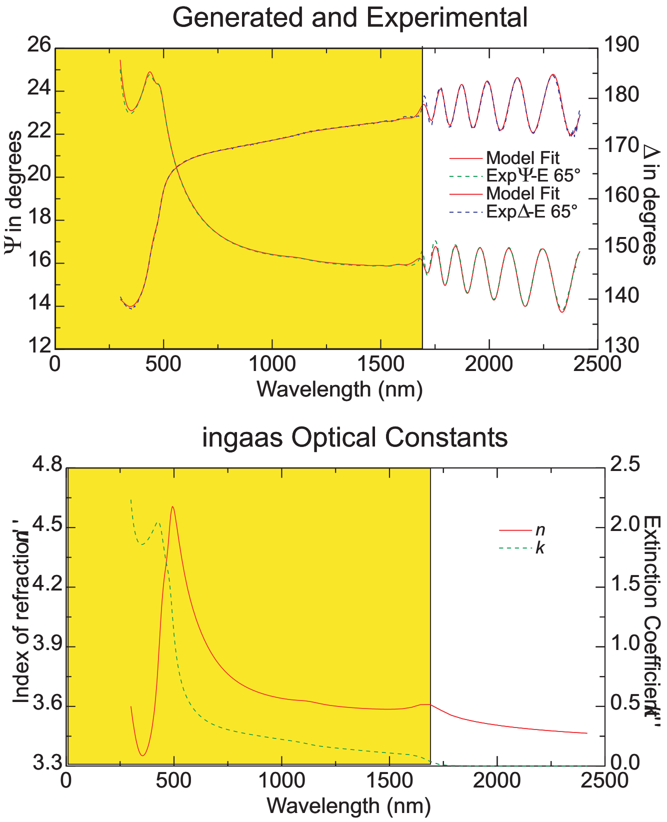

FIGURE 4: InGaAs (A) data and (B) resulting optical constants using an extended NIR detector (traditional SE range shown in yellow).

This text is a section from larger article to be published in 2002. Please contact the Woollam Company for more details.

1. VCSEL Vertical Cavity Surface Emitting Laser
2. DWDM Dense Wavelength Division Multiplexing
3. EDFA Erbium Doped Fiber Amplifiers
4. Amnon Yariv, Optical Electronics, 4th Edition, Saunders College Publishing, Philadelphia, (1991) p 565.
5. P.G. Snyder, et al. “Modeling AlxGa1-xAs optical constants as functions of composition,” J. Appl. Phys. **68** 11 (1990), 5925.
6. B. Johs, J. Hale, J. Hilfiker, “Real-time process control with in situ spectroscopic ellipsometry,” III-Vs Review, **10** 5 (1997) 40-42.
7. LED Light Emitting Diode
8. M Schubert, et al. SPIE Proc., 4449-8 (2001).