PLANAR SCANNING PROBE MICROSCOPY – THE ART OF LOW-LEVEL FLIGHT AT THE NANOSCALE

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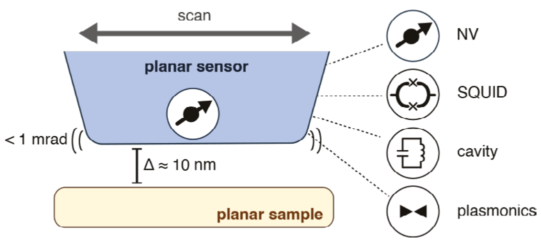

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An unorthodox optical approach to scanning probe positioning is opening a realm of novel applications in various fields of research. By using optical interferometry to carefully align a sensor parallel to a sample, even millimeter-sized sensors can be brought into nanometer-scale proximity of samples. Extended circuits and massively parallel arrays of sensors can thus be used as a scanning probe, a feat that would be impossible using established sharp tips.

Figure 1. If an extended (10 µm – millimeter)-sized planar sensor is carefully aligned parallel to a planar sample, the sensor and the sample can be brought into nanometer-scale proximity of each other.

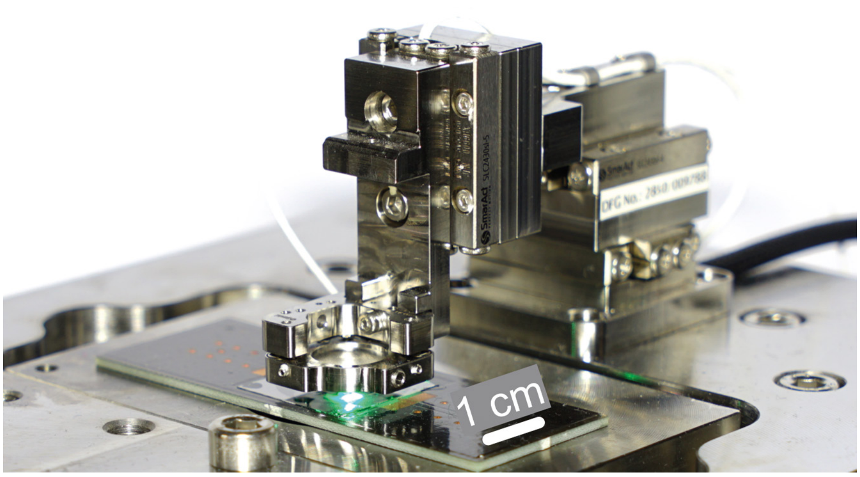
For decades, scanning probe microscopy has been probing surfaces with various forms of sharp tips. Sharp conductive tips extract a tunnelling current from a sample in scanning tunnelling microscopy (STM). Sharp mechanical tips literally touch and feel the surface of a sample to reveal its topography in atomic force microscopy (AFM), similar to the needle of a vinyl record player. In both techniques the sharpness of the tip is critical for the spatial resolution that can be obtained, so that sharp tips have become considered a strict necessity for any kind of scanning probe approach. Interestingly, this paradigm remained unchallenged when a new generation of nano-sensors emerged in the past decades and promised to greatly expand the range of quantities that can be measured with nanoscale resolution. These sensors comprise nitrogen-vacancy colour centers few nanometers beneath the surface of a diamond to measure magnetic fields, plasmonic optical antennas for near-field microscopy and microfabricated microwave cavities to measure electron spin resonance. All these novel sensors share a central challenge. The sensors themselves are natively planar devices, microfabricated circuits on a substrate or defects under a crystal surface, but the established approach to scanning probe positioning requires the sensor to be a tip to provide force-feedback and to approach the sample as close as possible. Much effort has been spent to merge these incompatible worlds and fabricate extended sensors onto tip-like structures, *e.g.* by anisotropic dry etching of diamond sensors into nanopillars, or sophisticated evaporation of superconducting films onto pulled glass nanofibers. In many cases, however, nanofabrication severely degrades the sensor quality and creates additional constraints on sensor layouts that can be fabricated.

We might, however, ask a radical question: do we really need a tip to do scanning probe microscopy? Surprisingly, the answer is negative. It is remarkably practical to bring an extended, (10 µm to millimeter sized), planar sensor surface nanometers close to a planar sample, if the sample is planar itself and free from any protruding contamination. Ensuring these constraints over a micron-to-millimeter large contact surface sounds like a daunting challenge, but is surprisingly well feasible. Already in the 19th century, optical machine shops mastered the technique of optical contact bonding, where two glass surfaces are ground to sub-nanometer scale smoothness and planarity, so that they can then be joined into optical contact and will hold together by intermolecular forces. Every hard drive in a computer employs a similar trick: the read-head slider is a millimeter-sized flat device which flies in nanoscale proximity to a planar recording medium, levitated by an air cushion. While the fly height can vary over the footprint of the slider, *e.g.* due to tilt, it reaches a minimum of only few nanometers at its trailing edge, where the read head is located. Preparing sufficiently flat and smooth surfaces thus is a century-old well-established technique. While even millimeter to centimeter scale surfaces can be machined with the necessary precision, in many applications it is preferable to restrict the planar surface to a smaller region, for example by fabricating the sensor or the sample into a 10-100 µm sized pedestal to relax the demands on alignment and contamination.

Mechanically aligning two flat surfaces with nanometer-scale precision parallel to each other is easily accomplished by commercial tip/tilt-positioners (Fig. 2). The key challenge is thus to measure the sensor-sample tilt and distance with sufficient accuracy to perform feedback control when aligning and approaching the sensor and the sample. It turns out that this is readily feasible for several optical schemes, even if this gap is only few nanometers small.

One straightforward choice for this task is interferometric microscopy. Conveniently, it can be implemented without an external reference arm by using reflection interference microscopy, a differential scheme where light reflected from the sensor-air interface interferes with light reflecting at the sample surface creating "Newton rings" [1,2] (Fig. 3). This differential scheme largely suppresses common-mode vibrations of the sample and the sensor. An alternative approach uses nanofabricated chirped optical gratings fabricated on the sensor and • • •

Figure 2. The positioning setup for planar scanning is a small modular add-on that can be installed on an inverted optical microscope.



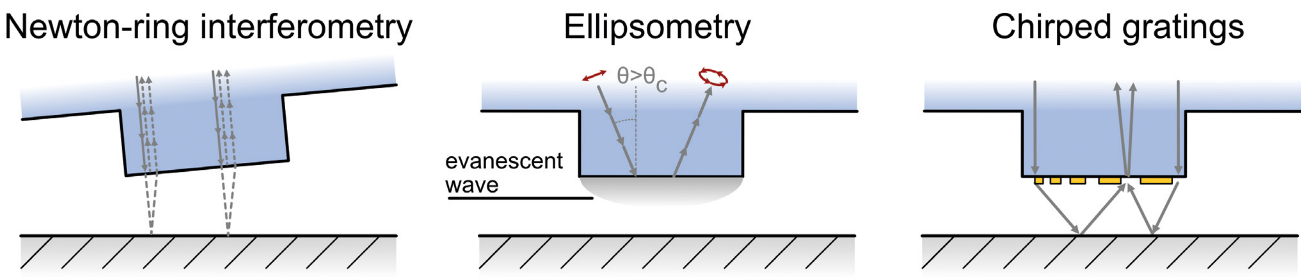


Figure 3. The tilt and the gap distance between the sensor and the sample can be measured by various optical schemes. θ_c critical angle.

the sample which create a far-field interference pattern that sensitively depends on the gap distance [3].

For sensor-sample gaps smaller than around 100 nm, the absolute value of the sensor-sample gap can also be measured by measurements based on optical polarisation, reminiscent of optical ellipsometry [2]. The sensor-air-sample multilayer is a dielectric multilayer system, similar to spin-coated photoresist films in nanofabrication, where ellipsometry is equally a workhorse technique to measure sub-wavelength film thickness. A suitable polarisation-sensitive imaging scheme is Brewster angle microscopy, where a polarized beam of parallel light is totally internally reflected off the sensor surface. If the gap is sufficiently small, the light can tunnel across it and instead reflect off the sample surface, giving rise to an altered polarisation. Crucially, this process can be modelled analytically, so that the gap can be quantitatively inferred from the polarisation rotation, similar to a film thickness measurement in ellipsometry. Notably, this measurement does not require to move the sensor and sample into contact to calibrate the zero-distance point, in contrast *e.g.* to "lift-mode" AFM. The sensor can thus be flown at a controlled height without ever physically touching the sample, enabling work with fragile sensors.

THE PAST – THE SURFACE FORCE APPARATUS AND EARLY PRECURSORS

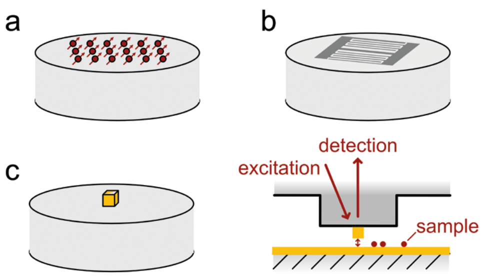
Approaching two planar surfaces into nanoscale proximity under optically controlled feedback has been explored in different contexts in earlier decades. One notable example is the "surface force apparatus" extensively used in nano-tribology. In this setup, two cylinders are approached into nanometer-scale proximity of each other under interferometric optical distance control to study forces between them. The use of cylinders greatly simplifies the design, because it ensures that the surfaces are parallel to each other at the contact point even without control of the tilt angle. Interestingly, even a scanning probe microscope with interferometric distance feedback has been demonstrated in the nineties to perform optical near-field microscopy [4]. Similar to the cylinder trick employed in the surface force apparatus, the sensor here was not planar but a hemispherical surface so that no tilt alignment was needed. However, the technique appears to have fallen out of fashion and to have been superseded by tip-based positioning schemes like shear-force feedback.

THE PRESENT – NANO-FLUIDICS, NEAR-FIELD OPTICS AND MAGNETOMETRY

The idea of aligning two planar surfaces parallel to each other and approaching them into nanoscale proximity has re-appeared in very different fields of research in the past decade, demonstrating its versatility and timeliness. Extensive work has been performed in the field of near-field optics, where it has been employed to position plasmonic antennas in plasmonic nano-lithography and study radiative heat transfer in nanoscale gaps [3], which is orders of magnitude faster than expected from blackbody theory for reasons still under discussion. The technique made an independent appearance in nano-fluidics where the planar setup is known as the "nanofluidic confinement apparatus" [1]. Here, the planar surfaces themselves are less of an interest than the fluid confined between them, which can be confined to a channel of constant and tuneable height by controlling the tilt and the distance of two planar plates. This approach has been employed to study the diffusion of nanoparticles in "Brownian ratchets", tooth-shaped surfaces where an alternating driving force together with random diffusion is rectified into a directed motion of the nanoparticles [5].

Finally, planar scanning probe microscopy has been introduced to the field of NV centers in diamond [2], where both defect-based near-field microscopy [2] and magnetometry [6]

Figure 4. Future possible sensors. a) arrays of NV centers. b) superconducting microcavities. c) plasmonic nanoparticles which can be operated as scanning nanogap cavities (right picture).



have been demonstrated with an extended planar bulk diamond. The technique here solves an outstanding challenge: NV centers have ideal properties when they are under a well-defined planar surface, but these properties easily degrade if nanofabrication is performed in their vicinity, *e.g.* plasma etching required to shape a nanoscale tip. Also, fabrication of a planar probe is considerably simpler than nanofabrication of nanoscale tips.

THE FUTURE – DIFFERENT SENSORS AND MASSIVE PARALLELISM

The most interesting question, however, is: what will we be able to do with planar scanning probes that could not be done with a scanning tip? One answer could be the wide variety of sensors that can potentially be used. Many emerging sensors are extended circuits, for example microfabricated superconducting magnetic resonance cavities which have recently become sufficiently sensitive to detect single electron spins. Even for pointlike sensors the ability to augment them by extended circuits is attractive. For instance, nitrogen-vacancy centers could be augmented by switchable nanomagnets to perform gradient-based magnetic resonance imaging of samples.

Another answer could be the ability to scan at a controlled nanoscale fly height without ever touching the sample. This could pave the way to using fragile nanoparticles as scanning probes, *e.g.* solution-synthesized epitaxial nano-cubes which have excellent plasmonic properties and promise much higher plasmonic enhancement than top-down-fabricated structures. Notably, arrangements of these nanoparticles, *e.g.* in the form of particle-on-mirror nanogap cavities, have achieved spectacular performance in stationary nano-fabricated assemblies, amplifying luminescence by up to four orders of magnitude and confining light to atomic scales [7]. Turning these plasmonic arrangements into a scanning probe scheme would open the door to optical microscopy with atomic resolution.

Finally, massive parallelism is an attractive perspective. More than one sensor can be embedded into a single planar probe and can be operated in parallel. This is especially promising for sensors like NV centers, which suffer from a slow readout. Using massively parallel arrays of centers could enable scanning at high resolution (e.g. 4K pixels) and/or large (10 µm-mm) field of view, while fully preserving the nanometer-scale resolution of scanning defect centers. At a high density of NV centers, scanning could even be replaced by superresolution microscopy. Simultaneous scanning with multiple centers could also enable imaging of spatial correlations of signals by correlating the signal of different centers or even by creating quantum entanglement between them, which would open a new window into transport phenomena and spatial correlations in solid-state physics.

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