

# **Thermophysical characterization of amorphous NiTa thin films for heat-assisted magnetic recording using frequency-domain thermorefectance**

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## Abstract

The rapid global growth in data volume has intensified the need to increase the recording density of hard disk drives (HDDs) while reducing storage costs. Heat-assisted magnetic recording (HAMR), a next-generation HDD technology based on laser-induced heating, requires accurate thermal design of the recording medium for high performance. This study examines the thermophysical properties of amorphous NiTa, a candidate material for heat sinks and adhesion layers in HAMR devices. Frequency-domain thermoreflectance (FDTR) measurements were performed on NiTa films with thicknesses ranging from 5 to 500 nm. The volumetric heat capacity was first determined using sufficiently thick samples, after which the effective thermal conductivity was measured across the full thickness range. The measured values, which include interfacial contributions from the glass substrate and aluminum transducer, were analyzed using a series resistor model. Fitting across all thicknesses yields a thermal conductivity of  $6.8 \pm 0.3 \text{ [Wm}^{-1}\text{K}^{-1}]$  for NiTa. The results indicate that the thermal conductivity remains practically independent of film thickness, consistent with typical transport characteristics of amorphous materials. Furthermore, the thermal conductivity of NiTa thin films is one to two orders of magnitude lower than that of representative crystalline metallic materials.

## Main Text

The rapid expansion of global data volumes, driven by the emergence of Industry 5.0 and the widespread use of big data, has increased the demand for higher storage density and lower Bit price.<sup>1,2</sup> Hard disk drives (HDDs) remain essential for large-scale data storage, and substantial efforts are directed toward improving their recording density to enhance performance while reducing cost. However, HDD technology faces a fundamental trilemma involving the competing requirements of reducing the grain size of the magnetic medium, maintaining high thermal stability, and lowering the magnetic field required for magnetization switching.<sup>3,4</sup>

Heat-assisted magnetic recording (HAMR)<sup>4-6</sup> has been proposed to address this limitation. HAMR employs FePt granular films as a recording medium,<sup>6,7</sup> which exhibit high thermal stability and small grain size owing to their large magnetocrystalline anisotropy ( $\sim 7$  MJ/m<sup>3</sup>). Laser pulse heating increases the medium temperature to the Curie point (Fig. 1), thereby reducing the energy barrier for magnetization switching. This approach enables writing with a relatively low magnetic field and preserving thermal stability upon cooling. A typical HAMR medium consists of a heat-resistant glass substrate, a heat sink layer, a soft underlayer (SUL), a texture control layer, and a recording layer.<sup>4,5</sup>

From a thermal design perspective, several requirements must be satisfied to achieve high-performance HAMR.<sup>8,9</sup> First, to reduce heating energy consumption, maintain an

appropriate thermal gradient within the recording medium, and limit temperature increase in the near-field transducer (NFT), the thermal resistance of the recording medium should exceed that of the NFT.<sup>8,10</sup> Second, rapid cooling after writing is necessary to ensure thermal stability, which requires reducing the thermal resistance.<sup>9</sup> Third, high-density recording demands spatial confinement of the heated region, necessitating increased in-plane thermal resistance of the recording medium.<sup>9,11</sup> Furthermore, steep temperature gradients within the device can induce thermal spin-transfer torques, which, in turn, affects the recording performance.<sup>12,13</sup>

An effective thermal design that reconciles these potentially conflicting and intricate requirements necessitates the precise characterization of the thermophysical properties of the HAMR components. However, experimental studies on the thermal properties of HAMR materials remain limited. Previous studies<sup>10,14,15</sup> have examined thermal time constants associated with variations in heat sink materials, but did not directly measure the intrinsic thermophysical properties. Although several studies have reported the thermal properties of HAMR materials, most have focused on the FePt recording layer,<sup>11,16–18</sup> while other components have received comparatively little attention.<sup>19</sup>

Amorphous NiTa is a key material widely employed as a heat sink in HAMR devices.<sup>4,7,15</sup> Its surface enables highly oriented growth of MgO or Cr seed layers, which are required to induce *c*-axis orientation in the subsequent recording layer. In addition, NiTa functions

as an effective adhesion layer on glass substrates.<sup>4,20</sup> Despite its technological importance, comprehensive thermal characterization of NiTa remains limited. Furthermore, the amorphous structure of NiTa presents an intriguing subject for examining thermal transport in disordered materials, particularly its thickness dependence at nano- and microscale dimensions.<sup>21–23</sup>

In this study, the thermal properties of amorphous NiTa, relevant to HAMR applications, were systematically investigated. NiTa thin films with thicknesses ranging from 5 to 500 nm were deposited on heat-resistant glass substrates used in HAMR. Frequency-domain thermorefectance (FDTR)<sup>24–27</sup> measurements were performed to determine the thermophysical properties of the films, and the thickness dependence of thermal transport was analyzed.

Figure 2(a) illustrates the measurement principle of the FDTR system. FDTR is a pump–probe technique for thermal characterization at the nano- and microscales. In this method, a modulated pump laser induces periodic heating at the sample surface, while a probe laser is reflected from the same region. Owing to the thermorefectance effect, the surface reflectance varies with temperature, allowing temperature fluctuations to be inferred from changes in the reflected probe intensity. This effect enables the determination of the phase lag between the pump modulation and probe response. The thermophysical properties are obtained by fitting a heat-transfer model to the frequency-dependent phase lag. To increase sensitivity, a metallic transducer layer, such as Al or Au, is typically deposited on the sample surface to enhance the

thermoreflectance coefficient at the probe wavelength.

Figure 2(b) presents a representative FDTR experimental setup. The pump and probe wavelengths are selected according to the transducer material. A 488 nm laser is used as the pump, while a 515 nm probe is used for the Au transducer and a 785 nm probe for the Al transducer. Both beams are focused onto the sample using a 20× objective lens to achieve a small spot size. The pump intensity is sinusoidally modulated by a voltage signal from a lock-in amplifier to generate periodic heating. The reflected probe beam is detected by a balanced photodiode and converted into a voltage signal. A reference probe beam is simultaneously measured to suppress common-mode noise. The resulting differential signal is processed by the lock-in amplifier using the pump modulation as the reference for phase-sensitive detection.

The measurements were conducted over a frequency range of 25 kHz to 150 MHz at room temperature. The  $1/e^2$  spot radii of the pump and probe beams were 1.25 and 1.16  $\mu\text{m}$ , respectively, as determined by the knife-edge method.<sup>27,28</sup> The pump and probe laser powers were set to 10.7 and 2.9 mW, respectively. Based on subsequent analyses, the steady-state temperature increase during the measurements was in the range of 9.9–11.7 K across all the measured samples. To reduce radio-frequency noise, background signals were measured and subtracted from both the pump and probe signals for frequencies above 10 MHz. The phase lag was analyzed using a two-dimensional diffusive heat-transfer model,<sup>24,26,29</sup> with fitting performed over the frequency

range to extract the thermal properties. Measurement uncertainty was evaluated using the method reported by Yang et al.<sup>30</sup>

For thermophysical characterization, NiTa( $x$  nm)/Al bilayers were deposited on heat-resistant glass substrates (HOYA N105Z) via magnetron sputtering. The target NiTa thickness,  $x$ , was set to 5, 7, 10, 15, 20, 30, 40, 50, 70, 100, 200, 300, and 500 nm. The base pressure was maintained below  $5.0 \times 10^{-6}$  Pa. Ar gas was introduced at a flow rate of 10 sccm during deposition, and the target-to-substrate distance was 100 mm. Prior to the deposition, the target was pre-sputtered for at least 3 min to remove surface contaminants. The NiTa and Al layers were deposited at Ar pressures of 7.7 and 6.0 mTorr, with deposition rates of approximately 2.8 and 1.9 nm (min)<sup>-1</sup> using 20 and 10 W power, respectively, at room temperature. To promote the (001) texture of the Cr layer, the NiTa surface was exposed to O<sub>2</sub> at a flow rate of 2 sccm for 2.5 min.<sup>31</sup>

Microstructural and compositional characterization was performed using scanning transmission electron microscopy (STEM) and energy-dispersive X-ray spectroscopy (EDS) with a Titan G2 80–200 system (Thermo Fisher Scientific). Cross-sectional TEM lamellae were prepared by focused ion beam (FIB) milling using a Helios 5 UX instrument (Thermo Fisher Scientific). Figure 2(c) presents a cross-sectional high-angle annular dark-field (HAADF) STEM image of the glass/NiTa/Al sample. The Al layer thickness was measured to be 69 nm for all the

samples. An uncertainty of 3 nm was assigned based on surface roughness measurements via atomic force microscopy (AFM). The thicknesses of the NiTa films were obtained from multiple samples, as detailed in Section 1 of the Supplementary Material. EDS elemental maps shown in Figs. 2(d) and 2(e) confirm the chemical uniformity of the NiTa layer. The amorphous structure of the NiTa films was further verified by X-ray diffraction (XRD); the XRD patterns are provided in Section 2 of the Supplementary Material.

To predetermine the thermal properties of the glass substrate and the Al transducer, glass/Au and glass/Al reference samples were prepared. The thermophysical properties of the glass substrate were evaluated using the flash method and FDTR measurements on the glass/Au sample, as described in Section 3 of the Supplementary Material. Subsequently, FDTR measurements were performed on the glass/Al samples 10 times, and averaged values were used to determine the thermal conductivity of the Al thin film. This approach accounts for deviations from the Wiedemann–Franz law arising from the grain structure of the sputter-deposited Al films.<sup>32,33</sup> Although sputtered films may exhibit reduced specific heat or anisotropic thermal conductivity, the present analysis assumes bulk-equivalent specific heat and isotropic behavior. The volumetric heat capacity of the NiTa films was obtained by performing FDTR measurements three times on samples with nominal thicknesses of 300 and 500 nm, followed by averaging. For each dataset, a four-parameter fit was applied to extract the thermal boundary conductance at the

Al/NiTa and NiTa/glass interfaces, along with the thermal conductivity and volumetric heat capacity of NiTa.

Then, the effective thermal conductivity of the NiTa films was determined by fitting, and the results were analyzed using the series resistor model.<sup>21</sup> In this framework, the effective thermal conductivity incorporates the thermal boundary resistances ( $R_{\text{interface}}$ ) at the Al/NiTa and NiTa/glass interfaces, as well as the intrinsic thermal conductivity of NiTa ( $k_{\text{NiTa}}$ ), and is expressed as:<sup>21,34</sup>

$$R_{\text{total}} = \frac{d}{k_{\text{eff}}} = R_{\text{interface}} + \frac{d}{k_{\text{NiTa}}}, \quad (1)$$

where  $d$  is the film thickness,  $R_{\text{total}}$  is the total thermal resistance, and  $k_{\text{eff}}$  is the effective thermal conductivity. As indicated by the sensitivity analysis in Section 4 of the Supplementary Material, for NiTa films thinner than 100 nm, decoupling the individual contributions of the NiTa layer and the two interfaces is difficult. Therefore, the series resistor model was applied across the entire thickness range, and the thickness dependence of NiTa thermal conductivity was evaluated using this framework.

Figure 3 presents representative FDTR measurement results for the glass/Al and glass/NiTa/Al samples. The thermophysical properties of the Al thin film obtained from the FDTR analysis, together with the parameters used in the fitting, are summarized in Table I. The volumetric heat capacity of NiTa is determined to be  $2.30 \pm 0.07$  [MJm<sup>-3</sup>K<sup>-1</sup>].

**TABLE I.** Material properties from FDTR analysis.

| Layer                     | Material                             | Thickness<br>[nm] | Thermal<br>conductivity<br>[Wm <sup>-1</sup> K <sup>-1</sup> ] | Volumetric heat<br>capacity [M]m <sup>-3</sup> K <sup>-1</sup> |
|---------------------------|--------------------------------------|-------------------|----------------------------------------------------------------|----------------------------------------------------------------|
| Transducer                | Al                                   | 69 ± 3            | 143.3 ± 3.5                                                    | 2.44 ± 0.05                                                    |
| Subject of<br>measurement | NiTa                                 | Varied            | Fitted                                                         | 2.30 ± 0.07                                                    |
| Substrate                 | Heat-resistant glass<br>(HOYA N105Z) | Infinity          | 1.04 ± 0.03                                                    | 1.96 ± 0.04                                                    |

Figure 4 shows the thickness dependence of the effective thermal conductivity and effective thermal resistance of the NiTa films. Fitting using Eq. (1) yields  $1/R_{\text{interface}} = 76 \pm 7$  [MWm<sup>-2</sup>K<sup>-1</sup>] and  $k_{\text{NiTa}} = 6.8 \pm 0.3$  [Wm<sup>-1</sup>K<sup>-1</sup>]. The fitted curves agree well with the experimental results, indicating that the series resistor model provides an adequate description over the investigated thickness range. The solution obtained by varying  $k_{\text{NiTa}}$  by  $\pm 20\%$  is also shown in Fig. 4 (blue line), which further supports the robustness of the fit. The results indicate that the thermal conductivity of NiTa varies by less than  $\pm 20\%$  with film thicknesses from 5 to 500 nm, suggesting that diffusive transport dominates heat conduction in amorphous NiTa. The low thermal conductivity and weak thickness dependence are consistent with the behavior of amorphous materials.

Considering the validity of the effective thermal conductivity analysis, in general, the reliable determination of effective thermal conductivity requires that the thermal penetration depth exceed the film thickness.<sup>21,35</sup> For the thermophysical properties of NiTa, the thermal penetration depth exceeds 500 nm at approximately 4 MHz. Consequently, even for the thickest samples, more than half the data points correspond to the condition where the penetration depth is greater than the film thickness. However, since the series resistor model is based on the assumption of one-dimensional heat conduction, evaluating whether the thermal penetration depth at a given modulation frequency satisfies this condition provides useful insights. To explore this aspect, an additional analysis considering the relationship between the modulation frequency and penetration depth was performed; the details are provided in Section 5 of the Supplementary Material. The thermal conductivity values obtained from this analysis ( $k_{\text{NiTa}} = 5.1 \pm 1.5 \text{ [Wm}^{-1}\text{K}^{-1}\text{]}$ ) agree with a margin of 25% of those reported above. Estimation of the thermal penetration depth involves qualitative approximations; therefore, both analytical approaches entail their respective assumptions. Accordingly, both analyses are presented and discussed herein for a comprehensive evaluation.

Next, we address the electronic contribution to heat conduction in the amorphous NiTa thin films. In the absence of a protective layer, NiTa thin films are susceptible to oxidation upon ambient exposure. Furthermore, owing to the amorphous nature of these films, validating the

applicability of the Sommerfeld value of the Lorenz number in the electronic thermal conductivity estimation is challenging. Consequently, a rigorous quantitative evaluation of the electronic contribution remains difficult. Nonetheless, a reference value can be estimated from literature data<sup>36</sup> on co-sputtered NiTa thin films with varying Ta fractions. For a 50-nm-thick NiTa thin film with a Ta/Ni ratio of 0.483, an electrical resistivity of  $9.15 \mu\Omega\cdot\text{m}$  has been reported. Assuming the Sommerfeld value of the Lorenz number at room temperature (298.15 K), the electronic thermal conductivity is calculated to be  $0.80 \text{ Wm}^{-1}\text{K}^{-1}$ . This value is less than one-fifth of our estimated total thermal conductivity, indicating that the electronic contribution is relatively minor. Importantly, a direct comparison of the results of this study with the literature data<sup>36</sup> is not straightforward because the deposition conditions and sample microstructures reported in the literature<sup>36</sup> differ from those of this study.

Finally, the thermophysical properties of candidate heat sink materials, including Ag, Au, Cr, and NiTa, are considered.<sup>4</sup> Bulk Cu and Au exhibit high thermal conductivities of approximately  $400$  and  $300 \text{ Wm}^{-1}\text{K}^{-1}$ , respectively; however, their thermal performance degrades substantially in thin films with thicknesses comparable to the electron mean free path.<sup>19,37</sup> Ag has an even higher bulk thermal conductivity of approximately  $420 \text{ Wm}^{-1}\text{K}^{-1}$  at room temperature, although its nanoscale thermal behavior remains insufficiently characterized.<sup>14</sup> Cr is of interest because of its strong adhesion and role in promoting  $L1_0$  orientation,<sup>38</sup> however,

its bulk thermal conductivity is relatively low ( $\approx 90 \text{ Wm}^{-1}\text{K}^{-1}$ ) and is expected to decrease further in the thin-film form. The NiTa films examined in this study exhibit thermal conductivities one to two orders of magnitude lower than those of these metallic candidates. However, the measured thermal conductivity of amorphous NiTa varies by less than 20% over a thickness range of 5–500 nm. This weak thickness dependence enables reliable prediction and control of thermal behavior, which is advantageous for precise thermal management required in HAMR devices.

In this study, the thermophysical properties of amorphous NiTa thin films, considered for heat sink and adhesion layer applications in HAMR devices, were systematically investigated over a thickness range of 5–500 nm via FDTR. The measured effective thermal conductivity was analyzed using a series resistor framework. The results show that the thermal conductivity of amorphous NiTa remains essentially independent of film thickness, in contrast to crystalline metallic films (e.g., Au, Cu, and Ag), which exhibit pronounced size effects and reduced thermal conductivity at the nanoscale. This behavior indicates that heat transport in amorphous NiTa is governed by diffusive mechanisms, consistent with the characteristics of disordered materials. In addition, the thermal conductivity of NiTa is one to two orders of magnitude lower than that of representative metallic candidates. These characteristics ensure a stable and predictable thermal performance, making amorphous NiTa thin film a unique candidate for precise thermal management in HAMR devices.

Supplementary material provides detailed information on the thickness calibration, XRD, glass properties, FDTR sensitivity, and series resistor analysis.

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## **Conflict of interest**

The authors have no conflicts to disclose.

## **Author Contributions**

Y. Ikeda: Conceptualization (lead), data curation (lead), formal analysis (lead), methodology (lead), resources (lead), software (lead), visualization, and writing – original draft.

Y. Akura: Conceptualization (supporting), formal analysis (supporting), methodology (supporting), resources (equal), and software (supporting).

R. Takechi: Conceptualization (supporting), methodology (equal), resources (equal).

Y. K. Takahashi: Conceptualization (lead), project administration (lead), funding acquisition, methodology (lead), supervision, writing-review, and editing (lead).

J. Hirotani: Conceptualization (lead), project administration (lead), funding acquisition, methodology (lead), supervision, writing-review, and editing (lead).

## **Data Availability**

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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## Figure Caption

**FIG. 1.** Schematic of heat-assisted magnetic recording (HAMR).

**FIG. 2.** (a) Schematic of frequency-domain thermoreflectance (FDTR) measurements of the glass/NiTa/Al sample. (b) Schematic of the FDTR experimental setup. (c) Representative cross-sectional high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) image of the glass/NiTa/Al sample. (d) Energy-dispersive spectroscopy (EDS) elemental maps. (e) Atomic fraction distribution obtained from EDS mapping, extracted from the region indicated by the red rectangle in (d).

**FIG. 3.** Phase lag as a function of modulation frequency obtained from FDTR measurements. Black squares denote the glass/Al sample, while the remaining data correspond to glass/NiTa/Al samples. The legends indicate the NiTa film thicknesses.

**FIG. 4.** (a) Measured effective thermal conductivity as a function of amorphous NiTa film thickness. (b) Total thermal resistance as a function of amorphous NiTa film thickness. Solid red lines represent fits to the experimental data based on the series resistor model. Blue dashed and dash-dotted lines indicate calculated curves with the thermal conductivity increased and

decreased by 20%, respectively.

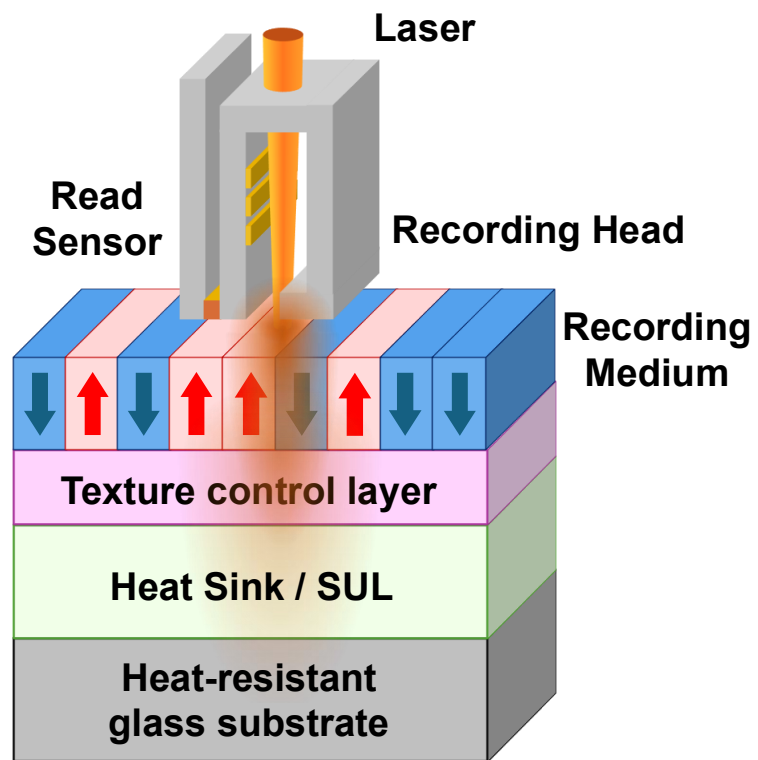


Figure 1

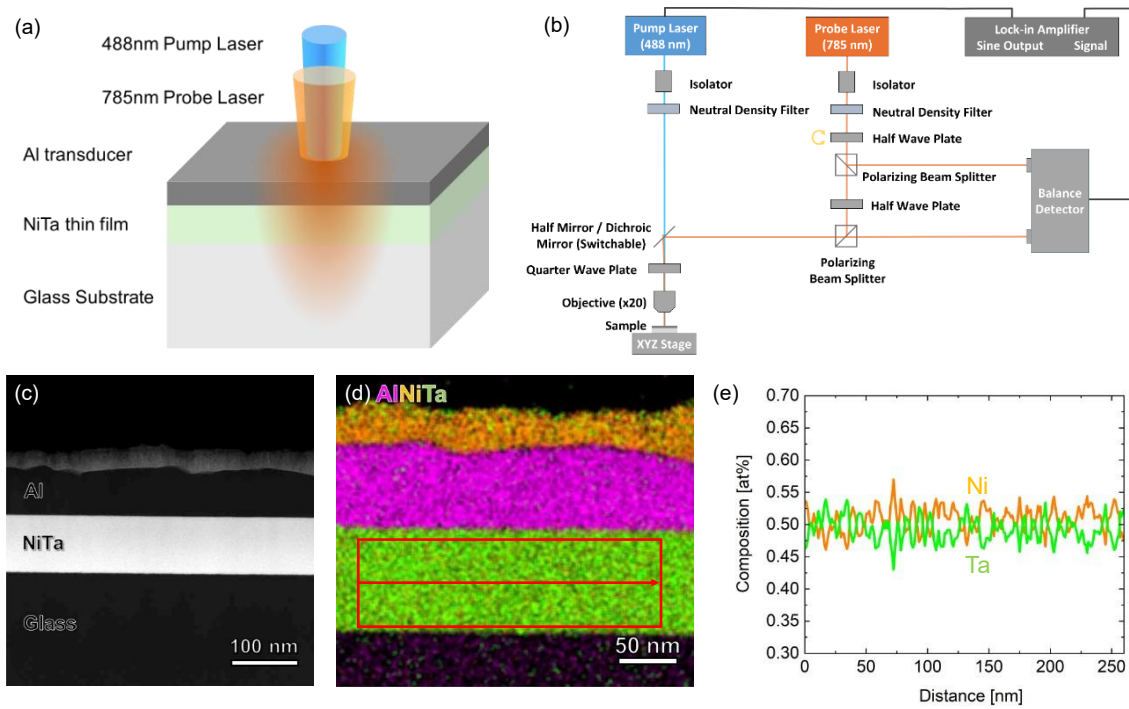


Figure 2

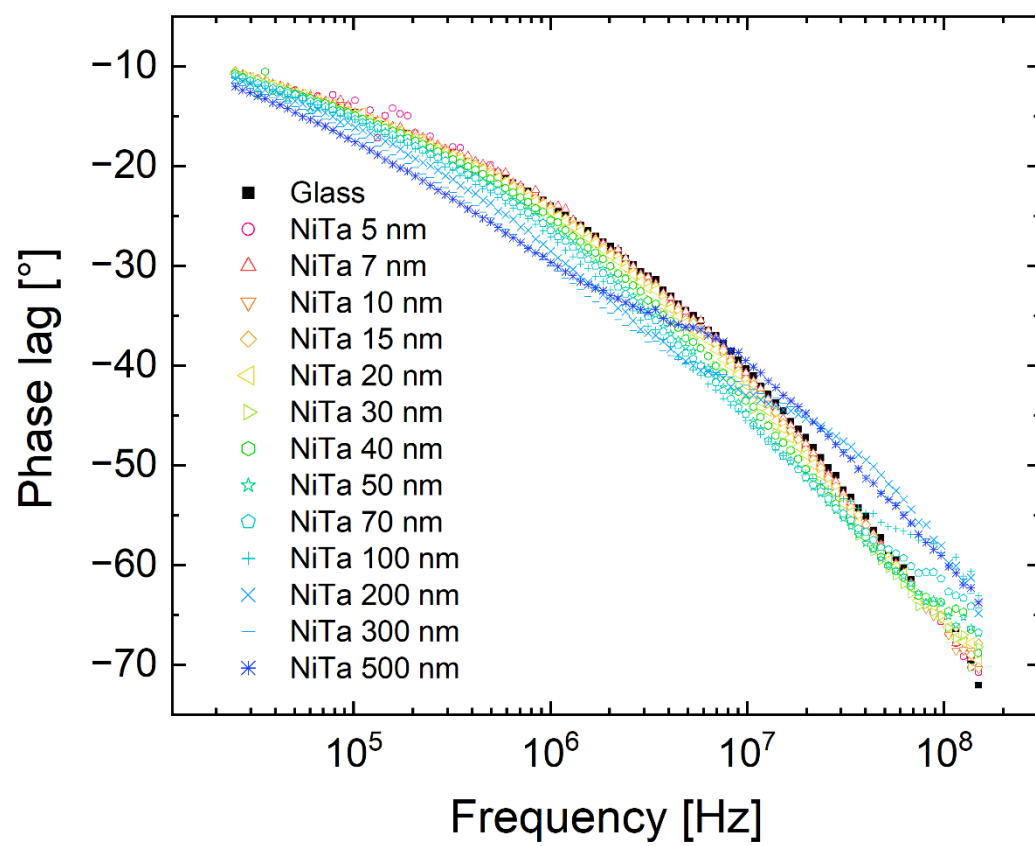


Figure 3

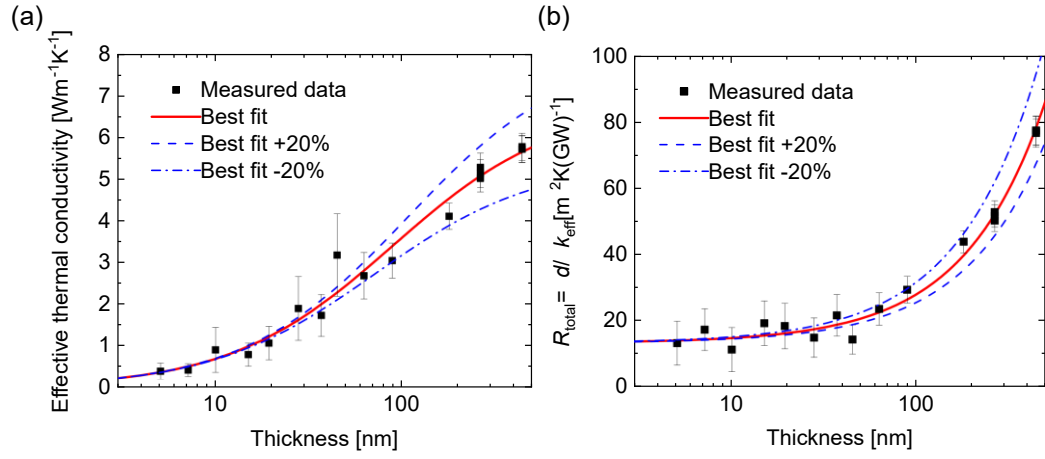


Figure 4