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Nanomanipulation in a scanning electron microscope

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Abstract

An increasing variety of nano-scale products and devices in key application areas like nanoelectronics, nanotechnology and biotechnology demands novel tools for three-dimensional handling, assembly, characterisation and testing of fundamental building blocks like nanotubes and nanowires. In this paper, the state of the art in nanomanipulation systems based on a bottom-up technology for the manufacturing of nano-devices is reviewed, and a novel sensor-based manipulation and processing system for nano-scale objects which can be integrated in a scanning electron microscope (SEM) is presented. A series of tools for nanopositioning, nanomanipulation and microgripping devices has been developed. The control and vision system is based on a client–server approach to ensure positioning task execution and SEM image processing in real-time. The evaluation of the nanomanipulation system is shown by means of gripping of micro-sized powder particles, and by the attachment of carbon nanotubes on tips for atomic force microscopes. With future enhancements, which are currently under development, like a micro-tools exchanger, this system is expected to be a valuable tool for research laboratories and in industry for rapid prototyping in the nano-world.

Keywords: Nanomanipulation; Nanotools; Microgripper; Scanning electron microscope; Visual control; Carbon nanotubes

1. Introduction

A major obstacle nanotechnology faces today is the lack of effective processes and devices for building and characterising nano-scale structures and systems needed for applications like data storage and nanomanipulation of materials, such as DNA, polymers or nanotubes, or the development of prototypes of nanoelectronic and optoelectronic devices made up of nanowires. Generally, there are two converging technologies to built nano-scale structures and devices, top-down and bottom-up technology, respectively. The top-down technology uses well-known processes from semiconductor industry to fabricate small structures with optical lithography. X-ray and electron-beam lithography can further reduce the smallest feature size, however, at the cost of an increase in complexity and much higher investments for production lines. Thus, the top-down technology is less promising for building nano-devices, and, especially, hardly affordable and adequate for research laboratories as well as small and medium-sized enterprises.

Alternatively, nano-devices can be built from the bottom by directly assembling atoms, molecules, or other nano-objects. The bottom-up technology can be implemented using two different approaches. The first one is based on self-assembly. Self-assembly is the autonomous placement of components in predefined locations. It is driven by the tendency of physical systems to minimise their potential energy. The second bottom-up approach is characterised by the controlled manipulation and positioning of atoms, molecules, clusters or nanometer-sized objects, one-by-one, with the aid of elaborate equipment and tools, such as atomic force microscopes (AFMs) or dedicated nanomanipulators in scanning electron microscopes (SEMs). The

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work described hereinafter focuses on the SEM-based approach.

SEM-based nanomanipulation systems must be adaptable to various applications, not only in manipulation and assembly but also in the characterisation of materials, small-scale structures and devices [1]. Thus, a modular design is required to ensure a high flexibility, and an easy reconfigurability. Particularly with regard to semi-automated nanomanipulation, complex and repetitive tests without the need to open the SEM chamber have to be accomplished. This will reduce the handling time, increase the reliability and quality and generate a user-friendly process. One of the biggest challenges evolves from the fact that nano-scale objects require new strategies for their visualisation, analysis and manipulation both as single objects and in a batch. It is obvious that to attain further advances in nanotechnology, focused effort is necessary in developing new measurement and manipulation tools that can be integrated into high spatial resolution SEMs.

The manual processing of a workpiece by a craftsman in the macro-world has, in its most primitive form, three main functions: (i) hold the workpiece in one hand, (ii) process the workpiece with a tool by the other hand and (iii) observe the processing with the eyes and by tactile means [2]. When going from manual processing at large-scales to the handling of nano-objects, it becomes necessary to transmit and scale human operations from the macro-world to the nano-world (by graphical user interfaces, telemanipulation devices and actuators), and, vice-versa, information from the nano- to the macro-world (mainly by vision/force sensors and displays). Ideally, information from the nano-world addressing all human senses would be acquired by sensors, transferred, scaled and appropriately presented to the operator.

In order to map a manual, macro-world process to the nanometer world, a nanomanipulation system has to provide several essential functions: manipulation, positioning, fixation and visualisation of nano-objects, displacement and force sensing capabilities. The semi-automated execution of tasks additionally requires three-dimensional coordinate measurements on a sub-micron scale, e.g. through stereo images or three-dimensional reconstruction, and the development of robust algorithms to detect the position and the orientation of nano-objects from SEM images within an often-high noise.

Starting from a review of the state of the art in nanomanipulation systems, the development of a novel, SEM-based system for manipulation and processing at the nano-scale is described in this article. Finally, the evaluation of this system is shown by means of the vision-based attachment of carbon nanotubes on AFM tips.

2. Review of the state of the art in nanomanipulation systems

Two different approaches are pursued in the development of nanomanipulation systems: (1) researchers coming mainly from physics and chemistry use adapted scanning tunneling microscopes (STMs) and atomic force microscopes and (2) researcher and engineers working in the fields of robotics, precision engineering and microtechnology developed novel systems based on their experiences in the respective fields. The second approach led to the development of a great number of versatile systems, including different actuation principles, sensors, image processing and control systems.

2.1. Nanomanipulation using scanning tunneling and atomic force microscopes

The manipulation of nano-scale objects, and of matter even at the atomic level is a comparatively new research field. It has been opened up by the invention of the scanning tunneling microscope by Binning and Rohrer in the early 1980’s [3,4], and the subsequent invention of the atomic force microscope by Binning et al. [5]. Even though both types of microscopes were designed for investigating surfaces of electrically conduction materials and insulators, respectively, it was soon discovered that they could also be used to modify these surfaces, and manipulate objects as small as atoms. Eigler and Schweizer were the first who manipulated atoms in an STM on a single-crystal nickel surface and formed the IBM logo out of 35 xenon atoms [6].

The environmental conditions required to manipulate atoms, ultra-high vacuum (UHV) and low temperatures (4 K), and the limitation to electrically conducting surfaces add up to too large constraints to be used as a universal technique for the processing and assembly of nano-scale objects. AFMs, however, can operate in ambient conditions, image insulators, and therefore overcome several drawbacks of STMs. Consequently, AFM-based nanomanipulation has rapidly gained in importance during the last 10 years and several kinds of manipulation systems have been developed [7–11].

The main drawback of this technique is the lack of visual feedback of the manipulation process in real-time. Each operation has to be designed offline based on a static AFM image and transferred to the AFM control system to carry out the task in open loop. The success of the operation has subsequently to be verified by a new image scan. Therefore, AFMs have been combined with different haptic devices, such as NanoMan (Veeco, USA), NanoManipulator^{TM} (3rdTech, USA), NanoFeel^{TM} 300 manipulator (NanoFeel, Switzerland) and the Omega Haptic Device (Force Dimension and Nanonis, Switzerland). Additionally, virtual reality (VR) interfaces to facilitate feedback during nanomanipulation have been developed [12,13]. Haptic devices provide the operator with real-time force-feedback but they cannot compensate for visual feedback. Virtual reality interfaces can display static, virtual environment and a dynamic position of the tip. However, they do not reflect any environmental changes in real-time and the operator is still kind of “blind”.