

Sputtered permalloy as novel material for THz-thin film technology: fabrication process, physical and electromagnetic properties

Pranesh Kondamarri¹, Julien Petit¹, András Kovács¹, Ulrich Mescheder¹, Volker Bucher¹, Anil Badisa², Michał Herbko², Adam Żywica², Marcin Ziółkowski², Przemysław Łopato²

¹ Furtwangen University, Robert-Gerwig Platz 1, 78120, Germany

² West Pomeranian University of Technology, Szczecin, al. Piastów 17, Poland
ReddyPranesh.Kondamarri@hs-furtwangen.de

Summary:

Sputtered permalloy thin-film technology has been developed for terahertz (THz) filters. The current work describes its fabrication process and characterisation process. The investigated thickness range of the films is 100-1000 nm. The film surfaces and the growth of the film is analysed using FIB-SEM measurements. The magnetic behaviour is evaluated with vibrating sample magnetometer. The THz behaviour is characterised using sheet-resistance measurements followed by time domain spectroscopy (THz-TDS). It is demonstrated that films with thickness greater than 400 nm show a large out-of-plane magnetisation and a THz-shielding performance of more than -50 dB at 1 THz.

Keywords: THz-filters, magnetic films, Metasurface, MEMS, sputtering, permalloy, THz-TDS, resonant frequency, split-ring resonators.

Introduction

Terahertz (THz) waves ($(0.1-30) \times 10^{12}$ Hz) and their interaction with materials gained an increased research-interest in the past two decades. Invention of THz sources (such as photoconductive antennas, backward-wave oscillators, quantum-cascade lasers [1]) paved a way towards THz-TDS technology e.g., for biosensors. Currently, there is a growing need to develop tunable filters for sensing different frequency ranges. One possible way to realize this is through so-called 'metasurfaces (MS) [2].'

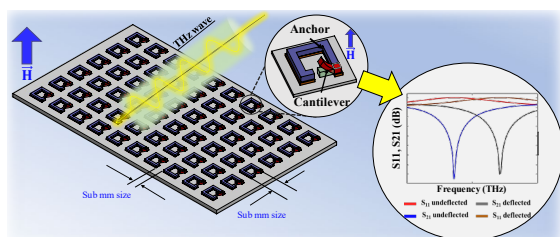


Figure 1 Magnetically tunable THz MS. SRR with a cantilever arm in red (in inset) which is sensitive to external H leading to f_R shift shown using S_{21} transmission parameters [5].

MS are 2D artificial materials which respond unusually to EM waves (compared to natural materials) due to sub-wavelength size structural units. Typical examples of such units are cross structures or split-ring resonators (SRR) which behave as an LC oscillator and are realized by

suitable high conductive thin film metal structures with sufficient shielding properties in the THz range. As the SRR dimensions determine the resonance frequency f_R , they can be tailored to operate in THz range [3].

The current work is a part of a project which aims to develop magnetically tunable THz metasurfaces using MEMS processes (Figure 1). The structural unit is an SRR whose one arm is a deflecting cantilever (cl) while the rest is an anchor. In case that the cl is made of ferromagnetic material, the cl can be deflected by an appropriately chosen external magnetic field ($\vec{H}$), and thereby leads to a shift in f_R . Permalloy ($\text{Ni}_{80}\text{Fe}_{20}$ or Py) has a high permeability ($\mu_r \sim 100,000$), low resistivity ($\rho_{\text{bulk}} = 16 \mu\Omega\text{-cm}$) and is therefore in principle very well suited for magnetically tunable filters [4]. However, the THz shielding behavior must be investigated which is the purpose of this study. Therefore, films are characterised based on thickness (t), surface and layer growth. The magnetic hysteresis behavior is studied using a vibrating sample magnetometer (VSM). The sheet resistance (R_s) and the shielding behavior are also evaluated. Based on this evaluation, passive MS structures of Py are further fabricated and tested for their THz absorption performance. The processes and results are described in detail in the following sections.

Material and methods

Thin film fabrication

Py films are sputtered at room temperature (RT) in DC mode (Alcatel SCM650). To minimize THz absorption in substrate, low doped Si wafers with $\rho > 10 \text{ k}\Omega\text{-cm}$ are used. The base pressure is kept at 7.5×10^{-7} mbar. Argon pressure is set to 0.09 mbar. Films are sputtered at 75 W and at a target-substrate distance of 60 mm with a sputter rate of 0.084 nm/s. The range of t for the films is in 93-975 nm.

Passive metasurface fabrication using lift-off process.

Based on the characterisation of the complete Py layers, a process flow is developed to fabricate SRR based MS structures described in Figure 2. A positive resist AZ1518 is used as a liftoff layer. This is spin coated using KarlSüss RC8 CT-62 at 4250 RPM, 2500 Accn for 25 s. Diluted HMCTS is applied prior to resist as an adhesion promoter. The coated AZ1518 is soft-baked at 100°C for 50 s and subjected to UV exposure with SRR mask using KarlSüss MA6 SN-50 for 11 sec at RT and 44% humidity. The exposed resist is patterned in diluted AZ351B for 60 s. A layer of Py is then sputtered onto the resist and as a final step, the sample is immersed in acetone placed in ultrasonic shaker for 300 s for lift-off.

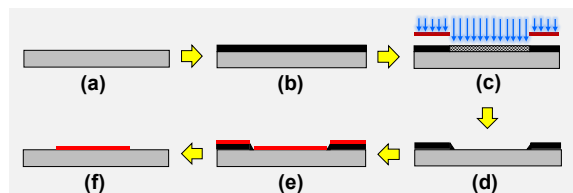


Figure 2 Process flow for passive structure fabrication. (a) Uncoated Si substrate (b) Spin coated AZ1518 photoresist, $t = 1.8 \mu\text{m}$ (c) UV exposure using SRR mask (d) Resist patterning with AZ351B diluted in 5 parts of water (e) Sputter deposition of py layer. (f) Lift-off in Acetone in an ultrasonic bath.

Characterization methods

The metal film thickness is measured using a Dektak profilometer. FIB-SEM device (Zeiss Crossbeam 550 L117442) and laser-confocal microscope (Keyence VK-X3100) are used to evaluate surface topography, layer growth and surface roughness. The hysteresis behaviour of the film is studied in Out-of-plane (OP) direction with a vibrating sample magnetometer (VSM). 4-point measurement is used to measure R_s of the films. The transmission properties are evaluated in 0-6 THz frequency range using THz-TDS spectroscope (Toptica Teraflash Smart). In contrast to vector network analyzers, where the frequency is physically swept during the measurement, THz-TDS performs time-domain

measurements, and the frequency response is obtained using Fast Fourier transform (FFT) technique. The blank substrate is taken as reference.

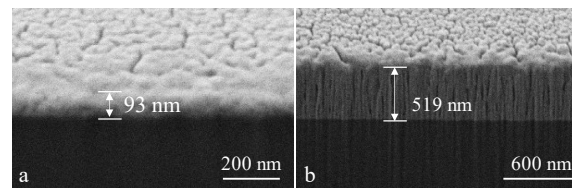


Figure 3 FIBSEM cut of deposited films. The film is crack-free but ridged. The roughness is in nm scale initially at 93 nm (a) but, results in a columnar layer growth at higher thickness (b).

Results and conclusion

Complete layers

The film surface is shown in Figure 3. At 93 nm, the surface is complete, crack-free but, ridged. The roughness of the film is in the nm-scale. As t rises, the layer grows in columnar fashion. The magnetisation curve for a film with $t = 436 \text{ nm}$ is presented in Figure 4. The curves exhibit a large magnetisation ($\vec{M}$) in OP direction which is essential for a deflection in applied external $\vec{H}$.

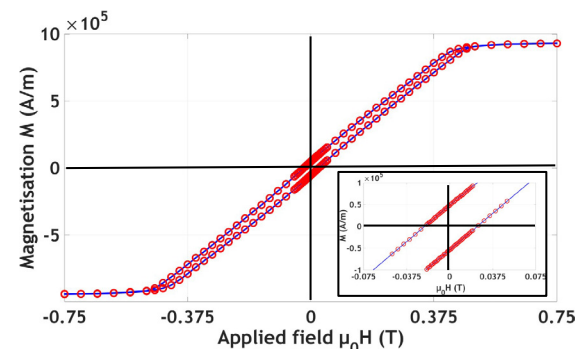


Figure 4 Hysteresis behaviour of a 436 nm-thick Py in the OP direction. The sample has a large $\vec{M}$ and a saturation around 600 mT and have a remanence (M_r) is at 54 kA/m and $\mu_0 H_c$ is at 23 mT.

The THz transmission ($|T|$) for varying t is shown in Figure 5. The inset describes the R_s drops between 93 and 219 nm and saturates at higher thicknesses and the fitted curve follows $R_s = a/(t + b)$ where $a = 4363$, $b = -33.97$. In the region of interest (ROI, 0-3 THz), as t rises from 93 to 219 nm, the signal attenuates by more than -20 dB at 1 THz. With further rise in t , signal reaches noise level. The according absorption coefficients are analyzed under assumption of constant Py-reflectivity in that range. Absorption coefficients between $10\text{-}30 \mu\text{m}^{-1}$ were found with a maximum at around 1 THz. It results in an attenuation of -50 dB for $t = 400 \text{ nm}$ implying that Py is a potential material for MS-based THz-filters.

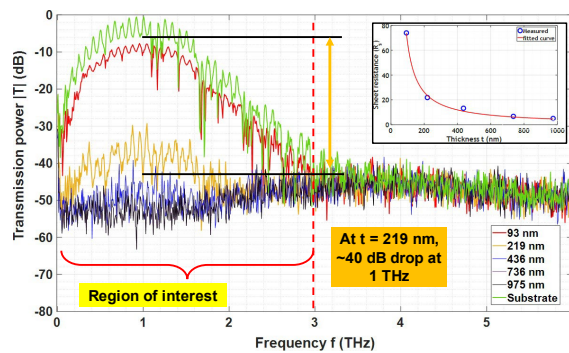


Figure 5 THz transmission in Py films. With increase of t signal attenuates rapidly and reaches noise level for $t > 436$ nm. The inset describes the variation of R_s with t . The blue circles represent mean in R_s (5 values around the wafer). The error is negligible.

Structured passive SRR metasurface

The fabricated passive MS is presented Figure 6a. The outer dimensions of SRR are $\sim 110 \times 110 \mu\text{m}$ and the capacitive plates are $\sim 25 \mu\text{m}$ wide and have separation distance of $\sim 16 \mu\text{m}$. The Py has a $t = 589 \pm 46$ nm, which is higher than 400 nm, the minimal thickness required for reasonable THz shielding and exert an $\vec{M}$ in OP for a deflection in external- $\vec{H}$. The THz response is presented in Figure 6b. The incident THz wave was polarized with its electric field vector ($\vec{E}$) oriented horizontally, with respect to the SRR ($\vec{E}$ horizontal in Fig. 6a), to maximize the coupling between the $\vec{E}$ -field and the LC resonant mode of the structure. This configuration enables efficient excitation of the SRR fundamental resonance and enhances the observed THz response. Its response is compared with the response of an unstructured 436 nm-thick Py layer. Also, for the comparison of THz resonance peaks, an SRR chip fabricated with Al as metal layer, $t = 536 \pm 40$ nm is considered too. Compared to the total attenuated response (in the ROI) of the unstructured Py layer, both Al and Py-SRR samples exert a resonance at 0.57 THz. For an in-depth analysis, the de-embedded response is computed where the influence of the Silicon substrate is eliminated. The obtained-response is further subjected to low-pass filtering and presented in Figure 7. The results show that for the same SRR structures, the THz transmission of a ~ 600 nm-thick Py exerts a resonance of 11 dB which is considerably lower than the 35 dB attenuation for the ~ 500 nm thin Al-SRRs. To conclude, Py as a complete unstructured layer is a suitable material for THz absorption. In case of SRR structures, a resonance exists but, further design optimisations are necessary to address the specific properties of Py and Si-wafer as it has a high p value compared to Al. Also, thermal annealing can be implemented to minimise the intrinsic stress of the Py layer and

reduce p value. Further, a bi-layer approach with Al for THz shielding and Py for magnetic deflection can also be implemented.

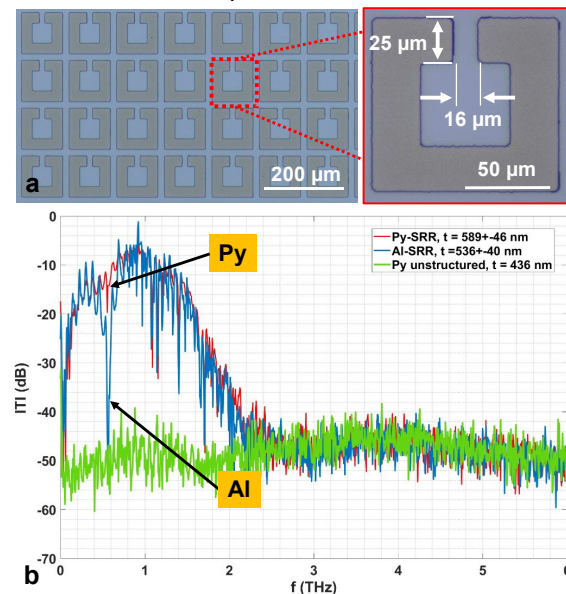


Figure 6(a) 15x15 mm passive THz-MS chip with SRR as a structural unit. For THz-response, the spot-size of the incident wave at 1 THz is expected to be around 2 mm (frequency-dependant). In that case, the unit cells within the array pertaining to the spot-size are ~ 1256 in number. (b) Raw THz response for SRR metasurfaces. In the ROI, both layers exert a resonance at 0.57 THz.

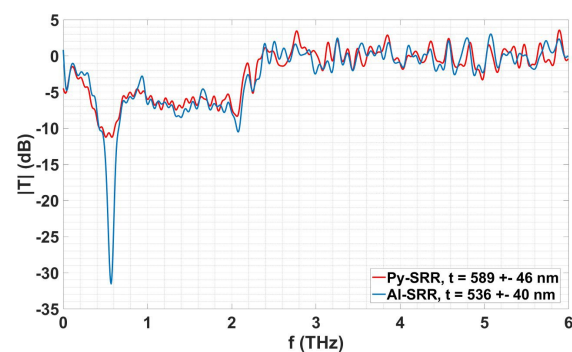


Figure 7 De-embedded-filtered THz response of passive SRR metasurface chip. At 0.57 THz, the transmission drops by ~ 31 dB for Al layer. In case of Py, there is a drop but, of a weaker magnitude of ~ 11 dB.

Acknowledgement

This work is funded by German Research Foundation (DFG, Project Nr. 525135725) and the National Science Centre, Poland (NCN, grant no. 2022/47/I/ST7/02055). FIBSEM device is funded by the DFG within the program Major Research Instrumentation (Project number: 505067193) under GG91b and by the state Baden-Württemberg as well as by Furtwangen University. VSM measurements are carried out at the Centre de compétences Magnétisme & Cryogénie, Institut Jean Lamour, Uni-Lorraine, France.

References

- [1] H. A. Hafez *et al.*, "Intense terahertz radiation and their applications," *J. Opt.*, vol. 18, no. 9, p. 93004, 2016, doi: 10.1088/2040-8978/18/9/093004.
- [2] S. S. Bukhari, J. Vardaxoglou, and W. Whittow, "A Metasurfaces Review: Definitions and Applications," *Applied Sciences*, vol. 9, no. 13, p. 2727, 2019.
- [3] X. Zang *et al.*, "Metasurfaces for manipulating terahertz waves," *Light: Advanced Manufacturing*, vol. 2, no. 2, p. 148, 2021, doi: 10.37188/lam.2021.010.
- [4] S. Tumański, *Handbook of Magnetic Measurements*, 1st ed. (Series in Sensors Ser). Baton Rouge: Taylor & Francis Group, 2011.
- [5] B. Szymanik *et al.*, "MP69 - Simulation and Optimization of Magnetic Field Actuated MEMS-Based Metasurface for Terahertz Applications," in *Poster I*, Wrocław, 2025, pp. 341–342, doi: 10.5162/EUROSENSORS2025/MP69.