Non-contact distance measurement and profilometry using thermal near-field radiation towards a high resolution inspection and metrology solution

Roy Bijster[a,b], Hamed Sadeghian[b], and Fred van Keulen[a]

[a]Precision and Microsystems Engineering, Faculty of Mechanical Engineering, Delft University of Technology, Stieltjesweg 1, 2628CK, Delft, The Netherlands
[b]Nano-Opto-Mechanical Instruments (NOMI) group, Department of Optomechatronics, Netherlands Organisation for Applied Scientific Research TNO, 2628CD, Delft, The Netherlands

ABSTRACT

Optical near-field technologies such as solid immersion lenses and hyperlenses are candidate solutions for high resolution and high throughput wafer inspection and metrology for the next technology nodes. Besides sub-diffraction limited optical performance, these concepts share the necessity of extreme proximity to the sample at distances that are measured in tens of nanometers. For the instrument this poses two major challenges: 1) how to measure the distance to the sample? and 2) how to position accurately and at high speed? For the first challenge near-field thermal radiation is proposed as a mechanism for an integrated distance sensor (patent pending). This sensor is realized by making a sensitive calorimeter (accuracy of 2.31 nW root sum squared). When used for distance measurement an equivalent uncertainty of 1 nm can be achieved for distances smaller than 100 nm. By scanning the distance sensor over the sample, thermal profilometry is realized, which can be used to inspect surfaces in a non-intrusive and non-contact way. This reduces wear of the probe and minimizes the likelihood of damaging the sample.

Keywords: thermal microscopy, near field, high resolution inspection

1. INTRODUCTION

At a beating pace the semiconductor industry finds itself facing increasingly more difficult challenges with every technology node; not only in manufacturing, but also in inspection and metrology. For the 14 nm node and beyond, high resolution full surface imaging and high throughput seem to be mutually exclusive. Scanning probe technologies, such as atomic force microscopy (AFM), offer the potential of imaging at atomic resolution by scanning a microscopic probe over the sample and recording the response.[1] The high resolution in AFM, however, comes at a cost of an inherently low speed and the need for (intermittent) contact between the probe and the sample. Especially for imaging high aspect ratio features such as FinFETs,[2] non-contact methods are preferred. With this in mind, a generation of new imaging techniques needs to find its way to industrial application: the meta-instrument. These instruments go beyond the performance of conventional optical instruments by the use of non-contact near-field imaging techniques such as solid immersion lenses[3,4] (SILs), hyperlenses[5] and superoscillatory lenses[6] (SOLs). By imaging areas of tens of micrometers across at once, these all offer the potential of high throughput, high resolution imaging. These technologies, however, share a major challenge: the need for exceptional position control at extreme proximity to the sample. A hyperlens or SIL can only provide the required sub-diffraction limited resolution when the lens is positioned at a distance from the sample that is measured in tens of nanometers. In contrast, superoscillatory lenses can be used at micrometers from the sample, but require a position accuracy of nanometers. These requirements raise two important questions: 1)

Further author information: (Send correspondence to R.B.)
R.B.: E-mail: r.j.f.bijster@tudelft.nl, Telephone: +31 (0)88 866 61 82
H.S.: E-mail: hamed.sadeghianmarnani@tno.nl, Telephone: +31 (0)88 866 43 55

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how to determine the distance between lens and sample in a nanoinspection system and 2) how to keep the lens at the required distance, without the risk of contact?

The first question can be solved in multiple ways. Depending on the chosen imaging method, one may be able to check whether the image is in focus or out of focus, and correct the distance between lens and sample accordingly. When this is not possible, a dedicated sensor system is necessary that is capable of measuring nanometer sized gaps at (sub-)nanometer resolution and similar accuracy. Candidate solutions that come to mind for this are interferometry and capacitive sensors. While the first requires the sample to be sufficiently reflective, the second needs the sample to be conductive. For a robust distance sensor neither of these conditions can be guaranteed. In other words, both techniques are substrate dependent.

A potential alternative lies in using thermal resistance as a proxy for distance. As the separation between the probe and the sample changes, so does the thermal resistance between them. When both are at distinct temperatures, this leads to a changing heat flux. The change in heat flux can either be measured directly, or via a change in temperature of the probe. This is not a new idea and has been applied in scanning thermal microscopy. To our knowledge, Williams and Wickramasinghe[7] were the first to demonstrate the idea of using a microscopic thermocouple to measure changes in probe temperature as the probe was scanned over a surface. Similar devices that were based on similar principles were built by others[8–11] and were demonstrated under ambient conditions.

In vacuum, however, heat is transferred between the probe and the sample only through radiation. In 1969, Hargreaves showed experimentally the existence of what he called "anomalous radiative heat transfer between closely-spaced bodies".[12] For distances below 6 µm it was shown that the heat transferred through radiation exceeded the blackbody limit of Planck's theory of radiation. Theoretical research in the last two decades[13–17] and experimental verification[18–23] show that interference, photon tunneling and at very short distances even phonon tunneling are at the heart of this so called 'superplanckian' behaviour. These effects become evident at distances smaller than Wien's wavelength, which is given by

$$\lambda_{\mathrm{Wien}} = b/T, \tag{1}$$

where Wien's displacement constant $b \approx 2900\,\mu\mathrm{m\,K}$ and T is the temperature in Kelvin. At room temperature this results in a wavelength of approximately 10 µm.
Although current experimental work is mainly focused at measuring heat flux as a function of distance, applications for distance/displacement measurement or scanning probe microscopy rely on the inverse: distance as a function of measured flux. Pioneering microscopes that rely on these near-field phenomena were proposed and demonstrated using microscopic thermocouples[24,25] and the collection of scattered near-field infrared radiation.[26,27]

In this paper, we propose using near-field thermal radiation as a mechanism for an integrated distance measurement system for the meta-instrument and describe the experimental setup that serves as our development platform for distance sensing and scanning thermal microscopy.

2. METHOD

The measurement principle described below is based on prior work by Rousseau *et al.*[20] and Shen *et al.*[21] and uses a scanning probe microscope to construct a sensitive calorimeter. The thermo-mechanical response of the microcantilever that comprises the calorimeter, transduces the heat flux that is transferred between the probe and the sample to a mechanical deflection.

2.1 Description of the setup

The flux is measured using the tabletop scanning probe microscopy setup as presented schematically in Figure 1. Therein a microsphere is glued to the bilayer cantilever probe. When heat is transferred to or away from the tip of the cantilever, a temperature gradient is created over the length of the cantilever. Because both layers have a distinct thermal expansion coefficient, this thermal gradient causes differential expansion of the two layers, resulting in deflection of the cantilever. The deflection is recorded using a method that is known as the optical beam deflection (OBD) method.[28] In this method, a collimated laser beam is focused on the cantilever surface and is reflected onto a position sensitive detector (PSD). As the deflection of the cantilever changes, so does the

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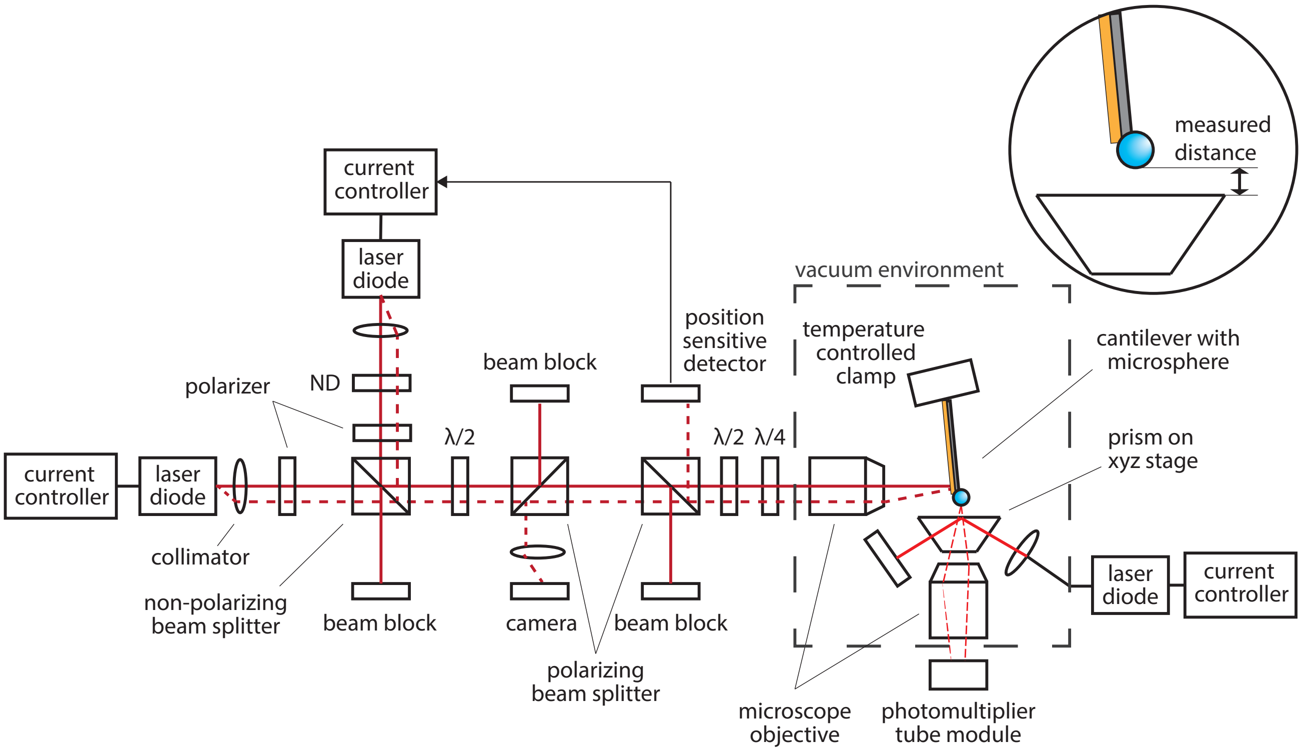

Figure 1. Schematic representation of the experimental setup. The design is based on work by Herfst *et al.*,[30] Rousseau *et al.*[20] and Shen *et al.*[21] The primary laser (left) is reflected of the cantilever surface on the position sensitive detector (PSD). The output power of this laser is tuned for shot noise limited performance of the PSD. The second laser beam (top) is used for nanowatt control of the power that is absorbed by the probe. It is mixed in, after attenuation by a neutral density (ND) filter (optical density 3.0), by a non-polarizing beamsplitter. Both beams pass through polarizers that are used to match the polarizations. By using polarizing beam splitters in conjunction with half-wave and quarter-wave plates, the outgoing and returning beams are optically separated. A camera is used for the alignment of the laser spot on the cantilever surface. The distance between the prism and the microsphere is measured using a total internal reflection microscope. This is constructed using a prism that is illuminated under total internal reflection from below using a laser diode. The scattered evanescent field is collected with a microscope objective and imaged on a photomultiplier tube module. The prism is mounted on a three-axis piezostage for in plane scanning relative to the probe and to change the separation between probe and sample.

angle under which the beam is incident, causing the reflected beam to move across the PSD.
A silica microsphere with a diameter of 20 µm is glued to the tip of the cantilever to serve as the interacting surface of the probe. Because a microsphere is point symmetric to first order (ignoring local features and surface roughness[29]), this makes this configuration less sensitive to rotations and at the same time increases the interacting surface area to realize larger thermal fluxes. The reduced sensitivity to rotations eases the efforts for alignment and for future parallelization of the system. For initial verification of the setup and comparison with theoretical models, both the microsphere and the substrate are made of fused silica (SiO_2); a material that is very well characterized and that supports the phonons that are considered necessary for enhanced radiative heat transfer. For those reasons it makes for the ideal reference material.

The described measurement architecture, however, has several characteristics that hamper a reliable and truthful measurement of radiative heat transfer. We propose the solutions described below.
The first fundamental problem is that the temperature of the tip, and thus the temperature difference over the gap, changes as a function of distance as the thermal equilibrium changes. Because the underlying processes are wavelength and thus temperature dependent, it is imperative for proper validation of the theory, that the temperatures are stabilized and kept constant. Controlling the temperatures, implies that the temperatures need to be measured. However, the measurement of the tip temperature is complicated by the limited dimensions

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of the system. While others have chosen to create custom probes with embedded temperature sensors,[23] we mitigate the problem by maintaining a constant heat flux at the cantilever tip. This is realized by, on one hand, stabilizing the temperature of the cantilever base (at its clamp) and the sample at constant temperatures, while modulating the incident laser power on the other hand. By doing so, the distance dependent components of the heat flux are compensated for. Using this method, the temperature of the tip can be kept constant throughout the measurement, independent of the separation between the probe and the sample.

Because contemporary laser controllers cannot be tuned finely enough to achieve nanowatt resolution in the power absorbed by the probe, such high resolution is realized by introducing a secondary laser. While the primary laser is stabilized at constant power and only used for realizing a signal-to-noise ratio that is sufficiently high for a reliable readout in the OBD (described above), a second laser is mixed in for modulation of the incident power.[31] The power of this secondary laser is attenuated by a neutral density (ND) filter of optical density 3.0, to scale the optical output back to the required range.

By closing the loop in this way, the measured flux is no longer obtained from the cantilever curvature, but in stead from the control signal of the secondary laser. This has the added advantage that the laser power can be easily calibrated using an optical power meter. After calibration of the power meter in accordance with ISO standards, this renders the entire heat flux measurement traceable to the SI system of units.

The second fundamental problem lies in the determination of the distance between the probe tip and the substrate. In this case the tip is formed by the bottom side of the microsphere. Previous attempts rely on relative measurements, that require contact between the probe and the substrate.[20,21,23] In that case, contact serves to establish a datum that is from thereon known as "zero distance". After contact, the probe is retracted using a (piezo)actuator to create the required gap. The separation between probe and sample is determined from the control signals of the aforementioned actuator.

Surface roughness, however, makes the condition for contact ill-defined. In addition, the methodology is sensitive to temperature induced drift and to geometrical changes caused by contact. One can think of scenarios where the sphere is no longer in its original position or in which either probe or substrate have been damaged locally. To remedy this situation, the distance between the probe and the substrate is measured using total internal reflection microscopy (TIRM).[32] While the probe approaches the sample from the top, the substrate is illuminated from below using a laser beam that is incident under total internal reflection (TIR). Although TIR implies that all light is fully reflected, an evanescent field is introduced on the opposite side of the reflecting interface. This field is scattered by the tip of the probe (in this case the microsphere) in all directions. A part of this scattered light passes back through the sample and is collected using a microscope objective that projects it on a photomultiplier tube module. This scheme is depicted on the right hand side of Figure 1. The intensity of the collected scattered radiation is exponentially proportional to the gap size.[33–36] This proportionality is driven by the exponential decay of the intensity of the evanescent field with a penetration depth equal to:[34]

$$\zeta = \frac{4\pi n_1 \sqrt{\sin^2\Theta - \sin^2\Theta_C}}{\lambda}, \tag{2}$$

where λ is the wavelength of the source illumination in vacuum, n_1 is the refractive index of the substrate, Θ is the angle of incidence and Θ_C is the critical Brewster angle. Like the microsphere, the substrate is made of fused silica. The illumination source is laser diode emitting at $\lambda = 635\,\text{nm}$. This results in an effective refractive index of the substrate of 1.46 and a critical angle of 43.34°. A small deviation from the critical angle of 0.5° yields a penetration depth of 371 nm. As demonstrated by McKee *et al.*,[33] the effective range of this measurement technique is in practice limited to three times the penetration depth, or approximately 1 µm in this case.

To limit the effect of gas conduction and convection on the heat transferred to and from the probe to less than $1 \times 10^{-4}\%$, the experiment is conducted at a pressure of $< 1 \times 10^{-7}\,\text{mbar}$. Because the expected heat fluxes are at magnitudes in the order of 1 µm, the contribution of medium related transfer mechanisms is limited to nanowatts. Using the analytical gas conduction model of Masters *et al.*,[37] the heat transferred through gas conduction is calculated for gaps ranging in size from 10 nm to 10 µm. The results of this calculation are summarized in Figure 2. The heat transferred by radiation Q_r is calculated using the Stefan-Boltzmann law,

$$Q_r = \sigma\left(T_H^4 - T_C^4\right), \tag{3}$$

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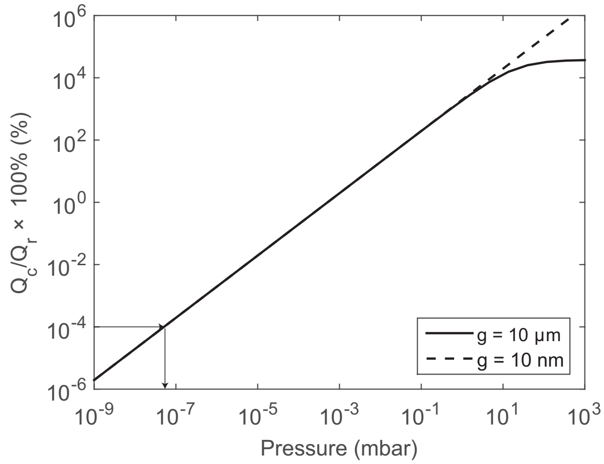

Figure 2. Ratio of heat transferred between two bodies through gas conduction Q_c to heat transferred through radiation Q_r as a function of chamber pressure. Both bodies are considered perfect black body radiators at 293 K and 303 K, respectively, and are separated by a gap of size g. The calculations for gas conduction is based on a model by Masters *et al.*[37]

where Stefan's constant $\sigma = 5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-1}}$, and T_H and T_C are the hot and cold temperatures of the bodies, respectively. Because the actual heat flow is expected to be higher than the black body limit, this is considered a realistic lower bound for the heat transferred through radiation.

2.2 Heat transfer measurement uncertainty

The measurement uncertainty is driven by the performance of the key components in the chain of measurement. The contributions are summarized in Table 1. In this section, the main sources of uncertainty are discussed.

Unwanted motions of the cantilever hamper the measurement of the heat flux and introduce uncertainty in the measured data. Two sources of unwanted motion are induced by thermal effects: random Brownian motion and spurious temperature changes. In an optimized measurement system, the uncertainty is limited by the Brownian motion. Using the probe geometry and the theory developed by Butt and Jaschke,[38] the equivalent measurement noise was derived to be 2.14 nW when the probe is at an average temperature of 305 K.
Because the motion of the cantilever is only measured close to its tip, changes induced by a flux at the tip of the cantilever or temperature drifts at it clamp cannot be discriminated. Therefore, the temperature of the clamp is controlled to a stability of 1 mK. Combined with the thermal response of a rectangular bilayer cantilever,[39] this results in an added measurement uncertainty of 0.86 nW.

The third largest contribution to the measurement uncertainty is introduced by the laser illumination. Due to (thermal) instabilities of the laser diode,[40] the optical intensity varies in time. This variation was measured by coupling the laser diode to a high speed photo detector and probing its output spectrum using a performance spectrum analyzer. This method was demonstrated before by Shi *et al.*[41] and is also the method proposed by the Agilent corporation[42] for laser intensity noise measurements. A detailed description of the used setup and the corresponding measurements will be published elsewhere.[43] From the data that was obtained with this method, can be concluded that the noise is limited to ≤ 1.7 nW root mean squared in a 10 kHz bandwidth. This upper limit is set by the 1/f noise performance of the spectrum analyzer. The gold reflective coating of the cantilever absorbs 7% of the total intensity, yielding an uncertainty of 0.12 nW in the thermal flux measured using the cantilever probe.

The PSD and data acquisition system have minor contributions to the overall uncertainty that are introduced by electronic noise, digitization noise and quantization noise. When using the National Instruments PCI-6251, the root sum square (r.s.s.) uncertainty adds up to a total of 2.31 nW. The worst case, linear summation of the uncertainties results in 3.15 nW.

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Table 1. Uncertainty budget for heat flow measurement

Source	**Value (nW)**
Brownian motion of the cantilever	2.14
Clamp temperature uncertainty	8.58×10^{-1}
Laser intensity noise	1.19×10^{-1}
Laser power setpoint uncertainty	2.10×10^{-2}
Electronic noise of PSD	4.40×10^{-3}
Digitization noise	1.85×10^{-2}
Quantization noise	3.36×10^{-3}
Root sum squared error	2.31
Worst case summation	3.16

So far not included in the budget are the mechanical vibrations that are introduced by external sources, the effects of the roughness of both the substrate as well as the microsphere, and calibrations errors. To minimize the effect of floor vibrations, the setup is placed on a pressurized, passively damped isolator table. Part of the total system is placed under (ultra) high vacuum conditions by means of the combined action of a membrane pump and a turbo-pump. To minimize the effect of pump induced vibrations on the system, the pumps are shut down during the measurements. To maintain the operating pressure, the turbo-pump is locked off using a gate-valve and an ion getter pump, which has no moving components, is switched on to keep the system at its working pressure. The net effect of the mechanical vibrations remains to be quantified.

The open loop resolution is limited by the digitization of the data acquisition system and was determined to be 18.5 pW. The closed loop resolution is limited by the resolution to which the incident power can be controlled. When power absorbed by the cantilever is considered, this is equivalent to 21 pW.

3. APPLICATION

The high resolution and low noise performance of the described setup enable multiple applications. On the one hand it allows for further reliable validation of the theoretical models that describe near-field radiative heat transfer. On the other hand, it serves as a platform for the development of a distance sensor and thermal profiler that rely on the thermal near-field.

The sensitivity and measurement uncertainty in the distance measurement can be estimated based on existing theory that models the equivalent conductance of the gap. Using the Derjaguin approximation as is provided by Rousseau *et al.*,[20] the distance dependent conductance for the geometry described above (a silica microsphere of 20 µm above a silica prism) was calculated. Multiplication of the conductance with the temperature difference over the gap, results in the total heat flux as function of distance $Q(z)$.
For a distance sensor or profiler, one is interested in translating measured heat into distance. The corresponding sensitivity, dz/dQ, is easily estimated and plotted in Figure 3. It is instructive to consider, that a 1 nW uncertainty in the heat measurement would result in a sub-nanometer uncertainty at distance smaller than roughly 100 nm. For a meta-instrument using near-field optics, this is the range of interest.

It takes little imagination to go from the concept of a distance/displacement sensor to a thermal scanning probe microscope/thermal profiler. By simply scanning the probe over the sample at constant height, a topological map of the surface can be constructed.
In comparison with other scanning probe techniques, no (intermittent) contact with the substrate is required which significantly reduces wear of the probe and simultaneously reduced the risk of damage of the sample. As such a microscope largely utilizes the existing architecture of scanning probe microscopes, it can be a cost-effective extension to the currently existing toolbox.
Both theoretical models and experimental results point out that phonons are instrumental to the enhancement of radiative heat transfer in the near-field. This limits the described sensing method in terms of resolution when phonons are not supported by the materials in consideration. However, the proposed setup has a high resolution and accuracy in terms of flux measurements and is therefore not limited to measuring heat transferred through radiation. Distance sensing and profilometry can also be performed under ambient conditions.

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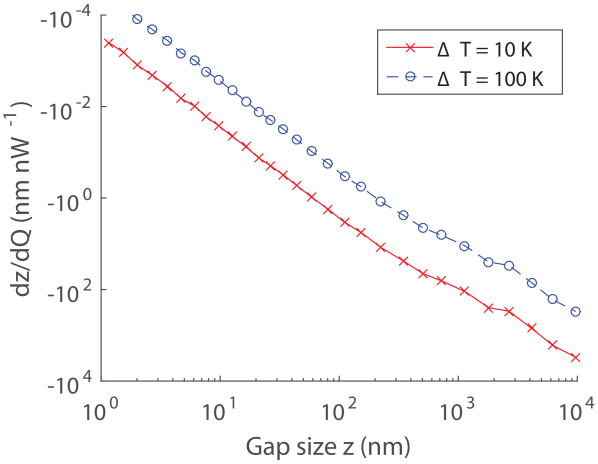

Figure 3. Sensitivity of a distance measurement derived from radiative heat-flux measurements in the thermal near-field. The figure is based on conductance calculations provided by Rousseau *et al.*[20] for a silica sphere with a diameter of 20 µm and a flat silica substrate.

4. OUTLOOK

The need for new distance and displacement sensors is evident from the miniaturization of instrumentation and the need to position optical elements at tens of nanometers from the substrate. However, challenges remain before distance sensors using the thermal near-field can be integrated.

The integration of such sensor in actual instrumentation will require miniaturization of the read-out system. Great steps are taken in this direction by miniaturization of the OBD systems,[44] but further size reduction can be achieved using piezoresistive cantilevers.[45,46] Combined with the development of miniature thermocouples and integrated heaters in the probes,[23] a large part of the measurement system can be reduced to chip level. Further work here will be necessary to increase the sensitivity and to find possibilities for traceable calibration.

Although a scanning thermal profiler was already proposed by Williams and Wickramasinge in 1986,[7] the use of the thermal near-field for enhanced sensitivity is relatively new,[47] and there is much left to be explored in terms of attainable resolution, sensitivity and understanding of the contrast mechanisms. The proposed platform will aid in experiments to support research to understand this mechanism better.

Our current efforts are focused on testing and calibration of all subsystems. Full scale tests will be performed using a cantilever probe with the attached microsphere, as described in Section 2. The results will be initially be compared with theoretical models that are available in literature. The probe will eventually be replaced by other geometries to increase measurement speed or spatial resolution.

5. CONCLUSIONS

Three issues have been identified that hamper the reliable measurement of radiative heat transfer in the thermal near-field, being:

1. the distance between probe and sample not being measured at the point of interest;
2. a changing thermal equilibrium as function of distance, yielding a change in probe temperature;
3. and measurements not being traceable to international standards.

We propose that these issues can be resolved by 1) measuring the distance between the probe and the sample at the point of interest using total internal reflection microscopy (issue 1); and 2) closing the measurement loop by controlling the incident power (issues 2 and 3). By closing the loop the thermal equilibrium of the probe can be maintained. The measurements can be made traceable to international standards, by calibrating the actuating

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laser using an optical power meter.
The setup is designed for a total uncertainty of 2.31 nW root sum squared for heat flux measurement. When the heat flux is used for determining the distance, this implies sub-nanometer uncertainty for distances smaller than 100 nm. This is particularly relevant for distance sensing applications in instrumentation such as the meta-instrument, but also opens up the possibility for thermal profiling.

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