Measurements of the thickness of a paint film on a metal surface by a double-modulation terahertz ellipsometer

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Abstract

We propose a double-modulation terahertz (THz) ellipsometer for measuring the thickness of the paint film coated on the metal surface. In order to eliminate the flicker noise due to a pump laser, the bias voltage of the photoconductive antenna (PCA) used for a THz pulse emitter was modulated at 100 kHz and a first lock-in amplifier (LA1) was connected to an electro-optic (EO) sampling unit for signal detection. For ellipsometric measurements, a wire-grid-polarizer (WGP) was rotated at 100 Hz and the output signal from the LA1 was fed into a second LA (LA2) synchronized with the polarization modulation. By operating the LA2 in a two-phase mode, we can obtain two waveforms simultaneously as a function of the time delay: one is an in-phase waveform and the other an out-of-phase waveform. After the Fourier transformation of the two waveforms, we can obtain ellipsometric parameters, $\Delta(\omega)$ and $\Psi(\omega)$, directly as a function of frequency ω. The lower detection limit in the thickness measurement was 4.3 μm with a relative standard deviation of 6.7 %

1. Introduction

A THz wave has promising properties, such as propagation in free-space, high transmittance, and low scattering, which are of use for non-destructive testing of industrial products. One of the most practical applications in the industry is the non-contact and in-line measurement of the thickness of the paint film coated on the car body. Although it seems simple, the precise measurement is not always easy. The reason is that the paint film is opaque for the usual optical-frequency band. The conventional methods have to make their probes contact to the sample. As the result, they become difficult to measure wet films. Therefore, the THz wave has been introduced. As far as the thickness measurement is concerned, a time-of-flight technique (TOF) in THz time-domain spectroscopy (THz-TDS) seems promising. However, it is still difficult to measure the thickness less than 20 μm, even if mathematical deconvolution or multivariate analysis technique has been used [1]. In addition, one has to know the frequency-dependent group-refractive-index of the sample in advance. To this end, we have to introduce a frequency-domain (FD) THz ellipsometer (THz-ELP). In the FD-THz-ELP, two time-series waveforms should be measured by scanning the optical-delay stage two times: one is to obtain a *p*-polarized component and the other an *s*-polarized one. Then, two ellipsometric parameters, $\Delta(\omega)$ and $\Psi(\omega)$, as a function of the frequency ω, are derived directly by Fourier transformation. As mentioned above, two measurements are required in the conventional FD-THz-ELP, [2]. Apart from such a problem, improvement in the SNR in measurement is always required for precise measurements [3].

In the present paper, we propose a double-modulation, reflection type FD-THz-ELP. Adopting the EO sampling method, the bias voltage of the PCA was modulated at 100 kHz and a WGP was rotated at 100 Hz (polarization modulation frequency; 200 Hz). For the treatment of the signal, we used two LAs connected in tandem. By operating the second LA in a two-phase mode, we can obtain an in-phase mode signal and an out-of-phase mode signal simultaneously. Finally, we can derive the two ellipsometric parameters directly through Fourier transform by a single measurement.

2. Double-modulation reflection-type THz ellipsometer

Figure 1 shows a schematic diagram of FD-THz-ELP. A laser beam from a mode-locked Ti-sapphire laser (Ti-S; wavelength; 800 nm, pulse width; 80 fs, repetition frequency; 80 MHz) was divided into a pump and a probe beam by a beam splitter (BS). The pump beam was focused on the PCA, where bias voltage of the PCA was modulated. The THz pulse emitted from the PCA passed through two wire-grid polarizers (WGP1, 2; frequency range; 0.1~1.5 THz) and a rotational WGP (RWGP). Orientation angles (or transmission axes) of WGP1, WGP2, and RWGP are θ_1, θ_2, and θ_R, respectively, where $\theta = 0°$ means a *p*-polarized light and $\theta = 90°$ an *s*-polarized light. For measuring isotoropic samples, we set $\theta_1 = 45°$ and $\theta_2 = 0°$. The

RWPG was roatated at f = 100 Hz. The THz pulse was finally focused into an electro-optic crystal (ZnTe), where the electric-field strength of the THz pulse is sampled.

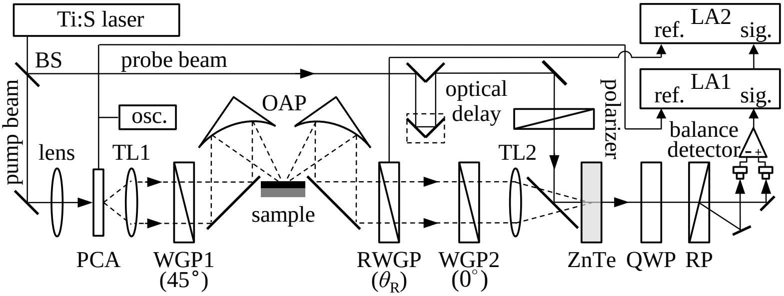

Figure 1: Schematic diagram of the double-modulation THz ellipsometer.

The probe beam reflected by BS, after being polarized, was also incident into the ZnTe crystal. The slight change in its polarization state was detected by a balanced light detector followed by a quarter wave plate (QWP) and a rochon prism (RP). The output signal from the detector was fed into the LA1 and then LA2. From the in-phase output of the LA2, we can obtain the signal that is proportional to the difference of the electric-field strength between when θ_R = 0° and θ_R = 90°. From the out-of-phase output, we can obtain those between when θ_R = 45° and θ_R = -45°. The two components are recorded as a function of the time delay. Then, by Fourier transformation, we can obtain two complex electric-field components in the frequncy domain: the in-phase, $E^{\mathrm{in}}(\omega)$, and the out-of-phase, $E^{\mathrm{out}}(\omega)$, component. The sweep range of the optical delay is 27.0 ps and a step interval is 53.4 fs. The time constants of the LA1 and LA2 are τ_1 = 300 μs and τ_2 = 300 ms, respectively.

3. Ellipsometric measurements

From the Jones calculus, we can derive $E^{\mathrm{in}}(\omega)$ and $E^{\mathrm{out}}(\omega)$ as follows:

$$E^{\mathrm{in}}(\omega) = E_p(\theta_R = 0^\circ, \omega) - E_p(\theta_R = 90^\circ, \omega) \propto r_p(\omega)\,, \tag{1}$$

$$E^{\mathrm{out}}(\omega) = E_p(\theta_R = 45^\circ, \omega) - E_p(\theta_R = -45^\circ, \omega) \propto r_s(\omega)\,, \tag{2}$$

where $r_p(\omega)$ and $r_s(\omega)$ are Fresnel's complex amplitude reflectivities for the p- and the s-polarized light, respectively. Therefore, ellipspmetric parameters, $\Delta(\omega)$ and $\Psi(\omega)$, can be derived from the following equation:

$$E^{\text{in}}(\omega)/E^{\text{out}}(\omega) = r_p(\omega)/r_s(\omega) \equiv \rho(\omega) = \tan[\Psi(\omega)]\exp(i\Delta(\omega)) \ . \qquad (3)$$

Once the ellipspmetric parameters are derived, the thickness of the film and/or its complex refractive index can be estimated by a usual manner in ellipsometry.

4. Measurement of the thickness of the paint film

In order to demonstrate the fundamental performance of the system, we have measured the thickness of a black lacquer film coated on an Al substrate. We prepared four samples of which thicknesses were known: 20.0, 10.4, 5.3, and 4.3 μm, which were measured by an eddy-current meter thirty times. Table 1 summarizes the thickness values measured by the double-modulation FD-THz-ELP. For deriving those values, we have measured a relatively thicker film (170.0 μm), from which we have estimated the frequency-dependent complex refractive index of the film. Also, we used a Drude model to derive the complex refractive index of aluminium. Finally, we used a three layer (air/film/metal) model as a usual fashion in ellipsometry.

Table1: Measurement results of the thickness of the black lacquer film.

eddy-current meter	20.0±0.6 μm	10.4±0.2 μm	5.3±0.4 μm	4.3±0.6 μm
FD-THz-ELP	19.6±0.2 μm	9.9±0.3 μm	5.6±0.4 μm	4.5±0.3 μm

5. Conclusions

We have constructed a double-modulation, reflection-type THz ellipsometer for measuring the thickness of the paint film coated on the metal surface. We have demonstrated that the thickness measurement of less than several micrometres is possible with a relative standard deviation around 6.7 %.

References:

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