

Novel Technique Advances Super-Resolution Thermoreflectance Microscopy

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As electronic devices become smaller and more densely populated with components, thermal management, and thus characterization, becomes increasingly important. Because semiconductor devices must operate under higher energy density, the ability to test by viewing thermopixelization at the nanometer scale is vital.

However, conventional thermography methods (e.g., IR microthermography and wide-field thermoreflectance microscopy) with limited spatial resolution cannot provide detailed insight into thermal behavior for such small devices. Scanning probe thermoreflectance microscopy (SPTRM) is a novel technique that overcomes these barriers, providing sub-100 nm spatial resolution to enable clear thermal imaging of 100-nm-wide electronic features.¹

SPTRM Improves On Existing Thermography Methods

Conventional thermography methods suffer from inherently limited spatial resolution — IR microthermography, which utilizes wavelengths longer than 1 μm , struggles to image features below the micrometer scale, while wide-field thermoreflectance microscopy (TRM), though operating at shorter wavelengths, remains diffraction-limited and cannot resolve nanometer-scale features. On the other hand, although scanning thermal microscopy (SThM) can be adapted for nanometer-scale thermal imaging, it is a contact method that can interfere with the heat distribution of the device and makes it susceptible to surface roughness issues.

TRM measures a component's thermal distribution via the thermoreflectance effect: as temperature changes, the material's optical constant, or refractive index, also changes.

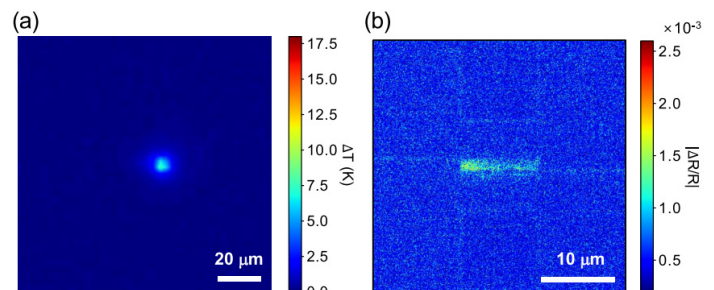


Fig 1: Thermal images of a 200-nm-pitch (i.e., 100-nm-wide lines and spaces) resistive heater obtained using (a) an IR microthermography system and (b) a wide-field TRM system.

By monitoring changes in the material's reflectance, users can derive precise temperature changes. To take accurate measurements, TRM requires sample-specific calibration and management of background noise that can impact measurement of the sample's change in reflectivity.

SPTRM combines thermoreflectance microscopy (TRM) and scanning probe microscopy, adopting shear force microscopy (ShFM) methods to locate an optical fiber probe close to the sample surface, minimizing light diffraction. Unlike SThM, which requires a larger apparatus near the sample, SPTRM's compact probe can be positioned close to the sample surface, enabling electrical contact without physical interference and facilitating sub-100 nm measurements.

Further, SPTRM offers the ability to test devices in the same power environment as they will be used, separating it from techniques like SThM, which requires additional power inputs. SPTRM operates using visual light, and the probe beam intensity is kept sufficiently low to minimize any effect on the sample. Because the measurement relies on reflected light with no mechanical contact, it does not disturb the thermal or structural state of the operating device. This also allows SPTRM to test devices within their actual power environment, in contrast to contact-based techniques such as SThM, where tip-sample interaction can perturb local heat flux.

How SPTRM Works

Because SPTRM's ~50 nm optical fiber can get close to a sample without touching it, the instrument can accurately measure the temperature of devices as they operate under intended working conditions. By using a co-localized configuration,

which uses the same aperture for both illumination and collection, SPTRM eliminates "blind regions" and shadowing effects typical of other configurations (e.g., combination of far-field and near-field). Further, because spatial resolution is decoupled from the illumination wavelength in SPTRM, system users can choose wavelengths tailored to their specific sample material's thermorefectance coefficient (e.g., 532 nm for gold) to optimize thermal sensitivity.

The instrumentation is a combination of optical, scanning probe, and stage components (Fig. 2). Illuminating light emanates from the laser diode and travels through an optical fiber line to the probe tip. The light passes through the aperture, is reflected by the sample surface, and then the reflected light is collected through the same optical fiber. The reflected optical signal is then acquired by a photomultiplier tube (PMT) and amplified by a current amplifier for analysis before entering an analog-to-digital converter and being saved to a designated location.

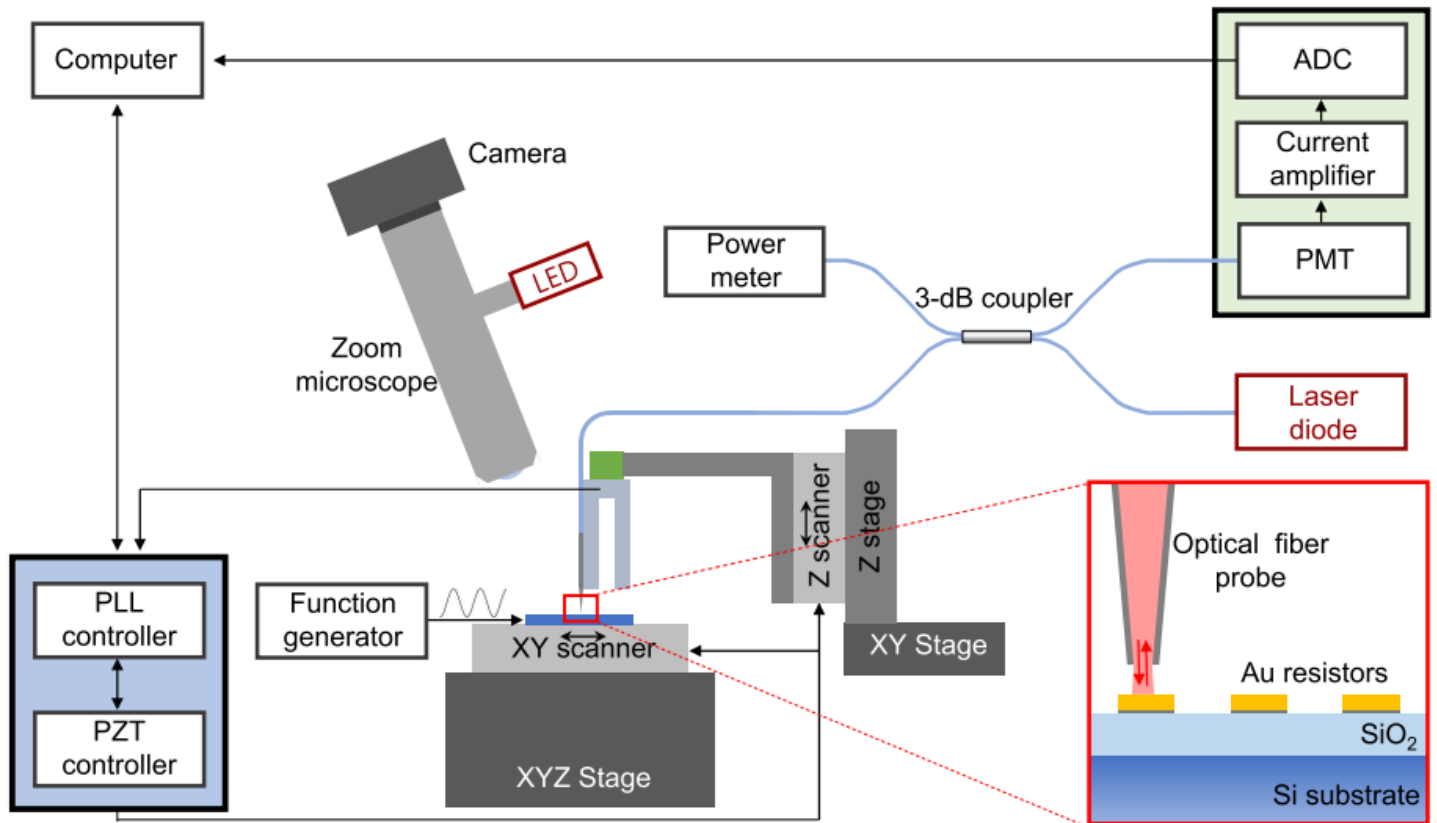


Fig 2: Schematic of the SPTRM system. The inset shows a zoomed-in view of the optical fiber probe mounted on the tuning fork and the test device positioned on the sample stage. Optical components are highlighted in red, scanning probe parts in blue, and stage parts in green. Abbreviations: analog-to-digital converter (ADC), piezoelectric transducer (PZT), phase-locked loop (PLL), and light-emitting diode (LED).²

The optical fiber vibrates at a predetermined frequency, the amplitude of which is monitored with a phase-locked loop (PLL) controller that moves in response to amplitude changes to maintain the same frequency. Oscillations may affect the quality of the measured light signal, but the amplitude itself is so small compared to pixel size that the actual impact is minimal.

The probe tip's scans result in a two-dimensional map of thermal distribution, with a single pixel taking about 50 ms to resolve (about 5 seconds for a 100-pixel line), with very high spatial resolution. As noted above, distance from the probe tip to the sample is important: closer is better, because farther reduces spatial resolution. Accordingly, tip control must be precise and stable at the sample.

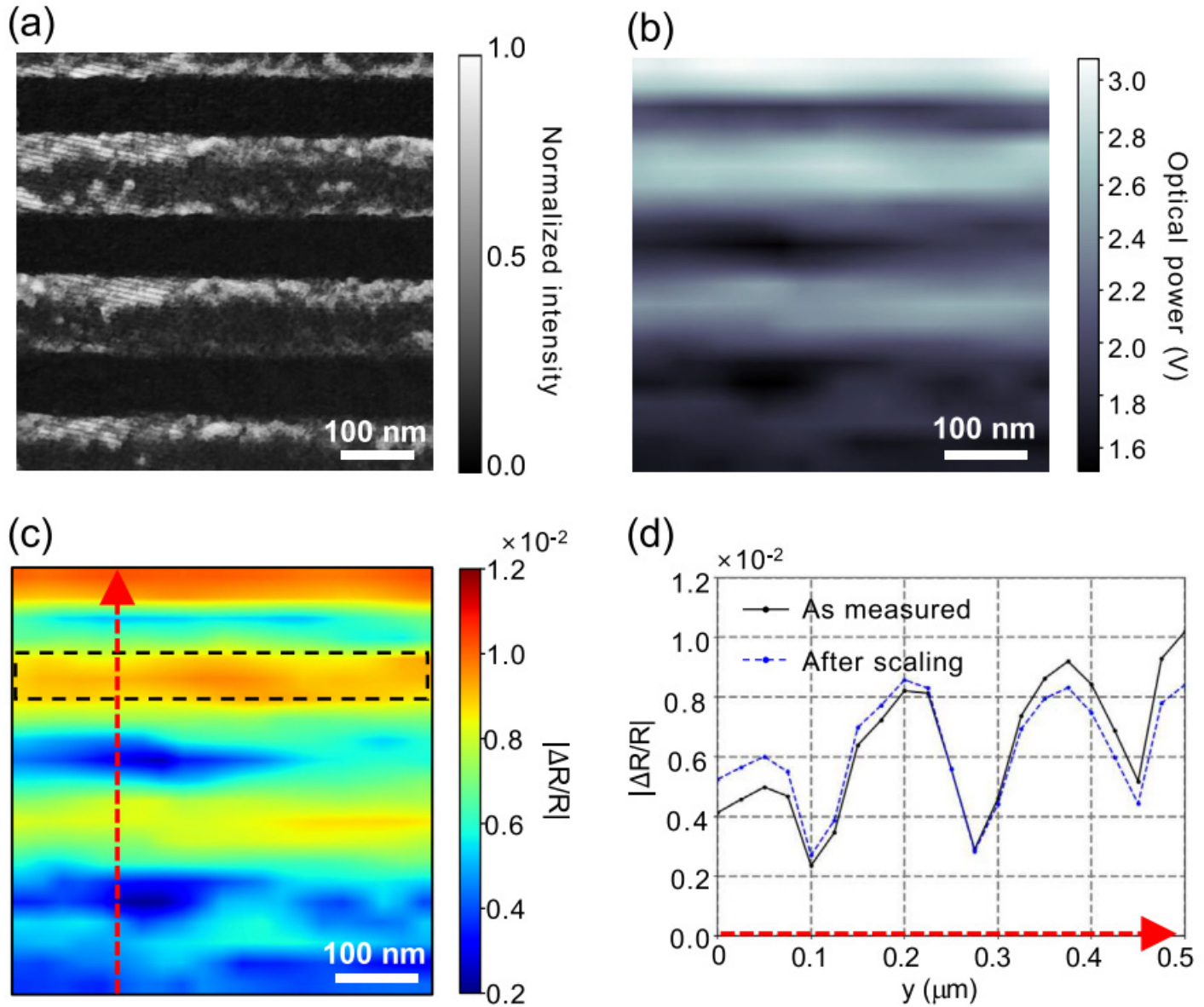


Fig 3: (a) Scanning electron microscope (SEM) image with a normalized intensity scale bar; (b) and (c) SPTRM images, including an optical power image of reflected light (b) and a thermorefectance image (c) of a 200-nm-pitch (i.e., 100-nm-wide lines and spaces) resistive heater. The black dashed rectangle in (c) indicates the region where the thermorefectance signal is obtained to examine the noise floor. (d) Thermorefectance profile along the red dashed arrow in (c). All scale bars are 100 nm.

Enabling More Widespread Use

SPTRM is a breakthrough in thermorefectance imaging, and researchers are actively working to enable more widespread use. Efforts are focused on improving the stability and quality of the optical fiber and tuning fork to improve experiment throughput. While measurements with a spatial resolution of near an aperture size (~50 nm) are theoretically possible, those are projections built on perfect fiber control and perfect probe shape and simply are not achievable in practice right now. To learn more, visit the SPTRM researchers' Korea Basic Science Institute (KBSI) website and contact Mad City Labs.

References

1. <https://www.kbsi.re.kr/board?menuId=MENU003020302000000&boardId=BOARD00319&siteId=SITE00003>
2. M. G. Jeong et al., "Scanning-Probe-Based Noncontact Thermorefectance Microscopy With Subwavelength Resolution," in *IEEE Transactions on Instrumentation and Measurement*, vol. 74, pp. 1-7, 2025, Art no. 4514907, doi: 10.1109/TIM.2025.3627336.

About The Experts



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