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테라헬츠 포토닉스와 여러 가지 나노박막의 유전 및 광학적 특성의 측정

THz Photonics and the meaurement of dielectric and optical properties of thin films

이광수, 인하대학교 물리학과
leek2@alum.rpi.edu

As feature sizes of circuits and devices approach 100 nm and chip frequencies climb into the upper gigahertz to terahertz range, it becomes increasingly important to have a convenient method of characterizing properties of thin dielectric films in the GHz to THz frequency range [1]. To measure the dielectric and optical properties of materials at THz frequency, a THz time-domain spectroscopy has been utilized during past decade. However, if the thickness of the material is comparable or thinner than the wavelength of the terahertz wave, the phase and amplitude changes by dielectric materials tends to be difficult to measure with the THz time-domain spectroscopy. To solve this difficulty, a THz differential time-domain spectroscopy was introduced [2], [3].

In this paper, the dielectric and optical properties of a 100 nm tantalum oxide dielectric film at THz frequency is investigated, using the THz differential time-domain spectroscopy. If a THz wave is incident on a thin layer 2 between air 1 and a substrate 3 from the air toward the substrate, a transmitted electric field due to multi-reflection is given by [4],

$$E_t(\omega)=\frac{t_{12}t_{23}\exp[i\delta(\omega)]}{1-r_{21}r_{23}\exp[2i\delta(\omega)]}t_{31}E_0(\omega), \tag{1}$$

where E_0, t_{12}, t_{23}, r_{21}, and r_{23} are incident electric field, transmission, reflection coefficients between interfaces, and $\delta(\omega)$ is the phase shift of thin film medium. On the other hand, if defined as $E_{\mathrm{ref}}(\omega)=t_{13}t_{31}E_0(\omega)\exp(i\omega d/c)$ and $E_{\mathrm{diff}}(t)\equiv E_t(t)-E_{\mathrm{ref}}(t)$ and assumed as $d \ll c/\omega$, $E_{diff}(\omega)/E_{ref}(\omega)$ for an absorbing material is approximated and extended to following equation.

$$\frac{E_{\mathrm{diff}}(\omega)}{E_{\mathrm{ref}}(\omega)}\approx i\frac{\omega}{c(n_1+n_3)}d[(n+ik)^2+n_1n_3-n_1-n_3)], \tag{2}$$

where n and k are the real and imaginary parts of complex refractive index of the thin layer. If one can measure the phase and amplitude of $E_{\mathrm{diff}}(\omega)/E_{\mathrm{ref}}(\omega)$, the dielectric and optical properties can be deduced from relations, $\varepsilon'=n^2-k^2$, $\varepsilon''=2nk$, and $\alpha=2\omega k/c$. For the experiment, a THz emitter was used, which was driven by a 100 femto-second pulse from a Ti:sapphire laser to produce the coherent THz wave radiation while the electro-optic detector was gated by the laser pulse split from the laser for the coherent THz wave detection.

A 100 nm tantalum oxide film was prepared by reactive sputtering (ion bombardment) of a Ta metal in oxygen atmosphere and the differential measurement of the THz wave was performed. The dielectric property of tantalum oxide was known in the megahertz range [5] and it varies 20 to 100. Figure 1(a) shows the differential waveform in the 100 nm tantalum oxide film. The amplitude of the measured differential signal was 3 % of the reference signal. Figures 1(b)-(d) show the measured dielectric and optical properties of the 100 nm tantalum oxide film. The measured averaged values of the real and imaginary parts of the dielectric constant and optical constant of the tantalum oxide film were ε' = 59, ε''= 1.8, n = 7.7, k = 0.07 ~ 0.17, and a = 24 ~ 100 cm^{-1}.

In conclusion, the THz differential time-domain spectroscopic method is applied to characterize the dielectric and optical properties of the 100 nm tantalum oxide thin film at THz frequency. The dielectric and optical properties of the tantalum oxide show reasonable data with previously available data. The THz differential time-domain spectroscopy might be applied to the measurement of the dielectric and optical properties of nano scaled thin films of several materials, which cannot be done by any other method.

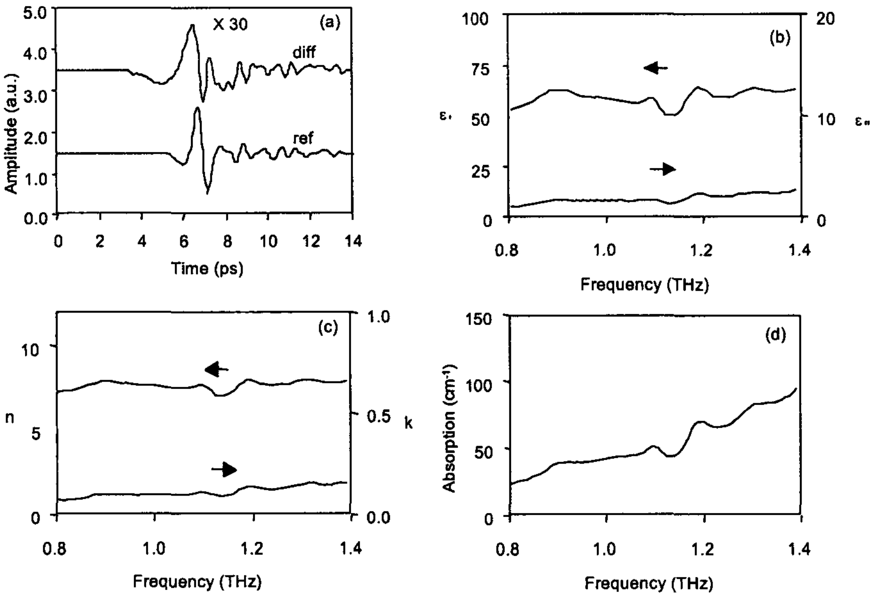

Figure 1. The THz differential signal (a), ε', the real part, ε'', the imaginary part of complex dielectric constants (b), n, the refractive of index, k, the extinction coefficient (c), α, absorption coefficient (d) in the 100 nm tantalum oxide film.

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