WEB ISSN 2535-003X
PRINT ISSN 2535-0021

SPECTROSCOPIC ELLIPSOMETRY TECHNIQUE FOR CHARACTERIZATION OF THIN FILMS

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Abstract: *In our daily life we are surrounded by electronic devices which have inside some or many microelectronic parts even though we do not see them. The quality of their constituent components will influence in the working performance of electronic devices in general and especially in microelectronics. Among the key components of modern microelectronic and photonic products are various types of thin film materials, which play an important role in their performance. Based on it, thin films have to meet the demands for specific device requirements. A thin film in our context is a layer of solid material ranging in thickness from fractions of a nanometer (monolayer) to several micrometers. One of the advanced measurement techniques used in thin film measurement is Spectroscopic Ellipsometry (SE). It has become common technique for its advantages in fulfilling several important measurement requirements in thin film industry. This paper will be focused in SE measurement technique for characterization of the thin films especially grown by ALD.*

Keywords: THIN FILMS, SPECTROSCOPIC ELLIPSOMETRY, ATOMIC LAYER DEPOSITION, ELECTRONIC DEVICES, MICROELECTRONIC.

1. Introduction

In our daily life we are surrounded by electronic devices which have inside some or many microelectronic parts even though we do not see them. The quality of their constituent components will influence in the working performance of electronic devices in general and especially in microelectronics [1, 2]. Among the key components of modern microelectronic and photonic products are various types of thin film materials, which play an important role in their performance. Based on it, thin films have to meet the demands for specific device requirements [3, 4]. A thin film in our context is a layer of solid material ranging in thickness from fractions of a nanometer (monolayer) to several micrometers.

On the manufacturing yield of integrated circuits, small variations in film uniformity can have a large influence. For very-large-scale integrated (VLSI) circuits, at present, film uniformity deviations, should not exceed 5%. Even more stringent the uniformity requirements are expected to become in the near future, decreasing to a deviation limit of 1 to 2% [4]. Uniformity of thickness is an important requirement for thin solid films used in electronic and optoelectronic devices (Fig. 1). The one method which is particularly suitable for making uniform and conformal film layers is atomic layer deposition (ALD) [5].

Fig. 1 *Main applications of thin films in daily products. a) a household mirror, b) sunglasses, c) a very-large-scale integrated (VLSI) circuit* [3].

In a device fabrication process sequence, thin films have to be deposited even on a non-planar surface and the film deposited should be uniform across all structural details of the substrate topography. For example, in VLSI circuit structures, contact holes with micron or submicron dimensions should be uniformly coated with metal films not only inside the small contact cavities, but also on their vertical walls [4]. This is referred to as step coverage or conformality.

One of the advanced measurement techniques used in thin film measurement is Spectroscopic Ellipsometry (SE). It has become common technique for its advantages in fulfilling several important measurement requirements in thin film industry. Ellipsometry measures the change in polarization state of light as it reflects or transmits from a thin film material structure [6]. This paper will be focused in SE measurement technique for characterization of the thin films especially grown by ALD.

2. Experimental Setup

A Sopra GES-5E variable angle spectroscopic ellipsometer (VASE) was used to determine the thickness (d) and optical properties (n, k) by using 'Winelli II' software as can be seen in (Fig. 2) and simplified schema in (Fig. 3).

Fig. 2 *The main physical parts of ellipsometer GES-5E instrument: 1. light source, 2. polarizer, 3. analyzer, 4. detector, 5. sample stage, 6. Goniometer.*

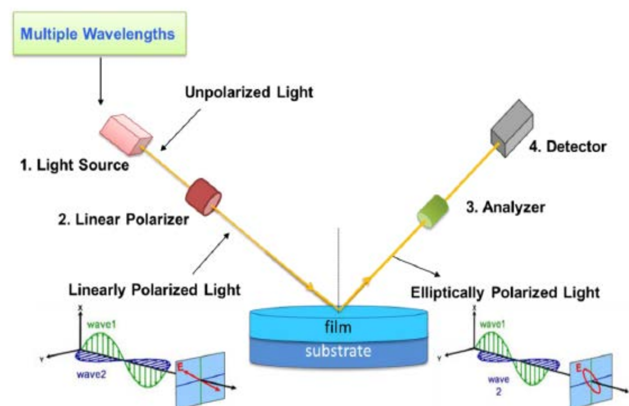


Fig. 3 *The simplified schema with main instrumental components of a SE.*

A light source (a xenon lamp in case of SE) produces unpolarized light which passes through a linear polarizer. The polarizer allows only a preferred electric field orientation of light to

pass through while the polarizer axis is oriented between the p- and s- planes (noticed as wave 1 and 2 in Fig. 3), in such a way that both arrive at the sample surface. The linearly polarized light becomes elliptically polarized after reflection from the sample surface, and travels through a continuously rotating polarizer (referred to as the analyzer). The amount of light which will go through the analyzer will depend on the exact elliptical polarization state of light coming from the sample. Further, a detector converts it to electronic signal to determine the polarization of reflected light. This information will be compared to the known linearly polarized input light to determine the polarization state changed by the sample's material reflection. Furthermore, layer thickness and optical constants (n, k) were determined from the ellipsometric tan ψ and cos Δ parameters by using equations (1) and (2).

$$\tan \psi = \frac{|r_p|}{|r_S|}, \qquad (1)$$

$$\cos \Delta = \delta_{rp} - \delta_{rs} \qquad (2)$$

Where, δrp and δrs are the phase changes and, rp and rs are originally defined by the ratios of reflected electric field to incident electric field for p and s components.

All the main parameters, d, n, and k parameters were obtained for each layer by using a Levenberg–Marquardt non-linear regression algorithm. Ellipsometric measurements were generally made at incidence and reflectance angle of 75°. Layers of Ho_2O_3 and TiO_2 were modeled as homogeneous mixtures of supposedly dense materials and addition of void content for refractive index, n, and absorption coefficient, k, adjustment.

The optical properties of thin films were examined in air at ambient conditions. Optical constants quoted in this paper will further refer to those measured at 633 nm wavelength. In addition, using the same optical model, thicknesses were measured as a matrix laid over an area of 25 cm^2 with steps of 7 mm in X and Y horizontal directions in order to profile the thickness along and across the gas flow direction in the ALD reactor as can be seen in (Fig. 4).

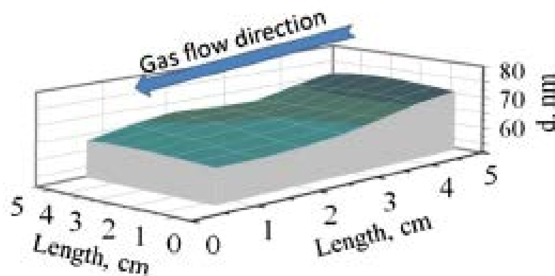
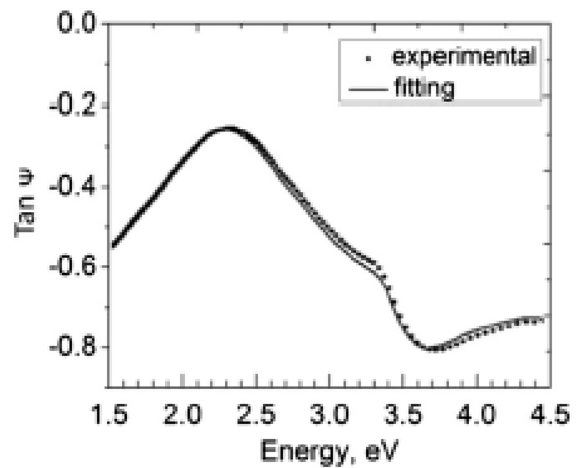


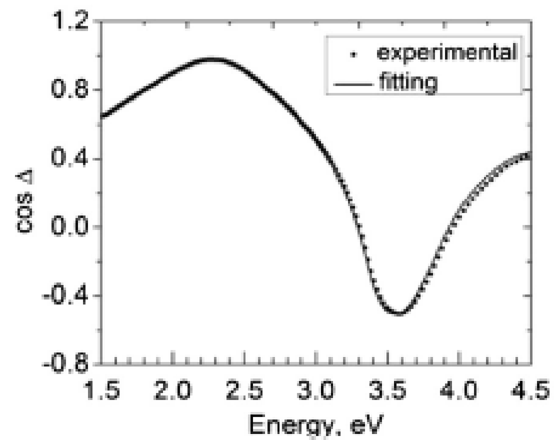
Fig. 4 *The gas flow direction in the ALD reactor.*

3. Experimental Results

The results for characterizations of the thin films by using SE are shown in the (Fig. 5).



(a)



(b)

TiO_2 d= 2.18 ± 0.06 nm n=2.39 ± 0.01
Ho_2O_3 d= 4.36 ± 0.09 nm n=1.99 ± 0.02
TiO_2 d= 1.97 ± 0.07 nm n=2.38 ± 0.01
Ho_2O_3 d= 4.32 ± 0.08 nm n=1.98 ± 0.03
TiO_2 d= 1.88 ± 0.03 nm n=2.43 ± 0.04
Ho_2O_3 d= 4.37 ± 0.05 nm n=2.02 ± 0.01
TiO2 d= 1.89 ± 0.01 nm n=2.42 ± 0.02
Ho_2O_3 d= 4.35 ± 0.06 nm n=2.01 ± 0.01
TiO_2 d= 1.89 ± 0.04 nm n=2.38 ± 0.01
Ho_2O_3 d= 4.38 ± 0.09 nm n=2.03 ± 0.02
TiO_2 d= 1.87 ± 0.05 nm n=2.36 ± 0.04
Ho_2O_3 d= 4.39 ± 0.05 nm n=2.01 ± 0.03
TiO_2 d= 1.92 ± 0.04 nm n=2.38 ± 0.01
Ho_2O_3 d= 4.38 ± 0.07 nm n=1.99 ± 0.01
TiO_2 d= 1.87 ± 0.09 nm n=2.42 ± 0.03
Ho_2O_3 d= 4.37 ± 0.05 nm n=2.03 ± 0.04
TiO_2 d= 1.81 ± 0.05 nm n=2.43 ± 0.04
Ho_2O_3 d= 4.39 ± 0.02 nm n=2.01 ± 0.02
TiO_2 d= 1.82 ± 0.08 nm n=2.39 ± 0.01
Ho_2O_3 d= 4.42 ± 0.08 nm n=2.02 ± 0.01
TiO_2 d=2.53 ± 0.03 nm n=2.52 ± 0.03
SiO_2 d=1.42 ± 0.01 nm n=1.45 ± 0.01
Si(100) substrate

(c)

WEB ISSN 2535-003X
PRINT ISSN 2535-0021

Fig. 5 *The spectrum fitting accompanied with results (a), (b) and thickness of the films (c).*

By relying on fitting spectrum obtained on (Fig. 5ab), it was possible to estimate thickness (d) and refractive index values (n) for each layer of laminate Ho_2O_3-TiO_2.

The (Fig. 5c) shows results obtained from fitting in one of 49 measurement points on the laminate structure). It was supposed to get higher values of thicknesses for each layer of TiO_2 and Ho_2O_3 based on theoretical calculations (growth rate and number of cycles) from single-layers. There is a slightly increase of refractive index values in multilayer stack's results for Ho_2O_3 and TiO_2 comparing to single-layer values of Ho_2O_3 (1.91) and TiO_2 (2.38), especially in the layers near to silicon substrate. The reason for such an increase in refractive index values could be the densification of layers especially near to silicon substrate, as a result of increasingly longer time spent at temperature for layers deposited earlier in the process [7]. This phenomenon of densification can be also the main reason for such a reduction in thickness values. Small variations in thickness may be caused as well due to errors in fitting procedure during data analysis process.

Thickness distribution over an area of 25 cm^2 was profiled as mentioned in (Fig. 4). The film thickness is often higher at the leading edge of the substrate, i,e, closer to the inlet of precursor gases, plausibly due to some overlap of the fronts and tails of the precursor pulses, and decreases towards the trailing edge of the substrate.

4. Conclusions

In this paper it was shown that Spectroscopic ellipsometry (SE) is a very suitable measurement technique for atomic layer deposited thin films and probably thin films in general. Application of SE technique has enabled accurate determination of film thicknesses and refractive indices of thin films. SE is useful not only for single-layer films but also for multilayer-films consisting of multiple thin films alternately deposited. Accurate determination of film thicknesses and refractive indices for single and multilayer thin films, sensitivity to very thin films, uniformity determination etc., make SE a proper measurement tool for characterization of thin films in general and ALD thin film especially.

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