An Overview of Return-Path Ellipsometry

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Abstract

Ellipsometry is an optical method used for characterizing materials and thin films. The principle is based on the polarization change at a sample due to the reflection or transmission at boundaries. By the measurement of the amplitude ratio Ψ and the phase difference Δ, the complex refractive index can be obtained. Ellipsometers can be used in various industries, e.g., semiconductor, chemistry, and display industry. The typical applications are quality control of film growth and defect inspection. In the configuration of return-path ellipsometry (RPE), the light beam is reflected twice from the sample. Thus, RPE has a higher sensitivity to the optical properties of samples. Some configurations of RPE have high tilt tolerance which is an important requirement for inline measurement. This report gives an introduction to the principle of ellipsometry and an overview of four different types of RPE.

1 Introduction

Ellipsometry is a widely used optical method for characterizing materials and thin films. Ellipsometers measure polarization changes at a sample in reflection or transmission configurations. This method can be applied to many different applications, for example, semiconductor, chemistry, and display industry. The advantages of ellipsometry are nondestructive measurement, high precision, and inline measurement is possible.

There are many different types of ellipsometry, for example, rotating-analyzer, phase-modulation, and return-path ellipsometry (RPE). In the configuration of RPE, the light beam reflects on the surface of the sample and returns to the same position by reflecting or retroreflecting optical elements. Compared to the conventional ellipsometry, the main feature is that RPE has a higher sensitivity to the optical properties of samples because of the double reflection from the sample. Other merits are the setup is simple, it is easy to align the system, and only one optical window is necessary for inline measurement. These merits increase the feasibility for monitoring of film growth. In this paper, we will review and compare four different types of RPE.

2 Principle of ellipsometry

Light is an electromagnetic wave which can be described by Maxwell's equations. The electric field $\boldsymbol{E}$ of a plane wave which travels along z axis can be expressed as:

$$\boldsymbol{E}(z,t) = E_0 \exp\left[\mathrm{i}\left(\omega t - Kz + \delta\right)\right],$$

where E_0 is the wave amplitude, K is the propagation number, t is the time of the wave traveling, and ω is the angular frequency. We can decompose the polarization state of the plane wave $\boldsymbol{E}$ by two fields $\boldsymbol{E}_x$ and $\boldsymbol{E}_y$ whose directions are perpendicular to each other and parallel to the z axis. Then, the full form of a plane wave can be expressed:

$$\begin{aligned}\boldsymbol{E}(z,t) &= \boldsymbol{E}_x(z,t) + \boldsymbol{E}_y(z,t)\\ &= E_{x0}\exp\left[\mathrm{i}\left(\omega t - Kz + \delta\right)\right]\boldsymbol{x} + E_{y0}\exp\left[\mathrm{i}\left(\omega t - Kz + \delta\right)\right]\boldsymbol{y},\end{aligned}$$

where $\boldsymbol{x}$ and $\boldsymbol{y}$ are unit vectors along x and y axes.

Ellipsometers can measure the complex refractive index which is defined as: $\bar{n} = n - \mathrm{i}k$, in which n is the real refractive index and k is the extinction coefficient. Fig. 2.1 shows light refraction and reflection on a substrate. In this section, only homogeneous and isotropic materials are discussed and the backside reflection is not considered. The incident light is linear polarized, of which the phase difference is 0 or 2π. After the reflection from the substrate, the reflected light becomes elliptically polarized. The Fresnel equations can be used to describe the reflection and refraction of light at boundaries. The polarization change can be defined as the ratio ρ of the amplitude reflection coefficients for p- and s-polarizations:

$$\rho = \frac{r_p}{r_s} = \tan\Psi e^{i\Delta}. \tag{2.1}$$

In Eq. (2.1), $\tan\Psi$ is the amplitude ratio for the p- and s-polarizations ($|r_p| / |r_s|$) and Δ is the phase difference $(\delta_{rp} - \delta_{rs})$. δ_{rp} and δ_{rs} are the phase changes after reflection for the p- and s- polarizations, respectively. The angle of incidence θ_i and the refractive index of ambient $\bar{n}_i$ are usually known parameters. After the determination of Ψ and Δ by ellipsometers, the complex refractive index of the substrate can be solved by Eq. (2.2) [AB99].

$$\bar{n}_t = \bar{n}_i \tan\theta_i \sqrt{1 - \frac{4\rho}{(1+\rho)^2}\sin^2\theta_i}. \tag{2.2}$$

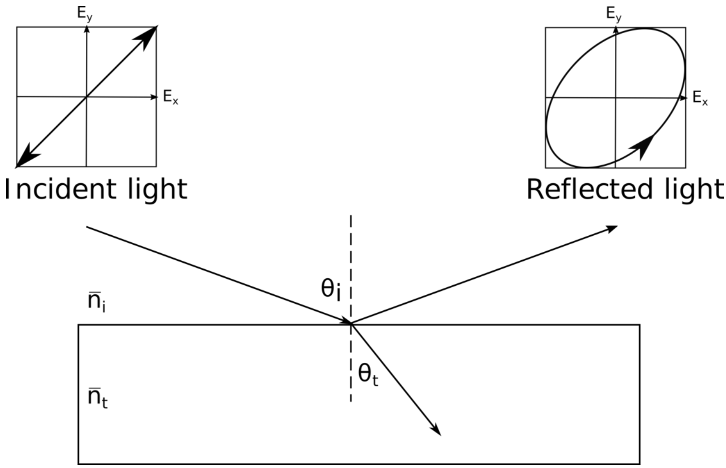

Figure 2.1: Reflection and refraction at a substrate, where $\bar{n}_i$, $\bar{n}_t$, θ_i, and θ_t are the refractive index of the ambient, and the refractive index of substrate, the incident angle, and the refraction angle, respectively.

3 Configurations of return-path ellipsometers

In this section, four existing configurations of RPE are presented. The basic principle and the main feature of these configurations will be introduced.

3.1 Plane mirror configuration

The simplest configuration of RPE was presented by O'Bryan [O'B36]. Fig. 3.1 shows a optical schematic of the plane mirror type of RPE. In his design, a Nicol prism was used as a polarizer, and a plane mirror was used to reflect the light back to the same posistion from the sample's surface. Yamaguchi and Takahashi [YT76b] modified the design of O'Bryan by replacing the Nicol prism with a Babinet-Soleil compensator and a quarter waveplate. The modified setup can measure samples at arbitrary angles without varying the incident angle. Azzam [Azz77a] used a linear polarizer and a linear retarder to replace the Nicol prism. This configuration can measure isotropic material at oblique angles of incidence and anisotropic material at a normal angle of incidence. The main feature of the plane mirror configuration is that the polarized optical components can be shared for the light source and the detector. In other words, it can reduce the number of optical elements and decrease the complexity of the system.

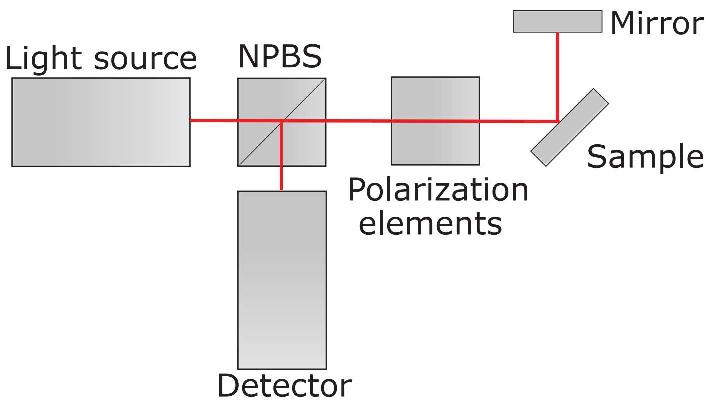

Figure 3.1: Plane mirror type of RPE: NPBS is the non-polarized beamsplitter.

3.2 Spherical mirror configuration

The plane mirror configuration, which is presented in section 3.1, is only suitable for flat surfaces because of the law of reflection. The light can be reflected back to the detector only when the plane mirror is perpendicular to the reflected ray. Slight misalignments or curved surfaces might lead to significant experimental errors. Haberland et al. [HHP$^+$98] overcame the constraint by using a spherical mirror to replace the plane mirror. Fig. 3.2 shows the spherical mirror configuration of RPE.

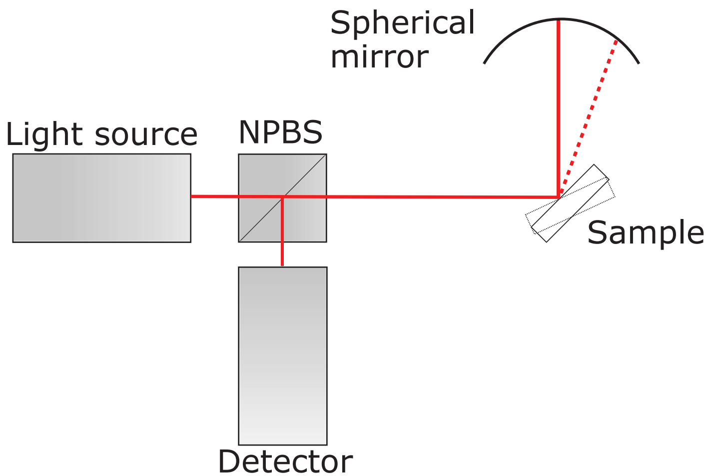

Figure 3.2: Spherical mirror type of RPE.

In geometry optics, every ray which passes the center of curvature of the spherical mirror is reflected back along the original path. Hence, the sample should be placed in the geometry center of the mirror. This configuration can effectively reduce the error from the angle deviation for sample rotation and sample wobbling, which usually occur in manufacturing process, e.g, epitaxial film growth. However, non-polarized beamsplitters usually have narrow wavelength range (e.g., 400-700 nm or 700-1100 nm) and polarization distortion [LLL16]. These disadvantages are not suitable for spectroscopic ellipsometry. Johs and He [JH11] modified the design of Haberland et al. by replacing the non-polarized beamsplitter with two right-angle prisms.The prisms have a wide wavelength range and no polarization distortion because the double reflection from the prisms cancels the change of the polarization state. The main advantage of the spherical mirror configuration of RPE is high angle tolerance while the sample is rotating or curved.

3.3 Glass hemisphere configuration

In the measurement of anisotropic material, the normal incident angle is important for the characterization of substrate birefringence. Conventional ellipsometers with two arms are difficult to measure samples at a normal incident angle due to the mechanical constraint. Fu et al. [FGS$^+$95] proposed a method to solve this problem. The configuration is demonstrated in Fig. 3.3.

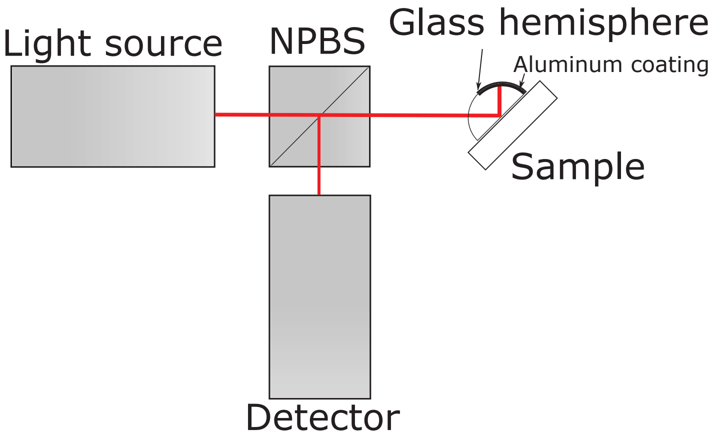

Figure 3.3: Glass hemisphere type of RPE.

A glass hemisphere is placed on the sample's surface. Half of the convex surface has aluminum coating to increase the reflectivity and the other half keeps transparent. There is no refraction in the glass hemisphere because the incident ray is perpendicular to the hemisphere all the time. Therefore, there is no polarization distortion induced by the hemisphere. The function of the hemisphere is the same as the function of the spherical mirror which was mentioned in section 3.2. The hemisphere setup, which only uses one arm, can measure samples at oblique and normal angles without obstruction and can measure samples in a transmission mode by using a transparent glass hemisphere on the top of the sample and another glass hemisphere with aluminum coating under the sample. The combined shape of two hemispheres and the sample should be a perfect sphere, which means the thickness of the sample cannot be too thick. Using glass hemispheres can reduce the size of the ellipsometer because every component is only on the same side.

3.4 Retroreflector configuration

In general, ellipsometry is a single point measurement technique and is not suitable for large-area measurement because the alignment between the sample and the system is very time-consuming. For large objects, usually only several points would be measured which would cause sampling error. Hartrumpf and Negara [HN17] developed a laser scanner with a retroreflector to overcome this limitation by using a retroreflector which is shown in Fig. 3.4. The light source is a circular polarized laser beam and a polygon mirror is used for the line scanning. The retroreflector can reflect the laser beam back to the detector with the same path and preserve the polarization state during the retroreflection [Neg14]. The advantages of the laser light source are high intensity, long coherent length, and long depth

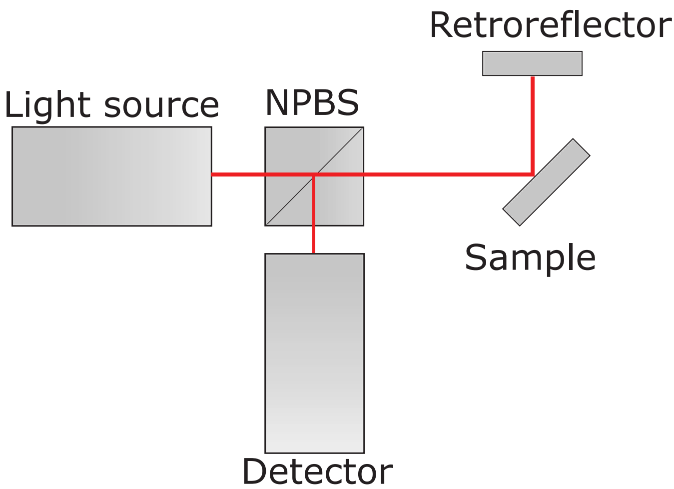

Figure 3.4: Retroreflector type of RPE.

of focus with proper focusing lenses. Because of these features and high tilt tolerance of the retroreflector, this method can be applied to curved surfaces, for example, headlight lenses, car windows, and curved displays. On the other hand, this configuration has high feasibility for inline measurement and large objects.

4 Discussion and Comparison

RPE has high sensitivity of optical properties of materials. Nevertheless, double reflection from the sample and the non-polarized beamsplitter lose a large amount of power of the light source. If a beamsplitter with a split ratio 50:50 (R:T) is used in the RPE, the power of the light source decreases to 25% because the light ray passes the beamsplitter twice. If an gold mirror ($\bar{n}_{Au} = 0.184 + 3.431\text{i}$ [JC72]) is measured at 70° with a wavelength 632.8 nm, the reflectance becomes 0.878 after double reflection from the sample. The overall power drops to 21.9%. For the low reflectivity material (e.g., N-BK7: n = 1.5151 at a wavelength 632.8 nm [Sch]), the reflectance becomes 0.03 at 70° measurement angle and the overall power drops to 0.8% . In order to compensate the power loss of the beamsplitter, the power of light source for RPE is at least four times higher than the power of the light source of conventional ellipsometers, and each surface of optical components should have anti-reflective coating to reduce the reflection loss. Another issue for the non-polarized beamsplitter is the polarization distortion. Although the beamsplitter has non-polarized effect, the polarization state of the light will change a little bit, when the light passes through the beamsplitter. Hence, the calibration for the reflection and the transmission for the beamsplitter is necessary for high-accuracy measurement. Johs and He [JH11] used two right-angle prisms to replace the beamsplitter for the elimination of the polarization distortion, but the trade-off is the positions of the first and the second reflection from the sample's surface are different. This modification of the beamsplitter is only suitable for surfaces with small angle deviation.

Table 4.1 lists the four different configurations and summarizes their advantages and disadvantages. The configurations of spherical mirror and retroreflector can overcome the angle deviation during the manufacturing process or the angle deviation of samples. The retroreflector setup has higher tilt angle tolerance compared to the spherical mirror setup because the condition of tilt immunity for the spherical mirror is only valid when the ray passes the center of the curvature of the spherical mirror. In other words, the alignment between the sample and the spherical mirror is critical. However, the retroreflector has higher polarization distortion compared to other configurations because the light beam is reflected once and refracted twice in the retroreflector. In Fresnel's equations, each reflection or refraction induces the polarization distortion. In the configuration of the glass hemisphere ball, the incident light beam is always perpendicular to the hemisphere ball for the phase conservation. This constraint increases the difficulty of the system alignment.

Table 4.1: Comparison of four different types of RPE.

	Plane mirror	Spherical mirror	Hemisphere ball	Retroreflector
Tilt tolerance	-	medium	-	high
Polarization distortion	low	very low*	low	medium
Alignment	normal	hard	hard	easy
Scanning measurement	-	-	-	possible

* The configuration of Johs and He.

5 Summary

In this report, we have introduced the basic principle of ellipsometry and four different configurations of RPE. Each configuration has its own advantages, disadvantages and suitable applications. Currently, most ellipsometers in the market are single point measurement. Measurements in these arrangements are only possible for plane surfaces or near plane surfaces. For the measurement of full-field surfaces, the measurement process is very time-consuming due to the difficulty of the alignment. In the future, we plan to use the retroreflector to design a laser scanning ellipsometer for full-field surface inspection and extend this method to curved surfaces.

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