Field and temperature-dependent thin film characterization with a continuous-wave terahertz magneto-spectrometer

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Abstract—We report on a non-contact, non-destructive evaluation system which utilizes frequency-domain THz transmission spectroscopy to examine the temperature and magnetic field-dependent conductivity of thin film on substrate materials.

I. INTRODUCTION

QUASI-OPTICAL THz frequency characterization offers a non-contact approach for electrical parameter extraction which alleviates destructive and time consuming sample preparation steps used in conventional contact-based electrical characterization methods. However, for ultra-thin film samples, it can be challenging to generate sufficient interaction of the THz electromagnetic wave with the material under analysis. For example, the phase noise in a single transmission THz-TDS pulse often exceeds the phase delay imparted by nanometer thick films typically found in materials used in functional semiconductor devices[1]. To overcome the weak interaction, both time and frequency domain THz spectroscopies make use of etalons or multiple reflections in the substrate to increase the number of interactions with the thin film overlayer[2]. In this work, we will report on temperature-dependent continuous-wave (CW) THz spectra for thin film permalloy films on silicon.

II. RESULTS

15nm and 30 nm thick permalloy films on high resistivity silicon were examined using a turn-key, CW-THz transmission spectrometer system operating from 5 K to 300 K and with magnetic fields up to 9 T[3]. In this platform, THz is generated and detected by broad-band photoconductive switches (PCS) oriented at normal incidence to the sample; the handedness of the circularly-polarized THz beam is set by the square spiral antenna patterned around the active area of the PCS.

For each permalloy sample, 24 individual THz transmission spectra were acquired from 0.2 to 1.5 THz with 1 GHz resolution then averaged together. Each sample measurement is amplitude and phased referenced by an additional acquisition with no sample in the THz beam. The permalloy-on-silicon transmission spectra exhibit a frequency-dependent Fabry-Perot etalon pattern which varies with the thickness and conductivity of the thin film. In this experimental configuration under zero-field conditions, magneto-optical and magnetization dynamics can be ignored, and the spectra can be fit to the complex-valued, frequency-domain transmission function for a thin conductive film on substrate:

\[ T(\omega) = \frac{4k_{0}n_{sub}\exp[-t(n_{sub} - 1)k_{0}d_{sub}]}{1 - \exp [-2in_{sub}k_{0}d_{sub}] \frac{n_{sub} - 1}{n_{sub} + 1} (2n_{sub}k_{0}X - 1)} \]  

where \( n_{sub} \) and \( d_{sub} \) are the substrate complex refractive index and thickness, respectively, and \( k_{0} \) is the free-space wavenumber. For algebraic convenience we use, \( X = (1 + n_{sub} + \sigma_{s}Z_{0})^{-1} \) where \( Z_{0} \) is the free-space impedance (377 Ω) and \( \sigma_{s} \) is the effective complex surface conductivity of the thin film. To demonstrate the sensitivity of the Fabry-Perot transmission approach, previously measured DC values for the thickness-dependent conductivity of permalloy are input into Equation 1 and the modeled CW-THz transmission spectra are plotted for several thicknesses of permalloy (Figure 1).

![Figure 1. Modeled continuous wave terahertz transmission spectra for annealed permalloy on 515 μm thick silicon substrate.](image)

In order to extract thin film conductivity values from a THz transmission measurement, the substrate thickness and THz frequency refractive index must first be determined by fitting equation 1 to the measured substrate transmission (\( \sigma_{s} \) is zero for the substrate). The bare substrate used in the permalloy deposition has a CW-THz measured refractive index of 3.41 and a thickness of 515 μm. For our purposes, the attenuation in the substrates is negligible. Conductivity values for the permalloy are extracted by fixing the substrate thickness and index in equation 1, then varying the sheet conductivity until the error between measured and model transmission and phase values is minimized. From this extraction, the measured optical resistivities of the films are 30 μΩ·cm and 24 μΩ·cm for the 15 nm and 30nm films, respectively, and are consistent in magnitude and thickness-dependence with previous results for grain boundary scattering in annealed, polycrystalline permalloy[4]. In a similar fashion to the room temperature measurements, low temperature THz transmission spectra were acquired for the 15 nm permalloy film at 10 K. We
observe an overall decrease in the THz transmission at this temperature corresponding to an AC resistivity of 20 \( \mu \Omega \cdot \text{cm} \). In the context of grain boundary scattering, the decrease in low temperature resistivity is consistent with an increase in mean free path relative to a fixed grain size in the film.

![Figure 2](image.png)

**Figure 2.** Modeled and measured THz transmission and phase for a 15 nm thick Permalloy film on silicon at 300 K.

### III. SUMMARY

In this work, the AC resistivity of ultra-thin permalloy films was extracted from non-destructive THz transmission measurements at room and cryogenic temperatures. The demonstrated non-contact evaluation methodology can be extended to other thin film on substrate systems such as semiconductor overlayers. In future work, the off-diagonal conductivity at THz frequencies can be evaluated for certain material systems with the addition of bipolar magnetic fields to the transmission methodology.

### REFERENCES


