Apertureless near-field optics on commercial AFM: Tip to sample gap control

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Abstract. Novel mode of AFM operation is proposed providing the small, few nanometers tip to sample gap, appropriate for the ANSOM experiments. A set-up open for the run-time adjustments, working at ambient conditions is considered. Efficiency of a method is demonstrated by applying it to the laser nano-lithography on different materials with a regular AFM tip.

1. Introduction
Near-field scanning optical microscopy (NSOM) relies on accurate Tip to Sample Gap (TSG) which is comparable to or less than the tip aperture. NSOM using tuning fork as a carrier of the optical fiber probe are quite common, and it is generally accepted [1] that monitoring the shear force acting on the probe in close proximity to the sample surface provides the necessary feedback to set and keep this gap in the range from one to few tens of nanometers with high relative precision. The invention of apertureless near-field optical microscopy (ANSOM) with its obvious advantages (high spatial resolution, tolerance to high-density electro-magnetic power) challenged many researchers to use commercial Atomic Force Microscopes (AFM) where the TSG is maintained by monitoring a laser beam reflected from the back of the cantilever into a Quadrant Position Sensitive Photo Detector (QPSPD) [2-6]. Theoretically such instruments should have provided high performance [7], but in practice, the accurate determination of the TSG, especially in real time, is far from being clear. Furthermore, the task of approaching a sharp tip to a solid surface harmlessly and holding it at a constant distance of only a few nanometers is still very difficult. The conventional scheme of a hard approach to the surface till contact followed by raising the tip nominally to the desired TSG does not work for several reasons: 1) Sharp fragile tips carried by stiff cantilevers (~40 N/m) are known not to survive the contact approach to solid surface; 2) Upon lifting, soft cantilevers (~2 N/m and less) remain ‘stuck’ to the surface by capillary, electrostatic and other surface forces. When released, the tip ‘jumps’ much farther than the desired few nm; 3) The large susceptibility to temperature and humidity of the ceramic bodies of the scanners makes practically impossible to maintain fixed TSG for a reasonable time without constant verification. On the other hand, the traditional AFM non-contact operational mode is characterized by a large mean distance between the tip and sample surface. Thus,
a new approach is needed for the maintenance of small, constant TSG. Here we propose an alternative solution of this problem.

2. Experiment and results

We used a commercial AFM (XE-120, Park Systems Corp.), working under standard ambient environment. The height of the tip above the sample controlled by stacked piezoelectric actuator (Z axis), physically separated from the X-Y scanner, on which the sample is mounted. The instrument enables external remote access to most operational system parameters. Probes with stiff and soft cantilevers were tested (Olympus AC160TS and AC240TS).

A schematic layout of the set-up for the TSG measurement is shown in figure 1. An independent variable in our experiments was the vertical shift of the Z-piezo-scanner, controlled with \( \sim 1 \) nm accuracy. As a measurable quantity uniquely dependent on the TSG, we chose the far field intensity of the evanescent field scattered by the tip over a glass dove prism (a common configuration for using total internal reflection, see e.g. [8]). A laser beam (532 nm), was modulated by a chopper and directed horizontally to the 45\(^{\circ}\) side face of the prism. The far field light scattered by the tip was measured with photo-multiplier and lock-in amplifier. The change in light intensity with the tip height followed very well the Fresnel evanescent wave formula

\[
I = I_0 \times \exp \left( \frac{-2z}{d_p} \right)
\]

with the characteristic decay parameter (penetration depth) \( d_p/2 = \frac{\lambda}{(2 \times 2\pi \times (n_2^2 \sin^2 \phi - n_1^2)^{1/2})} \approx 40 \text{ nm} \), in accordance with the known values of the refractive index of the glass and the incidence angle.

To control the TSG, we introduced two feedback loops: First, we forced very small (amplitude of less than 1 nm) tip oscillations along the vertical axis at a frequency of a few tens kHz (far from the mechanical resonance of the cantilever), and measured the amplitude and phase of the corresponding QPSFD signal (typically referred to as the (A-B)\(_{ac}\)). The ‘standard’ (A-B)\(_{dc}\) voltage was also monitored, providing information on the mean cantilever bending. In addition, we measured the lateral shear force by shaking the sample along one horizontal axis at a low frequency and small amplitude, and monitored the corresponding response of QPSFD (typically referred to as the (C-D)\(_{hc}\) signal). All measurements were taken in parallel, and the far field scattered evanescent field was measured simultaneously.

Each measurement run included the tip-sample contact approach followed by slow lift and then lowering back of the probe. Figure 2 presents the ascending part of a typical experimental data set obtained with a stiff cantilever (42 N/m). The tip height zero point on the left panel of figure 2 is somewhat arbitrary, while the absolute shift values along the abscissa are reconstructed from both the Z-scanner calibrated control voltage and internal Z-detector readings.

The tip-scattered light intensity follows the known exponential decay of evanescent fields over a wide range of the nominal tip heights above the prism surface, except at small values near contact. Here, for lack of knowledge of the accurate “zero” of the contact point, we cannot trust the Z-scanner and Z-detector readings and need to use an independent measurement to estimate the exact TSG. In the right panel of figure 2, the abscissa values are corrected using a calibrated fit of the scattered intensity.
The abrupt change of amplitude of the lateral movement (red, triangles) indicates the point of “loss of direct mechanical contact” and at the same time, the steep change of the phase of the vertical cantilever oscillation (black, circles) occurs in the most relevant TSG region, around 1-5 nanometers. This sensitive region is the distance where the low amplitude oscillations of the cantilever are changed from free driven oscillations in phase with the driver, to out of phase oscillations due to the proximity to the surface. This sharp dependence of $\Phi$ on the TSG provides the desired sensitive measure for the proximity to the sample surface. It is important to note that these cantilever oscillations are performed far from the main mechanical cantilever resonance, with very tiny amplitude (<1 nm), and therefore do not interfere with ANSOM experiments.

Figure 2. Tip height dependence of all measured variables

In order to exploit the sharp phase change vs distance, shown in figure 2 for “stiff” cantilever, we developed the following procedure: Start from the ordinary tip-sample approach in the non-contact mode. When approached, shift the cantilever up by few hundreds of nanometers for safety. At this safe height, switch the probe oscillator from the internal (resonance) mode to the external (nonresonant small oscillations) one. Slowly lower the probe while constantly monitoring the oscillation phase. When the preset phase is reached, the close loop is activated keeping the given TSG. At this point, slow scanning or lithography may begin. As an additional protection against accidental hard contact between the tip and sample, the mean cantilever bend was monitored simultaneously. Finally, each experiment was followed by the scanning of the AFM tip characterizer (TipCheck from BudgetSensors) and SEM test to make sure the sharp tip survived.

3. **Proof of the method**

To verify the technique described above, we performed several experiments on laser assisted nanolithography on different materials. The idea was to realize: 1) the electro-magnetic field enhancement in the nanometer gap between tip and sample to produce material ablation of high-melting sample and 2) "hot knife" machining of the polymer sample.

As a high power density source to illuminate the tip, we used a MICRA laser (Coherent), with pulse width of 20÷50 fs at central wavelength 800 nm, energy up to ~2nJ/pulse and repetition rate 80 MHz. The laser beam was focused on the AFM tip apex at the angle of incidence $\sim 70^\circ$ by a lens with 15 mm focal length, giving the focused radius about 3 $\mu$m. The advantage of this quasi-CW regime (comparing with the 1 kHz regime discussed in the literature [5, 6]) is that the thermal effects, such as
tip elongation and bi-metallic induced cantilever bending are automatically taken care of at TSG adjustment. The experiments below were done with the sharp stiff cantilevers Olympus AC160TS (Si tip without metal covering).

Figure 3 shows subdiffraction nano-writing on a thin gold film (30 nm Au on the Si wafer substrate with 5 nm Cr buffer layer; compare with [5]). The result of such experiments strongly depends on the shape and quality of the tip and the condition of the film surface (the instrument operated in the air at standard ambient), and as a result, the reproducibility is less than perfect.

Nano-writing on the polymer film, which we termed "hot knife" processing was much more reliable. Figure 4 depicts an example for writing on photoresist cured film AP2210A (thermal decomposition temperature 518°C). The scratch was produced at TSG close to zero.

In both cases the width of the features was about 10 - 15 nm and the depth 2 - 4 nm. Post-processing tip examination revealed no damage to the tips.

![Figure 3. EMF tip enhanced nano ablation of the thin gold film](image)

![Figure 4. "Hot knife" nano-lithography on thick polymer film.](image)

4. Conclusion

By adding to a standard AFM the ability to monitor and control the desired phase of nonresonant small amplitude cantilever oscillations, we were able to control the Tip to Sample Gap in the range of a few nanometers, leading the way to accurate nano writing on various surfaces.

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1 Image processing is done in the software WSxM [9]