Improving the resolution of interference microscopes

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Abstract

We have made an interference optical microscope (IOM) capable of improved resolutions, both vertically and laterally. Atomic steps of graphite have been imaged in phase shift mode (PSM) at large field of view through a proper averaging time during acquisition. We discuss the influence of the illumination and the CCD resolution on the ultimate achievable vertical resolution. To improve the lateral resolution, we report on the integration of the IOM to an atomic force microscope (AFM) in order to take advantage of the 2 nm resolution provided by AFM.

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1. Motivation

Interference microscopy is a 3D nanometrology technique that has many appealing features: it can map the surface topography with sub-nanometer vertical resolution, it is much quicker than mechanical profilers (either stylus or AFM) and it is entirely non-contact and non-destructive for the sample, as only low power monochromatic or white light interacts with the surface. The use of interference microscopes has quickly widespread as a quality control equipment for micro fabrication processes, i.e., in semiconductor and MEMS industries.

There are two modes of operation in interference microscopy, referred to as translation height mode (THM) and phase shift mode (PSM): the description of these basic imaging modes and how they have been implemented in our microscope is reported in Ref. [1]. In translation height mode (THM), white-light illumination is used and either the interference objective or the sample is vertically scanned over the entire topography range of the surface. The height topography is reconstructed on each pixel by computing the envelope of the correlogram (i.e., the intensity $I(z)$ as a function of the objective/sample separation $z$). In phase shift mode (PSM), monochromatic illumination is used and a phase map is generated with the help of 5 images taken $\lambda/8$ apart, i.e., with a phase shift of $\pi/2$, as the light passes twice the distance. THM has the advantage to overcome the phase ambiguity (i.e., the periodicity of the tan$^{-1}$ term in the phase map,
see Section 3), allowing steps larger than $\lambda/2$ to be images, while PSM is quicker and has a better resolution. Combined THM/PSM modes have also been proposed, including one to overcome the loss of lateral resolution due to defocus [2] and one using CCD frame averaging [3].

Nevertheless, although resolution is often claimed to be in the Angstrom level – especially in PSM mode – images showing such resolution in actual structures are seldom shown. For commercial instruments resolution is determined by testing the limit rms roughness of standard samples that can be resolved with this instrument. Also, as a far-field optical imaging system, the lateral resolution of an interference microscope is diffraction limited to typically 0.6 $\mu$m with standard white light illumination. Apart from lateral resolution, there are two other drawbacks of interference microscopy. The first is the strong convolution with the refractive index [4], which turns to be more problematic than the convolution with the tip geometry or the mechanical properties encountered in mechanical profilometries (either stylus or AFM). The second drawback is the requirement to take several images to reconstruct a topography, which limits its use for real-time application. Note however that a very efficient Fourier-based reconstruction algorithm with one single interferogram image has been proposed recently [5], which makes PSM very competitive with digital holography.

In this paper, we focus on the development of our home-built interference microscope to overcome several limitations in terms of resolution, both lateral and vertical.

2. Instrumental development

The motivation for building our own interference microscope is multiple. It gave us the versatility to choose the optimal components for a dedicated application, for example the most appropriate CCD or piezo translator. This versatility also enables us to mount the IOM in specific configurations, for example to interface it with other instruments such as AFM and nanoindentor [1]. Finally, developing the acquisition software allows to address recent applications like tomography [6].

Two examples of setup configuration of the interference microscope are shown in Fig. 1. In Fig. 1a, the sample is mounted on a 100 $\mu$m closed-loop piezo translator [7] whose measured rms noise is 0.31 nm at 20 Hz bandwidth. The piezo is itself mounted on the tilt stage and the xy translator stage. To accommodate larger, heavier or more corrugated samples, we can also mount a Mirau [8] objective on a closed-loop 200 $\mu$m piezo-actuator, itself directly mounted on the video tube. This piezo objective holder cannot however accommodate a Tolanski objective, which is too heavy.

Fig. 1. Interference optical microscope: (a) in stand-alone version with piezo translator supporting the sample and (b) integrated to the AFM with piezo translator supporting the interference objective.
Fig. 1b shows the integration of the interference microscope in the atomic force microscope. The piezo translator objective holds a 10× Mirau objective directly above the AFM head (Park System, XE-100). The tilt stage is located under the AFM scanner.

We used a 8-bit black and white CCD camera with either 640 × 480 or 1024 × 768 pixels definition. The higher definition CCD is mainly used with low magnification objectives, 2.5× or 10×. Indeed, the field of view of the 20× objective is 171 μm × 126 μm, which corresponds to 270 nm/pixel, a value already below the Airy disk. Optimum averaging acquisition time per frame in THM has been found to be 80 ms. Averaging time in PSM, which play a central role in vertical resolution, is discussed in Section 3.

A proper piezo calibration is necessary for the IOM operation. In PSM, a poor calibration degrades the vertical linearity of the measurement, but the long vertical range accuracy is not affected (as each phase step in the phase map will always occur at Δz = λ/2 nm). The situation is opposite in THM where a piezo miscalibration affects the long range accuracy. To investigate the best performance in THM, we have compared closed loop operation with an open loop mode where the CCD is triggered with the strain gauge signal. Since no significant noise reduction where observed in the open loop mode (both modes were equivalent in terms of rms roughness on a flat mirror), we always operate the microscope in closed loop.

3. Vertical resolution

The best vertical resolution in interference microscopy is obtained with phase shift mode (PSM), although very similar resolution has been obtained with Fourier transform based OPD reconstruction algorithm in THM [9]. For the sake of simplicity, we will restrict this discussion of the vertical resolution to PSM only and from a purely instrumental point of view.

The inset of Fig. 2a describes the model we use. The sample location (x, y) at a height z is observed through an interferometric objective (Mirau type). The intensity of the light detected at the CCD pixel corresponding to the (x, y) location depends on the phase φ = 2πz/λ. The Mirau objective is then displaced five times successively by an amount of λ/8, corresponding to a phase shift of n/2 at each step. The collected intensities are labelled I1–I5. If we assume that the illumination power is optimized in such a way that the full range of the n-bits of the CCD is fully exploited, then intensities can be written as:

\[ I_1 = \text{Int}[2^{n-1}(1 + \cos \phi)] = I_5 \]
\[ I_2 = \text{Int}[2^{n-1}(1 - \sin \phi)] \]
\[ I_3 = \text{Int}[2^{n-1}(1 - \cos \phi)] \]
\[ I_4 = \text{Int}[2^{n-1}(1 + \sin \phi)] \]

where Int represents the integer round value and \( \phi \) is the phase.

To recover the actual value of z from the \( I_1, \ldots, I_5 \) intensities, we use the 5-steps Schwinder–Hariharan algorithm [10]. The reason for this choice is its widespread use and its robustness with respect to calibration error.

The calculated value of the height z is given by [11]:

\[ z_{\text{calc}} = \frac{\lambda}{4\pi} \tan^{-1} \left( \frac{I_2 - I_4}{0.5(I_1 + I_5) - I_3} \right) \]

In Fig. 2a we represent the calculated height \( z_{\text{calc}} \) as a function of the actual height z for a 8-bit CCD with \( \lambda = 620 \) nm. The calculation is shown for a small range of height (15–25 nm) and for every Ångström in order to show the stepped nature of the curve. This is due to the analog to digital conversion (CCD quantification). We also see that various step heights occurs: indeed, depending on the integer \( n \), the resulting change in \( z_{\text{calc}} \) will take various values due to the \( \tan^{-1} \) term. Fig. 2b is the discrete derivative of Fig. 2a, showing therefore the values of the steps as z is ranging from 0 to \( \lambda/4 \) (the function is then periodic).

We choose to quantify the vertical resolution limit (vrl) in terms of mean value and variance of the collection of steps measured in Fig. 2b. For \( n = 8 \) and \( \lambda = 620 \), we found \( vrl = 0.624 \pm 0.194 \) nm. The calculations of \( vrl \) as a function of \( n \) for \( n = 8 \) and \( n = 10 \) are shown in Fig. 2c (error bars correspond to the standard deviation of \( vrl \)).

We then see that subnanometer resolution is indeed possible experimentally, at least within the frame of this model, even with an 8-bits CCD. However, to actually achieve this resolution, we found necessary to reduce the noise fluctuation on the CCD, a noise mainly originating from mechanical vibration and piezoelectric instabilities. As described below, a simple CCD frame averaging procedure was sufficient to get rid of this noise.
Fig. 2. Computation model of the vertical limit resolution. (a) Calculated height $z_{\text{calc}}$ as a function of the actual height $z$ with a 5-steps algorithm, for a 8-bit CCD with 620 nm illumination. (b) Detected steps as a function of height up to $\lambda/4$ ($n=8, \lambda=620$). (c) Vertical resolution limit (vrl) for a 8-bits and 10-bits CCD as a function of the illumination wavelength.
In Fig. 3, we show that a subnanometer resolution (atomic step) is possible in PSM provided a proper time averaging is chosen. We used a white halogen lamp illumination though a 5 nm bandwidth interference filter centred at 620 nm and a 20× Mirau objective. The sample was freshly cleaved highly oriented pyrolitic graphite (HOPG) which gives atomically flat terraces typically 2–20 μm wide. Such wide terraces are a necessity to images atomic steps in interference microscopy as the lateral resolution is diffraction limited.

Each of the five phase-shifted images were acquired \(N\) times and then averaged, resulting in an expected noise reduction of \(\sqrt{N}\). The \(N\) frames were actually digitalised (8-bit CCD) and stored in the computer. Each of the frames was acquired with 60 ms integrating time.

Fig. 3a shows the unwrapped image for 25 frames (i.e., \(n = 25\)). The step pointed by the arrow measured 1.3 nm. Due to surface relaxation, this corresponds to a double atomic step of HOPG, a structure often encountered in AFM images. Other steps on the image are single atomic steps. We performed acquisitions on the same location with \(n = 1\), \(n = 5\) and \(n = 25\). The cross sections for the various acquisitions are shown in Fig. 3b. The effect of averaging which leads to atomic steps is clearly visible. We found \(n = 25\) close to the optimum, as larger number of frame implies excessive acquisition time which degrades the signal due to drift.

Sub-angstrom value resolution in PSM interference microscopy is often claimed, but practically this value always correspond to the measured \(rms\) roughness on optical flats or mirrors. To our

![Fig. 3. Vertical resolution in PSM mode. (a) Atomic steps of cleaved HOPG (20× Mirau objective). The arrow indicate a 1.3 nm high step and the dotted line the position of the cross section. (b) Improvement of \(S/N\) ration due to frame averaging.](image-url)
knowledge, no optical images showing atomic terraces as clear as Fig. 3a have been produced yet, either in far field or in near field imaging (atomic steps shown in SNOM images comes from the ability of the probe to accurately follow the atomic steps: this is therefore a mechanical contrast and not an optical one). Images with the best vertical resolution have been obtained with scanning laser microscopy in differential phase contrast mode (see for example results on Si(100) in Ref. [12] and molecular resolution on Langmuir–Blodgett films in Ref. [13]). Nevertheless, as the contrast corresponds to the slope of the topography, no discrimination of the height of the terraces can be achieved as we did in Fig. 3a.

4. Lateral resolution

Lateral resolution remains a major weakness of any far field (i.e., diffraction limited) optical imaging system. According to Abbe the lateral resolution limit is \(0.6\lambda/\text{NA}\) (NA being the numerical aperture \(n\sin \theta\)), which is 496 nm for our blue LED illumination (\(\lambda = 455 \text{ nm}\)) and our 50\%/C2 Mirau objective (NA = 0.55 in air). Using a two dimensional silicon grating with 1 \(\mu m\) pitch in each direction, we show in Fig. 4 that this lateral resolution can be readily achieved in PSM, even with a 640 \(\times\) 480 CCD camera. Fig. 4a is a 33.2 \(\mu m\) \(\times\) 21.4 \(\mu m\) 3D view of the unwrapped topography of this grating, which is clearly resolved in both directions. A cross section

![Diagram](image)

Fig. 4. Lateral resolution in PSM with blue illumination on a 1 \(\mu m\) pitch grating. (a) 3D view of the unwrapped topography, FOV 33.2 \(\times\) 21.4 \(\mu m\). (b) Cross section showing the optical limit resolution.
through the silicon bumps is displayed in Fig. 4b with an indication of the optical resolution limit.

The most straightforward way to have better lateral resolution is to use UV light [14,15] which gives an improvement of a factor of 2 at best but for a cost typically ten times higher for the UV CCD. Along the same line, a design of a liquid immersion Mirau objective has been proposed [16] to increase the NA by increasing the refractive index of the medium. Other lateral resolution improvement in far field microscopy has been reported with the help of lateral modulation technique [17], the so-called “4pi” method [18,19], structured light illumination [20], etc., but the improvements, does not exceed a factor of 3 relative to the Abbe criterion.

These improvements, which are highly valuable and useful in the field of fluorescence microscopy, are not competitive with the lateral resolution one can achieve with a mechanical profiler. Therefore, instead of trying to improve the lateral resolution by optical ways, we have decided to integrate our interference microscope with a commercial Atomic Force Microscope. The lateral resolution can then easily reach 2 nm, i.e typically 200x better than any optical resolution.

Integrating an interference microscope in an AFM is actually rather simple as most AFM have an optical microscope to facilitate the laser alignment on the cantilever and to choose the area of interest. The main difficulties arise from the working distance (WD) of the interference objectives, which might be too short for the design of the AFM head. In our case, with minor mechanical modifications, we could use the 10× Mirau objective (WD = 7.4 mm) on two commercial AFM’s [21]. Another way would have been to build a small AFM below an interference microscope objective. Such a system has been reported recently [22], where a piezoresistive AFM cantilever is used in order to get rid of the space required for the optical component for a beam bounced cantilever AFM. This simplifies the integration and at some degree the use of the system (no laser beam to align) but at the expense of limitation for the AFM: indeed, piezoresistive cantilevers are very stiff (their spring constants are too large to measure soft samples) and they cannot be used for lateral force mode (LFM) neither, as the piezoresistor cannot measure the torque of the cantilever. Fig. 1b is a picture of the integrated IOM/AFM, where we can see the interference objective mounted on a 200 μm piezo translator above the AFM head and scanner (XE-100).

An example of use of the combined microscopes (AFM/IOM) is shown in Fig. 5. The sample, a one-dimensional grating 1.5 μm high, is first imaged at large field of view (10×) with the interference micro-

![Fig. 5. Integration IOM-AFM integration. (a) IOM topography in THM, 355 μm × 266 μm. (b) AFM image (9.5 μm × 2 μm) on the selected area. (c) AFM zoom, 650 nm × 650 nm.](image-url)
scope in THM (Fig. 5a). By sliding back the AFM head in its normal position, the area of interest (red rectangle in Fig. 5) can be selected. The AFM scanner is then automatically offset to the desired position, the tip is approached to the surface sample and the AFM image is acquired (Fig. 5b). Additional zoom can then be performed to take advantage of the AFM lateral resolution, as shown in Fig. 5c with the 600 nm × 600 nm field of view image. We found practical application of this combined system in quality control of micro fabricated devices (IC, MEMS). For this specific industrial application, the acquisition time is important. For PSM, this ranges from 2 s (no frame averaging) to 15 s for maximum vertical resolution (average over 25 frames). For THM, the acquisition time is typically 3 s per micron in the surface topography (i.e. if the total surface topography range to be measured is 12 μm, the acquisition time is 36 s). In the future, we also think to integrate the combined AFM/IOM in our nanomanipulation system [23].

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References

[4] Indeed, the beam reflected from the sample has a phase shift which depends on the complex refractive index for a metal and on the optical thickness (t/λ) for a dielectric.
[7] All piezoelectric translators we have used were equipped with a strain gauge sensor and were operated in closed-loop for convenience (open loop operation does not give significant improvement in term of noise). The PID parameters of the feedback loop is optimised as a function of the desired motion (typically 20 nm steps at 15 Hz for THM) and of the mass of the supported device (either the objective or the sample).
[8] A Mirau objective is an interferometric objective on which the reference mirror is in the center of the objective lens and a plate beam splitter is placed between the objective lens and the sample. This compact and light construction design is compatible with middle magnification (10× to 50×). For smaller magnifications, a cubic beam splitter and an external reference mirror has to be used (Tolanski objective), which is a more bulky and heavier construction.