SCANNING ELECTRON MICROSCOPY BASED MANIPULATION AND CHARACTERISATION OF NANO-SCALE OBJECTS

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Abstract: Two scanning electron microscopy (SEM) based devices for positioning, manipulation and imaging at the nano-scale have been developed. The control and vision system is based on both a commercial scanning probe microscopy (SPM) controller and a client-server approach to ensure that nanopositioning and SEM image processing are executed in real-time. The evaluation of the two devices has been performed by implementing three different applications: (i) attachment of carbon nanotubes on SPM tips, (ii) investigation of mechanical properties of nanowires and (iii) tensile strength measurements for focused electron beam deposits.

Keywords: Cartesian manipulators, image processing, manipulation tasks, mechanical properties, robot control, robotic manipulators, telemanipulation.

1. INTRODUCTION

In recent years, the manipulation and characterisation of nanowires (NWs) and carbon nanotubes (CNTs) became a matter of particular interest in research. Due to their unique structure, small size, high aspect ratio and low density as well as excellent mechanical and electrical properties, nanotubes are expected to find use in a wide range of applications. Mounted on tungsten tips they can be applied as field emitters in displays or in high-resolution electron beam instruments (Bonard, *et al*., 1998; De Jonge, *et al*., 2003). CNTs mounted on atomic force microscopy (AFM) tips promise to overcome the limitations of standard tips regarding resolution and wear (Stevens, *et al*., 2000). Nanowires are of interdisciplinary interest to applications in the fields of bio-medical sensing, nano- and optoelectronics and photovoltaics due to their electrical, optical, mechanical and geometrical properties that deviate quite substantially from bulk (Law, *et al*., 2004).

For all these applications dedicated tools are essential to functionalise, manipulate and characterise – both mechanically and electrically – CNTs and NWs and assemble them into nano-devices. In addition, novel processes and strategies for nano-scale visualisation have to developed based on high spatial resolution imaging instruments like scanning electron microscopes (SEMs).

The manipulation and characterisation of nano-scale objects and of matter even at the atomic level has been opened up by the invention of the scanning tunneling microscope by Binning and Rohrer in the early eighties, and the subsequent invention of the atomic force microscope by Binning, *et al*. (1986). Scanning probe microscopy (SPM) based nanomanipulation has rapidly gained in importance during the last ten years, and several kinds of manipulation systems have been developed (Schaefer, *et al*., 1995; Requicha, *et al*., 1998; Theil-Hansenyk, *et al*., 1998; Li, *et al*., 2003). To overcome the main drawback of these systems, i.e. the lack of visual feedback in real-time, SPMs have been combined with haptic devices (NanoManipulator, NanoFeel, Omega Haptic Device), and virtual reality interfaces have been developed, for instance (Sitti and Hashimoto, 1998; Guthold, *et al*., 2000). Further on, SPMs have been integrated into SEMs combining the advantages of both instruments, e.g. allowing the combination of nano-scale chemistry, crystallography imaging via electron-matter interactions with information from tip-sample interactions like topography or magnetic/electrostatic force imaging. Several of such hybrid SPM/SEM systems have been developed, e.g. (Stahl, *et al*., 1994; Ermakov and Garfunkel, 1994; Troyon, *et al*., 1997; Joachimsthaler, *et al*., 2003).

In parallel to the use of SPMs, dedicated nanomanipulation systems have been developed and integrated into SEMs. This work was pioneered at the University of Tokyo by Hatamura and Morishita (1990). Subsequently, worldwide research activities in this field have been started (Yu, *et al*. 1999; Schmoeckel and Fatikow, 2000; Dong, *et al*., 2001). Compared to SPMs, these systems offer a larger workspace, greater flexibility, more degrees of freedom and dedicated control systems. However, their automation level is still low. SEM image processing, for instance, is hardly used for positioning or pick-and-place operations. Most of the systems still rely on the operator's attention to the movement of the positioning tables as shown on the SEM screen, and closed-loop nanomanipulation is still an exception.

2. SEM-BASED NANOMANIPULATION AND CHARACTERISATION SETUPS

Two different systems for the manipulation and characterisation of nano-scale objects have been developed and integrated into an SEM: (i) an atomic force microscopy setup, (ii) a six-axes Cartesian nanomanipulator. Both systems are described in the following.

2.1 AFM integrated into an SEM

The AFM setup can be used in scanning, i.e. imaging, and manipulation mode. It is composed of two different manipulators (Fig. 1). The sample is mounted on a three-axes Cartesian nanopositioning stage with integrated capacitive position sensors (P-620 series, Physik Instrumente, Germany). Piezoelectric actuators and a flexure guiding system provide a travel range of 50 µm for each axis and a sub-nanometer resolution. This stage is used to generate the scanning trajectory in scanning mode and for fine positioning of the sample in manipulation mode. For coarse positioning towards the sample, the AFM tip is mounted on a three-axes nanomanipulator with two rotational and one linear degree of freedom (MM3A, Kleindiek Nanotechnik, Germany). The manipulator is driven by piezo actuators with sub-nanometer precision; by operating the actuators in slip-stick mode a working range of more than 100 cm^3 can be achieved. For AFM imaging as well as manipulation and characterisation of nano-scale objects a piezoresistive AFM

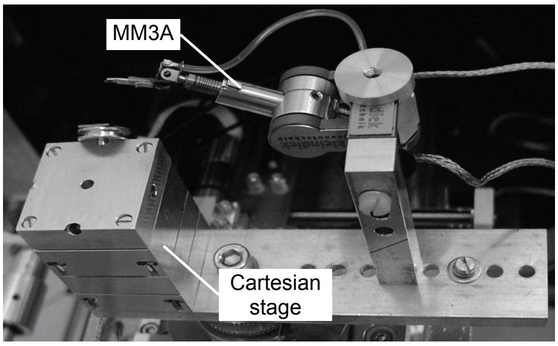

Fig. 1. AFM setup inside SEM.

cantilever can be mounted on this manipulator. Additionally, standard or specially shaped AFM cantilevers, e.g. Arrow™ probe (NanoWorld, Switzerland), can be used for nanomanipulation.

The whole setup is mounted inside an SEM such that the sample is at an angle of 60° with the electron beam. With the SEM sample stage, the sample's area of interest can be moved into the field of view. In scanning mode, the AFM is controlled using a fully digital control system for SPMs (Nanonis GmbH, Switzerland, www.nanonis.com). In manipulation mode, both nanomanipulators are controlled using the SPM controller's graphical user interface and a teleoperation device.

2.2 Cartesian nanomanipulator

The second system is based on a six-axes Cartesian nanomanipulator. This approach allows for semi-automated manipulation and characterisation of nano-scale objects and samples using different tools inside an SEM. The setup consists of four main components: nanomanipulator, nanotools, control system and SEM vision system.

Nanomanipulator. The nanomanipulator is driven by piezoelectric actuators combined with a slip-stick motion principle. The stepping-mode allows long displacements at a relatively high velocity of typically 5 mm/s. The resolution is limited to one step, typically 200-400 nm. Once the position is within less than one step distance of the target, the piezo actuators are deformed slowly until the final position is reached. In this so called *scanning mode*

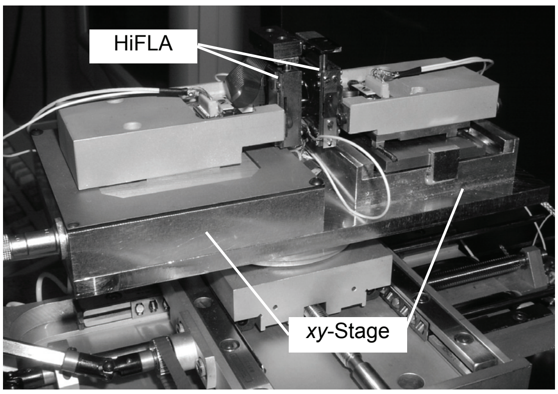

Fig. 2: Six-axes Cartesian nanomanipulator mounted on an SEM stage.