Massively Parallel Atomic Force Microscope with Digital Holographic Readout

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Abstract. Massively Parallel Scanning Probe Microscopy is an obvious path for data storage [1][2]. Current experimental systems still lay far behind Hard Disc Drive (HDD) or Digital Video Disk (DVD), be it in access speed, data throughput, storage density or cost per bit. This paper presents an entirely new approach with the promise to break several of these barriers. The key idea is readout of a Scanning Probes Microscope (SPM) array by Digital Holographic Microscopy (DHM). This technology directly gives phase information at each pixel of a CCD array. This means that no contact line to each individual SPM probes is needed. The data is directly available in parallel form. Moreover, the optical setup needs in principle no expensive components, optical (or, to a large extent, mechanical) imperfections being compensated in the signal processing, i.e. in electronics. This gives the system the potential for a low cost device with fast Terabit readout capability.

1. Introduction

Today, a large part of tools used to interact with nanoscale structures are based on scanning probes technology founded with the invention of the scanning tunneling microscope (STM) by Gerd Binnig and Heinrich Rohrer of IBM's Zurich Lab in 1981. The working principle is based on a micro-lever carrying a probe on its end which is brought in proximity of the sample to be manipulated/studied. The deflection of the lever induced by the atomic forces in the vicinity of the sample is measured by a sensor, allowing the reconstruction of the desired information, be it topographical information or information about the nature of the sample (DNA molecule identification, etc …). Today, the scanning probe microscope (SPM) technologies based on individual probe have reached their limit, principally by the slow data acquisition frames rate due to their sequential readout. This last decade, great deals of efforts have been carried out for developing multiprobes SPM in order to increase range and acquisition speed. The concept is to make multiple cantilever probes on one chip which are controlled independently and coupled with a multiplexed cantilever detection method [3][4]. Developed in linear or in 2D configurations, manufactured starting from very diverse materials and coupled with a large range of sensors, the scanning probes devices extend nowadays their applicability to many different domains, starting from the observation to the direct interaction with nanoscale structures.

However, an important limitation appears when using multiprobes SPM with multiplexed integrated sensors. Indeed, as density of probes increases, number of contact and interconnections wires increase and space for the leads decrease as much. Moreover, this contributes to enhance the
complexity of the parallel electronics. With regards to these limitations, current studies and developments depict a limit up to 100 x 100 probes/mm². This work is to our knowledge the first successful experiment which shows how to overcome this interconnection limit. The setup proposed here separates physically an entirely passive probes array, without any electrical correction, from massively parallel CMOS standard readout electronics. This contribution first details the working principle of the device based on the readout of a large array of scanning probes by Digital Holographic Microscopy (DHM) [5]. The MEMS fabrication technology of the SPM array is then described. Using a commercial DHM for the acquisition of the phase information of a first 7 x 7 free bending SPM cantilevers, the topography reconstruction of large samples brought in contact is validated.

2. Readout Principle
The readout setup is composed by four main elements which are the Digital Holographic Microscope, the SPM array device, the sample carrying the studied topography and a XYZ piezoelectric stage which can bring the sample in contact with the SPM device and can move it according Cartesian axes. The Digital Holographic technology directly gives phase information at each pixel of a CCD array, available in parallel form, at the acquisition rate of the camera. This means that no electrical wiring to each individual SPM probe is needed, given the cantilever’s array the potential to reach very high density on large surface. Fig. 1 illustrates the working principle of this DHM Parallel SPM array readout system with the different constitutive elements. The readout of the sample shape is done in contact mode by bringing the sample in close contact with the SPM array and then scanning it in X and Y directions. Depending on the topography, each independent cantilever is deflected as an AFM. These deflections are stored within digital holograms in the camera of the DHM and are restituted after reconstruction of the phase information from these holograms.

![Figure 1. DHM Parallel AFM Readout working principle](image)

3. Digital Holography
3.1. Basics of Holography
A reflected wave coming from an illuminated object carries all the information concerning its optical and physical properties, indeed, intensity and phase of the wavefront can be related with respectively object's reflectance and topography. Standard optical sensors record only the amplitude of an optical wavefront and are not suitable to directly capture its phase. The holography is a method that allows reconstruction of whole optical wavefields, suitable to recover the topographical information hides in the phase. A hologram is made by acquiring the interference pattern between a propagated wave coming from an illuminated object $\Psi$ and a reference wave $R$, coherent with the object wave. The
resultant intensity of their interference is called “hologram”. Amplitude and Phase store in this hologram allow us to accurately reconstruct the object wavefront by re-illuminating the hologram with a replica of the reference wave $R$. In digital holography, the interference pattern is stored numerically in a CCD camera. The hologram becomes a “digital” hologram after spatial sampling through the CCD. At this stage, the re-illumination of this digital hologram can be simulated as the diffraction of a perpendicular digital reference wave passing through an aperture defined by the hologram patterned [6]. Assuming the digital reference wave is a plane wave; this diffraction can be calculated by the Fresnel-Kirchhoff integral and then digitized in a discrete formulation by 2D Fast Fourier Transform (FFT) for rapid effective calculations. The reconstruction sequence is resumed on Fig. 2.

Figure 2. Resume of the digital reconstruction of the phase information coming from a 7x7 cantilevers area: Far left: Commercial used DHM from the Lyncée Tec SA. Left: Storage of the hologram on a CCD camera. Centre: Only the image of interest is kept from the transmitted field (the 2D FFT) by filtrating the zero-order and one of the twin images. Right: Phase information of the observed object can be mathematically reconstructed.

4. AFM probes array
Although one goal of the project is to reach high density of cantilevers, the driven objective of our setup stays to demonstrate the feasibility of the optical readout of these AFM cantilevers by the DHM. A trade-off between these two targets imposes some requirements on the design. The process realized within the clean room facility of the Center of Microtechnology of Lausanne is illustrated on Fig. 4. For first experimentations, a 2D array of 27 x 27 cantilevers with a 150 $\mu$m pitch has been processed on a 5 mm$^2$ device (one array is illustrated in Fig.3). The cantilevers are 100-$\mu$m-length, 10-$\mu$m-width and 1.5-$\mu$m-thick, allowing contact AFM mode with stiffness between 1 and 10 N/m. Working on the high aspect ratio of the Bosh sequence used during the last DRIE step, a 2D array of 80 x 80 cantilevers, also on a 5 mm$^2$ device, is currently micro-machining with a pitch of 50 $\mu$m between the cantilevers.

Figure 3. On the left: Topside view of a 27 x 27 cantilever array. On the right: One closed view of a passive bended cantilever. The final deflection is measured at 3 $\mu$m.
5. Sequence and performances

The mechanical setup is placed directly behind the DHM objective. An objective holder allows placing the 2D scanning probes array at the focal plane of the objective. The topside of the 2D array, i.e. the functional side with the bended cantilevers and the scanning probes, is facing the sample. This one is mounted on several piezoelectric and screwing systems which allow its positioning for the contact mode and the scanning in the lateral directions. Due to the chosen objective offering a FOV of 1 x 1 mm², the first observable array is constituted of 7 x 7 cantilevers. The parallelism between both surfaces is ensured by the piezo Pan/Tilt/Z actuator and by direct observation of the deflection of periphery cantilevers. Once the setup is ready, the sample is scanned in X and Y directions and the acquisition of the hologram is launch at the frames rate of the camera. For the current DHM setup, not specialize for our application, a 512 x 512 pixels phase image reconstruction is performed at 15 fps. A dozen of pixels per cantilever being sufficient to ensure a good resolution of the phase, the acquisition rate can be increased up to 280 fps. At this frames rate, with the pitch between two adjacent cantilevers define to 150 μm, a 256 x 256 pixels image taken by each cantilevers resulting (for 7 x 7 cantilevers) in a 1792 x 1792 pixels image covering 1 mm² can be taken in 4 minutes. The system acting in a fully parallel way, keeping the resolution constant, the reconstruction time for a large surface is defined by the time made to scan the surface covered by one cantilever. Indeed, a 2 mm² image of the same surface would be taken also in 4 minutes. With regards to the current developments which allow increasing the density by reducing the pitch of the MEMS device by at least a factor 3, as density of cantilevers and reconstruction time decrease accordingly, the same image would be formed in 25 seconds.

6. Results

In order to validate our setup, a large grating of 3-μm-periodicity and 50-nm-thick indentations has been scanned on a 350 μm surface. The current piezo XY stage having a 50 μm limited full stroke, i.e. less than the pitch between two adjacent cantilevers, the full surface can not be fully represented. Left Fig. 5 represents the topography of the gratings for the area cover by one probe. The final image of the total surface covered by 3 x 3 cantilevers (for representation convenience), acquired in 4 minutes is represented in right Fig. 5.
Figure 5. Left: Grating topography measured with one probes of the DHM parallel SPM setup. The surface of 100 x 100 pixels covered 50 x 50 μm. Right: Final image obtain form the phase information reconstructed from 3 x 3 cantilevers. The scanning area of each probe (without overlapping) is defined by the mechanical gap. The blank areas have not been scanned due to the limited piezo range of the scanning elements. The surface of 700 x 700 pixels covered 350 x 350 μm.

7. Conclusion
This paper has presented a digital holographic microscope which allows the real-time reconstruction of the phase information of a whole surface. Coupled with a parallel scanning multiprobes array, this system can be used as a large range AFM in order to image large surface for device with total dimensions above the hundred of microns. A first setup, using a 1 mm² field of view which allows the acquisition and the reconstruction of the phase information coming from 7 x 7 cantilevers spaced by 150 μm has been introduced and, with limitation coming from piezoelectric scanning elements, first large image of a nano-indent grating has been scanned. As the optical setup of this system needs in principle no expensive components, this gives the system the potential to be miniaturized and low cost. Moreover, always specifically applied to the readout of a scanning probes array, the software of the DHM can be highly simplified. Coupled with the development of very high density scanning probes array, this system is able to reach high frames rate for very large surface covering. Indeed, a 20 x 20 cantilevers array, each of them being spaced by 50 μm (and scanned over 50 μm) can cover a 1 mm² area with a 50 nanometer resolution in a few minutes.

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