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Piezoresistive and self-actuated 128-cantilever arrays for nanotechnology applications

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Abstract

A major limitation for future nanotechnology, particularly for bottom-up manufacturing is the non-availability of 2-dimensional massively parallel probe arrays. Scanning proximity probes are uniquely powerful tools for analysis, manipulation and bottom-up synthesis: they are capable of addressing and engineering surfaces at the atomic level and are the key to unlocking the full potential of Nanotechnology. Generic massively parallel intelligent cantilever-probe platforms is demonstrated through a number of existing and groundbreaking techniques. A packaged VLSI NEMS-chip (Very Large Scale Integrated Nano Electro Mechanical System) incorporating 128 proximal probes, fully addressable with control and readout interconnects and advanced software will be presented.

Keywords: Piezoresistive micro-cantilever; Self-actuated micro-cantilever; Cantilever arrays

1. Introduction

After the revolutionary work by Young et al. [1] on scanning probe microscopy (SPM), Binnig and Rohrer developed the scanning tunnelling microscope STM in 1982 [2,3]. The semiconductor industry has recognized

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the power of the SPM technique for applications such as data storage, scanning lithography, quality and CD (critical dimensions) control. To validate this novel technology, a series of demonstrators are being considered where the goal is to carry out sub-10 nm metrology for high throughput measurements. There are two common approaches to increase the speed of the scanning system: (i) to construct the stage as small as possible [4] and (ii) to use cantilever array for parallel operation of self-actuated piezoresistive cantilevers. In this case, bandwidth in the vertical direction (Z) can be significantly increased. The actuator can be operated in a SPM broad bandwidth feedback loop [5]. The piezoresistive effect in silicon was discovered by Smith [6] and theoretically explained in case of n-type Si by Herring [7]. Recently, a technique allowing improvement of the design with respect to force sensitivity was developed [8]. As is well known from the quantum mechanical point of view, this is a limit below which the quantum confinement begin to have a significant influence on the electrical properties of the resistor [9]. In this paper, we present the aims of the European PRONANO-Project and first results of the novel massively parallel scanning probe (nanotool) with VLSI ASNEMS (application specific nanoelectromechanical systems) chip inside.

2. General concept

Two issues are considered as fundamental in the realization of this idea (i) the integration of the piezoresistive readout and the actuator provides the best solution to realize high speed noncontact-AFM. Piezoresistive detection is an attractive technique compared to the conventional optical beam deflection technique, especially laser-based detection can be cumbersome (ii) for signal conversion from the electrical to the mechanical domain it is necessary to add conversion elements compatible with CMOS processing, using thin film technology. The micro-actuators described in this article are based on the so-called bimetal effect. In the previous work, we demonstrated construction of cantilevers with piezoresistive readout and integrated bimorph actuators for noncontact–AFM as an alternative to optically detected devices with piezotube z actuator [5]. The feedback speed can be improved through integration of the actuator with the cantilever providing a feedback directly by applying an acting force to the cantilever. This causes the resonance frequency to be much increased compared to the normally used piezoelectric-actuator stage in commercial systems. The high resonance frequency of the cantilever, feedback loop with smaller time constants and bigger gain determine the surface scan speed by which the tip can accurately follow the topography features. In our set-up the cantilever is driven by thermal actuation at its resonance frequency (f_{res}) by an ac current with frequency ($f_{res/2}$) while z axis actuation in the z axis is provided by applying a dc current. The magnitude of the dc current determines the deflection of the cantilever, controlled by the proportional integral differential (PID) feedback loop. In this manner, a stable actuator and a soft cantilever for probing of the surface of the sample is provided. If the cantilever is operated in vacuum the quality factor increases. The phase signal shift of the driving voltage and voltage drop response of the piezoresistive sensor is monotonic, ensuring a stable and reproducible control over the full z range of probe sample interaction.

3. Cantilever array fabrication

We have fabricated piezoresistive AFM probes with integrated Si tips, which are formed at the beginning of the cantilever micro-machining process. The fabrication procedure for the cantilever beam is similar to that outlined by Rangelow et al. [10]. Here, silicon on insulator wafer of $\langle 100 \rangle$ orientation are used for wet chemical etching of the tips. The thickness of the top layer may be varied depending upon the required height of the Si tip. If the silicon tip has to be integrated on the cantilever, a thermal oxide needs to be grown and patterned to form the 8000 Å thick mask which is subsequently used for wet etching of the Si tip. After a standard RCA clean, an 8000 Å thick oxide is grown. This film is patterned and the resist mask over the oxide is employed as a mask for the boron contacts implantation. This resist mask is removed using microwave plasma striping and this is followed by growth of a passivating thermal oxide layer. Using again a resist mask the piezoresistors are configured in the oxide layer and boron implanted followed by growth of a passivating oxide layer. Aluminum for the contacts to the piezoresistors and the metal layer, forming the micro-heater and bimorph actuators are then deposited. To form the cantilever beam and to cut the single sensor chip employing RIE step, a thick resist mask is used. Finally, the resist mask is removed and the SPM cantilever arrays (Fig. 1) are separated mechanically. Fig. 2 shows schematic of the measurement and control system of the PRONANO array cantilever. The piezoresistive sensor is supplied using a precise and stable current source with output current 200 μA. Next, the AC signal corresponding to the amplitude of the cantilever vibration is amplified with a gain of 10,000 V/V and filtered using a bandpass filter with a quality factor 10 (Block2 – Fig. 2). In order to detect the higher eigenmode PRONANO cantilever vibration the bandwidth of the input amplifier is 2 MHz and to ensure high signal to noise ratio (SNR) the thermal voltage noise density of the input stage is 1 nV/Hz$^{0.5}$. The amplified and filtered vibration signal is converted using a precise and fast AC/RMS converter with time constant 50 μs (Block 3 – Fig. 2). Alternatively a phase shift detector can be applied in order to detect the interaction forces acting between the micro-tip and the surface. The output signals of the AC/RMS converter or phase shift detector is connected with an anologue proportional integral and derivative (PID) controller, whose output changes the DC current flowing through the cantilever deflection actuator (Block 4 – Fig. 2). In order to enable flexible adjustment of the cantilever feedback loop we designed a

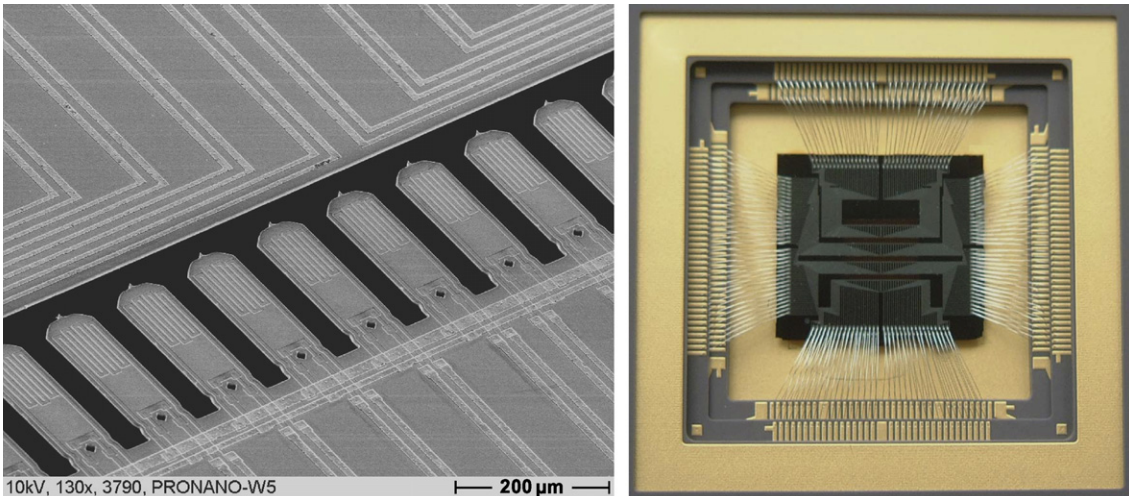

Fig. 1. A packaged, fully addressable self-actuated piezoresistive cantilever array VLSI NEMS-chip (Very Large Scale Integrated Nano Electro Mechanical System) incorporating 32 and 128 proximal probes and details of the array and an integrated Si-tip.

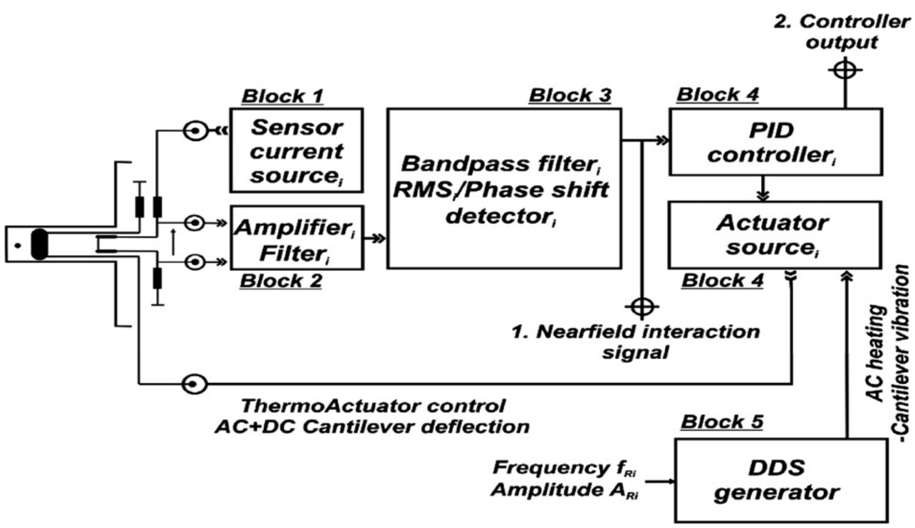

Fig. 2. Measurement and control system of the PRONANO array cantilever.

digital micro-processor controlled system which sets all parameters of the PID controller. In this way the DC PRONANO cantilever deflection is modulated so that the force interaction acting at the cantilever micro-tip remains at the defined level. In order to reduce the system response time it is proposed to excite vibration of the cantilever in higher resonance eigen mode. Therefore the frequency range of the direct digital synthesis (DDS) signal generators applied for the cantilever resonance oscillation is 2 MHz. The total AC driving power supplied to the micro-heater is below 1 mW. While surface scanning analogue signal line controller output (Fig. 2) will be monitored. Additionally the signal line nearfield interaction (Fig. 2) can be observed in order to enable efficient PID controller tuning. When the array of 32 PRONANO cantilevers is used in surface measurement, the data size of the picture, which was recorded with a resolution of 512×512 scanning lines is 33.8 MB. This corresponds to the data transfer speed of 0.66 MB/s for scanning frequency of 10 Hz. Therefore, in our experiments we utilize data acquisition system basing on a TIGER Sharc 101 digital signal processor (DSP) with internal 128 MB RAM memory [11]. In this case we are able to compress the observed data and calculate in real time the picture parameters. Additionally in order to enable integration of the cantilever arrays with the host control units we are developing field programmable gate arrays (FPGA) block which will serve to acquire data corresponding to the cantilever deflection. In this manner transfer of the data from 128 cantilevers is possible. Using the developed system we defined the requirements of the ASIC system which will control the operation of the cantilever arrays. The amplitude changes of the actuated cantilever caused by the atomic forces between the cantilever tip an the surface represent the change of the distance between the cantilever and the object surface. Sensitivity of the cantilever has been determinated by using a nanomeasuring

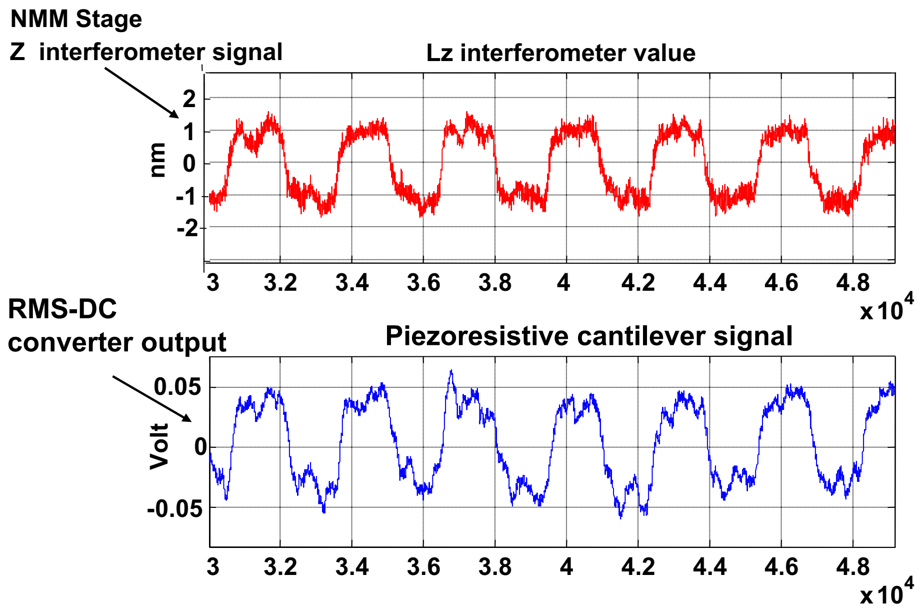

Fig. 3. Calibration of the PRONANO array cantilever using nanopositioning machine.

and nanopositioning machine (NMM), that has been developed at the Technical University of Ilmenau. The main advantage of the NMM is the possibility of the Abbe-error free interefrometric measurements and control of the object movements in the range of $25 \times 25 \times 5$ mm with a resolution of 0.1 nm. Cantilevers excited with an amplitude of 20 nm, have been brought to a distance of 50 nm above the silicon object surface. While moving the object in the Z direction of the NMM in nanometer steps, the changes of the cantilever vibration amplitude and the values of the object position measured by interferometer have been sampled simultaneously. The amplitude of the cantilever vibration has been measured at the DC output of the high sensitivity AC/RMS converter. The stage with a fixed object has been moved ± 1 nm around a fixed position, so the mean distance between the cantilever and the surface did not change. The response of the cantilever, represented by the DC output of the RMS-DC converter, that is proportional to the amplitude changes of the cantilever vibration, is shown in the lower curve of Fig. 3. The result demonstrates the very high sensitivity of the cantilever system at that working point. The cantilever reacts not only to the object steps of 1 nm but registers also the distance changes below 0.3 nm. The sensitivity of the output signal is very high – in the range of 40 mV/nm. Such signals can be used for further processing very conveniently. Fig. 4 shows the image of the silicon grating structure [12] which was recorded with the PRONANO cantilever. In this investigation the cantilever was vibrating with the frequency of 32 kHz and the amplitude of the thermally excited cantilever oscillations was about 2 nm. While surface scanning we controlled the DC current flowing through the micro-heater so that the amplitude of the tip vibration was reduced by 30%. The topography image of the test sample reveals the height of 67 nm, which corresponded with the change of the DC heating current in the range of up to alternatively 300 μW.

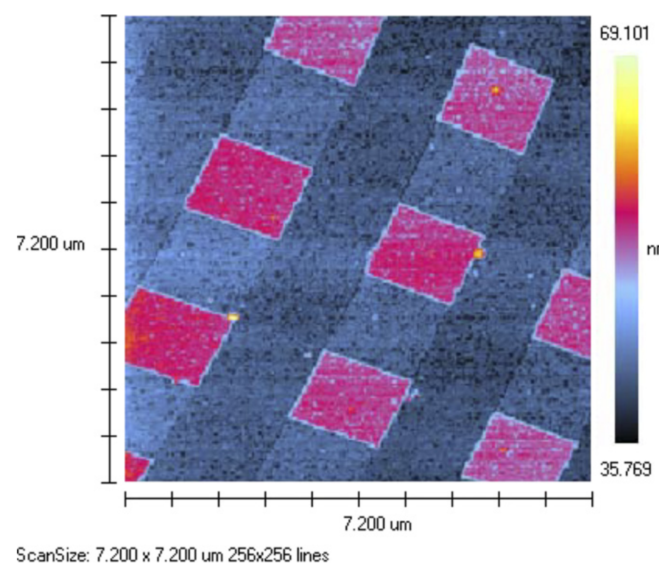

Fig. 4. Typical topography image of the test sample recorded with the PRONANO array cantilever (scanfield 7.2×7.2 μm; 256×256 lines).

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References

[1] R. Young, J. Ward, F. Scire, Rev. Sci. Instrum. 43 (1972) 99.

[2] G. Binnig, H. Rohrer, Ch. Gerber, E. Weibel, Phys. Rev. Lett. 49 (1982) 57.
[3] G. Binnig, H. Rohrer, IBM J. Res. Dev. 30 (1986) 4.
[4] G.E. Fantner et al., Ultramicroscopy 106 (2006) 881.
[5] R. Pedrak et al., J. Vac. Sci. Technol. B 21 (2003) 3102.
[6] C.S. Smith, Phys. Rev. 94 (1954) 42.
[7] C. Herring, E. Vogt, Phys. Rev. 101 (1956) 944.
[8] Tzv. Ivanov, T. Gotszalk, T. Sulzbach, I.W. Rangelow, Ultramicroscopy 97 (2003) 377.
[9] Tzv. Ivanov, T. Gotszalk, T. Sulzbach, I. Chakarov, I.W. Rangelow, Microelectron. Eng. 67–68 (2003) 534.
[10] I.W. Rangelow et al., Proc. SPIE 2879 (1996) 56.
[11] <www.analog.com>.
[12] NT-MDT SPM accessories TQ1 silicon calibration grating, <www.ntmdt-tips.com/>.