A Dummy-Pattern-Assisted Lift-Off Method for Small and Dense Nanostructures

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Abstract. Nanostructures have attracted much attention because of wide application. Moreover, most of the nanostructures play the function through small and dense patterns in irregular shape, which indicates that the fabrication process is utmost important. In general, a lift-off process is used to transfer the pattern from resist to substrate. However, for small and dense patterns, the lift-off does not work well. In this paper, a dummy-pattern-assisted lift-off method is present. With added dummy patterns, a deep and thin valley forms on the resist but does not contact the substrate. The following deposited metal film may not fully cover the valley or form a weak connection in the valley. Therefore, the metal film is easily lifted off in the valley when the sample is dipped in the acetone, which could result in a successful lift-off. This novelty method is able to improve the quality of nanofabrication by lift-off process.

Keywords. Nanostructure, lift-off, fabrication process, electron beam lithography.

1. Introduction

Nanostructures have unique properties because the nanoscale dimension presents surface effect and quantum effect, and its application becomes really hot \cite{1-3}. Metalens could replace the traditional optical elements with simple and effective optical system \cite{4-6}. Virtual Reality (AR) and Augmented Reality (VR) smart glasses are based on nanoscale grating patterns \cite{7-10}. Electron beam lithography (EBL) can provide excellent patterning solution and flexible pattern variation, therefore EBL is widely used in the nanostructure fabrication.

Since E-beam resist is not a perfect hard mask for etching in extremely small dimension, it is necessary to transfer the nanostructure from the resist to the metal film by lift-off process \cite{11}. Because the nanostructure has small and dense patterns in irregular shape, the metal film is always trapped during lift-off process. This leads to the distorted nanostructures. Consequently, a simple and effective lift-off method need to be developed.

2. Experiment

A p-doped silicon wafer is selected as the substrate. After the standard cleaning procedure (SC1, SC2,
BOE), the wafer is baked at 180°C for 10 minutes (mins), followed by polymethyl methacrylate coating (PMMA, AR-P 672.03, ALLRESIST Company). The resist thickness is 230 nm measured by ellipsometer. After coating, the wafer is baked at 150°C for 3 mins and then the sample is transferred to the EBL. The EBL (nB5, NanoBeam) with 80 kV acceleration voltage and a beam current of 9 nA is applied in this process. The sample is developed in a developer (IPA:MIBK=3:1) for 3 mins and then dried by N₂ gas. Chromium (Cr) film with thickness of 70 nm is deposited by electron beam evaporator (TF500, HHV), following by a lift-off process in acetone for 5 mins to remove the unnecessary metal film. Finally, the wafer is cleaned by DI water and dried by N₂ gas. All the samples are investigated in scanning electron microscopy (SEM, ZEISS).

3. Results and Discussion

The mask layouts used in EBL are shown in figure 1 to explain the role of dummy patterns in the lift-off process. Figure 1a is the original layout and the blue region is for exposure. With this mask, the metal film always trapped in the small and closed patterns after liftoff process. If we use sonicate to enhance the liftoff, the pattern always destroyed. In general, a successful lift-off process depends on the metal film disconnection between the resist and the substrate or the film on the resist suffers bad coverage, so the acetone could contact and dissolve the resist. Based on the latter reason, a line of small square patterns with the width of 20 nm is added in the unexposed area in order to form a valley in the resist but not contact the substrate, which could destroy the film coverage to let acetone contact resist easily, as shown in figures 1b and 1c. The added square patterns are dummy patterns which would be exposed. The dummy region has the same exposure doses as the previous exposure region. In this experiment, we do a dose matrix and the exposure doses are 6, 6.5, 7 and 7.5 C/m² respectively. For lift-off process, the thickness of the metal film is expected to be smaller than 1/3 of the thickness of resist according to previous experience. Thus, a 70 nm Chromium (Cr) film is deposited after development, as shown in figure 2a. After that, the dummy patterns would open a line in the unexposed area. It looks like a deep and thin valley on the resist and the metal film cannot fully cover the valley or form a weak connection in the valley region, which results in bad metal film coverage on the resist, as shown in figure 3. As a result, the metal film is pretty easy to be broken near the valley and acetone could easily contact the resist through the opened line and realize a complete nanostructure, as shown in figure 2c.

The optimal exposure dose for the dummy pattern is expected to be figured out through experiment. In this paper, the best exposure dose is 7 C/m². If the dummy pattern exposure dose is smaller than the optimal dose, such as 6 and 6.5 C/m² in this experiment, the valley in the resist is shallow thus the metal film fully covers the valley, so the dummy pattern cannot play the role of destroying the metal film. However, if the dummy pattern exposure dose is larger than optimal dose, such as 7.5 C/m² in this experiment, the dummy pattern in the resist is fully exposure and the following film could contact with substrate through the dummy pattern, as shown in figure 2c. The unexpected dummy pattern appears in the nanostructure and this should be avoided.

The dummy pattern is the critical part of the novelty dummy-pattern-assisted lift-off method. First, the addition of dummy pattern cannot affect the original pattern exposure. Hence the dummy pattern is supposed to be in small size and locate in the center of the closed pattern. Normally, the exposure dose is same for both the targeted pattern and the dummy pattern. However, if the dummy pattern exposure affected the targeted pattern, the exposure dose of dummy could be smaller than the targeted pattern. Second, the pattern could be in any shapes such as cube, circle and triangle but cube could be simplest one for layout design which would have the same outcome as circle in scale of tens of nanometers. Additionally, in order to form a valley, the dummy patterns should arrange in a line. Third, dummy pattern should disappear after the lift-off so that the dummy patterns cannot contact the substrate after development.

4. Summary

In this paper, a new lift-off method is presented. With dummy patterns added to the original mask, a
deep and thin valley is formed on the resist. After the metal film deposition, a weak film connection is built on the valley and the acetone could contact the resist through the valley, leading to a successful and effective lift-off. This method is simple and has great maneuverability.

Figure 1. (a) The original mask, (b) and (c) dummy patterns are added in the unexposed regions.

Figure 2. (a) A 70 nm Chromium (Cr) film is deposited on the PMMA. (b) After a lift-off process in acetone, the pattern is lift-off clearly. (c) With wrong exposure dose, the resist in the dummy pattern is fully exposed and the dummy pattern could appear in the original nanostructure.

Figure 3. The dummy patterns form a deep and thin valley on the resist.
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