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A negative tone lift-off method for small metal holes using PMMA/SiO_2 double layer

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Abstract. We propose a novel method to fabricate small apertures in a metal film using polymethyl methacrylate (PMMA). A PMMA/SiO_2 double layer is employed to perform a negative tone lift-off with SiO_2 as a sacrificial layer. Through this method, we succeeded in making sub-50 nm holes in a metal film using well-established individual fabrication steps. The proposed method will be more reliable and economical compared to the hydrogen silsesquioxane/PMMA bilayer method.

Keywords. E-beam lithography; lift-off; metal-hole.

1. Introduction

Submicron size holes or slits in a metal film are often required in recent optical devices, such as single photon light emitting diodes or microcavity single photon emitters [1,2]. While the removal of metal for small apertures can be done by focussed ion beam milling, this process is likely to damage the active emitters which are shallowly located below the apertures [3,4]. On the other hand, lift-off after patterning small holes by electron beam lithography (EBL) and depositing metal film is a good method to fabricate these structures without damaging the active emitters.

Polymethyl methacrylate (PMMA) has been studied extensively and is the most frequently used resist for EBL with its fabrication recipes being already well-established. Fabrication of nm-size PMMA patterns on SiO_2 with EBL is also routinely used [5,6]. Recently, a lift-off method employing multilayer resists, such as PMMA/MMA bilayer or other multilayer resists, has been used to achieve better lift-off patterns [7,8]. However, PMMA is a positive resist for which the exposed area is removed in the development process. As a consequence, to make small holes in a metal film, the whole area except for the small holes should be exposed to the electron beam, which results in a very long electron beam writing time and makes its fabrication almost impossible. In addition, proximity effects make it difficult to achieve accurate sizes and shapes of the desired pattern.

Alternatively, in EBL using a negative resist (Ar-N 7500.18), only small areas need to be exposed for lift-off so that the writing time is minimal and the pattern quality can be high. However, proximity effects in this process induce the over-cut shape resist pattern which makes lift-off very difficult, as shown in figure 1 [9,10]. To overcome this problem, an EBL fabrication method using a hydrogen silsesquioxane (HSQ)/PMMA bilayer was recently developed [11,12]. Although development of its recipes are currently ongoing, HSQ is still not commonly used as it is expensive and very sensitive to the environment when compared to PMMA [13].

In this work, we propose a reliable and straightforward fabrication method for small open holes in a metal film using PMMA/SiO_2 double layers where the individual steps are well-established. Sub-50 nm size holes in a metal film are demonstrated using simple and standard fabrication processes.

2. Experimental

The proposed negative tone lift-off process is detailed in figure 2. First, a 200 nm SiO_2 layer is deposited by plasma-enhanced chemical vapour deposition on a GaAs wafer. This layer acts as a sacrificial layer for the final lift-off. On top of the SiO_2 layer, an 80 nm PMMA (c950K A2) layer is spin-coated for 40 s at 3000 rpm (figure 2a). The layer is then pre-baked for 1 min at 180°C and EBL is conducted at 20 keV. The exposed PMMA is developed for 40 s at room temperature in a mixed solution of methyl isobutyl ketone (MIBK) and isopropyl alcohol (IPA) in a 1:3 ratio, followed by rinsing with IPA for 20 s (figure 2b). A 50 nm nickel is deposited by an electron beam evaporator (figure 2c), followed by PMMA lift-off to form a etch metal mask on

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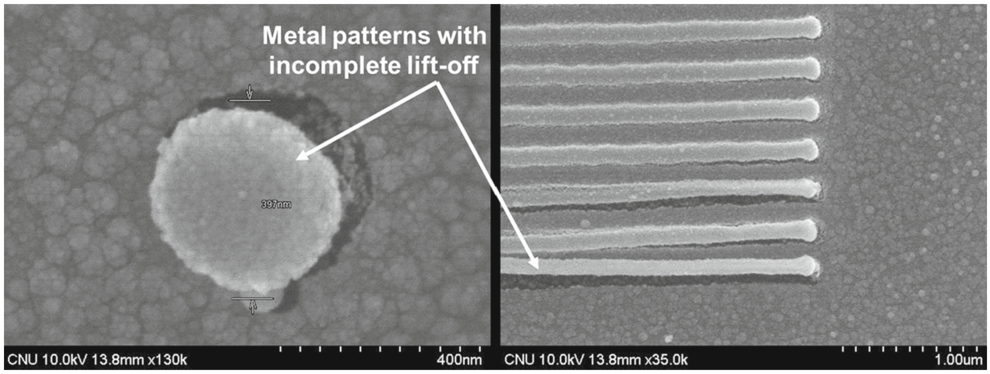

Figure 1. Scanning electron microscope (SEM) images of lift-off results using a negative resist.

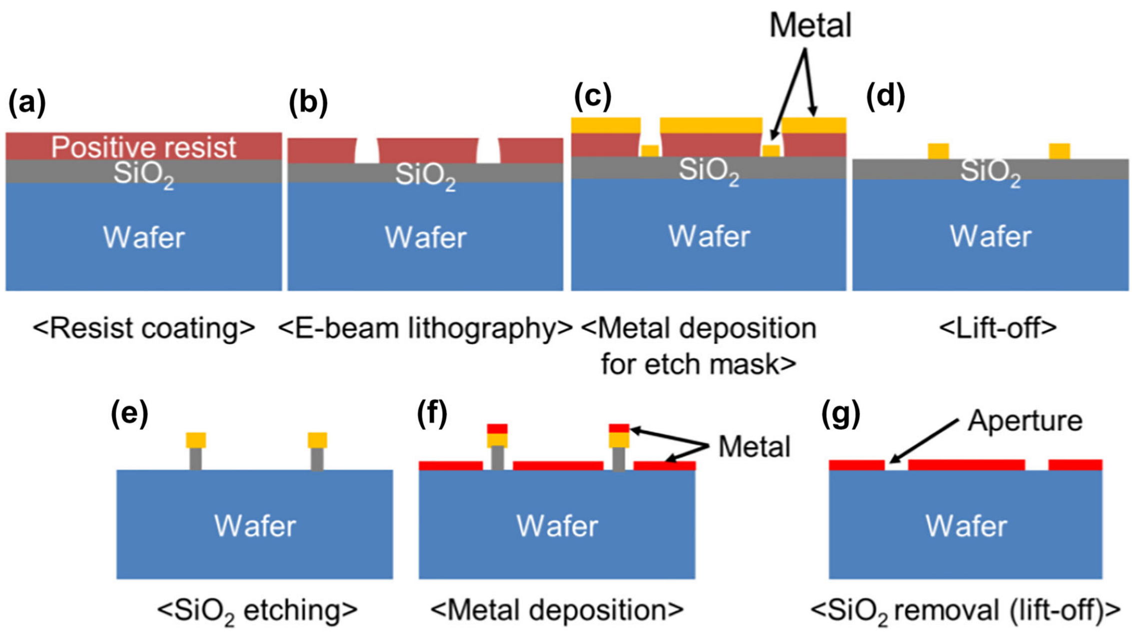

Figure 2. Schematic diagram of the negative tone lift-off process using PMMA/SiO_2 double layer.

the SiO_2 layer (figure 2d). With the metal mask, the SiO_2 layer is dry-etched by an inductively coupled plasma reactive ion etcher (ICP-RIE) (figure 2e). Then, 50 nm nickel is deposited by the electron beam evaporator to form a metal film (figure 2f), followed by SiO_2 lift-off. This final lift-off is done by immersing the sample in buffered oxide etchant (BOE) solution for 4 min in a top-side down configuration, revealing small apertures in the metal film (figure 2g).

3. Results and discussion

Figure 3a is an SEM image of a fabricated nickel etch mask on SiO_2, corresponding to figure 2d. The metal mask was fabricated without any problems since the PMMA patterning process on the PMMA/SiO_2 double layer and the PMMA lift-off process were very reliable. SEM images of SiO_2 pillars, at the centre of the sample sized 10 $\times$ 10 mm, etched from 200 nm thick SiO_2 film by ICP-RIE with a 50 nm thick etch metal mask are shown in figure 3b and c. To get an undercut profile for the SiO_2 pillars by over-etching the SiO_2 layer, the target etch depth was 250 (figure 3b) and 300 nm (figure 3c). The undercut profile is clearly observed in figure 3c due to the 100 nm over-etching, resulting in lateral etching of the SiO_2 layer. Figure 3d is an SEM image for a SiO_2 pillar with additional wet etching in a BOE 6:1 solution for 10 s to attain a more pronounced undercut profile. Nevertheless, we succeeded in achieving small holes in the metal film even with the SiO_2 pillars as shown in figure 3b and c.

Figure 4 is an SEM image of a metal hole with a diameter of $\sim$35 nm, finally obtained after electron beam evaporation of metal and lift-off. To obtain the better image for this small size hole, the structure was coated with 10 nm of Au/palladium.

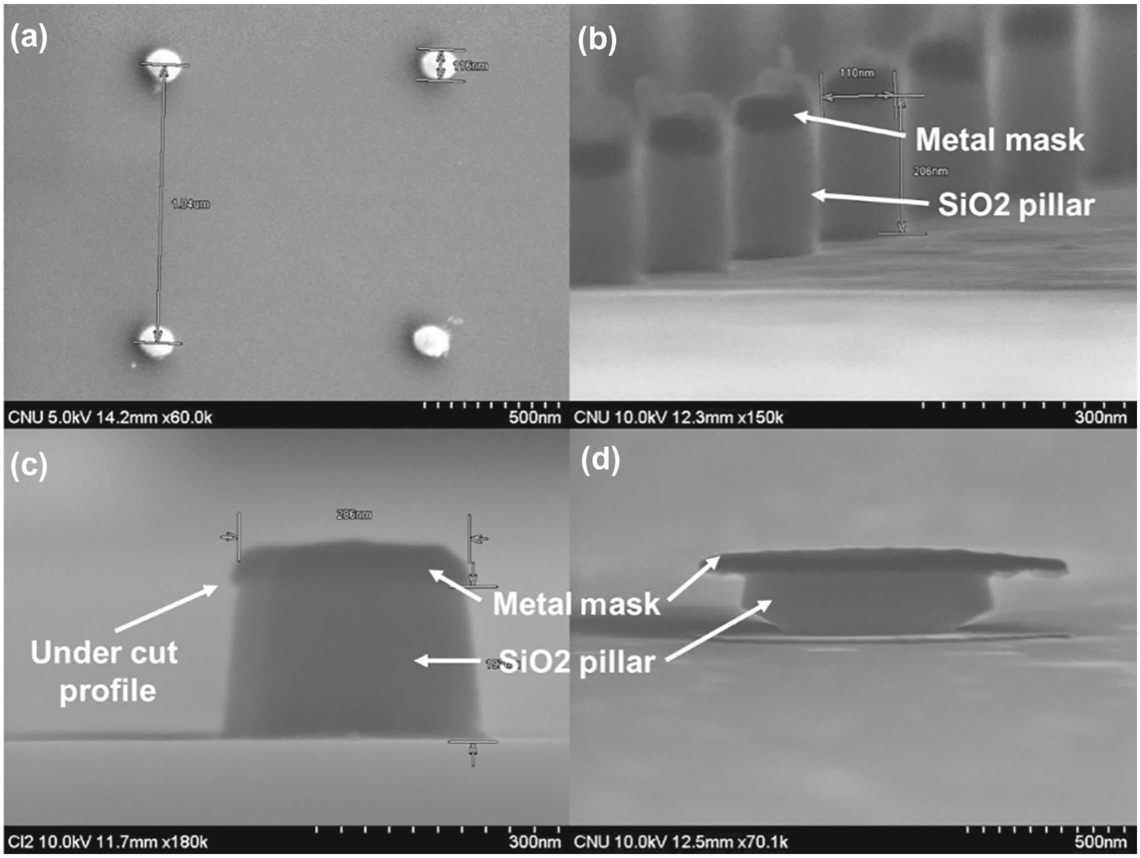

Figure 3. SEM images of fabricated structures: (**a**) etch metal mask, (**b**) etched SiO_2 pillars for 250 nm etching, (**c**) etched SiO_2 pillar for 300 nm etching, and (**d**) SiO_2 pillar with additional wet-etching to enhance the undercut.

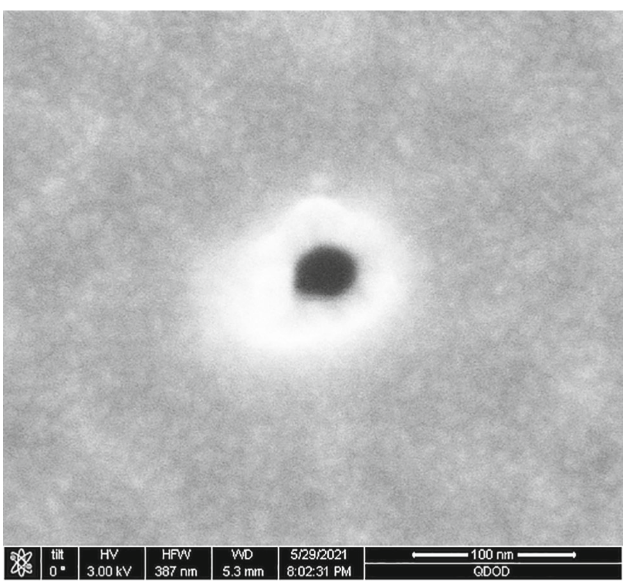

Figure 4. A $\sim$35 nm diameter metal hole fabricated by the PMMA/SiO_2 lift-off method.

Recently, a nanosphere lithography method using polystyrene nanospheres was applied to obtain sub-μm size hole-in-metal film [14]. However, the method cannot be used for positioning holes at specifics locations, which are often required for applications. Our method targets the deterministic fabrication of holes at the desired locations. This technique can be used, for example, for fabrication of a single photon source by isolating a single semiconductor quantum dot on a low density quantum dot epitaxial substrate, with a sub-50 nm hole, on the top of the single quantum dot, in a metal film.

4. Conclusion

We demonstrated a negative tone lift-off process using a PMMA/SiO_2 double layer to fabricate sub-50 nm holes in a metal film. The fabrication was easy and reliable since all the steps involved are already well-established. This method simplifies the fabrication of small apertures and also enables the deterministic fabrication without damaging the active emitters located below the holes.

Acknowledgements

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