Super-Resolution Imaging by Scanning Near-Field Optical Microscopy with Microfabricated Probes

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Abstract

Scanning near-field optical microscopy offers optical imaging with a resolution below the diffraction limit of λ/2. An introduction into the concept is given and its implementation into a real instrument illustrated. The most crucial part of the instrumentation is the optical near-field probe. Our efforts concerning near-field imaging with microfabricated cantilevered probe sare reviewed. The probes are silicon beams with solid quartz tip, which is completely covered with a 60-nm thick layer of aluminum. The demonstrated contrast mechanisms comprise transmission and fluorescence. In the latter case an artifact free 'true' optical resolution of 32 nm is shown. The influence of the polarization on the optical resolution is discussed. Best performance is achieved, when directly transmitted linear polarized is blocked and only components of radial polarized light, which originates from a supported eigenmode of the probe, is detected.

Introduction

Optical microscopy has been proven to be a very valuable and powerful tool in many scientific disciplines because it is only little invasive and neither requires special specimen treatment nor a special environment. No other microscopy technique offers such a wide range of contrast mechanisms such as transmission, phase, fluorescence, polarization etc., and chemical identification via Raman and fluorescence spectroscopy as optical microscopy does. However, the resolving power of common optical microscopes is limited to roughly 200 nm by light diffraction.[1] Modern science has meanwhile outpaced these dimensions. Particularly the evolving field of 'Nanotechnology' is interested in much smaller structure sizes. This is motivation enough for many researchers to find solutions to circumvent the constraint imposed by the diffraction limit and to extend the ability of optical microscopy to the nanometer scale.

One approach to achieve super-resolution imaging is scanning near-field optical microscopy (SNOM). In this contribution we provide a brief introduction into SNOM and review our efforts in developing a cantilevered optical near-field probe.

Scanning Near-Field Optical Microscopy

Already in 1928 Synge realized that such a sub-wavelength sized light source can be realized by fabricating an aperture with diameter *a* much smaller than the wavelength, i.e. $a<100$ nm, in an otherwise opaque metallic screen, which is illuminated from one side (Fig. 1).[2]

In this case only an evanescent, strongly diffracted light field exists behind the aperture. By positioning the aperture in a distance much smaller than the wavelength, i.e. 5-10 nm, only a very small spot with sub-diffraction dimension illuminates the surface. Light interacting with the sample in this region (by scattering, diffraction, fluorescence excitation etc.) is emitted into the optical-far-field and can be collected by a lens. Thus, optical resolution of SNOM is mainly determined by the size of the aperture and the distance between the aperture and the surface. An image can be reconstructed on a computer by raster-scanning the aperture over the surface and recording the response at each point of the sample.

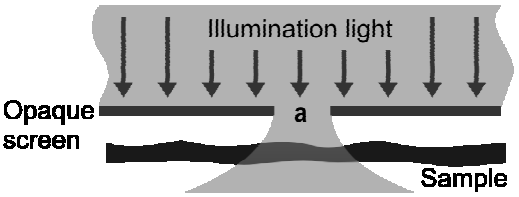

Figure 1. The concept of near-field optics

The implementation of this principle must account for the at these scales inevitable surface roughness. A real instrument features therefore a probe, which is sharp enough to approach and follow the surface topography and a feedback system that keeps the tip-surface gap constant. The feedback signal can be exploited to record a topographical image simultaneously with the optical image. Due to the small dimensions involved, it was not before 1984 that a SNOM could be realized in the visible light regime.[3,4] Since then, a number of different operation modes have been realized. The most common schemes are depicted in Fig. 2. The direct realization of Synge's idea is called aperture-SNOM (Fig. 2a). His concept still holds when the light path is reversed and the probe acts as detector. In a special implementation, called photon scanning tunneling microscope (PSTM), the probe frustrates locally the evanescent field of a total internal reflected beam and converts it into radiating light (Fig 2b). The aperture can also be replaced by the enhanced light field around a very sharp metal tip (Fig. 2c). Field enhancement can be caused by the big curvature of the tip and/or by creation of surface plasmons, which can increase the field amplitude by several orders of magnitude.

The crucial point of SNOM was and still is the fabrication of a nanometer-sized aperture at the end of a sharp tip. Widely used are tapered metal coated optical fibers.[5] However, this type of probes is tedious to produce, fragile and require an ill-understood feedback scheme. An elegant approach to overcome these problems offers microfabrication. Firstly, it allows parallel

production of hundreds of probes in a constant high quality. Secondly, it facilitates a cantilevered probe design, which enables the use of well-understood feedback schemes known from atomic force microscopy.

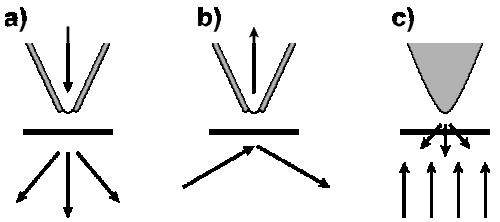

Figure 2. Operation modes: a) aperture type SNOM, b) PSTM, c) field enhancement at the tip

Imaging with Microfabricated Probes

Probe Properties

The probes in this work are silicon cantilevers with solid aluminum coated amorphous quartz tips (Fig. 3). A rectangular window underneath the tip base is used for illuminating the quartz tip from the backside (inset Fig. 3)

The probes have been microfabricated in a batch process, which allows us to manufacture hundreds of probes in parallel. During the course of the project, the original fabrication process[6] has been reconsidered and optimized in view of reproducibility, efficiency and cost. Main differences are reduced heights of the tips, which decreased from 25 µm to 12 µm and much sharper cone angles.

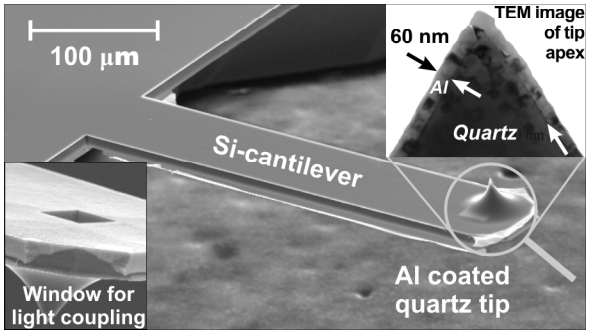

Figure 3. Electron micrograph of a cantilevered near-field optical probe. (Inset top-right) TEM indicates a continuous layer at the apex of the quartz tip. (Inset bottom-left) Window for feeding light into the tip

A metal layer of typical 60 nm covers the tip completely, including the tip's apex. This was verified by transmission electron microscopy (TEM) of probes before and after use (inset Fig. 3). Though no physical opening is present, the probes show high light transmittance in the order of 10^{-4} –10^{-2}. The transmittance varies with the used coating material and decreases with increasing skin depth of the metal. It also depends on the cone-opening angle of the tip whereby a smaller tip angle leads to a higher transmittance.[7] Their polarization and auto-fluorescence characteristic are comparable or superior to those of conventional fiber probes.[8]

Experimental Set-Up

Imaging with microfabricated cantilevered probes were performed using either commercially available near-field optical microscope (alpha-SNOM, WITec, Ulm, Germany) or a home-built microscope. Fig. 4 shows the schematics of the home-build microscope and explains the typical design characteristics of a SNOM set-up.

A tripod, which is mounted on an inverted microscope, holds the cantilever at an angle of 15° with respect to the sample. The cantilever deflection is measured by an optical laser beam deflection scheme. Scanning of the sample in the x-y-z plane is provided by a piezoelectric scanner. A beam splitter co-aligns the excitation (488 nm) and feedback (670 nm) laser beams. Both are focused onto the tip by the same lens. The different incident angles of the two beams guarantee that two spatially separated foci are formed. Transmitted excitation and fluorescence light is collected by an objective (100x, N.A.=1.25) and separated by a dichroic mirror (488/514 nm). The signals are coupled into multimode fibers, which serve as spatial filters in the confocal arrangement and guide the light to appropriate detectors. Commercial control electronics is used for data acquisition and controlling the instrument.

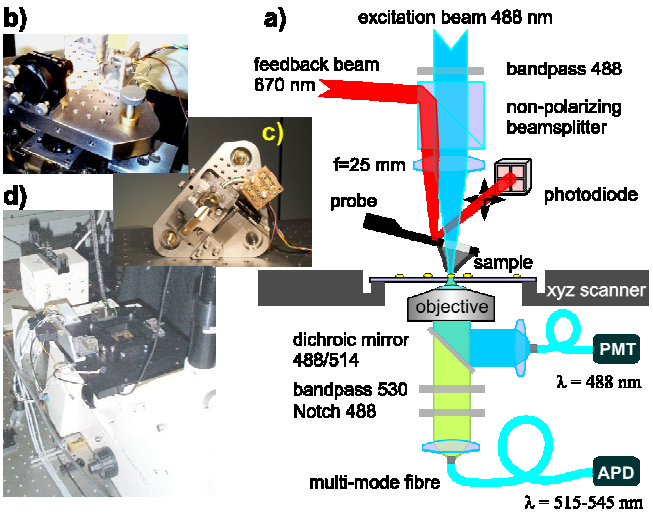

Figure 4. a) Schematics of the optical near-field microscope. The probe is mounted on a tripod (a and b), which is placed onto the microscope body (c)

Transmission Contrast

Super-resolution imaging using transmission contrast has been demonstrated with a pattern consisting of absorbing metal islands as sample.[8] The sample was produced by evaporating 35 nm of aluminum onto a closed-packed monolayer of latex beads of 220 nm diameter, which were subsequently dissolved leaving behind a regular array of small triangular shaped metal islands on the glass substrate.

Figure 5a shows the recorded near-field transmission image. The hexagonal periodicity of the structure is clearly visible with the metal islands appearing as black spots, along with some lattice defects appearing as larger black areas. An estimate of the optical resolution can be deduced from the width of the measured edges of

the islands. The cross section along the line in Fig. 5a suggests a resolution of ~28 nm (Fig. 5b). This is not a conclusive estimate though. Firstly, the exact edge geometry of the metal islands is not known. Secondly some residual interaction between tip and sample has been detected in the bending and friction signals (data not shown). Thus, the coupling between light and tip is constantly varying and the apparent optical resolution is probably due to topography artifacts.

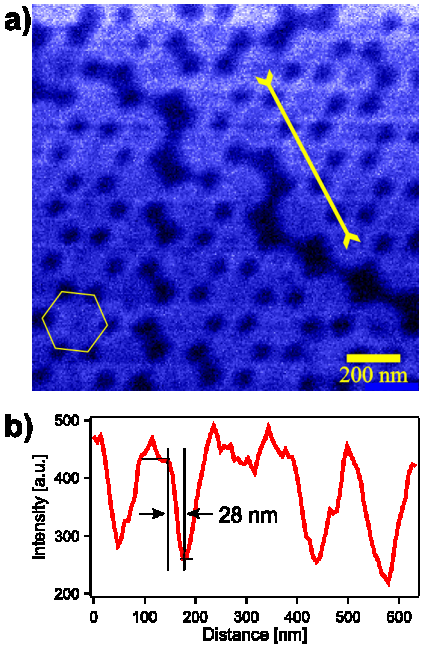

Figure 5. a) Near-field optical image of the light transmission. b) Cross section along the line in a)

Fluorescence Contrast

Single fluorescent molecules are therefore better test samples for determining the optical resolution because they are much smaller than the enhanced light field below the tip and have a vanishing topography. Figure 6a shows a near-field fluorescence image of single fluorescently labeled biomolecules, which were spin casted from a highly diluted solution (10^{-6} M) onto a glass cover slip.[8] The simultaneously acquired topography, bending and friction signals (data not shown) exhibit no variations over the whole scan confirming true constant-height operation.

The single molecules are visible as bright spots. A measure of the lateral optical resolution is the full width at half-maximum (FWHM) value of the fluorescence peaks. Cross-sections along the 47 brightest molecules were taken and fitted by a Gaussian distribution. An example is shown in Fig. 6b. The multi-peak fit can reproduce the four individual peaks revealing a resolution better than 32 nm.

Polarization Properties of Fully Coated Probes

Simulations of the optical fields, which exist at the tip of a fully coated probe, compute two propagating eigenmodes.[9] The first one corresponds to a linear polarization, which exhibits only poor field confinement at the tip apex. Instead, the mode is leaky when the tip diameter is smaller than its cut-off radius. Thus a diffraction limited spot of the sample is illuminated and no optical super-resolution can be expected. The second mode is characterized by radial polarized light and exhibits a high field confinement at the tip apex, facilitating a high optical resolution.

The model was confirmed experimentally by illuminating the probe with linear polarized light and analyzing the polarization state of the transmitted light (Fig. 7).[10] The sample is the same as in Fig. 5. When the analyzer is perpendicular (section I) to the plane of polarization of the incident light, the metal islands are resolved. This can be explained under the assumption that the linear mode couples partially to the radial mode at the tip apex. The crossed analyzer filters out the transmitted light of the 'linear' mode' and passes partly the light originating from the 'radial' mode. When the analyzer is parallel to the plane of polarization light from both modes pass and the islands are not visible since the 'linear' mode contains more power (section II). This situation is equivalent to that one where no analyzer is present (section III).

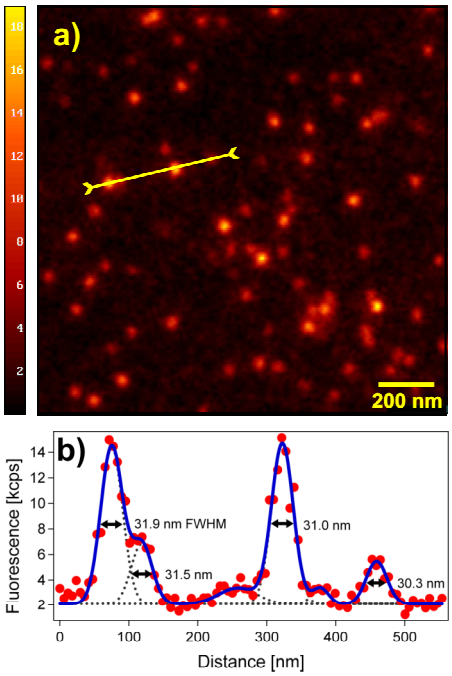

Figure 6. a) Near-field fluorescence image of single fluorescent molecules. b) Cross section along the line in a)

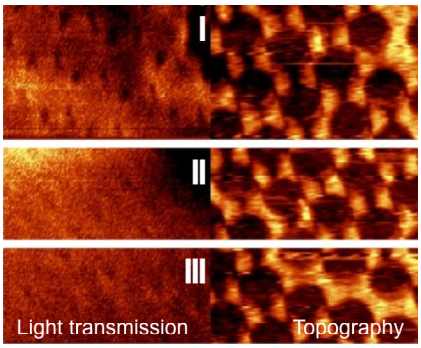

Figure 7. Polarization resolved near-field transmission images: Section I analyzer crossed, II analyzer parallel and III no analyzer

Conclusion

Near-field optical imaging using microfabricated cantilevered probes has been demonstrated in transmission and fluorescence contrast. An artifact-free 'true' optical resolution down to 32 nm was achieved. The obtainable resolution depends on the state of the polarization of the used light. Optimum resolution is achieved when the linear polarized mode propagating through the tip and the sample is blocked and only components of the radial polarized mode is detected. In practice, this means that radial polarized light should be used for illumination. Furthermore the performed experiments showed that only a small number of probes provide optical resolution below 100 nm. Probably the field confinement below the tip depends strongly on the grain structure of the metal coating, which can only poor controlled during the fabrication process.

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Author Biography

Rolf Eckert studied physics at the Universities of Bayreuth, Heidelberg (both Germany) and St. Andrews (UK). He received his MSc from the University of Heidelberg (1996) and his PhD in experimental physics (2001) from the University of Basel (Switzerland). From 1994-1997, he studied the adhesion of proteins to solid surfaces by scanning probe techniques at the EMBL (Heidelberg). In 1999 he joined the CSEM. Since then his worked has focused on near-field optical imaging and metal optics.