Atomic force microscope based nanomanipulator for mechanical and optical lithography

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***Abstract* — An atomic force microscope (AFM) based system has been built for the manipulation of materials at the nanometer scale. The AFM is combined with an inverse optical microscope and an UV-laser microbeam system for photoablation. The actuators of the AFM are controlled using a digital signal processor. Real-time routines and a graphical user interface have been programmed for high resolution imaging and nanomanipulation. The nanomanipulation can be pre-programmed offline or directly performed using a low-cost haptic interface. In this paper we discuss the whole system and the different methods for manipulation.**

***Index Terms* — Nanotechnology, actuators, atomic force microscopy, laser ablation, lithography, manipulators.**

I. INTRODUCTION

The standard application of the atomic force microscope (AFM) [1] is imaging of surfaces with subnanometer resolution. Taking advantage of the mechanical contact of the AFM tip with the sample, one can achieve surface modifications with a resolution far beyond the optical diffraction limit [2]-[5]. Another application of AFM manipulation is the precise positioning of individual nanoparticles on surfaces [6].

AFM does not require special preparations of the sample surface which is an advantage over other high resolution imaging methods such as scanning or transmission electron microscopy. Moreover, AFM imaging is also possible in a liquid environment. Therefore, the field of application of the AFM ranges from hard material surfaces to soft biological samples.

Laser ablation is a complementary tool in micro patterning. Laser techniques are suitable for hard, brittle and heat-sensitive materials. Pulsed ultraviolet lasers have been applied for ablation of biological samples due to their precision (±2000 Å) with which the depth of the cut can be controlled as well as the lack of thermal damage [7].

New methods taking into account sample properties and tip-sample interaction dynamics are needed in order for a better control of the AFM manipulation process and to obtain reliable results. On the complex surfaces of biological systems the sample properties exhibit such a strong local variation that predictable surface modification is difficult. The control of the manipulation by the human user using a haptic interface offers a very promising approach. As low-cost haptic interface it is possible to use a force-feedback joystick, offering the necessary tactile response and easy implementation in the system [8].

Standard AFM systems (hardware and controlling software) are designed for the acquisition of high resolution images. To fully develop the possibilities of the AFM as a nanomanipulation tool new AFM systems specifically designed for this task are required.

II. AFM SYSTEM

To position the sample in the planar coordinates a piezoelectric XY flexure stage is used (P-517 PZT Flexure Stage, Physik Instrumente GmbH&Co.). The XY flexure stage is equipped with capacitive position sensors. The XY positioner holds the sample and is fixed on top of an inverted microscope (Axiovert 100S, Carl Zeiss). The sample can be positioned laterally with 1 nm accuracy in a 100 μm range.

The AFM head is situated on the top of the inverted microscope. A piezoelectric stack actuator with capacitive sensors for closed-loop operation (P-753 LISA NanoAutomation Stage Actuator, Physik Instrumente GmbH&Co.) is fixed in the head supporting the cantilever holder. This z-stage controls the tip-sample distance with 0.01 nm accuracy in a 25 μm range.

For AFM operation the planar and vertical actuators are separated. In this way, common images artifacts that appear in AFM system are avoided that are related to the cross talk between the XY and the Z positioning [9].

A dither piezo (10x5x0.5 PICA51, PI Ceramic GmbH) in the cantilever holder allows for the operation in various dynamic AFM modi. The cantilever deflection is detected using the bouncing beam detection method.

III. LASER UNIT

An UV microbeam laser (P.A.L.M. Mikrolaser Technologies AG) is focused on the sample through the mi-

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croscope objective using the fluorescence illumination path via two high power beam splitters. The high power nitrogen laser is specified with a laser output of 337 nm, pulse width of 3 ns, pulse repetition rate between 0 and 60 Hz and maximum pulse energy of 300 µJ.

IV. ELECTRONICS

The piezoelectrics actuators are driven by commercially available electronics that also provides the signals from the capacitive sensors (E-500 Series PZT Control Electronics Physik Instrumente, GmbH&Co).

A digital signal processor (DSP) module (Adwin-Gold, Jäger Computergesteuerte Meßtechnik GmbH) generates the waveform for AFM operation and nanomanipulation using real-time routines.

V. SOFTWARE

The hardware is controlled by real-time routines. A graphical user interface (GUI) allows the experimentalist to take control of the system. The tasks to be performed by the system are defined in the GUI and loaded in the DSP for its real-time execution. During the execution, the DSP transmits the data to the GUI to give the user online visual feedback.

A. REAL-TIME CONTROL ROUTINES

Different routines have been programmed for the tasks to be accomplished by the system. The routines were programmed using the pseudo-BASIC language ADWin. The AFM routines generate the scanning waveform, regulate the tip-sample interaction during manipulation, and communicate with the GUI for the online representation of the data. The manipulation routines generate the necessary waveform to perform the tasks predefined in the GUI.

B. GRAPHICAL USER INTERFACE

The GUI has been programmed using Visual C++. The Microsoft foundation classes (MFC) were used to drastically reduce the programming efforts and to facilitate the farther development of the GUI. The GUI includes all the functionalities necessary to control an AFM and to obtain the acquired data. These functionalities are extended for manipulation purposes. One module allows to predefine lithography experiments, setting the trajectory of the tip, velocity, tip-sample distance and amplitude of oscillation for dynamic nanomanipulation. A second nanomanipulation module allows the user to take directly control of the system. The communication routines of the GUI with the positioning joystick and the haptic interface are implemented using DirectX® functions. DirectX® is a Microsoft programming interface designed to develop computer games.

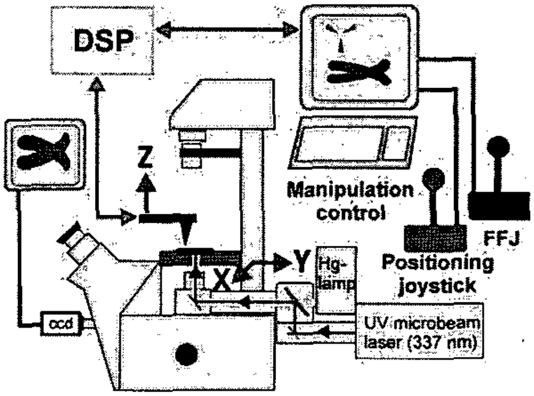

Fig. 1 System layout showing the main elements of the AFM based nanomanipulator.

VI. POSITIONING JOYSTICK AND HAPTIC INTERFACE

The force-feedback joystick (FFJ) implemented in the system was a *Wingman Force* of Logitech. In the *Wingman*, a system of motors and magnetic coils communicates forces to the user hand.

The main program retrieves the positioning joystick data and increments the corresponding voltage in the manipulation waveform every 10 ms. Thus, the sample is moved in the X and Y direction with a velocity proportional to the position of the joystick in each axis relative to its center. For vertical positioning of the sample a hat switch at the top of the FFJ is used. The response of the vertical piezoelectric actuator to the joystick output is analog as in the positioning joystick.

The acquisition time of the force along the vertical axis of the FFJ is 1 ms giving a real-time interactive signal to the user. To use the FFJ as a haptic interface between the AFM tip and the user, an interactive signal is A/D converted from the AFM electronics, scaled by the manipulator control system and returned in the FFJ. Therefore, the user feels a force proportional to the interactive signal. The delay between the returned force and the interactive signal is less than 2 ms.

VII. SURFACE SENSING

To give a real-time feedback of the sample surface, the topography signal from the AFM is fed to the FFJ while the human operator moves the tip using the positioning joystick. The user "feels" on his hand a force proportional to the height of the sample point interacting with the AFM tip. The topography signal from the AFM electronics is pre-processed in the DSP and then scaled to generate the response on the FFJ. The topography signal can be used as an interactive signal as long as the proportional-integral (PI) loop of the AFM control system is working. The force set at the FFJ is proportional to the height of the sample. This proportionality is set in the GUI by the user in order to scale the increment of the height to the range of the feedback force.

VIII. HUMAN GUIDED MANIPULATION

The user can directly perform surface modification taking control of the tip with the positioning joystick and setting the tip-sample distance. The normal force output from the AFM electronics, which is proportional to the normal deflection of the cantilever, is used as haptic signal during manipulation. The PI loop has to be disconnected in order to provide full interaction to the user. During manipulation, the use of the normal force as interactive signal is quite appropriate. The force set at the FFJ is proportional to the photodiode signal. This proportionality is set in the GUI by the user in order to scale the photodiode signal to the range of the feedback force. This adjustment depends on the characteristics of the cantilever, sample properties and loading forces onto the sample.

IX. LITHOGRAPHY MODES

A straight forward approach for mechanical nanomanipulation is to bring the AFM tip directly into contact with a surface while a constant contact force is achieved. If the pressure at the AFM tip apex exccedis the plastic yield strength of the material surface modifications can easily be produced.

Another approach relies on the excitation of the AFM cantilever at its fundamental resonance frequency which is typically in the range of a some hundreds of kilo Hertz. There, surface modifications are obtained varying the amplitude of the excitation piezo. This increases the free amplitude of the oscillating tip and thus increases the tip sample forces.

The open architecture allows us to implement and test various manipulation methods.

V. CONCLUSIONS

We have constructed a AFM system specially designed for nanomanipulation. Nanomanipulation experiments can be arranged predefining the necessary parameters (lithography) or by direct steering (manipulation). In the latter mode the human operator handles a positioning joystick while he obtains feedback of the tip-sample interaction through a low-cost haptic interface. Due to the open architecture different AFM lithography and manipulation methods can be used in combination with UV laser ablation.

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REFERENCES

[1] G. Binnig, C.F. Quate, and C. Gerber, "Atomic force microscopy", *Phys. Rev. Lett.*, vol. 56, no. 9, pp. 930-933, 1986.

[2] S. Thalhammer, R.W. Stark, S. Müller, J. Wienberg, and W.M. Heckl, "The atomic force microscope as a new microdissecting tool for the generation of genetic probes" *J. Struct. Biol.*, vol. 119, no. 2, pp. 232-237, 1997.

[3] R.W. Stark, F.J. Rubio-Sierra, S. Thalhammer, and W.M. Heckl, "Combined nanomanipulation by atomic force microscopy and UV-laser ablation for chromosomal dissection" *Europ. Biophys. J.*, vol. 32, no. 1, pp. 33-39, 2003.

[4] M. Guthold et al., "Controlled manipulation of molecular samples with the nanoManipulator" *IEEE/ASME Int. conf. advanced intelligent mechatronics*, pp. 3-8, 1999.

[5] M. Sitti, "Survey of nanomanipulation systems" *Proc. of the 1st conf. Nanotechnology*, vol. 1, pp. 75-80, 2001.

[6] M. Sitti, and H. Hashimoto, "Controlled pushing of nanoparticles: modeling and experiments" *IEEE/ASME Trans. on mechatronics*, vol. 5, no. 2, pp. 199-211, 2000.

[7] S. Thalhammer, R.W. Stark, K. Schütze, and W.M. Heckl, "Laser microdissection of metaphase chromosomes and characterization by atomic force microscopy" *J. Bio. Optics*, vol. 2, no. 1, pp.119, 1997.

[8] F.J. Rubio-Sierra, R. Stark, S.Thalhammer, and W.M. Heckl, "Force-feedback joystick as a low-cost haptic interface for an atomic-force-microscopy nanomanipulator" *Appl. Phys. A*, vol. 76, no. 6, pp. 903-906, 2003.

[9] Joonhyung Kwon et al, "Atomic force microscope with improved scan accuracy, scan speed, and optical vision" *Rev. Sci. Instrum.*, vol. 74, no. 10, Oct. 2003