

Measuring In-Plane Thermal Conductivity

Beam Offset and Stack Engineering with FASTR

Laser Thermal

Thermoreflectance techniques like FDTR and SSTR are most often associated with cross-plane thermal transport. The pump heats a small spot, the probe reads the surface, and the analysis returns the through-thickness conductivity of whatever sits beneath. For anisotropic materials, that is only half the story. Many of the materials our customers care about, including AlN, GaN, h-BN, layered chalcogenides, and most highly oriented films, can have in-plane and cross-plane conductivities that differ by an order of magnitude or more.

This note describes how Laser Thermal isolates the in-plane conductivity using two complementary approaches available on the FASTR platform: stack engineering with SSTR, and beam offset with FDTR. The two methods cross-check each other, and when paired with conventional zero-offset FDTR they let us extract the cross-plane conductivity, the in-plane conductivity, and both interface resistances from one sample stack.

We use a thick AlN film on silicon as the running example, because it is a clean case where every term in the resistance network has appreciable sensitivity and the answers can be checked against TDTR.

Why a Symmetric Beam Cannot See In-Plane on Its Own

In a standard FDTR or SSTR measurement, the pump and probe are coaxial. Heat flows radially outward from the heated spot. For a sample where the in-plane and cross-plane conductivities are similar, the surface temperature responds to the geometric mean of the two, and the model has weak independent sensitivity to either component.

Two levers change that. The first is the lateral length scale of the experiment relative to the film thickness. When the heated spot is small compared to the film, heat must travel laterally before it can reach the substrate, and the in-plane conductivity dominates the response. When the spot is large, heat takes the cross-plane path almost entirely vertically, and the cross-plane conductivity dominates.

The second lever is breaking the radial symmetry of the measurement. If the heat source and sensing beams are displaced from each other by a known offset, the temperature measured depends on how efficiently heat spreads laterally between the two spots. That dependence is the in-plane conductivity. This is the beam offset method, and our standard implementation runs it in FDTR, measuring thermal phase, at a fixed modulation frequency.

Approach 1: Stack Engineering for SSTR

The simplest way to make SSTR sensitive to in-plane conductivity is to force the heat to spread laterally. Putting a thermally resistive layer between the film of interest and the substrate does

exactly that. Heat from the pump cannot easily escape downward, so it spreads in-plane through the top film before sinking through the buried resistance into the substrate.

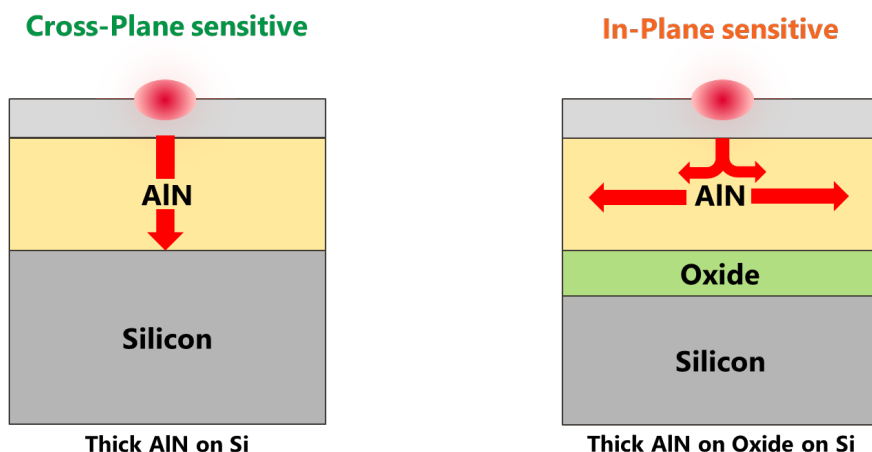


Figure 1. Stack design as a metrology variable. The bare AlN-on-Si stack on the left maximizes cross-plane sensitivity. Adding a thermal oxide layer between the AlN and silicon, shown on the right, forces heat to spread in-plane through the AlN before reaching the substrate. The same material is measured in both stacks, but the geometry shifts which property the model is sensitive to.

This is what the right-hand stack in Figure 1 accomplishes. A buried oxide thermally shorts the cross-plane path, and SSTTR on this stack returns an in-plane-dominated signal. SSTTR with a well-chosen stack is straightforward to run and tends to give the smallest uncertainty of any in-plane method we deploy, because there is no transient analysis and no phase fitting involved.

The cost is that it requires an engineered sample. When that is not available, beam offset is the right tool.

Approach 2: Beam Offset

Beam offset works on the as-received stack. Rather than redesigning the sample, we redesign the experiment. The heating and sensing beams are moved relative to each other in known increments, and at each position we record the FDTR phase. The result is a spatial profile of the thermal response.

The shape of that profile carries the in-plane signature. A material that spreads heat efficiently in-plane produces a wide, shallow profile. A material that does not spread heat well produces a narrow, deep profile. Fitting the full profile to a multilayer thermal model returns the in-plane conductivity directly. The cross-plane conductivity, the laser spot sizes, and the interface resistances are all part of the same model, but the profile width is dominated by in-plane spreading.

How the measurement is run

Our standard implementation is a fixed frequency beam offset. The sequence is:

- Run a conventional zero-offset FDTR frequency sweep on the stack and use the model sensitivity to identify the frequency with the highest response to in-plane transport.
- Lock the modulation at that frequency.

- Step a laser laterally relative to the other laser using the actively controlled steering mirror, recording the thermal phase at each offset position.
- Fit the resulting phase profile to the multilayer thermal model with the in-plane conductivity as the free parameter. Cross-plane and interface terms are constrained by the zero-offset frequency sweep.

FASTR can also run a full FDTR frequency sweep at every offset position as needed, however, the fixed frequency approach has been found to be the most effective for most highly conductive materials when measuring in-plane thermal conductivity.

Why fixed frequency works

In-plane sensitivity is not uniform across the FDTR frequency band. At low frequencies the thermal penetration depth is large and the response is dominated by the substrate. At high frequencies the response is dominated by the top interface and the near-surface region of the film. There is an intermediate band where the lateral spreading length is comparable to the offset range and the phase is most sensitive to the in-plane conductivity. Locking onto that band concentrates the measurement time where the information is, rather than spreading it across frequencies that contribute little to the in-plane fit.

Case Study: Thick AlN on Silicon

The sample is a thick AlN film on a silicon wafer with a buried oxide layer. We use the FASTR platform with an aluminum transducer to run three measurements on the same stack:

- **Conventional zero-offset FDTR** across a frequency sweep, sensitive to the cross-plane conductivity and both interface resistances.
- **SSTR on a stack designed to maximize in-plane sensitivity**, returning the in-plane conductivity directly from the steady-state response.
- **Fixed-frequency beam offset FDTR** on the same stack, returning the in-plane conductivity from the spatial profile of the thermal phase at a single modulation frequency.

In-plane: SSTR and beam offset agree

The two in-plane measurements were run independently and yielded values that agree within their stated uncertainty bands.

Method	$k_{ }$ ($\text{W m}^{-1} \text{K}^{-1}$)	Geometry
SSTR	61.1 ± 5.4	Buried oxide stack
Fixed-frequency beam offset FDTR	60.5 ± 9.2	Same stack, FDTR mode

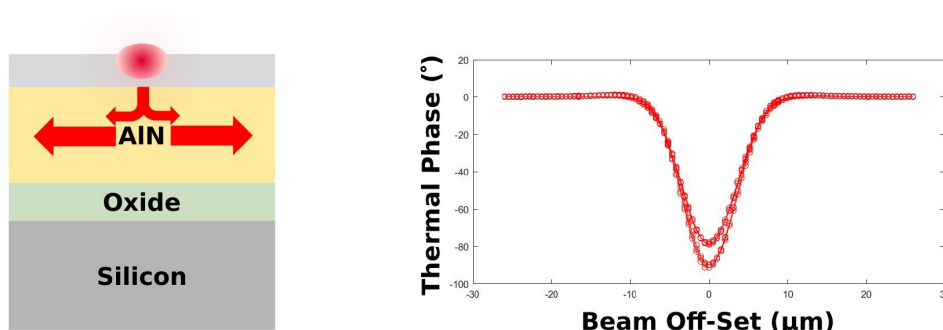


Figure 2. The in-plane SSTR and fixed-frequency beam offset FDTR measurements on the AlN-on-oxide-on-Si stack. Left: the heat-flow geometry once the buried oxide forces lateral spreading through the AlN. Right: the FDTR thermal phase is recorded at a fixed modulation frequency with the highest in-plane sensitivity.

Two methods, two physical models, the same answer. That is the cross-check that makes the result defensible. SSTR's tighter uncertainty reflects the simplicity of fitting a steady-state slope rather than a full phase profile, but beam offset has the advantage that it requires no special stack.

Cross-plane and interfaces: FDTR with in-plane fixed

Once the in-plane conductivity is known, conventional FDTR has clear sensitivity to the remaining unknowns. Different frequency regimes are sensitive to different parameters: the high-frequency regime is dominated by the top interface, the mid-frequency regime by the AlN cross-plane conductivity, and the low-frequency regime by the bottom interface.

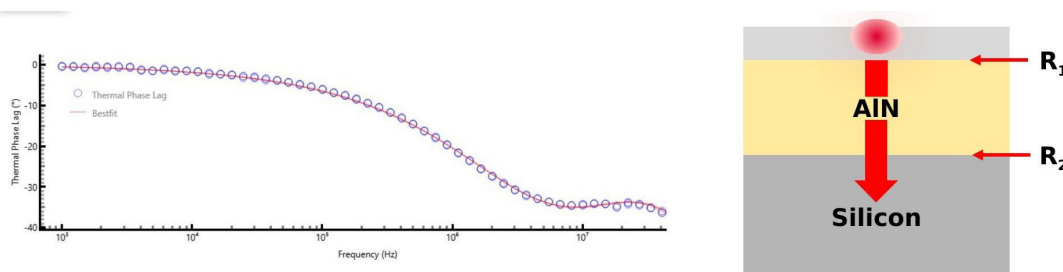


Figure 3. FDTR thermal phase lag versus frequency on the AlN-on-silicon stack. With the in-plane conductivity already constrained by the SSTR and beam offset measurements, the frequency sweep separates the cross-plane conductivity from the two interface resistances at distinct frequency regimes.

With the in-plane conductivity fixed, the FDTR fit returns clean values for the remaining three parameters:

Parameter	Value	Cross-check
Cross-plane $k_{\perp}$ ($\text{W m}^{-1} \text{K}^{-1}$)	119.1 ± 4.3	Matches TDTR within uncertainty
Top interface R_1 ($\text{m}^2 \text{K GW}^{-1}$)	4.8 ± 0.2	Matches TDTR within uncertainty
Bottom interface R_2 ($\text{m}^2 \text{K GW}^{-1}$)	7.5 ± 0.5	Independent constraint

This stack is anisotropic by roughly a factor of two, with the cross-plane direction being the higher conductivity. That ratio is consistent with highly oriented columnar grain growth, which is what we expect from the deposition conditions used for thick AlN films of this type. Phonon transport runs efficiently along the columns and is interrupted by the column boundaries in the lateral direction.

Practical Notes

When to use which method

- **Stack engineering with SSTR** is the lowest-uncertainty path when the customer can provide a stack with a deliberately resistive buried layer, or when we are involved early enough to recommend one. The fit is the cleanest because there is no transient phase to disentangle.
- **Fixed-frequency beam offset FDTR** is the right tool for as-received samples and for stacks where the geometry cannot be modified. On FASTR it adds only a few minutes per measurement location because the steering mirrors are already in the optical path.
- **Both together** is what we recommend when the stated goal is a fully resolved anisotropic conductivity tensor with separated interfaces. The two in-plane methods cross-check each other, and the joint solution is more credible than either alone.

Sample requirements

Beam offset has the same sample requirements as standard FASTR measurements: a smooth surface (target less than 10 nm RMS), a deposited metal transducer (typically 80 nm aluminum for the NIR system), and a film thick enough that the in-plane spreading length sits inside the film rather than the substrate. For most semiconductor films of interest, a film thickness of several hundred nm to a few microns gives the cleanest separation between in-plane and cross-plane terms. Thinner films can be measured but the interface terms tend to dominate the budget.

From measurement to process feedback

On a FASTR system in your facility, this entire workflow runs as a routine recipe. The zero-offset frequency sweep, the in-plane SSTR measurement, and the fixed-frequency beam offset scan can be queued back-to-back on the same sample stage and analyzed automatically. For a thick AlN film of this kind, the full set of fitted properties from start to finish takes well under an hour per location.

That cycle time matters because in-plane and cross-plane conductivity, along with both interface resistances, are the four parameters that connect deposition recipe to thermal performance. Sputter pressure, substrate temperature, bias, target purity, and post-deposition anneal all leave their fingerprint somewhere in that set. With high-throughput screening on the FASTR platform, those fingerprints become measurable on the same day a wafer comes off the tool, while the process is still close enough to its starting point to iterate on. A campaign that links deposition parameters to the intrinsic anisotropic conductivity tensor and the contact resistance to the stack above and below is exactly the kind of work the system was built for.

The same logic applies to other oriented and anisotropic films we routinely measure on FASTR: GaN, h-BN, oriented chalcogenides, layered nitrides and oxides, and many epitaxial heterostructures.

Summary

FDTR and SSTR are not inherently restricted to cross-plane measurements. Two well-tested approaches give clean access to in-plane conductivity. Stack engineering forces the heat path to be lateral and is the lowest-uncertainty option when the sample geometry can be tuned. Fixed-frequency beam offset breaks

the radial symmetry of the measurement directly and works on as-received samples. On FASTR, both are routine, and combining them with conventional zero-offset FDTR yields the full anisotropic property set: in-plane conductivity, cross-plane conductivity, and both interfaces, validated by independent cross-checks. That is the level of resolution needed to connect deposition and process choices to the intrinsic transport behavior of the film.

Whether the right answer for your group is a FASTR system in your own facility for high-throughput process screening, periodic contract testing through Laser Thermal, or some combination of the two, we are happy to talk through the options. If you can share the layer structure, approximate thicknesses, expected conductivity range, and what you are trying to learn from the measurement, we will recommend the path that gets you to a defensible answer with the least friction.