

Observation of microscopic domain effects in the metal-insulator transition of thin-film NdNiO₃

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Abstract

Perovskite oxides can display correlated electrical, magnetic, and thermal properties; these properties can be further tuned in the thin film limit, making them leading contenders for next-generation electronics. Thin-film thermal measurements are challenging because techniques are dominated by the substrate. Here, frequency-domain thermoreflectance (FDTR) of an epitaxial NdNiO₃ thin film reveals a sharp change in out-of-plane thermal conductivity across the metal-to-insulator transition. Complementary frequency-domain photo-reflectance (FDPR), performed for the first time on thin films, reveals a change in ambipolar diffusivity of photoexcited carriers. Unlike the hysteresis seen in in-plane electrical resistance, out-of-plane thermal and charge transport show negligible hysteresis. We attribute this discrepancy to anisotropy in

the percolative effects of nanoscale domains across the transition as the film thickness approaches the domain length scale. We establish FDTR and FDPR as sensitive probes of quantum material phase transitions and demonstrate the potential of NdNiO₃ for thermal control and memory applications.

Keywords

hysteresis, microscopic domains, metal-insulator transitions, thermal transport, charge transport

Introduction

As the demand for miniaturized, energy-efficient electronics grows, materials that undergo temperature-driven metal-insulator transitions (MIT) have emerged as candidates for next-generation technologies, including thermal switches for heat regulation, smart windows for thermochromic glazing, nonvolatile memristors for data storage, and neuromorphic computing elements for brain-inspired computing.^{1–4} Among these, rare-earth perovskite nickelates, $R\text{NiO}_3$ ($R = \text{La, Pr, Nd...}$), are model systems due to their highly tunable phase transitions.^{5–8} In particular, neodymium nickelate, NdNiO₃, undergoes a first-order phase transition from a paramagnetic metallic state to an antiferromagnetic insulating state, with a concomitant change in the crystal structure at the highest temperature of the $R\text{NiO}_3$ series. It exhibits thermal hysteresis due to percolation across domains that emerge during the transition.^{9–11} In single crystal NdNiO₃, this transition occurs near 200 K. However, in the thin-film limit, the transition temperature can be tuned through epitaxial strain and film thickness,^{5,12–15} making it highly adaptable for integration into electronic devices. While most studies have focused on the electrical and magnetic properties of thin film NdNiO₃, its thermal properties are highly relevant for its practical applications in devices. Fully exploiting these materials in next-generation devices, however, requires an understanding of

anisotropic charge and heat transport at the nanoscale, particularly as the thickness of the film approaches the length scales of domain formation during the phase transition.

Measuring thermal transport in ultrathin films remains challenging due to the limited sensitivity of conventional bulk techniques, as traditional measurements of thermal conductivity using an applied heat source and a voltage measurement are dominated by substrate contributions.¹⁶ While 3ω techniques offer improved sensitivity to thin films, they require complex and invasive sample preparation, and lack spatial resolution.¹⁷ Non-contact optical reflectance-based techniques provide an alternative avenue that addresses these limitations.¹⁸ In particular, frequency-domain thermoreflectance (FDTR)^{19,20} is capable of measuring the thermal conductivity of films as thin as several tens of nanometers, while requiring only minimal sample preparation (i.e., depositing a metallic transducer). FDTR can even measure thermal transport in monolayer materials like graphene, depending on the film composition and the substrate.^{21,22} The same optical setup without a transducer layer can be used to perform frequency-domain photo-reflectance (FDPR), further allowing the charge and thermal transport to be probed simultaneously.²³

In this work, we use FDTR to measure the thermal conductivity of a 57.5 nm thick epitaxial NdNiO₃ film grown on a LaAlO₃ substrate across its metal-insulator transition, the thinnest such epitaxial oxide measured with FDTR to date. While we observe strong hysteresis in the in-plane electrical transport, consistent with prior measurements,^{9,12,24} we observe significantly reduced hysteresis in the thermal conductivity during heating and cooling cycles. We also perform the first demonstration of FDPR measurements on a thin film; we model the laser-induced charge transport as ambipolar diffusion, in which electrons and holes diffuse according to their density gradients before recombination. We observe a significant change in ambipolar diffusivity across the transition, accompanied by weaker hysteresis. The suppressed hysteresis in both thermal and charge transport is attributed to geometric anisotropy in the thin-film architecture, where the domain size is constrained by the film thickness, limiting percolation in the out-of-plane direction. These findings demonstrate the

power of a local probe to resolve the nanoscale phase separation that governs the dynamics of tunable MITs in thin-film correlated oxides.

Results and Discussion

In bulk single crystals of NdNiO_3 , the MIT is accompanied by a subtle structural transition from orthorhombic (Pbnm) to monoclinic ($\text{P}2_1/\text{n}$) symmetry (Fig. 1a);^{5,7,25} the transition has a thermal hysteresis of ~ 4 K. In epitaxial thin films, the hysteresis increases to ~ 30 K due to epitaxial strain.^{11,26} Electrical transport measurements of our thin-film sample show a sharp change from metallic to insulating behavior in bulk resistivity measurements upon cooling at $T_{\text{cool}} = 91$ K, and we observe the inverse change at $T_{\text{heat}} = 124$ K during heating (Fig. 1b). The biaxial compressive strain imposed by the LaAlO_3 substrate lowers T_{MIT} by over 70 K, consistent with prior observations of strain-induced suppression of T_{MIT} .^{5,12}

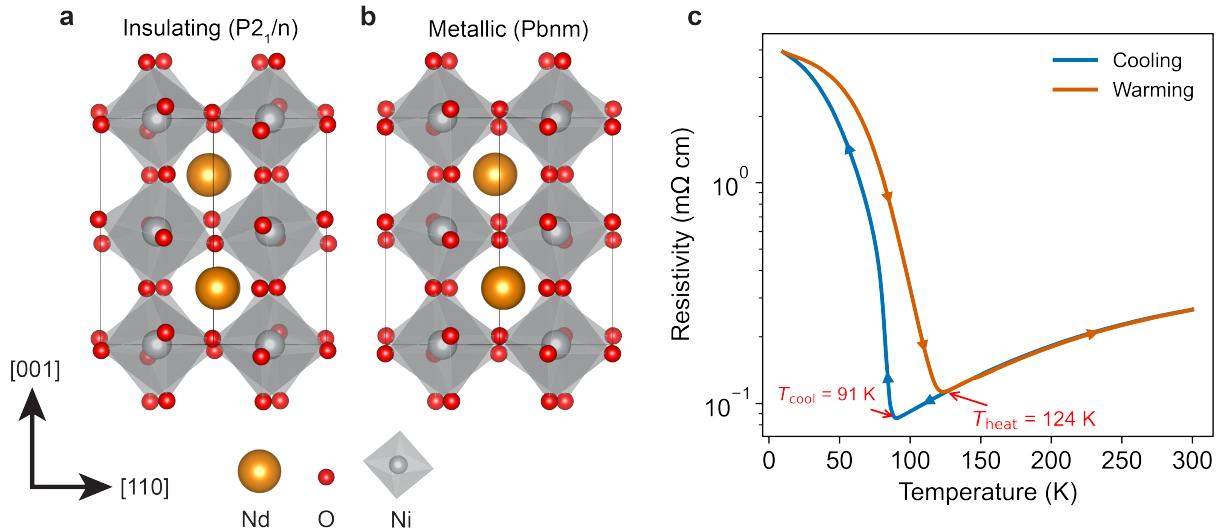


Figure 1: **a**, Distorted perovskite structure of NdNiO_3 in the insulating phase. **b**, The structure in the metallic phase. The changes in octahedral tilts drive the transition.⁷ **c**, Temperature-dependent resistance capturing the MIT (see Methods). T_{MIT} is 91 K during cooling and 124 K during heating. The film is 57.5 nm (150 unit cells) thick in the $(001)_{\text{PC}}$ direction, grown on LaAlO_3 (100) $_{\text{PC}}$.

We explore thermal and electronic transport through complementary techniques of FDTR

and FDPR on the same sample. As illustrated in Fig. 2a, to isolate the thermal response of the film, we perform FDTR measurements for a region coated with a gold transducer layer, which immediately converts electronic excitations into heat and ensures that the measured change in reflectance $\Delta R(\omega)$ is based only on the thermal properties of the sample (see Methods).^{19,20} To measure charge transport, we perform FDPR measurements on an adjacent uncoated region of the same sample; the photo-reflectance signal includes contributions from heat diffusion and charge transport. We then determine the ambipolar carrier diffusivity across the transition.

In FDTR, the thermoreflectance signal is proportional to the change in surface temperature of the gold transducer. The relative phase between the oscillations of the thermoreflectance signal and the pump modulation exhibits a distinct frequency dependence in the metallic phase compared to the insulating phase (Fig. 2b). According to the sensitivity analysis based on the Fourier heat conduction model, our FDTR measurement is exclusively sensitive to the out-of-plane thermal conductivity, κ_{\perp} (Fig. 2d). At high modulation frequencies, the phase shifts towards zero with increasing κ_{\perp} , while at low modulation frequencies, it shifts to more negative values with increasing κ_{\perp} (Fig. 2b). This relationship suggests that the out-of-plane thermal conductivity of the metallic phase is higher than that of the insulating phase, as expected.

In FDPR, the photo-reflectance from the bare sample is the sum of the carrier-induced and temperature-induced components, both of which are represented by complex numbers. As shown in Fig. 2c, at higher modulation frequencies, the carrier contribution can lower the overall phase lag compared to the temperature contribution alone, as carrier diffusion typically occurs much faster than heat diffusion. The different phase curves in the metallic and insulating states, especially at high modulation frequencies, are closely related to the difference in the carrier part of the signal. From the sensitivity analysis in Fig. 2e, we observe that the constant A_p that determines the magnitude of the carrier contribution to the signal, the carrier recombination time τ , and ambipolar diffusivity D_a are correlated,

allowing us to fit only one of these three parameters reliably (see Fig. S6). Given that D_a is substantially more susceptible to changes in transport than both A_ρ and τ , we fix the values of A_ρ and τ and treat D_a along with the thermal boundary conduction between the thin film and substrate, G_{FS} , as fitting variables (see SI for details).

Analyzing both FDTR and FDPR data requires knowledge of substrate properties. Therefore, we characterized the thermal properties of the LaAlO₃ substrate independently. We performed FDTR measurements on a LaAlO₃ substrate coated with a transducer layer (see Methods) and record its thermal conductivity and heat capacity over the temperature range of 80–140 K (Fig. 3a). The measured substrate heat capacity and thermal conductivity (Fig. 3a) agree well with literature values for the heat capacity and thermal conductivity of LaAlO₃.²⁷ Notably, our approach enables the simultaneous determination of both thermal conductivity and heat capacity from a single measurement. This is achieved by varying the modulation frequency over a wide range: at higher frequencies, the thermoreflectance's phase has a positive correlation with both thermal conductivity and heat capacity, while at lower frequencies, its dependence on thermal conductivity and heat capacity have opposite signs.

We then fix the substrate thermal conductivity and heat capacity in our heat conduction model and determine the out-of-plane thermal conductivity ($\kappa_{\perp,\text{tot}}$) of the NdNiO₃ thin film. We perform heating and cooling measurements between 80–140 K. Simultaneously fitting both κ and C_p for the film is challenging because of the high uncertainty and because these parameters are strongly correlated. Therefore, we fix the film's heat capacity using a Debye model derived from bulk heat capacity measurements on NdNiO₃ (See Fig. S10).^{24,28} With only the film's thermal conductivity as a free parameter, we achieve stable fits with uncertainty < 18%. Figure 3b shows the thermal conductivity κ of the thin film NdNiO₃ during cooling and heating cycles.

During cooling, the thermal conductivity $\kappa_{\perp,\text{tot}}$ of NdNiO₃ gradually decreases between 133.3 K and 123.3 K. Between 123.3 K and 110.0 K, it decreases more sharply by 33%, a phenomenon we describe as thermal switching. We compare the out-of-plane thermal

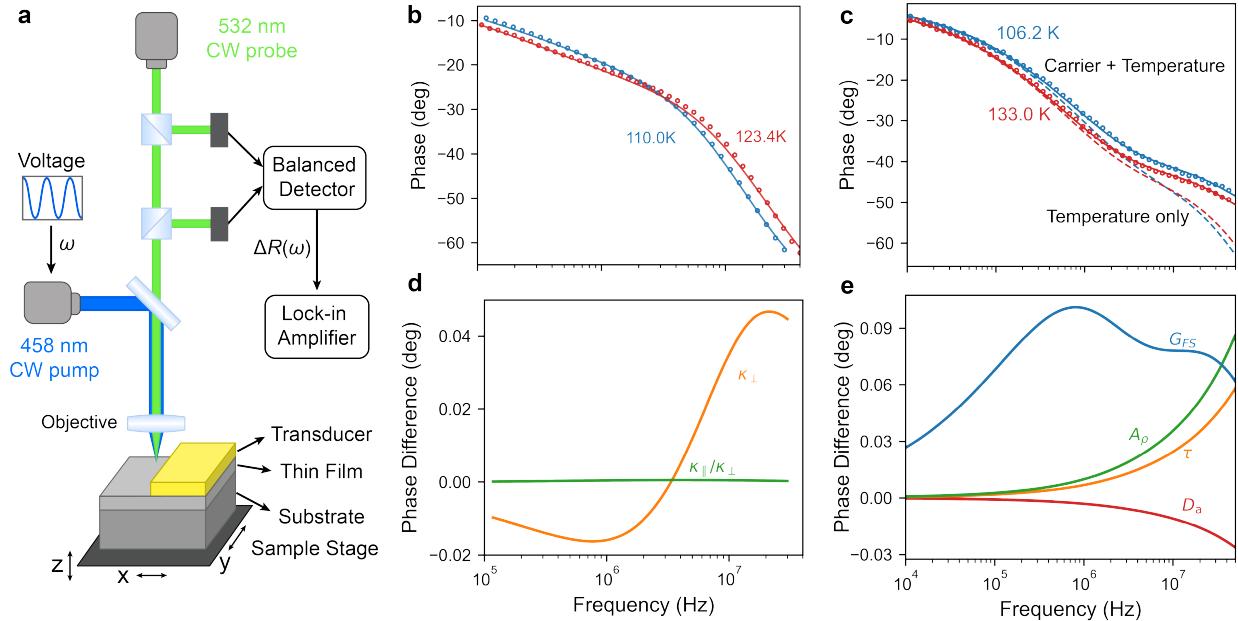


Figure 2: **a**, Schematic of an integrated frequency-domain thermoreflectance (FDTR) and frequency-domain photo-reflectance (FDPR) measurement setup. A continuous wave (CW) pump laser at 458 nm, power-modulated at a frequency $\omega/2\pi$, excites the sample. A CW probe laser at 532 nm reads out the perturbed reflectance. Both laser beams are focused to a 3 μm beam waist radius. The reference and reflected beams are first balanced and then detected by a balanced detector. The change in reflectance $\Delta R(\omega)$ is extracted from the output signal by a lock-in amplifier. FDTR and FDPR measurements are performed at the gold-coated (65.7 nm) and bare regions of the sample, respectively, with a piezoelectric stage being used to translate the sample in the xy-plane and to locate the beam focus along the z-axis. **b**, FDTR phase data (circles) in the metallic (123.4 K) and insulating (110.0 K) phases, along with best fits using the Fourier heat conduction model (lines). **c**, FDPR data in the metallic (133.0 K) and insulating (106.2 K) phases, along with best fits using the carrier and temperature model (solid lines); the phases of the temperature part of the signal are plotted in dashed lines. **d,e**, Sensitivity analysis for FDTR (**d**) and FDPR (**e**) data fitting at 110.0 K and 133.3 K, respectively. Specifically, κ_{\parallel} and κ_{\perp} correspond to the in-plane and out-of-plane thermal conductivity, respectively. G_{FS} is the thermal boundary conductance between the NdNiO₃ film and the LaAlO₃. A_{ρ} is related to the magnitude of the carrier contribution to the signal, τ is the carrier recombination time, and D_a is the ambipolar diffusivity. The phase difference is defined as the change in phase resulting from a +1% relative increase in the corresponding variable.

conductivity to the predicted electronic contribution to the in-plane thermal conductivity using the Wiedemann–Franz law. We calculate $\kappa_{\parallel,\text{el}} = L\sigma T$, where L is the Lorenz number, σ is the separately measured in-plane electrical conductivity (Fig. 1a) and T is the temperature. In principle, we expect no anisotropy in the properties of bulk NdNiO₃, so we attribute the

differences in thermal conductivity to finite scaling in the thin film limit.

On cooling, we observe the onset of thermal switching in $\kappa_{\perp,\text{tot}}$ more than 20 K higher in temperature than in $\kappa_{||,\text{el}}$. The heating curve of $\kappa_{\perp,\text{tot}}$ closely matches the cooling curve across the transition, suggesting that this transition temperature anisotropy arises from weak hysteresis in the out-of-plane direction. Consistent with this behavior, the out-of-plane ambipolar mobility during heating and cooling from FDPR decreases sharply from 120 K to 110 K and changes by much smaller amounts for $T < 110$ K (Fig. 3c), which reinforces the idea that an electronic phase transition occurs at T_{switch} . The DC contribution of the reflectance from the bare sample, related to the dielectric constants of the thin film, also shows a sharp discontinuity at around 115 K, providing additional evidence for the electronic phase transition occurring near T_{switch} (Fig. S8). Together, these measurements show that the transition temperature and the associated hysteresis measured in the out-of-plane direction differ substantially from those observed in the in-plane direction.

Both epitaxial strain and film thickness can tune the MIT in NdNiO₃, so we first consider whether differing strain in the out-of-plane direction can lead to anisotropic hysteresis. We expect that the film is under compressive strain in the in-plane direction due to the substrate, and therefore it is under tensile strain in the out-of-plane direction.²⁹ While bulk NdNiO₃ has a hysteresis loop width of ~ 4 K,²⁶ both compressive and tensile strain on thin films increase the hysteresis loop width to > 10 K.³⁰ We therefore expect hysteresis in the in-plane and out-of-plane directions, and anisotropic strain effects should not eliminate hysteresis in the out-of-plane direction. To understand the origin of the discrepancy, we then consider the length scale of the FDTR and FDPR measurements compared to electrical resistivity measurements, understanding the dimensionality of the transition in the thin-film limit. In NdNiO₃, nanoscale insulating domains begin to nucleate tens of Kelvin above the macroscopic transition, with domain sizes on the order of 100–300 nm.^{9,31} Electrical resistivity measurements average over several millimeters in the in-plane direction, measuring transport crossing hundreds of domains (Fig. 4b). Across the transition, percolation pathways

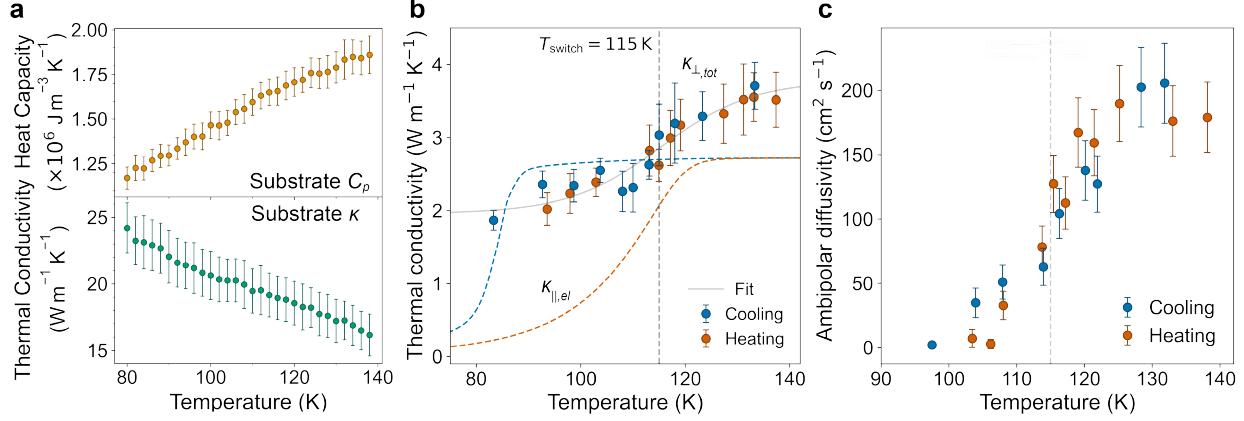


Figure 3: **a**, The thermal conductivity and heat capacity of the substrate LaAlO_3 measured using FDTR. **b**, Out-of-plane thermal conductivity, $\kappa_{\perp,\text{tot}}$, of thin film NdNiO_3 as a function of temperature, measured using FDTR over three cooling and two heating cycles (see Fig. S5 for the full data). The electronic contribution to in-plane thermal conductivity, $\kappa_{||,\text{el}}$, predicted using the Wiedemann–Franz law is plotted as dashed lines. The hysteresis is weaker in the out-of-plane direction than in the in-plane direction, highlighting the anisotropy of the thin-film geometry. A modified logistic function, $f(T) = a [1 + e^{-b(T - T_{\text{switch}})}]^{-1} + c$, is used to fit the thermal conductivity trend (gray line). The thermal switching temperature T_{switch} is found to be 115 K. **c**, The ambipolar diffusivity of NdNiO_3 , measured using FDPR, across the metal-insulator transitions during cooling and heating. The dashed line corresponds to $T_{\text{switch}} = 115$ K. Fixed parameters $A_\rho = 8 \times 10^{-25} \text{ m}^3 \text{ K}$ and $\tau = 0.11 \text{ ns}$ are chosen to minimize fitting residuals across all temperatures.

must form before significant changes in conductivity are observed, delaying the onset of the transition and causing hysteresis.^{11,25}

In contrast, our optical reflectance-based measurements probe out-of-plane transport in films where the average domain size exceeds the film thickness (57.5 nm). Although the laser beam, which has a 3 μm radius, covers many domains laterally, it measures transport through single phases. This columnar domain geometry reduces sensitivity to percolation and interface effects, resulting in the observed reduced hysteresis (Fig. 4c). FDTR and FDPR in a thin film geometry are therefore uniquely sensitive to domain emergence in a phase transition, capturing the early onset of localized phase separation that precedes changes in the macroscopic properties.

Our study reveals a microscopic, domain-mediated phase transition in NdNiO_3 preceding the MIT transition observed via bulk transport measurement. Thermal switching occurs

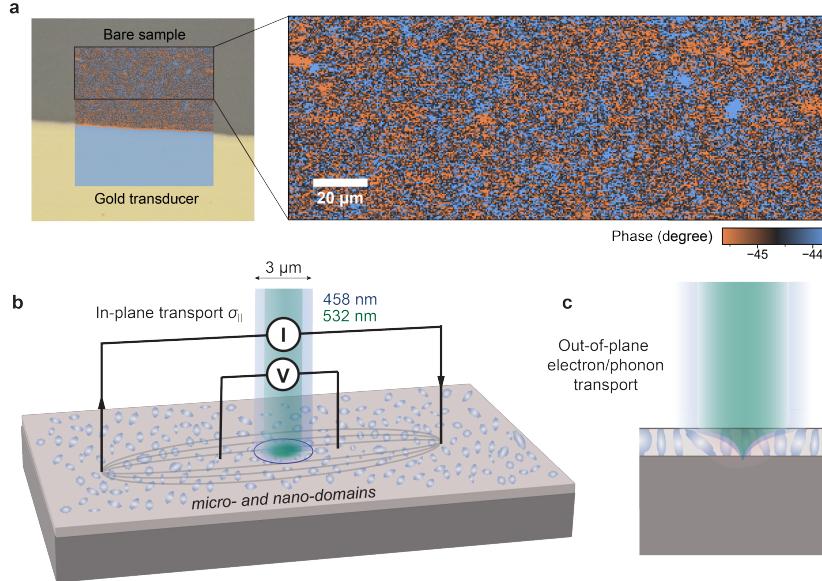


Figure 4: **a**, FDPR mapping of the sample over an area of $200 \mu\text{m} \times 200 \mu\text{m}$ at 113 K with a modulation frequency of 14.4 MHz, overlaid with the microscope image. The sharp phase contrast corresponds to the boundary of the gold transducer. The region in the black box on the bare sample is magnified on the right. The color represents the FDPR phase. The beam is too large to directly observe domains, which we expect to be 100-300 nm, but we can observe lateral fluctuations in the signal to high resolution. **b**, Qualitative (not to scale) schematic representing the formation of insulating domains in NdNiO_3 near the phase transition temperature. FDPR probes out-of-plane electron transport on a length scale covering several domains, whereas the electrical resistance measurement aggregates in-plane contributions from electrons percolating across on the order of 10^3 domains. **c**, Cross-sectional view of the beam penetration and domain formation (not to scale). Domains form instantaneously across the film thickness, directly creating single-phase transport channels without metal-insulator interfaces; hence, out-of-plane thermal and electron transport exhibits low hysteresis.

at a temperature significantly above the metal-insulator transition identified by in-plane electrical transport measurement, with significantly reduced hysteresis. The thin film geometry plays a significant role in the reduced hysteresis, as the length scale of the domains formed during the transition is larger than the film thickness, allowing us to reduce percolation across domains in the out-of-plane direction. These results position NdNiO_3 thin films within a growing class of correlated oxides that exhibit nontrivial transport behavior across electronic phase transitions. Violations of the Wiedemann–Franz law observed in VO_2 nanowires near the MIT³² suggest the involvement of unconventional quasiparticles or other

strongly correlated transport phenomena.³³ The unusual behavior of the reduced dimensionality in VO₂ nanowires highlights the macroscopic effects of fundamental length scales in correlated oxides with phase transitions. Our findings open new avenues for exploring the role of geometrical confinement and domain structure in such materials, advancing NdNiO₃ thin films as compelling candidates for realizing passive thermal switches and non-volatile memristors.

Our work demonstrates that FDTR and FDPR offer unique capabilities for probing phase transitions in thin films where the domain sizes exceed the film thickness. In contrast to bulk resistivity, which probes in-plane transport percolating across many domains, our reflectance-based measurements are more sensitive to the local emergence and distribution of metallic and insulating domains. FDTR measurements in ultrathin films, therefore, primarily average transport across single domains, minimizing percolative effects and hysteresis. The sharp features observed in both thermal transport and ambipolar diffusivity (D_a) near T_{switch} with weak hysteresis confirm the differences in the measurement due to the geometry of FDTR and FDPR. Spatial FDPR mapping further reveals nanoscale phase coexistence near the transition, reinforcing a picture of spatially inhomogeneous, domain-driven phase evolution.^{9,11,25,31} These insights demonstrate that FDTR is a powerful probe of phase transitions in complex oxides, enabling access to out-of-plane transport properties in regimes inaccessible to traditional bulk methods.

Beyond this central result, we introduce several methodological advances. We demonstrate that FDTR can simultaneously measure the thermal conductivity and heat capacity of a bulk substrate material (in this case, LaAlO₃) across a wide temperature range. We also report the first use of FDPR to extract ambipolar carrier diffusivity in a thin film system. The observed drop in D_a across the same temperature range as the thermal transition confirms the co-evolution of electronic and thermal transport across the MIT. This combined FDTR/FDPR framework opens avenues for studying nanoscale phase transitions, domain dynamics, and anisotropic transport in complex oxides, both in equilibrium and

under external stimuli such as strain or electric fields.

Methods

Sample Preparation

Thin-film NdNiO₃ was synthesized on LaAlO₃ (100) using ozone-assisted molecular-beam epitaxy (MBE).³⁴ LaAlO₃ has a smaller lattice mismatch than other possible substrates, enabling the thickest film without relaxation. During the deposition, the substrate temperature was kept at 555°C and the chamber pressure was maintained at $\sim 1.3 \times 10^{-6}$ torr distilled ozone (Heeg Vacuum Engineering). We expect biaxial compressive strain of 0.4%. The unit cell volume change across the transition is negligible. *In-situ* reflection high-energy electron diffraction (RHEED), X-ray diffraction, and X-ray reflectivity measurements (PANalytical Empyrean X-Ray Diffractometer) demonstrate a highly crystalline, epitaxially strained sample with a smooth surface, with measured thickness 57.5 nm, approximately 150 unit cells (see Fig. S1,S2). We measured the sample resistance (Fig. 1) via a standard 4-probe AC resistance measurement in a physical property measurement system (PPMS).

To determine the thermal properties of the substrate, we coated a sample of LaAlO₃ (Shinkosha) with a transducer layer. We deposited 56 nm Au with a 2.6 nm Cr adhesion layer and confirmed the thickness using x-ray reflectivity (PANalytical Empyrean X-Ray Diffractometer). We found that the Cr adhesion layer in the LaAlO₃ sample created nonequilibrium electron-phonon coupling in the transducer layer and increased the phase lag for modulation frequencies above 10 MHz;³⁵ this effect is beyond the scope of our model. We still obtained accurate thermal parameters from lower modulation frequencies in the LaAlO₃ sample, as the measurement of the substrate properties was sensitive to the phase at lower modulation frequencies (see Fig. S9).

We performed FDTR and FDPR measurements on the same sample of NdNiO₃ by coating half of the sample with a transducer layer. We deposited a transducer layer over a small

region of the sample’s surface, leaving much of the sample uncovered (see Fig. 2). For the NdNiO₃ sample, we deposited 65.7 nm Au with a 1.8 nm Ti adhesion layer using electron-beam evaporation (Denton E-beam Evaporator). We confirmed the thickness with X-ray reflectivity as above. Based on the results from the substrate FDTR, we chose to use a Ti adhesion layer for the NdNiO₃ to eliminate transducer electron-phonon coupling. We could then model the phase at higher modulation frequencies where it is sensitive to the film’s properties, as shown in Fig. 2c. The transducer we deposited on the NdNiO₃ film had a roughness of 14.16 Å (Fig. S3). These transducer layers were straightforward to model for our desired modulation frequencies, as gold is frequently used for FDTR, and its thin film thermal conductivity and heat capacity are known.³⁶ The gold coating thermal conductivity was independently measured using the 4-point probe method.

FDTR and FDPR

We use the FDTR setup supplied by Fourier Scientific. To change the pump frequency, we modulate the voltage of a 458 nm 20 mW pump laser (Coherent OBIS LX fiber laser) and sweep the modulation frequency. We record the amplitude and phase of $\Delta R(\omega)$ using a 532 nm 15 mW continuous-wave probe laser (Coherent OBIS LS laser) and a lock-in amplifier (Zurich Instruments HF2LI).

Both the pump and probe beams are nearly isotropic with Gaussian spatial profiles; the $1/e^2$ radius of the probe beam is 2.98 μm . They have the same optical path length. To minimize the noise in the probe signal, we rotate a half-wave plate in the probe beam path before it reaches the sample, which minimizes the difference in the intensity of the reference and reflected probe beams. Before we make a measurement, we measure the phase of the pump beam to subtract it from the measured phase. When measuring, we send the probe signal before and after reflection from the sample to a balanced photodetector.²³ The amplitude and phase differences can be compared by sending the signal from the balanced detector to the lock-in amplifier,¹⁹ and we obtain $\Delta R(\omega)$ for a range of frequencies ω . We

controlled the temperature using a flow cryostat (Instec HCP421V).

To extract thermal conductivity and heat capacity, we fit the phase of $\Delta R(\omega)$ using a nonlinear least-squares optimization. We solve an inverse fitting problem by minimizing the error between the measured phase of $\Delta R(\omega)$ and the model prediction based on a set of thermal parameters. Once these thermal transport parameters are established, we fit the phase of $\Delta R(\omega)$ for FDPR using the same least-squares nonlinear fitting algorithm to match the experimental curves to the ambipolar diffusion model. We use the carrier density calculated from the FDPR measurements to rule out the possibility of the laser inducing the metal-insulator transition, confirming that the MIT is temperature driven (Fig. S7). We set the thermal parameters, thermal conductivity and heat capacity, based on the FDTR measurements. A more detailed formalism can be found in the SI.

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Supporting Information Available

X-ray diffraction and X-ray reflectivity of NdNiO₃; X-ray reflectivity of the transducer layer; AFM of NdNiO₃; full derivation of the carrier and temperature model for FDPR signals, and data analysis.

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Supplemental Materials

Characterization of NdNiO₃ Film

Film Measurements

We measured the thickness and roughness of the film *in situ* and after the film growth. We used reflection high-energy electron diffraction (RHEED) to characterize the film *in situ*. Figure S1 shows the diffraction pattern of the film during growth in the (100) and (110) orientations. The pattern reveals a smooth, epitaxial film. Figure S2a shows the film's X-ray diffraction pattern, taken after growth. The peaks are consistent with epitaxial NdNiO₃ in the (001) orientation. The best fit for the X-ray reflectivity curve (Fig. S2b) shows the film to be 57.5 nm thick with a roughness of 6.5 Å. We examine the surface with atomic force microscopy (AFM), Fig. S3a. Terracing from the substrate miscut and some defects in the surface are visible. We measured bulk electrical transport (Fig. 1) on a Quantum Design Physical Property Measurements System (PPMS) by applying 0.01 mA AC at 18.31 Hz via wire-bonded contacts .

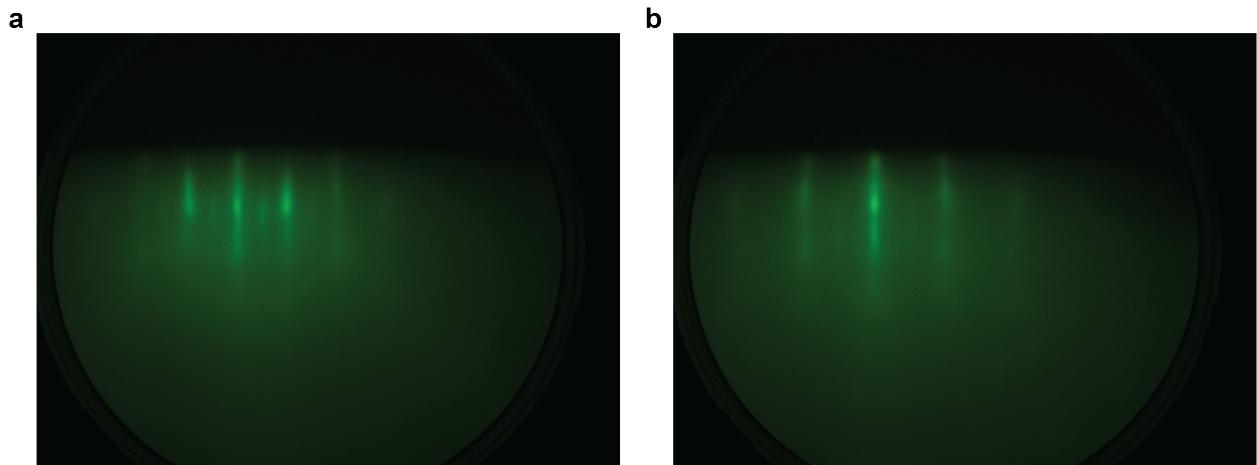


Figure S1: Reflection high-energy electron diffraction (RHEED) of NdNiO₃ on LaAlO₃ during MBE growth. Patterns recorded in the **a**, (110) orientation and **b**, (100) orientation.

Coating Measurements

The X-ray reflectivity (Fig. S2c) and AFM (Fig. S2b) of the gold-coated surface are also shown. The best fit for the X-ray reflectivity showed the coating to be 65.7 nm of gold and 1.8 nm of titanium, with a surface roughness of 14.16 Å (Fig. S2,S3). AFM confirms that the terracing is still visible, but the surface is slightly rougher overall, and there are still defects.

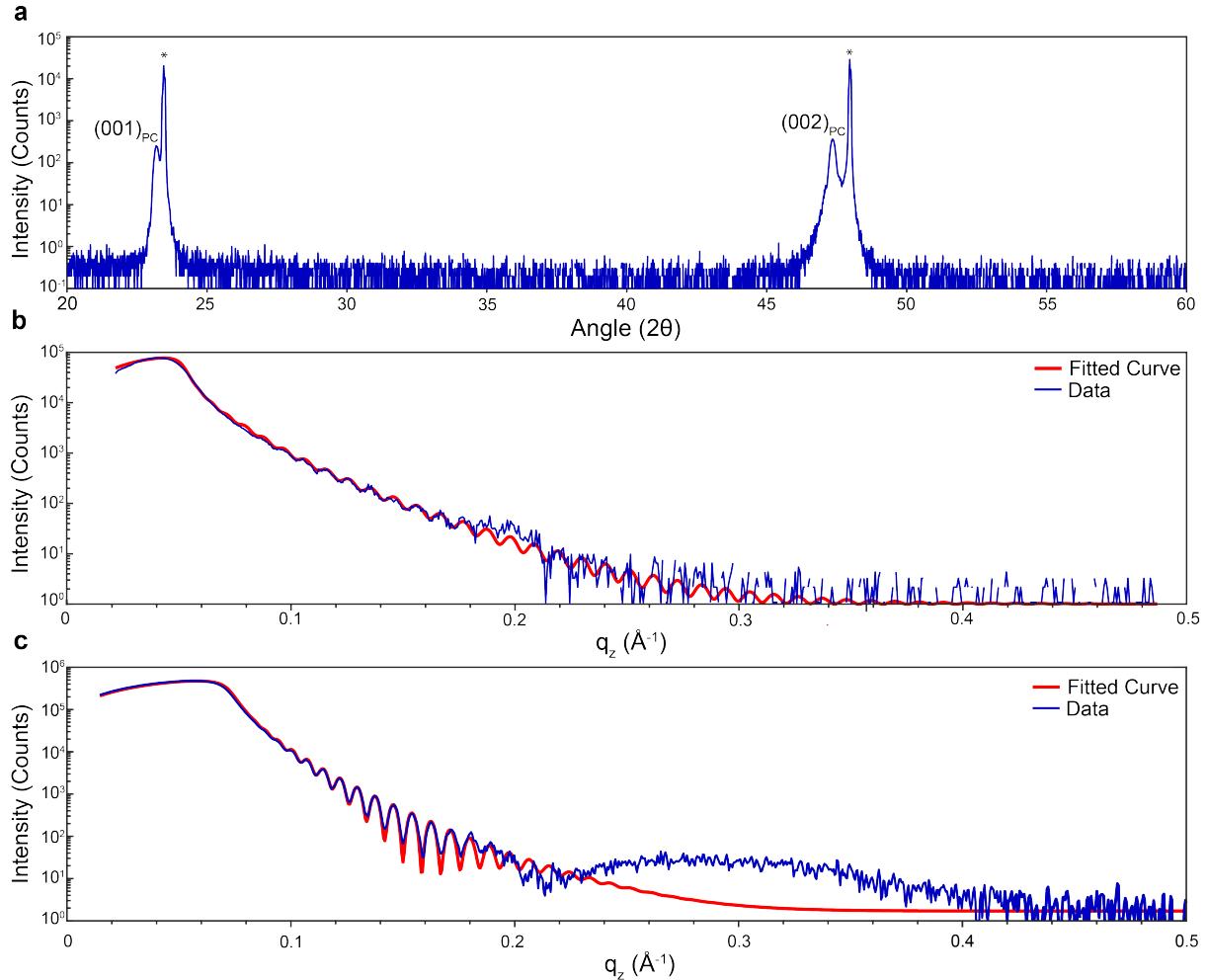


Figure S2: **a**, X-ray diffraction showing epitaxial NdNiO₃ $(001)_{PC}$ peaks. The asterisks denote LaAlO₃ (100) substrate peaks. **b**, X-ray reflectivity of the film after growth with the best fit overlaid. **c**, The X-ray reflectivity of the Au/Ti coating with the best fit curve overlaid. The bump after the oscillations is due to the silicon sample holder.

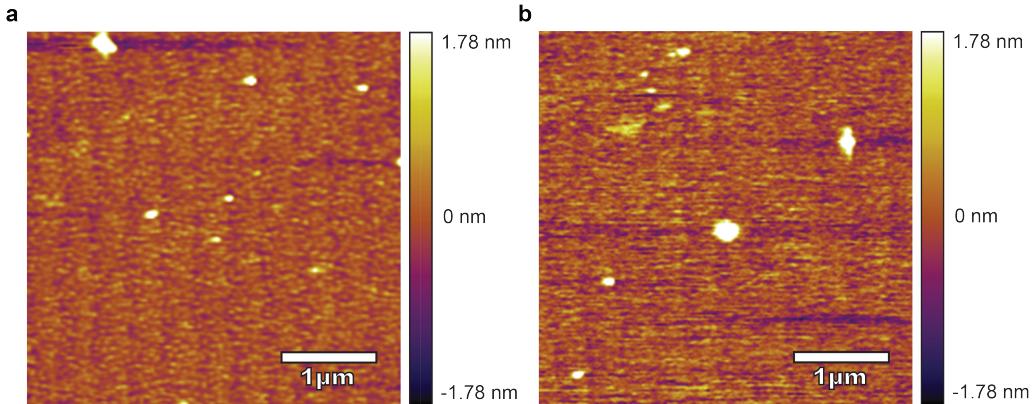


Figure S3: **a**, AFM characterization of NdNiO_3 film showing defects (bright spots) along with terracing due to the substrate miscut (vertical striping). **b**, AFM characterization of the NdNiO_3 film after being coated. The film is slightly rougher overall, but the terracing is still visible, and there are still surface defects.

Mapping Phase Fluctuations at Room Temperature

To attribute the regions we observe in Fig. 4 to phase separation, we recorded a map on the same sample at room temperature to measure the length scale of its fluctuations. We observe noise-induced fluctuations on a much smaller length scale, confirming that the domains we observe at the transition temperature are related to the MIT.

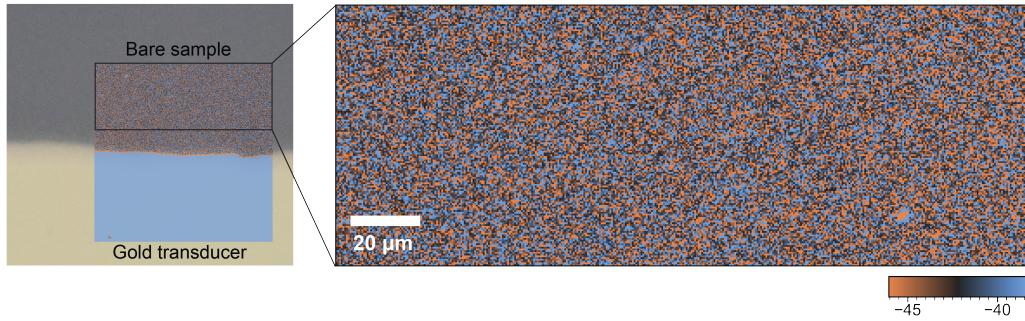


Figure S4: Map of the same NdNiO_3 film at room temperature. Some fluctuations due to noise are visible, but they visibly change on a smaller length scale than those observed at the transition. The strength of the fluctuations is a function of the objective aperture strength. This map was collected at a higher magnification than Fig. 4, so the phase fluctuations appear stronger.

Thermal Conductivity Data during Temperature Cycles

The data in Fig. 3b were collected over 3 cycles for cooling and 2 cycles for heating and averaged. The data without averaging is shown in Fig. S5.

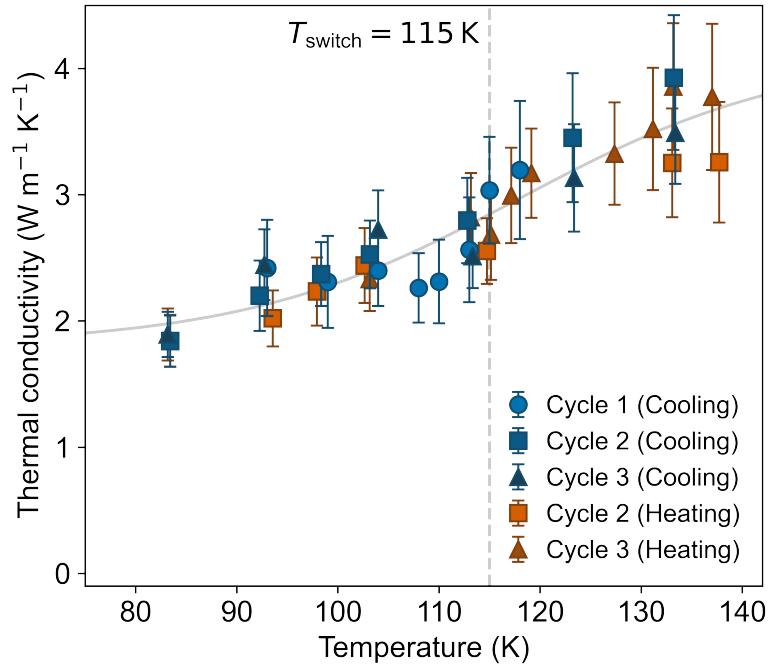


Figure S5: The thermal conductivity during heating and cooling cycles. The averaged values are presented in Fig. 3b.

Uncertainty Analysis for Multivariate Fitting

In processing the FDTR data with Au transducer, the heat transfer model involves the thermal boundary conductance between the metal transducer and the thin film, G_{TF} , the thermal conductivity of the thin film, κ , and the thermal boundary conductance, G_{FS} . The correlations between these variables prevent us from fitting them together. Here, we present the uncertainty analysis^{S37} for fitting κ and G_{TF} and for fitting κ and G_{FS} by examining the

confidence intervals in the multivariate fitting in Fig. S6. Because of the anti-correlations between κ and G_{TF} and between κ and G_{FS} , we fix the values of both thermal boundary conductances ($G_{\text{TF}} = G_{\text{FS}} = 45 \text{ MW m}^{-2} \text{ K}^{-1}$) and only fit the thermal conductivity.

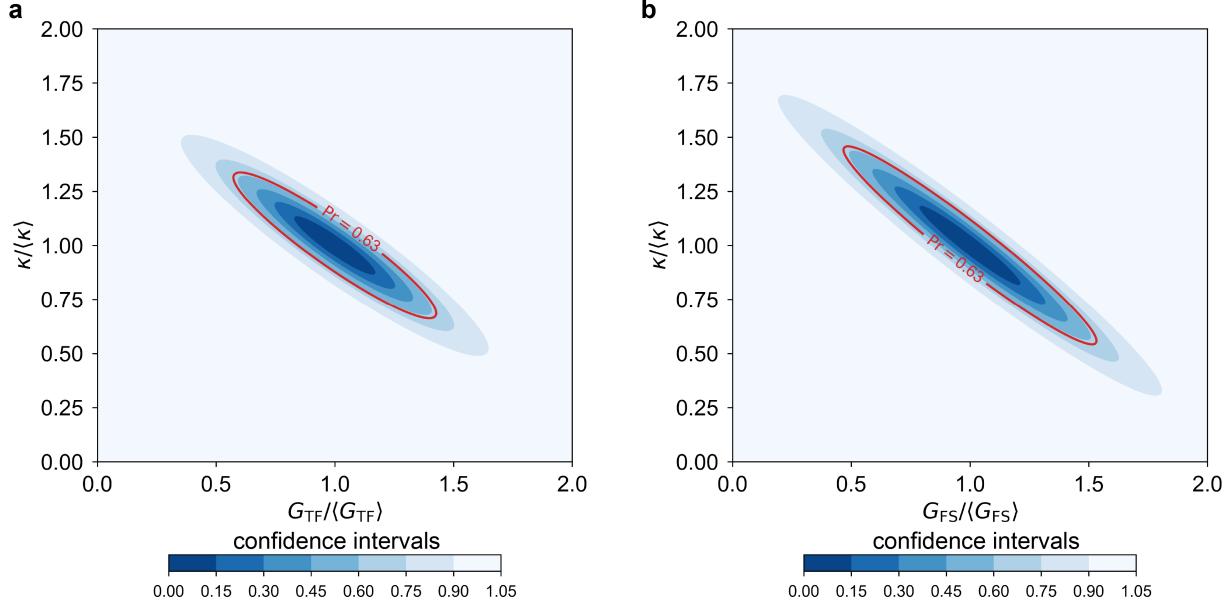


Figure S6: **a,b,** The confidence intervals for fitting κ and G_{TF} (**a**) and for fitting κ and G_{FS} (**b**) at 110 K. The contours correspond to the cumulative distribution function of a chi-squared continuous random variable evaluated at the same Mahalanobis distance. The Mahalanobis distance is defined by $D = (\mathbf{X} - \boldsymbol{\mu})^T \boldsymbol{\Sigma}^{-1} (\mathbf{X} - \boldsymbol{\mu})$, where \mathbf{X} is the random variable, $\boldsymbol{\mu}$ is the mean and $\boldsymbol{\Sigma}$ is the variance-covariance matrix. All non-fitting parameters are assumed to have a 3% uncertainty. The 0.63 confidence interval, equivalent to the generalized $1-\sigma$ confidence interval in the multivariate case, is marked in red. The bracket represents the mean value of the variable. We find that κ and G_{TF} and κ and G_{FS} are both anti-correlated, and that fitting the thermal conductivity of the thin film together with either thermal boundary conductance substantially increase the uncertainty in κ .

Refractive index of NdNiO₃

According to Ref., ^{S38} the real part of the dielectric constant of bulk NdNiO₃ is approaching a constant value of $\varepsilon_r = 1.7$ as the photon energy ω approaches 1 eV. This value remains nearly unchanged across temperatures both below and above the metal–insulator transition temperature. A similar asymptotic behavior has been observed in NdNiO₃/NdGaO₃ (110). ^{S39}

Therefore, we approximate the real part of the dielectric constant of the NdNiO₃ thin film with $\varepsilon_r = 1.7$ at photon energies of $\omega = 2.71$ eV (pump wavelength $\lambda = 458$ nm) and $\omega = 2.33$ eV (probe wavelength $\lambda = 532$ nm). As for the imaginary part of the dielectric constant, the optical conductivity measurements on a NdNiO₃ film on a LaAlO₃ (001) substrate in Ref. ^{S40} indicates that $\varepsilon_i = 2.86$ at $\omega = 2.71$ eV and $\varepsilon_i = 3.15$ at $\omega = 2.33$ eV at 298 K. Notably, the imaginary dielectric constant between 2 eV and 3 eV varies minimally across temperatures below and above the metal–insulator transition. Hence, we obtain that $\varepsilon_i = 2.86$ at the pump photon energy and $\varepsilon_i = 3.15$ at the probe photon energy. Accordingly, the real and imaginary parts of the refractive index are $n = 1.59$, $\kappa = 0.90$ at the pump wavelength, and $n = 1.59$, $\kappa = 0.97$ at the probe wavelength. Consequently, the optical penetration depths for the pump and probe beams are 40 nm and 43 nm, respectively.

Frequency-Domain Photo-Reflectance for the Thin-Film-on-Substrate Geometry

The frequency-domain photo-reflectance signal is contributed by the carrier density part, the electronic temperature part, and the lattice temperature part,

$$\frac{\Delta R}{R} = \text{Re}\{A\bar{\rho} + B\bar{T}_{\text{el}} + C\bar{T}_{\text{ph}}\} \quad (\text{S1})$$

where $\bar{}$ denotes the weighted average by the probe beam profile, and A , B , and C are material-dependent real constants. As pointed out by Ref., ^{S23} in the modulation frequency range we choose (< 10 MHz), the electron-phonon coupling is strong enough such that $T_{\text{el}} \approx T_{\text{ph}}$. As a result, we only need to consider the contributions from the carrier and the lattice temperature,

$$\frac{\Delta R}{R} \approx \text{Re}\{\text{CCR } \bar{\rho} + \text{CTR } \bar{T}\} \quad (\text{S2})$$

where CCR is the coefficient of carrier-induced reflectance, and $\text{CTR} = B + C$ is the effective coefficient of thermorelectance. In the following, we outline how to model the signal due to carriers and temperature.

We start with the dynamics of photo-excited carriers in a thin film described by,

$$\frac{d\rho}{dt} = D_{a,z} \frac{\partial^2 \rho}{\partial z^2} + D_{a,\parallel} \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \rho - \frac{\rho}{\tau} + P \quad (\text{S3})$$

where ρ is the excited electron density, P is the number density of pump photons absorbed by the thin film per unit time, $D_{a,\parallel}$ and $D_{a,z}$ are the in-plane and out-of-plane ambipolar diffusivity, respectively, and τ is the carrier recombination time. Taking the Fourier transform of Eq. S3 in the x- and y-directions, we obtain,

$$\frac{\partial^2}{\partial z^2} \tilde{\rho} - \Lambda \tilde{\rho} + \frac{\tilde{P}}{D_{a,z}} = 0 \quad (\text{S4})$$

where $\tilde{P} = \frac{P_0 \alpha}{h\nu_{\text{pump}}} e^{-\frac{\sigma_x^2 q_x^2}{8}} e^{-\frac{\sigma_y^2 q_y^2}{8}}$ and $\Lambda = \frac{D_{a,\parallel}}{D_{a,z}} q_\parallel^2 + \frac{1}{D_{a,z} \tau} + \frac{i\omega}{D_{a,z}}$. Here, P_0 is the absorbed pump laser power, $h\nu_{\text{pump}}$ is the photon energy, α is the inverse penetration depth of the pump laser beam, and σ_x and σ_y are the pump laser beam's radii along the x- and y-directions, respectively. The boundary condition at the two surfaces of the film is given by,

$$-D_{a,z} \frac{\partial \tilde{\rho}}{\partial z} + \tilde{\rho} S_j = 0 \quad (\text{S5})$$

where S_j ($j = 1, 2$) denotes the surface recombination velocities at the top and bottom surface, respectively. Note that the bottom surface corresponds to the interface between the thin film and the insulating substrate.

The solution to Eq. S4 takes the following form,

$$\tilde{\rho} = D e^{-\sqrt{\Lambda}z} + E e^{\sqrt{\Lambda}z} + F e^{-\alpha z} \quad (\text{S6})$$

where $F = \frac{P_0\alpha}{h\nu_{\text{pump}}D_{a,z}(\Lambda-\alpha^2)}e^{-(\sigma_x q_x^2 + \sigma_y q_y^2)/8}$ and,

$$D = \frac{-(D_{a,z}\alpha + S_1)(-D_{a,z}\sqrt{\Lambda} + S_2) + (-D_{a,z}\sqrt{\Lambda} + S_1)(D_{a,z}\alpha + S_2)e^{-(\sqrt{\Lambda}+\alpha)L}}{(D_{a,z}\sqrt{\Lambda} + S_1)(-D_{a,z}\sqrt{\Lambda} + S_2) - (-D_{a,z}\sqrt{\Lambda} + S_1)(D_{a,z}\sqrt{\Lambda} + S_2)e^{-2\sqrt{\Lambda}L}}F \quad (\text{S7})$$

$$E = \frac{-(D_{a,z}\alpha + S_1)(D_{a,z}\sqrt{\Lambda} + S_2) + (D_{a,z}\sqrt{\Lambda} + S_1)(D_{a,z}\alpha + S_2)e^{(\sqrt{\Lambda}-\alpha)L}}{(-D_{a,z}\sqrt{\Lambda} + S_1)(D_{a,z}\sqrt{\Lambda} + S_2) - (D_{a,z}\sqrt{\Lambda} + S_1)(-D_{a,z}\sqrt{\Lambda} + S_2)e^{2\sqrt{\Lambda}L}}F \quad (\text{S8})$$

with L denoting the thickness of the thin film.

We then take the inverse Fourier transform to obtain $\rho(\mathbf{r})$ and the signal measured by the probe beam is given by,

$$I_e(\omega) = \text{CCR} \frac{2\gamma}{\pi\sigma'_x\sigma'_y} \int \int_0^\infty \rho(\mathbf{r}) e^{-2x^2/\sigma'_x{}^2} e^{-2y^2/\sigma'_y{}^2} e^{-\gamma z} dz d^2\mathbf{r}_{||} \quad (\text{S9})$$

where γ is the inverse penetration depth of the probe beam, and σ'_x and σ'_y are the probe beam radii along x- and y-directions, respectively. Note that we extend the upper limit of the integration in the z-direction to infinity, as the light entering the substrate can be ignored given the fact that both penetration depths of the pump and probe beams are smaller than the film thickness. In oxide thin films, such as VO₂,^{S41} the electron mean free path is on the order of the lattice constant, and thus much shorter than the film thickness. Hence, we can assume isotropic diffusivity, such that $D_{a,||} = D_{a,z} = D_a$, and $\Lambda = q_{||}^2 + \frac{1}{D_a\tau} + \frac{i\omega}{D_a}$. Further assuming small surface recombination velocities (weak band bending), we have the following expression of the signal,

$$I_e(\omega) = \frac{\text{CCR}}{(2\pi)^2} \int \frac{P_0\alpha\gamma}{h\nu D_a(\Lambda-\alpha^2)} \left(\frac{1}{\alpha+\gamma} + \frac{D}{\sqrt{\Lambda}+\gamma} + \frac{E}{-\sqrt{\Lambda}+\gamma} \right) e^{-\frac{R_x^2 q_x^2}{4}} e^{-\frac{R_y^2 q_y^2}{4}} d^2\mathbf{q}_{||} \quad (\text{S10})$$

where

$$D = \frac{\alpha}{\sqrt{\Lambda}} \frac{1 - e^{-(\sqrt{\Lambda}+\alpha)L}}{-1 + e^{-2\sqrt{\Lambda}L}} \quad (\text{S11})$$

$$E = \frac{\alpha}{\sqrt{\Lambda}} \frac{-1 + e^{(\sqrt{\Lambda}-\alpha)L}}{-1 + e^{2\sqrt{\Lambda}L}} \quad (\text{S12})$$

and $R_x = \sqrt{\sigma_x^2 + \sigma'_x^2}$ and $R_y = \sqrt{\sigma_y^2 + \sigma'_y^2}$ are the effective beam radii along x- and y-directions, respectively. Eq. S10 is the formal expression of the carrier part of the signal. In Fig. S7, we present the representative spatial profiles of the carrier density. The probe-intensity-weighted integral of this distribution corresponds to the carrier part of the measured signal.

Next, we consider the temperature part of the signal $I_{\text{th}}(\omega)$. As derived in Ref.,^{S36} the phonon temperature profile within the thin film is expressed by,

$$\tilde{T} = \left(C e^{\sqrt{\lambda}z} + D e^{-\sqrt{\lambda}z} + F e^{-\alpha z} \right) e^{-\frac{\sigma_x^2 q_x^2}{8}} e^{-\frac{\sigma_y^2 q_y^2}{8}} \quad (\text{S13})$$

where $\lambda = i \frac{C_p \omega}{\kappa_{\perp}} + \frac{\kappa_{\parallel}}{\kappa_{\perp}} q_{\parallel}^2$, $F = \frac{1}{\kappa_{\perp}} \frac{P_0 \alpha}{\lambda - \alpha^2}$, and C_p is the volumetric heat capacity. Here, C and D are given by,

$$C = \frac{1}{2} \left[\frac{\alpha}{\sqrt{\lambda}} - \left(1 + \frac{M_4}{M_3} \right) \right] F \quad (\text{S14})$$

$$D = \frac{1}{2} \left[-\frac{\alpha}{\sqrt{\lambda}} - \left(1 + \frac{M_4}{M_3} \right) \right] F \quad (\text{S15})$$

Specifically, M_3 and M_4 are elements of the transfer matrix relating the temperature and heat flux at the bottom of the substrate to the temperature and the laser-heating-related term at the surface,

$$\begin{pmatrix} \tilde{T}_n(L_n) \\ \tilde{q}_n(L_n) \end{pmatrix} = \begin{pmatrix} M_1 & M_2 \\ M_3 & M_4 \end{pmatrix} \begin{pmatrix} \tilde{T}_1(0) \\ F e^{-\frac{R_x^2 q_x^2}{4}} e^{-\frac{R_y^2 q_y^2}{4}} \end{pmatrix} \quad (\text{S16})$$

The construction of such a transfer matrix requires the heat capacity C_p , thickness L , and thermal conductivity components κ_{\parallel} and κ_{\perp} of each layer, as well as the thermal boundary conductance G between adjacent layers.

Consequently, the temperature part of the signal is written as,

$$\begin{aligned} I_{\text{th}}(\omega) &= \frac{\text{CTR} \gamma}{(2\pi)^2} \int \left(\frac{C}{\gamma - \sqrt{\lambda}} + \frac{D}{\sqrt{\lambda} + \gamma} + \frac{F}{\alpha + \gamma} \right) e^{-\frac{R_x^2 q_x^2}{4}} e^{-\frac{R_y^2 q_y^2}{4}} d^2 \mathbf{q}_{||} \\ &= \frac{\text{CTR}}{(2\pi)^2} \int \left\{ \frac{1}{\lambda - \gamma^2} \left[\left(1 + \frac{M_4}{M_3} \right) \gamma - \alpha \right] + \frac{1}{\alpha + \gamma} \right\} \frac{P_0 \alpha \gamma}{\kappa_{\perp} (\lambda - \alpha^2)} e^{-\frac{R_x^2 q_x^2}{4}} e^{-\frac{R_y^2 q_y^2}{4}} d^2 \mathbf{q}_{||} \end{aligned} \quad (\text{S17})$$

Finally, by summing Eq. S10 and Eq. S17, we obtain the total signal measured at different modulation frequencies in the experiment,

$$I(\omega) = I_e(\omega) + I_{\text{th}}(\omega) \quad (\text{S18})$$

We refer to the combined expression in Eq. S18 as the carrier and temperature model. We emphasize that, to the best of our knowledge, such a parallel treatment of charge and thermal transport in a thin film under laser irradiation has not been previously reported.

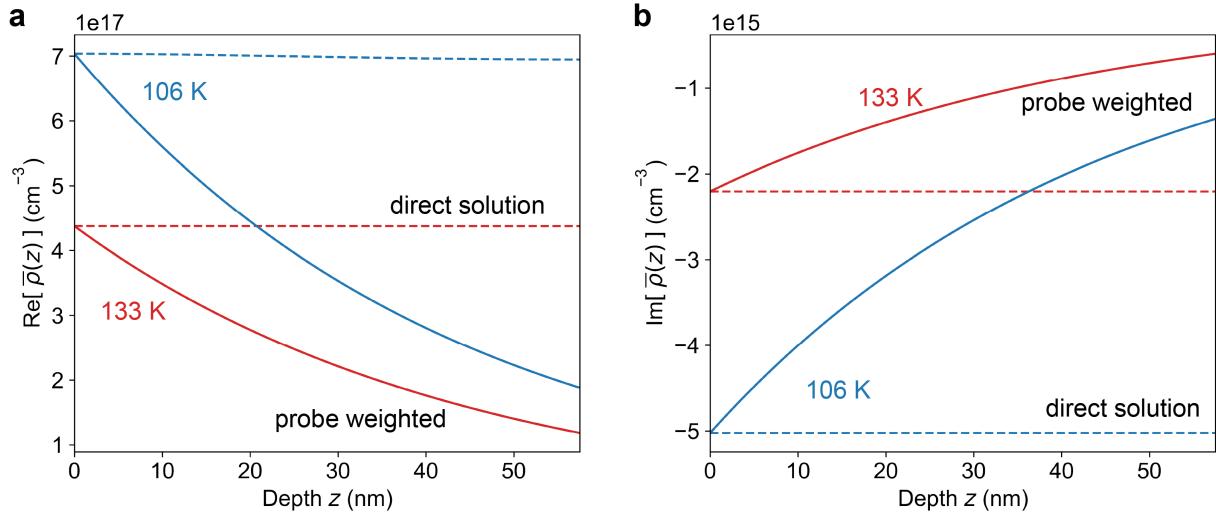


Figure S7: **a,b**, Real and imaginary parts of the photo-excited carrier density $\bar{\rho}(z)$ within the thin film at $f = 10.5$ MHz when the absorbed pump power $P_0 = 6$ mW. Solid lines represent the direct spatial profile $\bar{\rho}(z)$, while the dashed lines correspond to the carrier density weighted by the exponentially decaying probe intensity in the depth direction ($\propto e^{-\gamma z}$). The carrier part of the signal collected by the probe is given by $\text{CCR} \times \bar{\rho} = \text{CCR} \gamma \int \bar{\rho}(z) e^{-\gamma z} dz$. We rule out the possibility of a direct photo-induced metal-insulator transition due to the insufficient density of photo-excited carriers. Instead, the metal-insulator is temperature-driven.

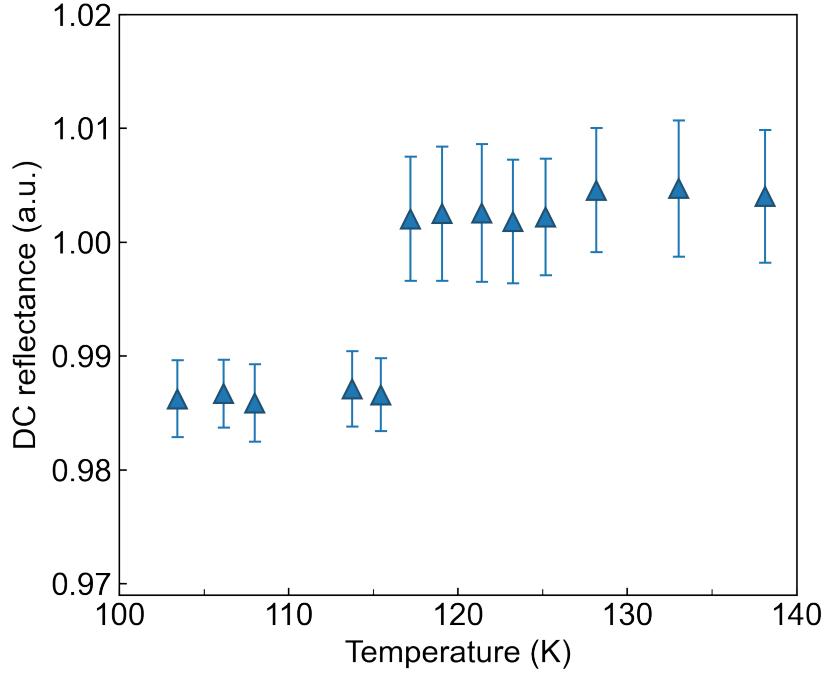


Figure S8: The DC photo-reflectance R as a function of temperature in FDPR measurements during heating. The error bars represent the standard deviations of the data across all modulation frequencies at the same temperature and indicate only a weak frequency dependence. A sudden jump in R is observed around 115 K, consistent with the transport measurements.

Sensitivity Analysis in FDPR

The total signal in Eq. S18 can be reorganized as,

$$I(\omega) = \text{CTR} \left(\bar{T} + \frac{\text{CCR}}{\text{CTR}} \times \bar{\rho} \right) \quad (\text{S19})$$

In fitting the phase data of the photo-reflectance to our model, the prefactor CTR does not influence the best, and the combined term $\frac{\text{CCR}}{\text{CTR}}$ effectively behaves as an independent variable. Therefore, we define,

$$A_\rho = \frac{\text{CCR}}{\text{CTR}} \quad (\text{S20})$$

By considering Eq. S2, we identify the physical meaning of A_ρ as the inverse of the temperature derivative of the carrier density,

$$A_\rho = \frac{\Delta T}{\Delta \rho} \approx \left(\frac{\partial \rho}{\partial T} \right)^{-1} \quad (\text{S21})$$

As a result, we need 3 unknowns to evaluate the carrier part of the signal: the ambipolar diffusion coefficient D_a , the inverse of the temperature derivative of the carrier density A_ρ , and the carrier recombination lifetime τ . The sensitivity to any variable x_i at the j th modulation frequency ω_j can be characterized by the phase difference,

$$\Delta\phi(\omega_j, x_i) = \arctan \left(\frac{\text{Im}\{I(\omega_j, x_i + \Delta x_i)\}}{\text{Re}\{I(\omega_j, x_i + \Delta x_i)\}} \right) - \arctan \left(\frac{\text{Im}\{I(\omega_j, x_i)\}}{\text{Re}\{I(\omega_j, x_i)\}} \right) \quad (\text{S22})$$

Here, we take the change in the variable, Δx_i , to be 1% of x_i , that is, $\Delta x_i = 0.01x_i$.

As illustrated in Fig. 2, the sensitivities to D_a and τ are similar in absolute magnitude but with opposite signs. This suggests that D_a and τ are anti-correlated in fitting. The sensitivities with respect to D_a and A_ρ exhibit a similar frequency dependence, differing only by a scaling factor on the order of unity. This indicates that D_a and A_ρ are positively correlated in fitting. As a consequence, we can fit only one out of the three variables with confidence. We argue that A_ρ and τ are more intimately connected to the band structure, which, within the energy range relevant to pump-excited electrons changes only minimally across the metal-insulator transition, whereas D_a is more strongly influenced by electron transport governed by electron-electron and electron-phonon interactions that are susceptible to metal-insulator transition. Hence, we treat A_ρ and τ as constants, and choose D_a as a fitting variable. Note that the thermal boundary conductance G_{FS} between the thin film and substrate and D_a are not correlated, and thus we include G_{FS} as an additional fitting parameter.

Sensitivity Analysis of LaAlO₃ Substrate

We find that our FDTR measurements are highly sensitive to the substrate parameters shown in Fig. 3a, measured on a substrate sample with no film. We show below the change in phase for a 1% increase in each of the shown parameters in the same way as calculated in Fig. 2d,e.

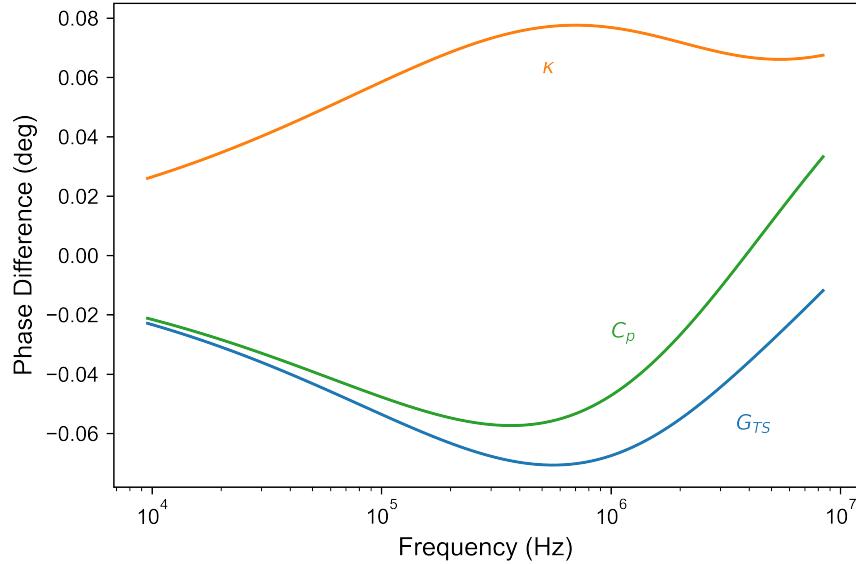


Figure S9: Sensitivity analysis of LaAlO₃ substrate parameters. These measurements were performed on a substrate without a film, coated in a transducer layer, and the results are shown in Fig. 3. Substrate thermal conductivity κ , volumetric heat capacity C_p , and the thermal boundary conductance between the transducer layer and the substrate G_{TS} are shown.

Heat Capacity of NdNiO₃

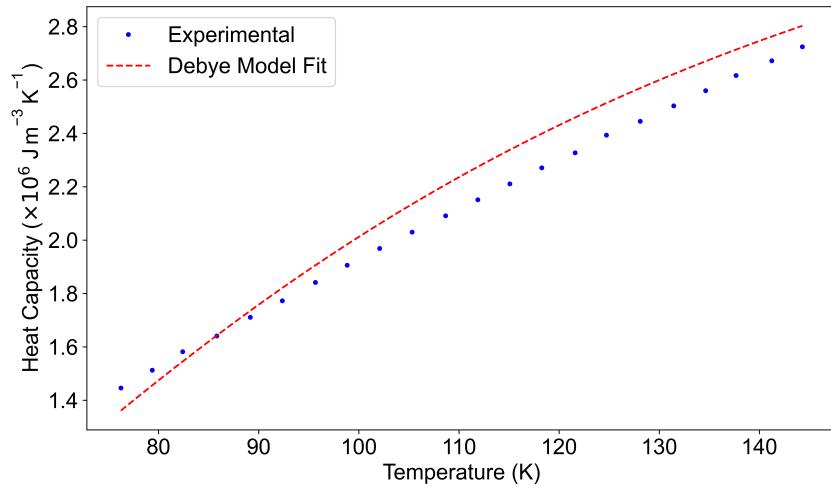


Figure S10: Heat capacity of NdNiO₃ as used to fit the FDTR thermal conductivity data. Blue dots represent volumetric heat capacity taken from literature measurements on bulk NdNiO₃, obtained using semi-adiabatic calorimetry on a PPMS.^{S24} Although the phase transition occurs at a higher temperature in the bulk NdNiO₃ and the epitaxy strain in thin-film NdNiO₃ can alter the lattice dynamics, we believe that these factors only minimally affect the sensible component (i.e., the baseline) of the heat capacity. The red dashed line represents the Debye heat capacity prediction used to fix the heat capacity parameter in FDTR and FDPR measurements.

Data for Fig. 3b: Thermal Conductivity vs Temperature

The following tables provide the measured thermal conductivity κ as a function of temperature T , along with the associated uncertainty $\Delta\kappa$, for both cooling and warming cycles as shown in Fig. 3b. The data were averaged over three cooling cycles and two warming cycles (see Fig. S5).

Table 1: Thermal conductivity during cooling and warming

(a) Cooling			(b) Warming		
T (K)	κ ($\text{W m}^{-1}\text{K}^{-1}$)	$\Delta\kappa$	T (K)	κ ($\text{W m}^{-1}\text{K}^{-1}$)	$\Delta\kappa$
83.30	1.87	0.135	83.30	1.87	0.146
92.67	2.35	0.183	93.55	2.02	0.222
98.68	2.34	0.222	97.93	2.23	0.270
103.72	2.55	0.166	102.91	2.39	0.195
108.00	2.26	0.275	113.15	2.82	0.351
110.00	2.31	0.332	114.95	2.62	0.221
113.05	2.62	0.197	117.15	2.99	0.379
115.00	3.04	0.423	119.10	3.17	0.354
118.00	3.20	0.548	127.38	3.33	0.405
123.30	3.29	0.332	131.17	3.52	0.485
133.32	3.71	0.320	133.14	3.55	0.331
			137.39	3.52	0.375

TOC Graphic

