Ultrabroadband terahertz characterization of highly doped ZnO and ITO

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***Abstract*—The broadband complex conductivities of transparent conducting oxides (TCO), namely aluminum-doped zinc oxide (AZO), gallium-doped zinc oxide (GZO) and tin-doped indium oxide (ITO), were investigated by using THz-TDS from 0.5 to 18 THz. The complex conductivities were accurately calculated using a thin film extraction algorithm and analyzed in terms of the Drude conductivity model. We find that a phonon response must be included in the description of the broadband properties of AZO and GZO for an accurate extraction of the scattering time, which is strongly influenced by the zinc oxide phonon resonance tail even in the low frequency part of the spectrum.**

I. INTRODUCTION

TRANSPARENT conducting oxides have been demonstrated as alternative plasmonic materials to conventional metals in the near infrared region[1], [2], and it is important to experimentally characterize these TCOs in the terahertz frequency region. Recently, due to the development of two-color femtosecond air plasma THz-TDS, it has become possible to extend THz-TDS measurements on chalcogenide glasses [3] and water [4] up to more than 18 THz. Here we report the complex conductivities of 10 wt% ITO, 2 wt% AZO and 6 wt% GZO with various thicknesses (from 110 nm to 260 nm) up to 18 THz, thereby covering the important crossover point where the scattering rate equals the frequency, $\omega\tau = 1$, thus allowing precise determination of the scattering time. We find that the ITO conductivities are well described by the simple Drude model, while the conductivity of GZO and AZO must be described by a Lorentz oscillator model in addition to the Drude response in order to take the phonon response of zinc oxide (ZnO) into account. The experiments were performed with broadband laser induced plasma THz-TDS, supplemented by traditional photoconductive antenna (PCA)-based THz-TDS [5].

II. RESULTS

The complex conductivities were extracted through the customized thin film conductivity extraction algorithm [6]. As shown in Fig. 1(a) and (b), the complex conductivities of GZO and AZO are well described by Drude model superimposed by a Lorentz oscillator[6]. For ITO, we obtain a good Drude fit for 110 nm thick ITO up to 11 THz and reasonable Drude fit up to 18 THz (as shown in Fig. 1(c)), while the Drude model only fits well up to 8 THz for the 210 nm thick ITO.

In ITO, the optical properties above 9 THz are influenced by a strong, broad band of several phonon modes. The additional resonance term in GZO and AZO originates from the ZnO phonon at 12 THz. we find the electron scattering time obtained from the Drude-Lorentz model is more reliable than the Drude model due to the ZnO phonon resonance, highlighting the requirement of an ultrabroadband measurement technique in order to fully understand conductivity dynamics in metal oxides. The conductivity of AZO is found to be more thickness dependent than GZO and ITO, indicating high importance of surface states and growth conditions for electron dynamics in AZO, and our results suggest that further investigation of the detailed dependence on the fabrication conditions will be valuable.

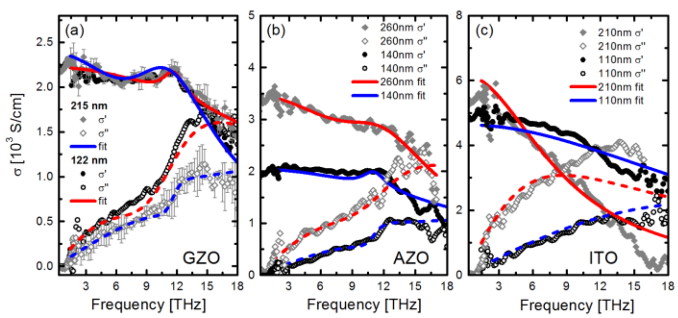

Fig. 1. The extracted real (filled symbols) and imaginary (open symbols) parts of the complex conductivity of the TCOs. Drude-Lorentz fits (red and blue curves) up to 18 THz for (a) GZO and (b) AZO. (c) Drude fits to 18 THz for ITO. The data between 0.5 and 2 THz were obtained with PCA measurements.

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