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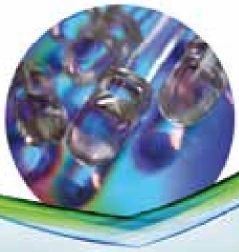

Application Note

Optoelectronic

Spectroscopic Ellipsometry

SE 27

Characterization of LED Thin Film Devices by Spectroscopic Ellipsometry

Driven by applications like LED-backlit TVs and solid-state lighting, the global LED market is growing rapidly. The main challenges for general LED lighting include reducing overall production costs and increasing efficiency and lifetimes. LED lighting is already used in a wide variety of applications such as signs and displays, back-lighting of LCD displays, traffic signals, automotive (dashboard and external lights), and for architectural displays. The performance of an LED which is characterized by its wall-plug efficiency depends on the design and overall material properties of the LED thin film structure.

Ellipsometry may be used for the accurate determination of the thickness and optical constants of the LED device for both research and industrial applications. Accurate control of thickness and refractive index is vital for the optimisation of device properties and for industrial quality control.

How does an LED work?

A semiconductor LED is a solid-state device that emits incoherent light in a narrow spectral range when a forward bias is applied. The wavelength of the emitted light is dependent on the energy bandgap (Eg) of the material used in the active region of the device.

An LED consists of a p–n junction with a multiple-QW active region and carrier-confining layers. The LED structure is normally formed on a lattice-matched, or nearly lattice-matched, substrate with a low dislocation density.

Figure 1b, An image of a packaged deep UV LED

However, in the case of III-nitride semiconductors, sapphire (which has about 16% lattice mismatch with GaN) is the most common substrate of choice owing to the fact that bulk lattice-matched substrates are not readily available. A typical UV LED structure (Fig. 1a) has a thin low-temperature nucleation layer (often referred to as a buffer layer) of GaN or AlN, which is used to accommodate the lattice mismatch with sapphire, and an n-type AlGaN contact layer followed by the active, top p-type and p-contact layers.

The active region typically consists of confinement layers (n-type and p-type) with either a single or multiple QWs between them. The alloy compositions of the well and barrier layers and their thicknesses are chosen based on the desired emission wavelength. The confinement layers are used to introduce an energy barrier on either side of the wells to prevent carriers — electrons and holes — from escaping the QWs without radiatively recombining. The p-contact layer is highly doped for ohmic contact formation. Most of the III-nitride-based UV LED structures are grown by MOCVD, although other methods such as molecular beam epitaxy and HVPE have also been used to a lesser extent.

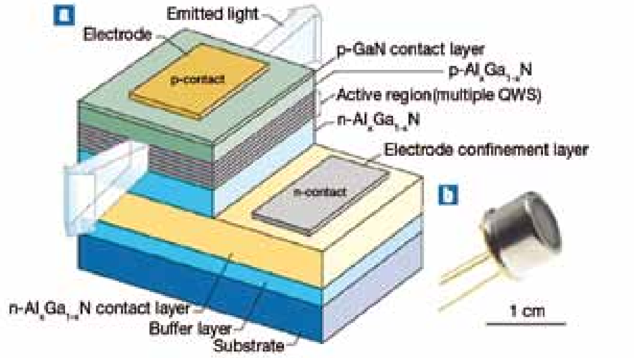

Figure 1 UV LED based on III-nitride semiconductors. a, A schematic of a typical UV LED structure.

Characterization by Spectroscopic Ellipsometry

The two examples below illustrate the non-destructive characterization of LED structures carried out by HORIBA Scientific spectroscopic ellipsometers. Determination of thicknesses and optical constants has been performed in the NIR/visible range using the UVISEL Spectroscopic Phase Modulated Ellipsometer for the first example and the Auto SE Ellipsometer for the second one.

First example

Ellipsometric measurements of the following LED structure Sapphire / AlN – LT / AlN – HT / AlN – LT / Al$_x$Ga$_{1-x}$N were collected at an angle of incidence of 70° across the spectral range 0.6-6.5 eV (equivalent to 190-2066 in nm). They are shown below in figure 2.

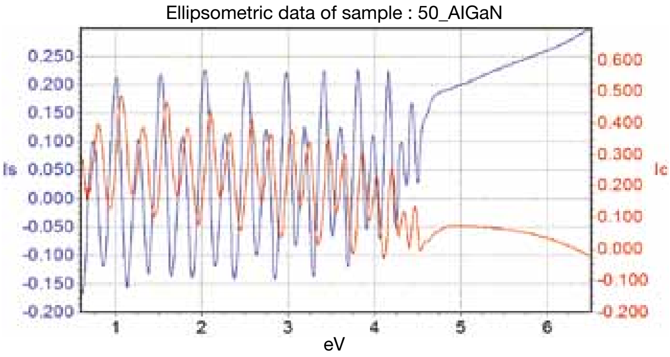
Ellipsometric data of sample : 50_AlGaN

Figure 2: Ellipsometric measurements of LED structure

One can observe that the spectrum is divided in two parts:

- The first spectral region from 0.6 to 4.5eV exhibits interference fringes which correspond to the transparent range of the materials. This spectral range enables accurate determination of film thicknesses.

- The second region from 4.5 to 6.5eV shows the absence of interference fringes due to the AlGaN semiconductor material absorption. Therefore this range mainly provides information on the sample surface. It also enables the calculation of the bandgap using the Tauc Plot method. From the spectrum, we can determine roughly that the bandgap is around 4.5 eV.

The following model (figure 3) has been used to fit perfectly the experimental data, given a χ^2 = 0.77 (figure 4). The three layers of AlN have been modelled by only one layer. Indeed the optical difference between the AlN Low Temperature and High Temperature is not significant enough to be determined by ellipsometry.

The introduction of a roughness overlayer, modelled by 50% Al$_x$Ga$_{1-x}$N + 50% void, improves significantly the goodness of the fit (described by the χ^2 value).

Overlayer	2.1 nm
Al$_x$Ga$_{1-x}$N	570.3 nm
AlN	669.5 nm
Sapphire substrate	330µm

Figure 3: Model found

The fitting process determines simultaneously the AlN and AlGaN thicknesses and optical constants. The optical constants of both materials have been determined using the Lorentz oscillator dispersion formula.

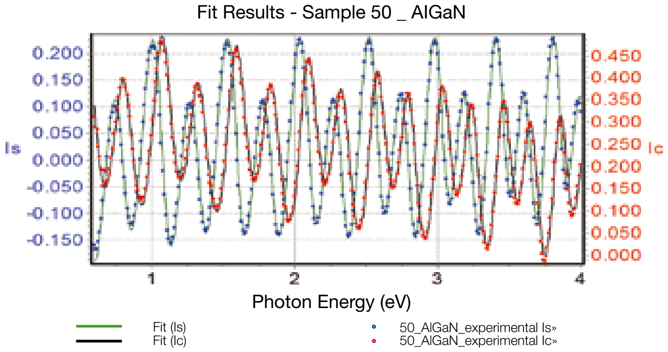
Fit Results - Sample 50 _ AlGaN

Figure 4: Graphical fitting results

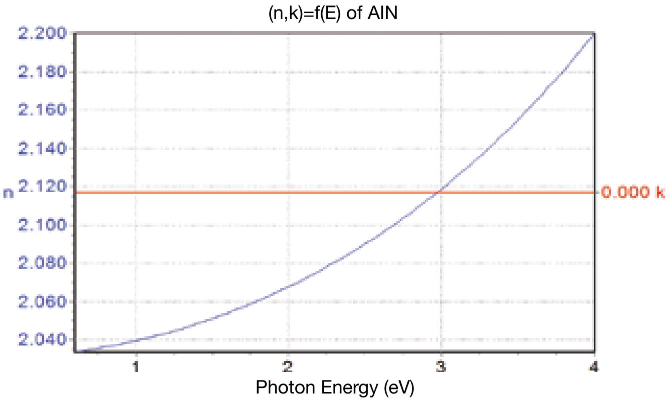
(n,k)=f(E) of AlN

Figure 5a: Optical constants of AlN

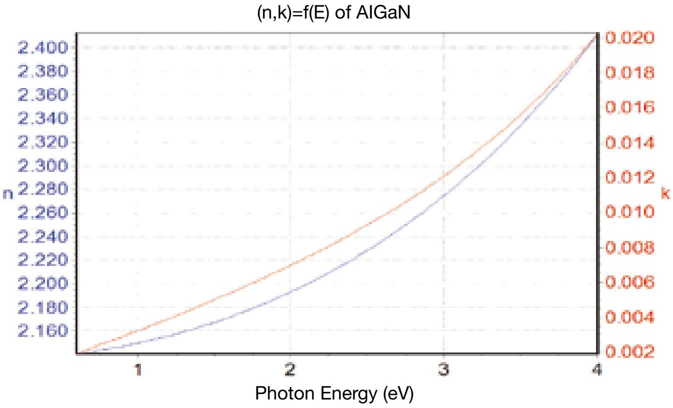
(n,k)=f(E) of AlGaN

Figure 5b. Optical constants of Al$_x$Ga$_{1-x}$N

Second example

This second example illustrates the use of ellipsometry to characterise a GaN light-emitting diode for quality control during its production process. The structure comprises of a thick photoresist layer used to form an etching mask on top of the GaN. The measured LED structure is hence a bi layers of Photoresist on GaN deposited on a Sapphire substrate.

The Auto SE ellipsometer was used to characterize the thin film structure inside a pattern area across the wavelength range 440-850nm.
Using the MyAutoView vision system coupled to the microspot of the Auto SE, it is a straightforward procedure to easily locate the measurement spot on the sample (figure 6).

Using the spot size 100x100µm one can measure different locations within the pattern, as shown on the pictures below with the corresponding ellipsometric measurements. The ellipsometric measurements are almost superimposable which means that the layers were deposited uniformly.

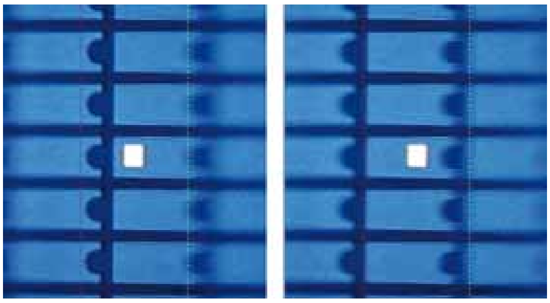

Figure 6: Ellipsometric beam spot placed inside a GaN pattern

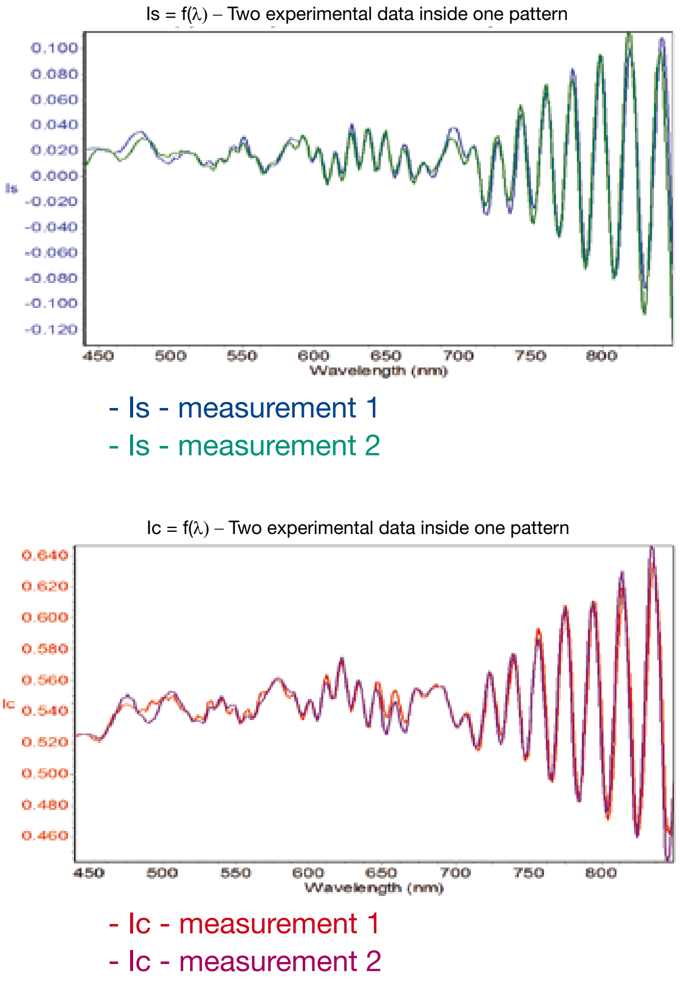

Figure 7: Ellipsometric measurements at two different locations inside the pattern

The model used to describe the sample is represented below. The structure comprises of a rough GaN layer that is modelled using two layers, a homogeneous GaN layer of 7200nm with a rough graded overlayer of 222nm made up from a mixture of GaN and photoresist.

Above the GaN is the thick photoresist layer of 2.55 microns, with a thin roughness layer (3.4nm) at the surface of the photoresist film. The model also takes into account the anisotropy of the sapphire substrate. The found thicknesses displayed in the model are expressed in nanometres.

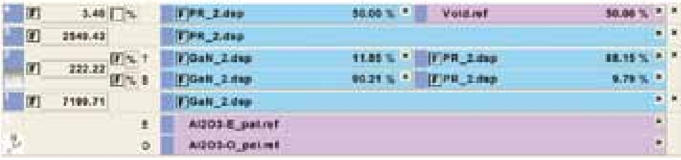
3.40 PR_2.dsp 50.00 % Void.ref 50.00 %
2549.42 PR_2.dsp
222.22 1 GaN_2.dsp 11.85 % PR_2.dsp 88.15 %
0 GaN_2.dsp 90.21 % PR_2.dsp 9.79 %
7199.71 GaN_2.dsp
E Al2O3-E_pal.ref
O Al2O3-O_pal.ref

Figure 8: Model found

The figure below shows the good agreement between the experimental data (dots) and corresponding fit (line) with a found $\chi^2 = 1.60$.

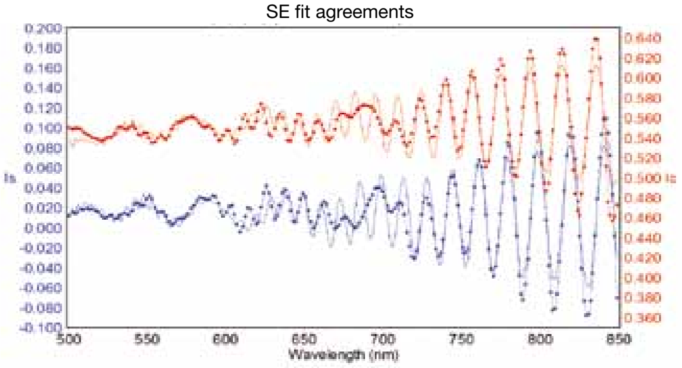

Figure 9: Model found

The optical constants of GaN & Photoresist layers have been modelled using the Single Lorentz Oscillator:

$$n^2 = \varepsilon = 1 + \frac{(\varepsilon_s - 1)\,\omega_t^2}{\omega_t^2 - \omega^2}$$

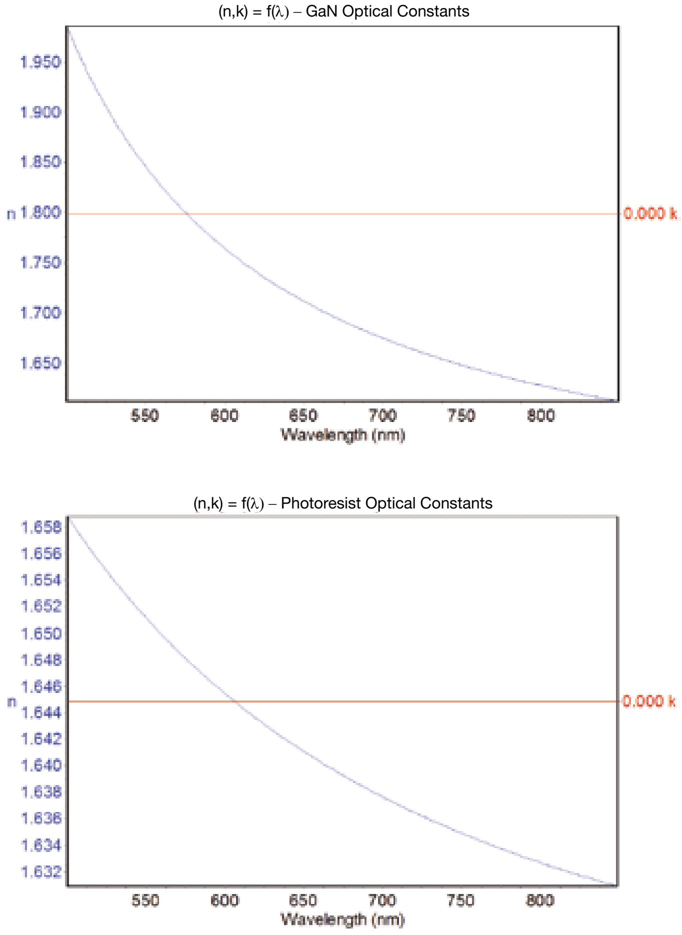

Figure 10: Optical constants of GaN and Photoresist

Conclusion

The ellipsometer instruments described here are perfectly suited to the characterization of LED structures, providing accurate information on the deposition of layers (thickness, optical constants, bandgap, uniformity, roughness, and more).

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