Spectroscopy of highly conductive SMO thin film in the THz range

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***Abstract*—The conductivity and dielectric function of a different $SrMoO_3$ (SMO) oxide thin film is characterized in the THz frequency range. The dielectric constant is determined to $\epsilon_2 = 1.6 \cdot 10^5$ at 200 GHz and $\epsilon_2 = 0.3 \cdot 10^5$ at 1.0 THz with almost vanishing real part ϵ_1 for a 20 nm SMO film on a $GdScO_3$ (GSO) substrate. We compare THz properties of different growth runs in order to evaluate influence of the film quality. All investigated SMO thin films show metal-like conduction similar to that of Titanium.**

I. INTRODUCTION

PEROVSKITES are promising materials for application in photovoltaic cells, as well as electrochemical coatings. Perovskite oxides of ABO_3 with transition metals at the B-site feature bandgaps from highly conducting $SrMoO_3$ (SMO) to highly insulating $Ba_xSr_{1-x}TiO_3$ (BST). These materials offer an excellent platform for new device concepts, such as BST varactors in the GHz frequency range [1-2]. SMO thin films are further promising candidates for highly conductive transparent electrodes with applications in photovoltaics and touch screens: They feature a resistivity below 20 μΩcm, i.e. in the range of metals [3]. Furthermore, they are transparent in the visible with an absorption of less than 10% for a 30 nm film [4]. This paper focuses on spectroscopy of highly conductive SMO thin films in the THz range. SMO thin films have so far only been characterized in the GHz, and visible part of the electromagnetic spectrum [2-5].

The 20 nm (001)-oriented SMO film for this study was grown epitaxially by pulsed laser deposition on a 0.5 mm thick (110)-oriented $GdScO_3$ (GSO) substrate. In order to promote high quality crystal structure of the SMO film, the substrate was covered with a 2 nm $SrTiO_3$ (STO) buffer layer (5 unit cells). Details of the growth process can be found in Ref. [2]. SMO thin films of similar high quality with a thickness in the range of 20 nm show a low DC resistivity of 31-35 μΩcm [4].

II. RESULTS

The Terahertz properties of the thin film are measured in a pulsed 1550 nm Terahertz time domain spectroscopy (TDS) system with a photoconductive THz source and detector from Menlo Systems/Fraunhofer HHI in a transmission setup. The system features a 90 fs laser pulse at a repetition rate of 100 MHz and a spectral coverage up to ~5 THz. However, the severe absorption and reflection losses of the highly conductive SMO sample limit the frequency range to about 2.2 THz. The measured transmission of the SMO thin film on the GSO substrate is compared to a reference transmission of the bare GSO substrate, yielding the relative (field) transmission coefficient t of the thin film.

The conductivity of the highly conductive thin film is extracted using Tinkham's formula [6,7]

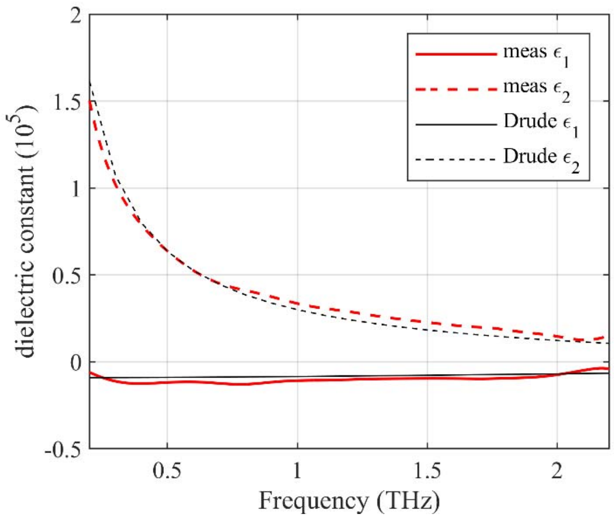

Fig. 1. Real and imaginary part of the dielectric constant ϵ_1 and ϵ_2 of the 20 nm SMO thin film on the 0.5 mm thick GSO substrate (red solid and dashed line). The Drude model is fitted to the measured data (black solid and dashed line).

$$\sigma = \frac{n_S+1}{Z_0 d}\left(\frac{1}{t}-1\right), \quad (1)$$

with the refractive index of the substrate n_s=4.7±0.3, the free-space impedance Z_0=377 Ω, and the thickness of the thin film, d= 20 nm. The dielectric constant $\epsilon_r = \epsilon_1 + i\epsilon_2$ is calculated as

$$\epsilon_r = \epsilon_\infty - \frac{\sigma}{i\omega\epsilon_0}. \quad (2)$$

The dielectric constant of highly conductive materials such as metals can be modeled in the THz range by using the Drude model [7]

$$\epsilon_r = \epsilon_\infty - \frac{\omega_p^2}{(\omega^2+i\omega/\tau)}, \quad (3)$$

with the plasma frequency ω_p, the scattering time τ and the constant offset ϵ_∞ from Lorentz resonators at higher frequencies. For highly conductive films with scattering times much shorter than the inverse angular frequency ω^{-1}, Eq. (3) can be approximated as

$$\epsilon_r \approx \epsilon_\infty - \omega_p^2\tau^2 + i\,\frac{\omega_p^2\tau}{\omega}. \quad (4)$$

Fig. 1 shows the extracted dielectric constants from the measurement along with the fitted Drude model according to Eq. (3). The dielectric constant is $\epsilon_2 = 1.6 \cdot 10^5 \pm 6\%$ at 200 GHz and $\epsilon_2 = 0.3 \cdot 10^5$ ±4% at 1.0 THz, in both cases with almost vanishing negative real part $|\epsilon_1| \ll |\epsilon_2|$. The measured dielectric constant can be described very well by the Drude model in the THz range. The extracted values of the Drude model are $\omega_p/2\pi = 340 \pm 150$ THz and $\tau = 45 \pm 25$ fs. The large fitting error bar is due to the fact that in the range $\omega\tau \ll 1$, ω_p and τ apper as products only according to Eq. (4) and are therefore hardly discernible.

Fig. 2 shows the complex conductivity of the SMO film, calculated with Eq. (1). The corresponding Drude model fitted to the dielectric constant is shown as a reference. The measured conductivity is close to $2\frac{1}{\mu\Omega m}$. Therefore, we conclude that SMO behaves metallic in the THz range.

Meanwhile, we have shown that SMO films with higher film quality even offer a conductivity of around $\sigma_{re} = 3.1\frac{1}{\mu\Omega m}$ with Drude parameters $\omega_p/2\pi = 760 \pm 100$ THz and $\tau = 15.5 \pm 4$ fs for the same SMO thickness (20 nm) on a 0.2 mm GSO substrate [8]. The conductivity was only less than a factor of 3 below a sputtered 20 nm Au film on GSO [8]. We note that in Ref. [8], we also recorded optical spectra, thus reaching the limit $\omega\tau > 1$ where Eq. (4) is not valid. Therefore, the fitting errors are substantially smaller.

We conclude that SMO films prove to be an excellent material choice for highly conductive thin films in the THz range despite some dependence on growth quality, in comparison with a different growth run in Ref. [8]. All films offered conductivities in the range of that of the metal Titanium ($2.5\frac{1}{\mu\Omega m}$).

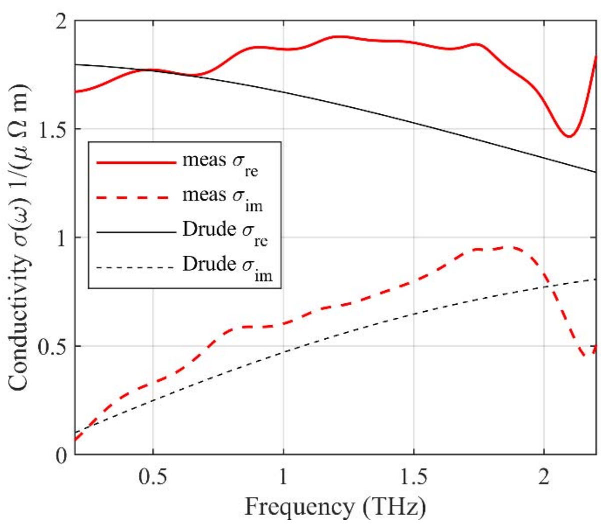

Fig. 2. Real and imaginary part of the dielectric constant σ_{re} and σ_{im} of the 20 nm SMO thin film on the 0.5 mm thick GSO substrate (red solid and dashed line). The Drude model fitted to the dielectric constant is included as a reference (black solid and dashed line).

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