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High Rate 3D Nanofabrication by AFM-Based Ultrasonic Vibration Assisted Nanomachining

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Abstract
This paper introduces a high precision 3D nanofabrication approach using ultrasonic vibration assisted nanomachining using an AFM operating in constant height control mode. Nanostructures with 3D features were successfully fabricated on PMMA film with the feature height manipulated through controlling the absolute heights of z-scanner in AFM. Two methods were used to move the AFM tip to create desire features, vector mode and raster scan mode. Relatively simple features, such as stair-like nanostructure with five steps was successfully fabricated in vector mode. Complex nanostructure with discrete height levels and continuous changes were successfully fabricated in raster scan mode. By carefully selecting the machining parameters, the feature dimension and height can be precisely controlled with only small variation from the designed value. Moreover, this paper explores the capability of transferring 3D nanostructures from PMMA film onto silicon substrate. After calibrating the recipe of Reactive Ion Etching (RIE) process, 3D nanostructures are successfully transferred to silicon wafer with controllable selectivity between PMMA and silicon. The results of fabricating 3D structures on silicon substrates show promising potential of many applications, such as mold preparation in nanoimprint lithography.

Keywords: 3D nanomachining, Tip-based nanofabrication, Atomic Force Microscope (AFM), Ultrasonic *vibration* Assisted Nanomachining

1 Introduction

Nanotechnology as a cutting-edge engineering branch has provided significant impacts not only in fundamental sciences in physics, chemistry and biology, but also in applied engineering including electronic and mechanical devices. Many nanofabrication techniques have been developed, including nanomanipulation (Rubio-Sierra 2005), nanopatterning (Rosa 1998), nanomachining (Fang 2003), nanosurgery (Firtel 2004), nanodissection (Wen 2004), and tip-based nanomachining (Martín 2005, Martinez 2008, Piner 1999), which are mostly applied for 2D nanofabrication. Three dimensional (3D) nanofabrication approaches have attracted a lot of attention recently, motivated by many applications in various fields, such as optics, plasmonics, nanoelectromechanical systems (Fu 2011, Kettle 2008,

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Keskinbora 2013, Yuan 2012). In order to satisfy the increasing needs of 3D nanostructures, a few 3D nanofabrication approaches have been developed recently. The typical approaches include grayscale e-beam lithography (EBL) (Yamazaki 2004), laser nanopatterning (Li 2011, Ali 2008), focused ion beam lithography (IBL) (Nellen 2006, Taniguchi 2006, and Villanueva 2006), UV nanoimprint lithography (Lee 2008), colloidal lithography (Yang 2006), anisotropic etching (Berenschot 2013), corner lithography (Berenschot 2008) and soft-lithographic techniques (Jeon 2004).

Among those 3D nanofabrication approaches, grayscale EBL is the most competitive one with the excellent resolution and process flexibility. The basic idea of grayscale EBL is to vary the writing dose of electron beam on resists based on pixel intensity. By changing the exposure dosage on resists at different locations, the exposed resist depth and the solubility of resists in the developer change accordingly. Stair-like 3D nanostructures have been fabricated through grayscale EBL (Hu 2003, Kim 2007, Lee 2008, Sure 2003, Totsu 2006). Despite the capability and flexibility of EBL, grayscale EBL has its own limitations due to the mechanism of the fabrication approach. The fabrication resolution is limited by the scattering effect of electrons in resists (Chang 1975, Owen 1983). Similar to focused ion beam lithography, the cost for EBL is relatively high due to the expensive EBL system.

Tip-based nanofabrication approaches have their unique advantages for 3D nanomachining. It is an approach with significantly lower cost compared with grayscale EBL when taking into account both the capital and maintenance costs. A combined AFM/precision-stage system has been developed to machine 3D nanostructures with complex geometries on Al samples by mechanical scratching (Yan 2010). An ultrasonic force regulated nanomachining approach was innovated for high rate nanomachining (Zhang 2012, Zhang 2013). A in plane circular xy-vibration and an ultrasonic vibration in z direction are utilized to improve the efficiency and performance of nanomachining processes. The xy-vibration is used as a means for controlling the width of trenches as well as increasing the material removal rate. The ultrasonic z-vibration is used to regulate the depth of machined features with the advantages of reduced normal force and lateral force (Zhang 2012, Zhang 2013). Trenches with widths ranging from tens to hundreds of nanometers and depths of a few to tens of nanometers can be created by a single machining path. Based on this high rate tip-based nanomachining approach, a 3D nanofabrication method was developed. A stair-like 3D nanostructure with 6 steps was fabricated layer-by-layer assisted by ultrasonic z-vibration under a given setpoint force. Convex and concave 3D circular features were fabricated by changing the setpoint force applied on sample surfaces (Deng 2015). Overlap rate in raster scan significantly affects the fidelity of final 3D nanostructures in this approach.

In this paper, an AFM-based precise 3D nanofabrication approach is developed using ultrasonic vibration assisted nanomachining in constant height control mode, in which absolute height values of the z-scanner are selected in AFM to regulate the feature depth in nanomachining. In the constant height control mode, the location of the cantilever tip is controlled directly when a rigid cantilever is used. During machining processes, the in-plane circular xy-vibration is utilized to control the virtual tool size and increase the machining speed. Two methods were used to move the AFM tip to create desire features, which are vector mode and raster scan mode. In vector mode, a stair-like 3D nanostructure with five steps is fabricated by moving the tip along the designed vector toolpath. In raster scan mode, the tip scans a predesigned bitmap image pixel-by-pixel with depth control by the grey scale value at each pixel. Nanostructures with discrete 3D levels of height were successfully fabricated. Moreover, 3D nanostructures with continuous changes in height were also fabricated in raster scan mode, including pyramids and cones. Discussions are made about the differences of fabrication processes under vector mode and raster scan mode. Finally, 3D nanostructures fabricated on PMMA surfaces were successfully transferred onto silicon surface by reactive ion etching (RIE). Resulting 3D nanostructures on silicon substrate indicate good feature transferability from PMMA to silicon.