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THERMAL MICROSCOPY WITH A MICROFABRICATED SOLID IMMERSION LENS

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The spatial resolution of infrared thermometry is limited by diffraction to dimensions close to the wavelength of the collected infrared radiation, typically 5 μm at room temperatures. Thermal properties variations, temperature gradients, and defects with dimensions smaller than the diffraction limit are inaccessible to far-field infrared thermometry. This work demonstrates a near-field method for improving the spatial resolution of infrared thermometry based on a solid immersion lens (SIL). The SIL is microfabricated from silicon and integrated with a cantilever that is scanned over the sample surface. Infrared radiation collected by the SIL is measured in a conventional infrared microscope, and we show that the SIL improves the edge response of the thermal microscope by a factor of four. This imaging approach is able to resolve differences in the radiance from a uniformly heated, patterned structure with feature sizes below the diffraction limit in air.

Infrared imaging of thermal radiation from microdevices is an effective and increasingly common means of identifying device defects, mapping thermal transport, and evaluating thermal properties on the scale of millimeters. With the reduction in feature sizes of microdevices, there is interest in extending measurement of thermal properties and performance to the micron scale and below. High spatial-resolution thermometry techniques include *in situ* electrical resistance thermometry [1], scanning thermal microscopy with micromachined cantilevers [2, 3], and near-field thermometry with tapered optical fibers [4, 5]. Infrared thermometry is an alternate technique for quantification of heating in microstructures based on the collection and measurement of emitted thermal radiation. The technique is not limited by electrical capacitance and voltage reflection effects that plague electrical resistance thermometry, and it does not require heat transfer to the probe like scanning thermal microscopy with a microfabricated thermocouple. Infrared thermometry also does not require pump or probe light sources as in reflectance thermometry. The primary requirements are a means for collecting and measuring the emitted radiation and calibration of surface emissivities.

The spatial resolution of infrared thermometry is limited by diffraction of the collected far-field radiation to approximately $\lambda/(2\ \text{NA})$. For an InSb detector with maximum responsivity at a wavelength of 5 μm and optics with NA $= 0.5$, the minimum resolvable distance between two points is approximately 5 μm. Improvements in spatial resolution come at the expense of radiation power and temperature sensitivity, particularly as feature

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sizes comparable to or smaller than the wavelength are targeted. The microfabricated silicon solid immersion lens (SIL) offers a method for imaging below the diffraction limit in air with high optical throughput [6, 7]. Thermal radiation is collected through a SIL scanned close to a surface, and spatial resolution can be improved by up to a factor equal to the index of refraction of the SIL material. We combine a conventional thermal microscope with a microfabricated silicon SIL and demonstrate scanning infrared microscopy of heated samples.

Commercially available thermal microscopes use refracting or reflecting optics to image thermal radiation from a sample onto a focal plane array detector. Our thermal microscope (InfraScope II, Quantum Focus Instruments) includes a liquid-nitrogen-cooled 256 × 256-element Indium-Antimonide (InSb) focal plane array detector and a 25X (NA = 0.5) Si/Ge refractive objective. Approximately 25% of the radiation emitted hemispherically from a heated surface is collected by the NA = 0.5 objective, assuming no reflection losses. The InSb detector is sensitive over a spectral range of 1.0–5.9 μm, with maximum responsivity at a wavelength of $\lambda = 5.0$ μm. A 120°C blackbody source radiates at a peak wavelength of $\lambda = 7.4$ μm given by Wien's Law, but the wavelengths close to 5 μm make the largest contribution to the measured power due to the spectral responsivity peak of the detector at 5 μm. For that reason, we expect resolution to be dominated by $\lambda = 5$ μm and use that wavelength to estimate spatial resolution. The combined collection efficiency of the 25X objective and InSb detector at 120°C, taking into account its spectral responsivity, is estimated to be less than 3%.

We modify the thermal microscope to include a scanning stage and cantilever mount for scanning thermal microscopy with the microfabricated SIL, as shown in Figure 1. The SIL is positioned at the focus of a Si/Ge collection objective, and a sample uniformly heated by a Peltier heater is scanned beneath the SIL in contact mode. Thermal radiation from the sample is collected by the lens and is imaged by the objective onto the InSb detector array. The sample is scanned at approximately 2 μm/s, and a series of 100 radiance images is taken at 20 Hz frame rate.

Thermal imaging with the SIL is demonstrated with metal patterns fabricated on an Si substrate. The lens and cantilever are transparent in the spectral range of the detector and alter the image only where there is refraction in the lens. Radiance collected through the lens is extracted from each frame by averaging four pixels centered over the lens. Using the scan rate to convert time into distance, a plot of radiance with distance is obtained for each line scan. Samples are imaged at a temperature of 120°C maintained by a Peltier heater below the sample, and differences in material emissivity and reflectivity create the radiance contrast. Temperature differences on a surface could also be used to create radiance contrast, but special structures are required to create temperature features on the order of a 1 μm that maintain sufficient contrast to be detected. The optical property differences between two surfaces create a sharp radiance contrast at thermal wavelengths that is useful for evaluating spatial resolution of scanning infrared microscopy with a microfabricated Si SIL.

Imaging closely spaced but separate features is a major challenge for optical thermometry techniques. We found that two metal lines that cannot be clearly resolved by a conventional thermal microscope are clearly resolved by the microfabricated Si SIL. The sample is uniformly heated from below and consists of 2000-Å–thick Al lines that are 1.0 μm wide and separated by 4.0 μm center-to-center. According to classical diffraction theory, features this close together are not expected to be clearly resolved in the thermal

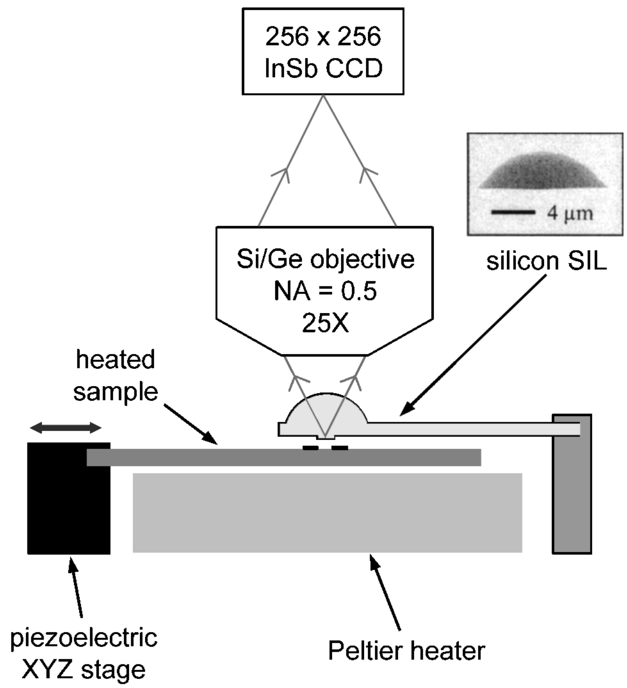

Figure 1. Experimental apparatus used for thermal imaging with the microfabricated Si SIL. A Peltier heater uniformly heats a sample held on a three-axis piezoelectric scanner. The SIL is fixed at the focus of the Si/Ge collection objective, and the sample is scanned below the SIL.

microscope image. Figure 2 shows a sequence of radiance images of the SIL as the pair of Al lines is scanned beneath it. A dotted circle is overlaid on each frame to indicate the central region of the SIL, and a continuous curve of normalized radiance at the center of the SIL is shown below the frames. In frame 2, a stripe appears in the lens corresponding to the Al line passing directly beneath the SIL. The line is magnified by the lens and clearly resolved from the second Al line appearing in frame 4. The plot of radiance through the lens with distance is shown in comparison to a line plot across the two lines from the thermal microscope alone in Figure 3. The data are normalized by the radiance of Al and Si with and without the SIL, respectively. The contrast observed by the thermal microscope alone is approximately 10%, while full contrast is observed with the SIL. Two Gaussian curves with a FWHM of 1.7 μm are fit through the data, corresponding to a spatial resolution of $\lambda/2.9$ at $\lambda = 5$ μm. The measured line separation in Figures 2 and 3 appears slightly larger than the expected 4.0 μm, due in part to the uncertainty in calibration of the piezoelectric scanner, which is approximately $+/-$ 0.2 μm.

The performance of infrared imaging with conventional far-field optics and with the microfabricated Si SIL can be directly compared with an edge response measurement. An edge of 3000-Å Cu layer on Si is scanned beneath the lens, as shown in the sequence of radiance images in Figure 4. A plot of radiance through the lens with distance is given in Figure 5, and a line plot across the edge from the conventional thermal microscope is shown for comparison. The data are normalized by the radiance of Cu and Si with and

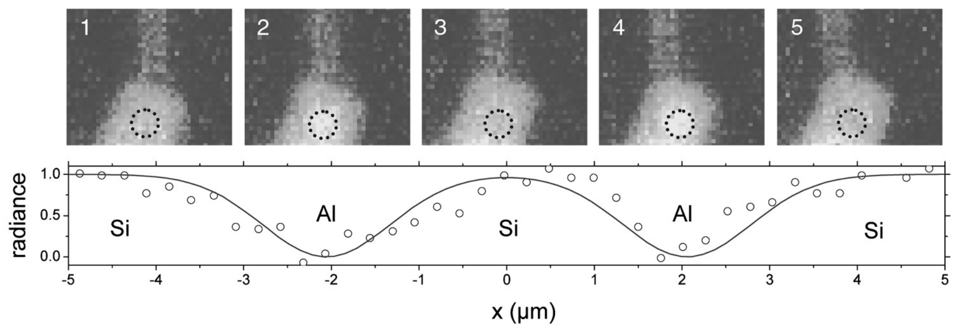

Figure 2. Sequence of radiance images of the microfabricated Si SIL as two 1.0-μm Al lines separated by 4.0 μm center-to-center are scanned beneath it. The two lines do not appear distinct in the CCD image but can be seen through the SIL in frames 2 and 4. The black dotted circle denotes the central region of the lens in each frame.

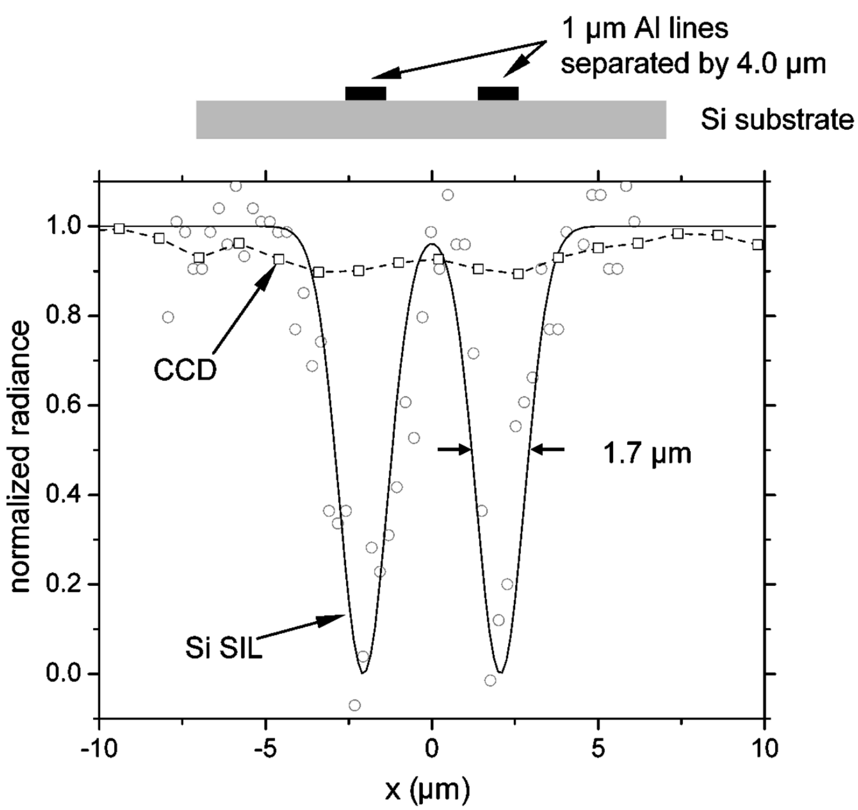

Figure 3. Line scans of two 1.0-μm Al lines separated by 4.0 μm center-to-center taken with the microfabricated Si SIL (circles) and with the InfraScope CCD (squares). The FWHM of a Gaussian profile fit to the data (solid line) is $\lambda/2.9$ at $\lambda = 5$ μm.

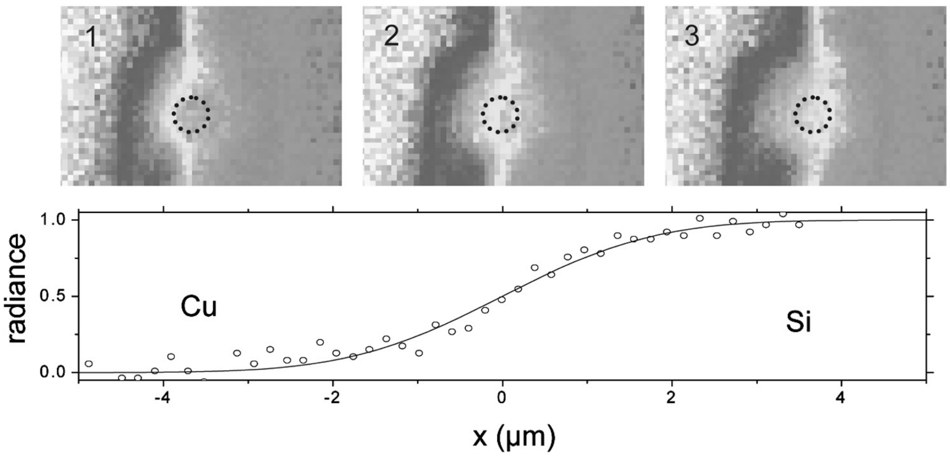

Figure 4. Sequence of radiance images of the microfabricated Si SIL as a Cu/Si edge is scanned beneath it.

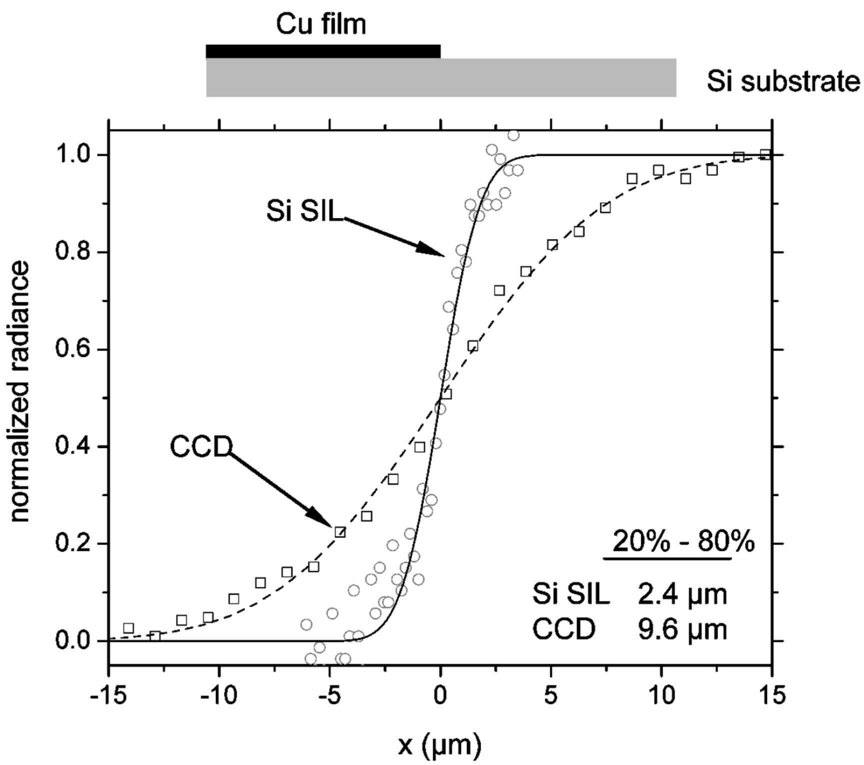

Figure 5. Edge scans of a Si/Cu edge taken with the microfabricated Si SIL and with the InfraScope CCD. The improvement in edge response is a factor of 4 over the CCD.

without the SIL, respectively, and an error function is fit to both curves. The 20%–80% edge response with the SIL is 2.4 μm, which is a factor of four better than the edge response without the SIL of 9.6 μm.

To detect temperature or radiance differences between two points on a surface, the power measured from each point must be large enough to be distinguished from noise in the detection system. As the collection area is reduced to improve spatial resolution, the measured power is also reduced; higher temperature differences are required to improve the signal-to-noise ratio. A trade-off exists between thermal imaging with high spatial resolution, in which light is collected from a small area, and thermal imaging with high temperature resolution, which requires large power differences. The minimum temperature difference that can be measured with the microfabricated Si SIL can be estimated from the noise-equivalent power of the detection system. For a shot-noise-limited detector with background radiation power P_b and signal power P_s, the noise-equivalent power (*NEP*) is given by

$$NEP = \sqrt{\frac{2h\nu B(P_s + P_b)}{\eta}}, \tag{1}$$

where $h\nu$ is the energy of the measured photons, B is the detection bandwidth, and η is the quantum efficiency of detection [8]. The signal P_s is produced by temperature oscillations of the background P_b according to

$$P_s = \frac{\partial P_b}{\partial T}\Delta T, \tag{2}$$

where ΔT is the temperature oscillation amplitude and

$$\frac{\partial P_b}{\partial T} = \frac{P_b}{T}\left(\frac{h\nu}{kT}\right) \tag{3}$$

for a detector with a spectral bandwidth centered on $h\nu$. A temperature difference is measurable when the collected signal power for the desired spatial resolution is greater than the *NEP* of the detector at a specified detection bandwidth. The temperature amplitude necessary to produce a signal-to-noise ratio of 1 ($P_s/NEP = 1$), called the noise equivalent temperature amplitude ($NE\Delta T$), is given by

$$NE\Delta T = \frac{NEP}{\partial P_b/\partial T} = \frac{T}{P_b}\left(\frac{kT}{h\nu}\right)\sqrt{\frac{2h\nu BP_b}{\eta}} \tag{4}$$

for small $P_s \ll P_b$ [8].

The $NE\Delta T$ of the combined Si SIL and thermal microscope is estimated to be 0.18°C at $T = 120$°C, assuming the *NEP* is equal to the standard deviation of the average radiance fluctuations from four pixels at the center of the SIL (approximately 0.3% of the background signal). This gives a temperature sensitivity comparable to that of the thermal microscope alone calculated on the basis of a single pixel. Although the SIL improves the spatial resolution of thermometry by a factor of approximately 4, it does not significantly reduce the minimum measurable temperature difference of the thermal microscope, as four pixels can be averaged together to reduce thermal noise. Further improvements in spatial resolution can be achieved by fabricating a metal aperture directly on the tip of the microfabricated Si SIL [9]; however, the collected power through a metal aperture of diameter d falls as d^6 for apertures much smaller than the wavelength of light [10]. Since the radiated power is limited for a given temperature, apertures are not a practical method for infrared microscopy with high temperature resolution.

The microfabricated Si SIL offers a novel method for improving the spatial resolution of infrared thermometry. Combined with a conventional thermal microscope, the Si SIL can clearly resolve metal lines separated by 4.0 μm that cannot be resolved by the thermal microscope alone. The SIL achieves an edge response four times that of the thermal microscope without reducing the noise-equivalent temperature sensitivity of the system. This technique may be useful for steady-state thermal measurements, particularly those with uniform surface optical properties, but time-resolved measurements would be limited by scanning speed. While recent scanning probe microscopy research has focused on improving scanning speed, collecting a 64 $\times$ 64 point image of a 20 μm $\times$ 20 μm sample at the scan speed used in this work would take approximately 11 minutes. Infrared imaging with the SIL may be more attractive than laser reflectance thermometry and AFM scanning thermometry when there are surface roughness features that influence local reflectivity and conductance to the AFM tip. While significant improvements in spatial resolution of the SIL with metal apertures are unlikely due to the dramatic loss in power with aperture diameter, further increases in temperature sensitivity may be possible by combining scanning infrared thermometry with lock-in detection methods.

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