

Determination of Optical Constants of Semiconductor Thin Films by Ellipsometry

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Abstract—Ellipsometry is an optical method based on the study of the behavior of polarized light. The light reflected on a surface induces a change in the polarization state which depends on the characteristics of the material (complex refractive index and thickness of the different layers constituting the device). The purpose of this work is to determine the optical properties of semiconductor thin films by ellipsometry. This paper describes the experimental aspects concerning the semiconductor samples, the SE400 ellipsometer principle, and the results obtained by direct measurements of ellipsometric parameters and modelling using appropriate software.

Keywords—Ellipsometry, optical constants, semiconductors, thin films.

I. INTRODUCTION

THE development of semiconductor materials as thin films has contributed to an increase of performance of electronic, photonic and photovoltaic systems including lower cost of components for mass production. The structure of the deposited films may be monolayer or multilayer with thicknesses varying from one atomic plane (several Angstroms) to several hundreds of micrometers. Their optical properties depend on microstructure.

The objective of this work is to determine the optical properties of thin films and semiconductor. The most common optical properties are the complex refractive index and thickness, as well as all notions of transmission and reflection. For this goal, ellipsometry is adapted as technique of characterization of semiconductor samples set on GaAs, GaN, GaP.

Ellipsometry is an optical method based on polarized light. Indeed, the light reflection on a plane surface induces a change in the polarization state which depends on the optical characteristics of the material.

Advanced applications of thin films have diversified in chemistry and physics fields while the optical applications have essentially allowed the development of radiation sensors [2]. However, the purpose of the systems made by thin films on a substrate is access to the electrical conductivity of the metallized surface for a scanning electron microscope, increase or decrease the reflection on optical surfaces (anti-reflective coating, a metallic mirror...), selecting of reflection

or transmission for a wavelength range (selective mirror, interferential filter...) and fabrication of protective layers. Between the conductors and insulators films, one can classify a number of solids which are semiconductors. Semiconductors of the III-V class are compounds formed by elements of the third and the fifth column of the periodic table, their properties, in particular the band structure, shows that the lightest elements give compounds with wide band-gap whose properties be similar to those of insulating compounds. The main semiconductors of III-V class are GaAs, GaP, GaN [3]. The existence of the band gap explains the transparency of semiconductor infrared radiation [3]-[5]. This work shows the principle of measurement by ellipsometry and the use of the SE400 ellipsometer to characterize the optical parameters of samples set by two methods: direct (by measurement) and indirect (by modelization).

II. PRINCIPLE OF ELLIPSOMETRY

We consider a surface illuminated at an incidence i_0 by a monochromatic plane wave (Fig. 1). The polarization direction of the incident wave linearly polarized is identified by the angle α . The field component parallel to Oy component is called S (transverse electric relative to the plane index), and the perpendicular thereto is called P (transverse magnetic) [1].

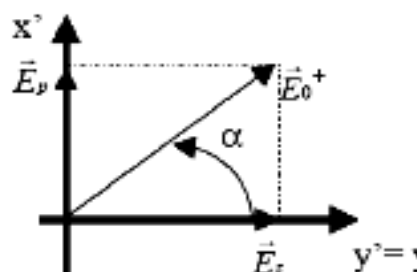


Fig. 1 Direction field in the plane normal to the incident wave vector

The incident wave can be written as:

$$\vec{E}_0^+ = \vec{A}_0^+ \exp(j\vec{k}_0 \cdot \vec{P}) \exp(-i\omega t) \quad (1)$$

$$\vec{E}_0^+ = \vec{E}_s + \vec{E}_p = E_s \vec{y}' + E_p \vec{x}' \quad (2)$$

$$E_s = E_0^+ \cos \alpha ; E_p = E_0^+ \sin \alpha \quad (3)$$

To accurately analyze the change in the state of polarization, a polarizer is introduced into the incident beam,

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and an analyzer of the reflected beam (Fig. 2).

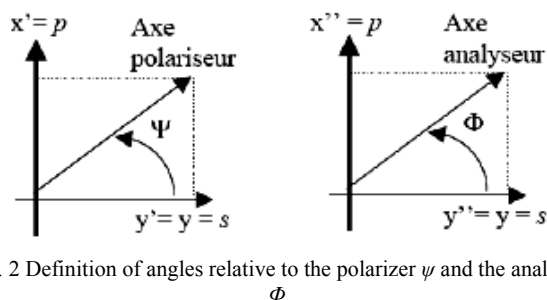


Fig. 2 Definition of angles relative to the polarizer ψ and the analyzer Φ

The angles Φ and ψ define the directions of the axes of the polarizer and analyzer, respectively, compared to the direction S , as shown in Fig. 2. After the polarizer, S and P components of the field can be written as:

$$\begin{aligned} E_s^+ &= E_0^+ \cdot \cos(\psi - \alpha) \cdot \cos \psi \\ E_p^+ &= E_0^+ \cdot \sin(\psi - \alpha) \cdot \sin \psi \end{aligned} \quad (4)$$

Reflection on the sample is written using the complex reflection factors:

$$\begin{aligned} r_s &= \sqrt{R_s} \cdot \exp(j\delta_s) \\ r_p &= \sqrt{R_p} \cdot \exp(j\delta_p) \end{aligned} \quad (5)$$

ρ is the ratio of the two reflection coefficients of both directions P and S :

$$P = \tan(\psi) \cdot \exp i\Delta \quad (6)$$

where $\tan(\psi) = \frac{|r_p|}{|r_s|}$ the ratio of the amplitudes and Δ is the phase difference.

Two values are used to describe the optical properties that determine how light interacts with a material. They are usually represented as a complex number. The complex refractive index of medium $\bar{n} = n + i \cdot k$ consists of the index n and extinction coefficient k .

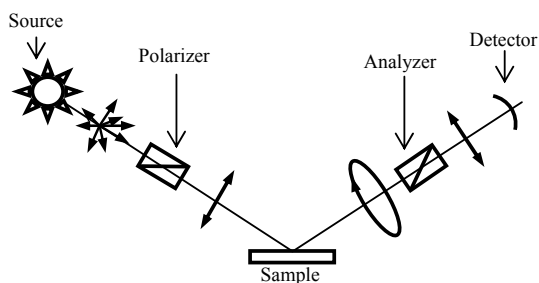


Fig. 3 Ellipsometer operating principle

The modulation of the polarized beam can be obtained by

rotation of the polarizer, the analyzer or a compensator.

III. EXPERIMENTAL WORK

A. The Ellipsometer SE 400

The ellipsometer SE 400 is mounted on a support module, in which a telescope auto collimator and two arms are attached. The left arm comprises the polarizer and He-Ne laser source, and the right comprises the analyzer. These two arms are pivoted about a common axis of rotation (Fig. 4).



Fig. 4 SE400 Ellipsometer apparatus

The associated software "SE400 Sentech Instruments Software GmbH" can be started automatically or manually. Thus, the computer can load the different commands directly from the program's main menu. From there, the execution may be transferred to one of the following commands.

The "Application" command contains a menu giving interactive access to any action performed by the ellipsometer. The "Setup" command is used for diagnosis, particularly for measuring ellipsometric parameters in this case, ψ and Δ , the refractive index and thickness of the layer depending on the model.

B. Measurements

Table I shows the different types of samples that we have measured and characterized using ellipsometry.

TABLE I
SAMPLES DESCRIPTION

Samples	Description
S1	GaAs-p (gallium arsenide)
S2	GaAs-n (gallium arsenide)
S3	GaP (gallium phosphide)
S4	GaN (gallium nitride)

Measurements are taken for an incidence angle of 70° , and five measurements are done at different positions on the surface of each sample. Table II shows the mean values for each sample, as well as calculation of errors.

Curve tracing is carried out by setting the values n_s , k_s , λ , and ϕ in the case of a monolayer on substrate and n_s , k_s , n_l , k_l , d_l , λ , and ϕ in the case of two layers on substrate by varying the parameters to be determined for two layers on substrate. Once found the global range of the index and the thickness, and then each sample is treated separately.

TABLE II
MEAN VALUES OF PSI AND DELTA

Ellipsometric parameters	S1	S2	S3	S4
$\bar{\psi}$ [°]	8.52	8.20	8.56	08.70
$\pm\delta\psi$ [°]	0.54	0.10	0.86	00.49
$\bar{\Delta}$ [°]	324.90	325.70	335.00	327.75
$\pm\delta\Delta$ [°]	10.64	4.24	15.80	13.49

After modeling with “Sentech Instruments GmbH” software and introducing the measured values, we get the curves in Fig. 5. According to this graph, we can determine the intervals of the index and the thickness of each sample as following:

S1: $2.8 \leq n_1 \leq 2.9$; S2: $2.9 \leq n_1 \leq 3$; S3: $2.9 \leq n_1 \leq 3$; S4: $2.8 \leq n_1 \leq 2.9$

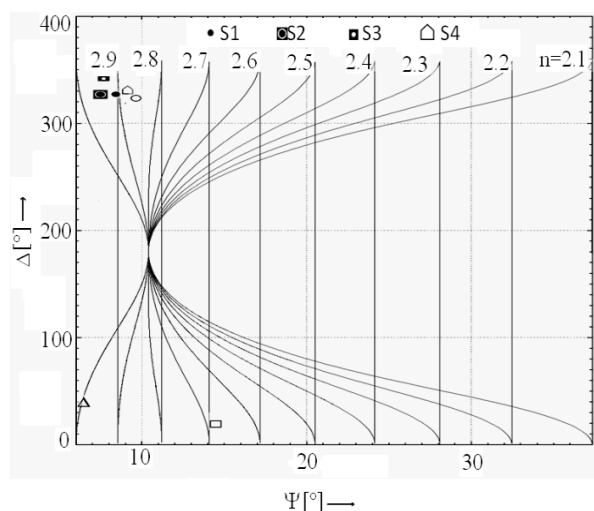


Fig. 5 Measured values represented as $\Delta = f(\psi)$ at incidence angle of 70°

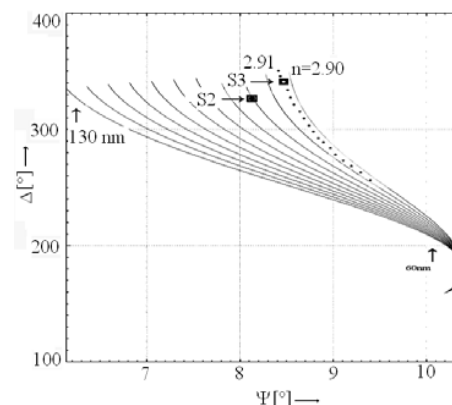
C. Results and Discussion

The results are shown in Fig. 6. The graph shows that the index of gallium arsenide doped p is equal to 2.91 and its thickness is about 110 nm, on the other hand, the index of gallium nitride is equal to 2.905 and its thickness is about 100 nm.

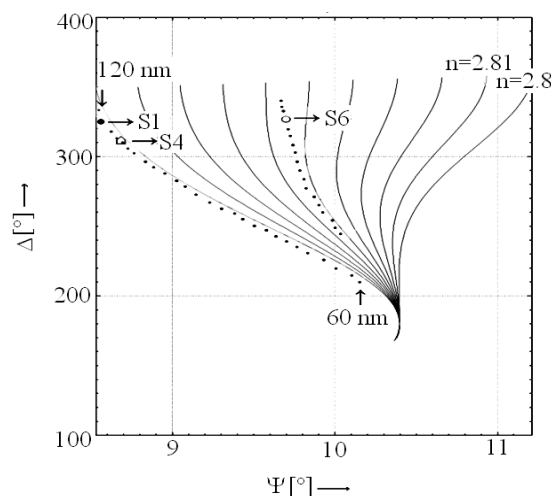
For gallium arsenide doped n, the index is equal to 2.92 and the thickness is about 110 nm, and the gallium phosphide refractive index is equal to 2.905 and its thickness is equal to 120 nm.

TABLE III
REFRACTIVE INDEX AND THICKNESS FOR MODELED DATA AT INCIDENCE ANGLE OF 70°

Samples	Refractive index n	Thickness [nm]
S1	2.910	110
S2	2.920	110
S3	2.905	120
S4	2.905	100



(a) Samples: S2 and S3



(b) Samples: S1, S4 and S6

TABLE IV
REFRACTIVE INDEX AND THICKNESS FOR MEASURED DATA AT INCIDENCE ANGLE OF 70°

Samples	Refractive index n	Thickness [nm]
S1	2.530	86.30
S2	2.110	86.34
S3	2.100	86.26
S4	2.520	86.00

Tables III and IV give refractive index and thickness by modeled data and measured values at incidence angle of 70° respectively, the following comments can be given: For the refractive index, the direct measurements with a 70° angle are closer to the values of the indirect method of modeling. For the thickness, we find that there is a difference between the two methods. The sources which influence on the results are the reference adjustment, the roughness of the surface and the sensor sensitivity. Because the receiving surface does not capture the entire reflected beam, so the change in the intensity of the beam influence on the measurements.

IV. CONCLUSION

Optical properties and mainly the refractive index, and the thickness are obtained by ellipsometry. We have shown that these properties can be obtained directly by ellipsometry and modeling. The results show an acceptable error range for the average direct measurements. We consider that the error range compared to modeling is nevertheless lower.

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