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RESEARCH ARTICLE

A novel hanging bowl-shaped mask for the fabrication of vertical sidewall structures

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Contact exposure is expected to occur in conventional lithography, and can be a source of process deviations (such as shrinking and distortion of templates) during reactive ion etching and inductively coupled plasma etching, as these deviations are induced by ion bombardment. This typically results in undesired sidewall effects, such as lower sidewall angles. Here we report a novel hanging bowl-shaped lithography mask that can effectively minimize sidewall effects in lithography applications. As a test case, standard silicon carbide pillars with vertical sidewalls are fabricated using this mask. The mask could be used for fabrication of high-aspect-ratio structures with ultra-violet lithography.

Keywords UV lithography, hanging bowl-shaped mask, sidewall effects, ICP, SiC

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1 Introduction

Lithography masks are an integral part of conventional lithography techniques, and also have a great impact on dry etching processes such as reactive ion etching (RIE) and inductively coupled plasma (ICP) etching [1–4]. However, conventional masks can be damaged by ion bombardment during dry etching [5], resulting in undesirable sidewall effects such as sidewall striation [6–8], profile distortion [9, 10] and decreased sidewall angles [11, 12]. Several methods such as mask cleaning strategies [13], buffer layer technique [14–16] and protective cap methods [17, 18] have been developed to mitigate these problems. Various repair techniques have been also employed for reversing mask damage [19]. However, many of these methods are too costly or too inefficient to realize their full potential.

In this paper, we present a novel hanging bowl-shaped mask that is shown to be more effective at avoiding sidewall effects, a mask that can be fabricated using lift-off techniques. Owing to its high Young's modulus and high hardness [20, 21], silicon carbide (SiC) pillars with nearly vertical sidewalls are fabricated as a test case for using this mask, showing its potential for use in lithography applications.

2 Fabrication process

A flowchart detailing the fabrication of the mask is shown in Fig. 1. To start, 6H-SiC(0001) wafers (Hefei kejing materials technology Co., LTD) were cleaned by ultrasonication in acetone, isopropyl alcohol and deionized water for 10 min each, and then dried under N_2 flow [Fig. 1(a)]. An ultraviolet photoresist layer (S1813) was then coated onto the clean SiC substrate [Fig. 1(b)] and cured in an oven for 5 min at 120 °C after which the substrate was exposed to ultra-violet lithography (MA6) for 40 s. After being developed for 40 s, an array of bowl-shaped pits was formed [Fig. 1(c)]. At that point, the array was treated using oxygen plasma with a power of 50 W for 30 s, and a 5 nm chromium layer was then deposited as an adhesion layer, with a 400 nm Cu layer then deposited via e-beam evaporation (OHMIKER-50B) [Fig. 1(d)]. The etch rate selectivity of the 6H-SiC substrate was ∼100× greater than that of the Cr/Cu layer. To ensure a higher aspect ratio of the final fabricated mask, and to avoid damaging the Cu layer, the Cu layer should be made to be a little thicker. Next, the bowl-shaped hanging mask with its Cu capping layer was obtained using a lift-off process [Fig. 1(e)]. Finally, the SiC pillar array was fabricated using ICP etching (SENTECH

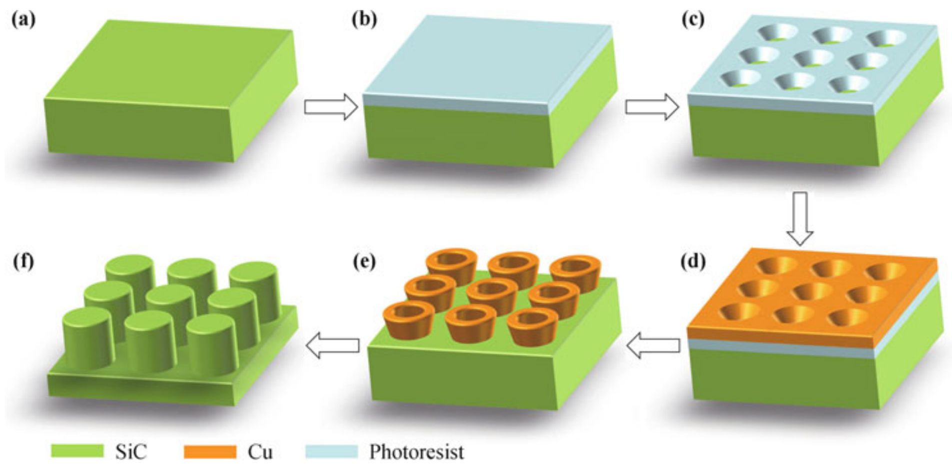

Fig. 1 Lithography process with hanging bowl-shaped masks. **(a)** Single crystal 6H-SiC(0001) wafer. **(b)** Ultraviolet photoresist was spin-coated on SiC substrate. **(c)** After ultra-violet lithography and development, bowl-shaped pits were formed. **(d)** 5nm chromium and 400 nm Cu layer was deposited on the photoresist in turn. **(e)** Bowl-shaped hanging masks were obtained by a lift off process. **(f)** SiC pillars with almost vertical sidewall were fabricated by ICP etching.

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PTSA ICP-RIE ETCHER SI 500), and immersed in nitric acid to remove residual Cr /Cu on the SiC pillars [Fig. 1(f)].

3 Results and discussion

The 6H-SiC(0001) wafer was characterized using X-ray diffraction (XRD) (D8 focus) and Raman (inVia Reflex) analyses. As shown in Figs. 2(a) and (b), these techniques confirmed the high purity and crystallinity of the 6H-SiC [22]. A scanning electron microscopy (SEM) (Hitachi S4800) image of the bowl-shaped mask is shown in Fig. 2(c), as viewed at a 30° angle from above. As can be seen here, the overall hanging bowl-shaped mask array was comprised of many bowls with flat bases. For comparison, a conventional mask consisting of many discs, having the same radius as the top edge of the bowls, was fabricated by a similar process (differing only in the type of ultrasonication used during the lift-off process).

SiC pillars were fabricated using ICP etching with conventional disc masks and hanging bowl-shaped masks under fixed conditions (gas mixture of SF_6/O_2= 24:6 sccm and 0.3 Pa; ICP power = 500 W; RF power = 150 W; bias voltage = −220 V; etching time = 21 min). Two types of SiC pillars were obtained using the conventional and bowl-shaped masks as shown in Figs. 3(a) and (b), respectively. The pillars in Fig. 3(a) have marked distortions that are not observed on the pillars in Fig. 3(b). Moreover, after the masks were removed by rinsing in nitric acid (1 min) and deionized water (1 min), sidewall effects are more apparent in Figs. 3(c) and (e) (corresponding to the conventional masks) than in Figs. 3(d) and (f) (corresponding to the hanging masks). The pillars obtained using the hanging bowl-shaped masks are more smooth and regular in appearance, and their sidewalls are almost vertical, showing the superior results of our method.

In general, ion bombardment during dry etching processes causes conventional disc masks to shrink and become distorted, and can decrease the sidewall angles of the SiC pillars as shown in Figs. 3(a), (c), and (e). However, the edges of the hanging bowl-shaped masks [Fig. 2(c)] are turned upwards; this geometry creates gaps

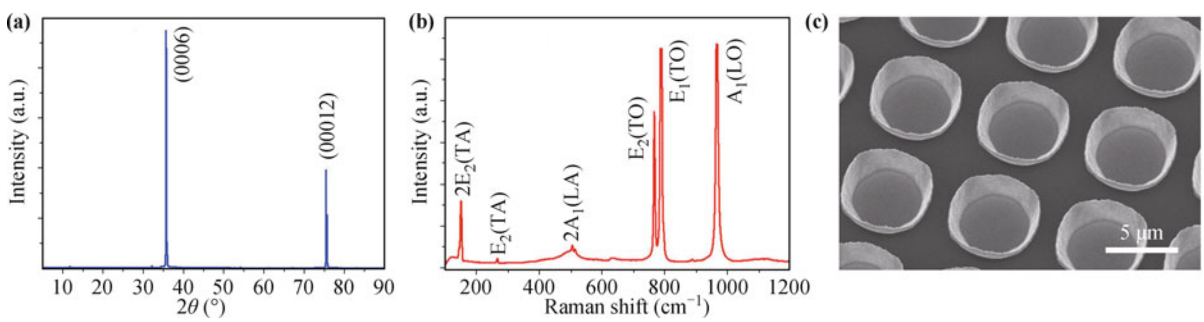

Fig. 2 **(a)** XRD analysis and **(b)** Raman spectrum of 6H-SiC(0001) wafers. **(c)** Top view of SEM images with a tilted angle of 30° of hanging bowl-shaped masks after lift-off.

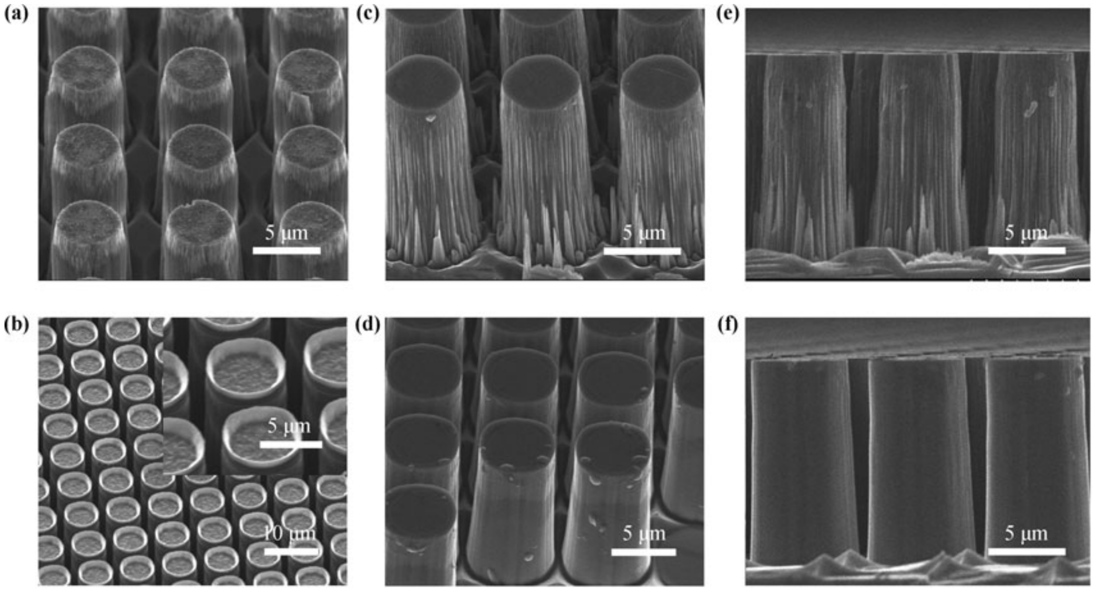

Fig. 3 Comparison of SiC pillars after ICP etching by conventional **(a, c, e)** and hanging bowl-shaped masks **(b, d, f)**. (a, b) show SiC pillars before removing masks. (c, d) and (e, f) respectively display SEM images with 45° tilted top view and cross-sectional view of SiC pillars after removing masks.

between the hanging bowl-shaped masks and the substrate, gaps which mitigate the damage caused by ion bombardment to the sidewalls [Fig. 3(b)]. In turn, this preserves the desired shape and dimensions of the final SiC pillars. It should be noted that such hanging masks can be comprised of several different materials and geometries, and are not limited to the current design; the substrate is also not limited to SiC. Therefore, our fabrication technique can be generally applied to high aspect ratio fabrication by UV lithography. If electron beam lithography [23, 24] is used, hanging bowl-shaped masks with smaller sizes might achieve finished structures of even higher resolution.

4 Conclusion

We proposed a new lithographic method featuring novel bowl-shaped hanging masks that can efficiently avoid sidewall effects, that cannot be avoided when using conventional masks. Experimental results demonstrated that sidewall striation and distortion were completely avoided in 6H-SiC(0001) pillars when fabricated using our proposed bowl-shaped Cu masks. It is believed that our method will help to realize high aspect ratio fabrication in UV lithography.

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