Invited: **Active scanning probes: versatile toolkit for fast imaging and emerging nanofabrication**

Ivo W. Rangelow, Tzvetan Ivanov, Ahmad Ahmad, Marcus Kaestner
Department of Micro- and Nanoelectronic Systems (MNES), Ilmenau University of Technology, Gustav-Kirchhoff-Str.1, 98693 Ilmenau, Germany

Iman S. Bozchalooi, Kamal Youcef-Toumi
Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Mathias Holz
Nano Analytik GmbH, Ehrenbergstraße 1, 98693 Ilmenau, Germany

The scanning probe microscope (SPM) has unique capabilities and is widely used for imaging as well as microfabrication. A wide variety of specialized scanning probe techniques have been developed that allow engineering of new nanoscale devices.

A major approach to SPM probe measurement is based on optical read-out [1]. However, the shortcomings of optical detection, rooted in diffraction limit and reduced sensitivity, necessitate development of novel means for probe-sample interaction measurements. Self-sensing probes have the potential to tackle these limitations. When combined with self-actuation capability, self-sensed probes also open up the possibility for parallel measurements for high throughput applications such as in semi-conductor quality control.

Active scanning probes include bending-read-out and actuation capability, which not only enable sensing of surface topology (or other surface characteristics) but also provide active control of the position of the tip. The bending-read-out in these probes is often piezoresistive [2]. Self-sensing capability based on piezo-resistivity was first introduced in 1991 [2], at Stanford University by Marco Tortonese who demonstrated real atomic resolution potential of these sensors.

In addition to imaging applications, by controlling the interaction strength between probe tip and sample it is also possible to fabricate well-defined nanometer-scale structures. As such, self-actuated and self-sensed probes can also be used as important tools in the fabrication of the next generation nano-electronic devices. In the last decade, a set of scanning probe tools for alternative lithographic techniques have been developed [3]. To summarize, the advantages of self-sensed and self-actuated probes can be listed as follows: (i) downscaling of the probe dimensions; (ii) on demand control of stiffness and resonance frequency; (iii) easy operation; (iv) capability for parallel operation; (v) and cost-effectiveness due to advanced SOI/MEMS/CMOS batch fabrication.

Our research focuses to further extend the capabilities of self-sensing and self-actuated AFM probes. To improve force sensitivity and measurement throughput (speed) we are working to increase the ratio of the probe resonance frequency to spring constant. In other words, we aim to make softer probes that feature faster dynamics. Fig.1 shows the cantilever development history in our team. In addition to probe fabrication, we have developed novel imaging modalities that use an array of probes ("Quattro" cantilever arrays) to improve imaging throughput [4]. "Quattro" cantilever array technology acts as a very powerful and low cost imaging device with an effective imaging speed of about 5mm/sec over a relatively large range. These characteristics makes our technology suitable for a wide range of novel applications e.g. for semi-conductor quality control or high-throughput nano-fabrication.

The distance between neighbouring active probes in a “Quattro” cantilever array is 125µm [4]. To be able to benefit from the full potential of these probes in high-throughput applications, the lateral scan range should be larger than the probe spacing. Over such a large lateral motion, the out of plane positioning range of self-actuating probes is not sufficient to handle large topological variations e.g. caused by sample tilt. To handle this difficulty we are also working to combine micro-actuated cantilevers with high-speed “macro” piezo actuators. We are developing a multi-actuated nano-positioner with more than 125µm lateral range and several microns of out-plane-range [5]. By combining the actuation capability of our micro and nano positioning systems we will be able to simultaneously meet the range and speed requirements of more challenging applications e.g. in surface engineering or in high-throughput nanolithography for single-digit nano devices [3]. The combination of all these capabilities makes the active scanning probes an unreplaceable tool for the creation of future emerging devices.

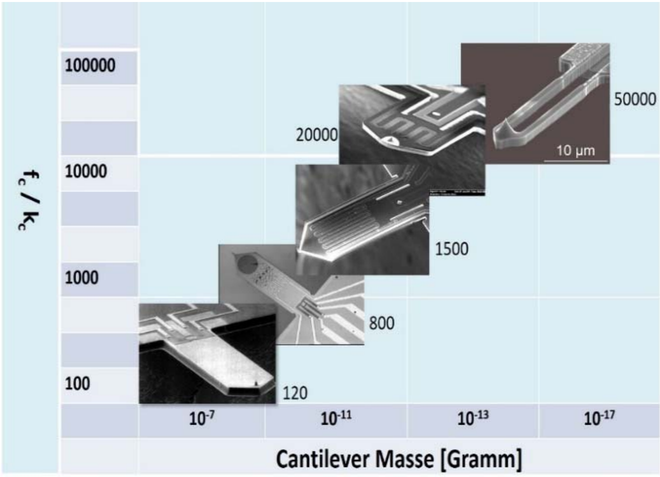

Fig. 1. Resonant frequency to spring constant ratio vs. cantilever mass of active cantilevers developed by our team.

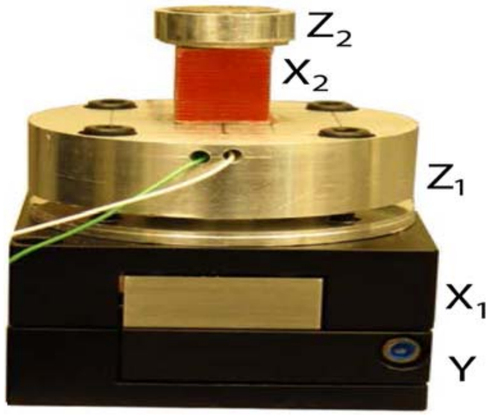

Fig 2. Our long-range and high-speed multi-actuated scanner. It contains five actuating components some short-range and high-speed and others slow and large-range. By combining, these actuators both range and speed requirements of the current applications can be met [5].

ACKNOWLEDGMENTS The research leading to these results has received funding from FP7/2007-2013 under Grant No. 318804 (SNM).

[1] Thomas Michels, Ivo W. Rangelow, Vladimir Aksyuk, Cantilever array with opto-mechanical read-out and integrated actuation for simultaneous high sensitivity force detection, International Conference on Optical MEMS and Nanophotonics (OMN), We2.4-2, Electronic ISSN: 2160-5041, 2016

[2] M. Tortonese, H. Yamada, R. C. Barrett, and C. F. Quate, "Atomic force microscopy using a piezoresistive cantilever" Transducers 97. 1997 International Conference on Solid-State Sensors and Actuators, pp. 448-451, 1991. DOI: 10.1109/OMN.2016.7565883

[3] I.W. Rangelow et.al. Pattern-generation and pattern-transfer for single-digit nano devices, Journal of Vacuum Science and Technology B34 (6); doi: 10.1116/1.4966556

[4] A. Ahmad et al. Large area fast-AFM scanning with active "Quattro" cantilever arrays, Journal of Vacuum Science & Technology B34, 06KM03 (2016); doi: 10.1116/1.4967159

[5] I. Soltani Bozchalooi, A. Careaga Houck, J. M. AlGhamdi, K. Youcef-Toumi, Design and control of multi-actuated atomic force microscope for large-range and high-speed imaging, *Ultramicroscopy*, 160 (2016) 213-224.