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Review

The fabrication of 3-D nanostructures by a low- voltage EBL

Seung Hun Oh[a], Jae Gu Kim[b], Chang Seok Kim[c], Doo Sun Choi[b], Sunghwan Chang[b], Myung Yung Jeong[c,*]

[a] *Department of Nano Science and Technology, Pusan National University, Republic of Korea*
[b] *Department of Nano-Mechanical Systems, Korea Institute of Machinery and Materials, Republic of Korea*
[c] *Department of Cogno-Mechatronics Engineering, Pusan National University, Republic of Korea*

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ABSTRACT

Three-dimensional (3-D) structures are used in many applications, including the fabrication of optoelectronic and bio-MEMS devices. Among the various fabrication techniques available for 3-D structures, nano imprint lithography (NIL) is preferred for producing nanoscale 3-D patterns because of its simplicity, relatively short processing time, and high manufacturing precision. For efficient replication in NIL, a precise 3-D stamp must be used as an imprinting tool. Hence, we attempted the fabrication of original 3-D master molds by low-voltage electron beam lithography (EBL). We then fabricated polydimethylsiloxane (PDMS) stamps from the original 3-D mold via replica molding with ultrasonic vibration.First, we experimentally analyzed the characteristics of low-voltage EBL in terms of various parameters such as resist thickness, acceleration voltage, aperture size, and baking temperature. From these e-beam exposure experiments, we found that the exposure depth and width were almost saturated at 3 kV or lesser, even when the electron dosage was increased. This allowed for the fabrication of various stepped 3-D nanostructures at a low voltage. In addition, by using line-dose EBL, V-groove patterns could be fabricated on a cured electron resist (ER) at a low voltage and low baking temperature. Finally, the depth variation could be controlled to within 10 nm through superposition exposure at 1 kV. From these results, we determined the optimum electron beam exposure conditions for the fabrication of various 3-D structures on ERs by low-voltage EBL. We then fabricated PDMS stamps via the replica molding process.

Contents

1. Introduction

Currently, there is an increasing demand for 3-D structures that can be used in many applications, including the development of optoelectronic and bio-MEMS devices [1,2]. Various methods for

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* Corresponding author.
E-mail address: myjeong@pusan.ac.kr (M.Y. Jeong).

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fabricating such structures have been demonstrated. Among them, nano imprint lithography (NIL) is a simple and attractive technique that allows for the fabrication of 3-D patterns at a low cost [3,4,5]. However, the resolution of the 3-D structures produced by NIL is directly affected by the shape and precision of the stamp used. Therefore, precise fabrication of 3-D stamps is essential in NIL. Nanoscale stamps are mostly fabricated via electron beam lithography (EBL) since the diameter of focused electron beams is on the order of a few nanometers. Normally, EBL is performed at a high acceleration voltage so that the electron beam can be subjected to additional focusing via external electromagnetic fields, and without any additional steps, in order to reduce the spot size to the 10-nm level. However, high-voltage EBL has several disadvantages, including low throughput, proximity effects, and high cost. Moreover, it is impossible to control the depths and profiles of the exposed patterns because of the high energy of the electrons. Therefore, it is difficult to fabricate 3-D patterns directly by high-voltage EBL.

Recently, many researchers have studied the feasibility of using low-voltage EBL for 3-D structure fabrication. In low-voltage EBL, the influence of proximity effects on structure fidelity is suppressed, and high sensitivity is achieved. Therefore, e-beam pattering using micro-column arrays at a low voltage (1–3 kV) has been proposed to overcome the difficulties associated with high-voltage EBL. But, a major drawback of low-voltage EBL is the inefficient penetration of the thick resist by the low-energy electrons used. However, this characteristic means that the depths of exposed resist patterns could be controlled through the proper choice of electron beam energy. Many studies on the fabrication of 3-D nanostructures by low-voltage EBL have been carried out [6,7,8,9]. Taniguchi et al. fabricated 3-D structures with depth variation by controlling the acceleration voltage over a constant dosage range [8,9]. They focused only on the depth variations caused by changes in the acceleration voltage. However, in low-voltage EBL, the depths and profiles of the exposed patterns are determined by many other parameters as well, such as dosage, aperture size, baking temperature, and step size. To date, there has been no study on the e-beam exposure characteristics in terms of these parameters.

In this study, we carried out experiments to compare low-voltage with high-voltage EBL and investigated the effects of several parameters such as acceleration voltage, aperture size, resist thickness, and baking temperature at the low-voltage EBL. From the results of these experiments, we could know the characteristic of electron beam energy at the low voltage according to e-beam parameters and fabricate 3-D original ER masters using these characteristics of low voltage EBL. We then precisely fabricated polydimethysiloxane (PDMS) stamps via the replica molding process with ultrasonic vibration.

2. Experiments

The fabrication of a 3-D stamp for NIL involves two major steps, as illustrated in Fig. 1. First, an original 3-D ER master is fabricated using characteristic of low-voltage EBL with respect to several parameters. A polymeric stamp is then fabricated via the replica molding process with ultrasonic vibration.

We used a cleaned SiO_2 substrate with a thickness of 1 mm for the EBL process. A 30-nm Cr layer and a 500-nm Au layer were deposited on the substrate by sputtering to prevent a substrate charging problem. Then the positive tone resist PMMA 495k (Micro Chem Co.), which is the most widely used in EBL, was spin-coated on a prepared substrate to thicknesses of about 30 nm, 300 nm, and 600 nm to investigate the influence of resist thickness. The samples were cured at 200 °C and 120 °C for 5 min to remove the solvents and to investigate the influence of baking temperature. The aperture size was set to 7.5 um. EBL was performed using the Raith 50 FE system. The exposure of this system varies from 200 eV to 30 keV, allowing us to study electron beam exposure at low voltages. The prepared samples were subjected to electron beam irradiation at various EBL parameters. The beam current was measured with a Faraday cup mounted on the sample stage. The samples were exposed by the area dose and line dose methods. The exposed resist was developed in a 3:1 solution of methylisobutylketone and isopropyl alcohol for 45 s, rinsed in isopropyl alcohol for 20 s, and then blow-dried with pure nitrogen gas. To measure the precise width and depth of the developed patterns, we used field-emission scanning electron microscopy (FE-SEM, Raith 50 FE system) and atomic force microscopy (AFM, PSIA Co., XE-150 model), operating in a non-contact mode and equipped with a silicon tip. The scan rate was set to the low value of 0.15 Hz for precise measurement of the exposed nano-patterns.

We compared the exposed patterns using low-voltage and high-voltage EBL. In the low-voltage case, we also analyzed the dimensional changes and profiles of the exposed patterns with respect to several EBL parameters. We determined the optimum electron beam exposure conditions for the fabrication of the various 3-D structures. Using these results, we designed patterns for the e-beam exposure and fabricated original ER masters with 3-D structures.

We then fabricated PDMS 3-D NIL stamps by replica molding of the original ER masters. The PDMS liquid was Sylgard 184 from Dow Corning Company, and the precursor and curing agents were mixed at the regular ratio of 10–1. After mixing, the PDMS liquid was stabilized and then poured into the original ER master to ensure an adequate thickness for use as a mold for UV imprint lithography. The PDMS liquid was fully cured on a hot plate at 70 °C for 2 h. We fabricated PDMS stamps for UV embossing after detaching the cured PDMS from the original masters.

3. Results and discussion

3.1. Characteristics of e-beam energy with respect to several parameters in low voltage EBL

In e-beam lithography, the size of the exposed pattern is determined by the dosage, which is the electron beam energy required to break the linking structure of the electron resist. The dosage is defined by

$$\text{Dosage} = \frac{I_{\text{probe}} \times t_{\text{dwell}}}{SSz^2} \tag{1}$$

where I_{probe} is the beam current, t_{dwell} is the dwell time, and SSZ (step size) is the distance between spots. The beam current depends on the acceleration voltage and the aperture size. The size of the exposed patterns varies with acceleration voltage, aperture size, resist material, substrate material, baking temperature, and resist thickness. We analyzed the effects of these parameters in low-voltage EBL. For the basic experiments, the line width was set to 300 nm and the spacing between the lines was 1500 nm at area dose method. The dosage was varied from 10 μC/cm^2 to 270 μC/cm^2. The step size was 6.4 nm for the area dose and the working distance was 5.9 mm. For line dose exposure, the dosage was varied from 1000 pC/cm to 10,000 pC/cm and the step size was set to 3.2 nm.

3.1.1. Effect of acceleration voltage and resist thickness

We first compared the fabricated patterns using high-voltage and low-voltage EBL. Fig. 2 shows the results obtained for various acceleration voltages (1 kV, 10 kV) and resist thicknesses (30 nm, 300 nm). The width of the exposed line patterns was much smaller at 1 kV than at 10 kV. At 1 kV, the width variation over all dosages was less than 60 nm. On the other hand, at 10 kV, the variation in the pattern widths exceeded 600 nm in the dosage range from