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John H Choi, Laurence Latu-Romain, Thierry Baron, Thierry Chevolleau, Edwige Bano. Hexagonal faceted SiC nanopillars fabricated by inductively coupled SF₆/O₂ plasma method. Materials Science Forum, 2012, 717-720, pp.893-896. 10.4028/www.scientific.net/MSF.717-720.893 . hal-00650069

HAL Id: hal-00650069

<https://hal.science/hal-00650069>

Submitted on 13 Oct 2022

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Hexagonal faceted SiC nanopillars fabricated by inductively coupled SF₆/O₂ plasma method

J. H. Choi^{1, 2, a}, L. Latu-Romain², T. Baron², T. Chevolleau² and E. Bano¹

¹ IMEP-LAHC/ Grenoble INP, MINATEC, 3, parvis Louis Néel-BP 257, 38016 Grenoble Cedex 1, France

²LTM/CNRS, 17 rue des Martyrs (CEA-LETI), 38054 Grenoble Cedex 9, France

^achoiji@minatec.grenoble-inp.fr

Keywords: Silicon carbide, Dry Plasma Etch, Inductively Coupled Plasma etching

Abstract. We demonstrate a top-down fabrication technique for nanometer scale silicon carbide (SiC) pillars by using inductively coupled SF₆/O₂ plasma etching. The obtained SiC nanopillars exhibit high anisotropy features (aspect ratio ~ 6.5) with high etch depth (>7 μm). The etch characteristics of SiC nanopillars obtained under these conditions show a high etch rate (550 nm/min) and a high selectivity (over 60 for Ni mask). We obtained hexagonal symmetry of SiC nanopillar, which might be attributed to the crystallographic structure of the SiC phase.

Introduction

As a wide band gap semiconductor material, silicon carbide (SiC) shows many excellent properties, such as high physical and chemical hardness, high thermal conductivity, and large breakdown field. One-dimensional SiC nanostructures, particularly nanowires (NWs), are expected to exhibit more interesting electronic and optical properties than their bulk counterparts due to their low dimensionality and quantum confinement. Common technique to fabricate of SiC NWs is the bottom-up approach, such as vapor-liquid-solid (VLS) [1] or vapor-solid (VS) [2] methods. However, critical problems of these methods are that as-grown SiC NWs present a high density of structural defects, such as stacking faults. This kind of defects leads to poor electrical performance (such as low mobility and low transconductance) of the related nano-FETs devices. The other method is the top-down approach. SiC substrate with good crystalline quality is now commercially available. Therefore, if top-down processing is applied into single crystalline SiC substrate, single crystalline SiC NWs with less structural defects are expected.

Due to the strong bond energy between the silicon and carbon (4.25 eV), plasma-based dry etching, such as inductively coupled plasma (ICP), is a promising method for top-down processing of SiC because it can be carried out at much higher plasma densities and low chamber pressure (< 10 mTorr). Consequently, high plasma density provides high etch rates of SiC and the operation at low pressure improves the directionality of the ion flux, which enables the achievement of anisotropy profile [3].

Many efforts have been made in order to etch SiC with ICP plasma methods, but it's mainly for the patterning of MEMS (micro-electromechanical systems) application [4] or the realization of via holes for power microwave devices [5].

In this work, we present the etching of nanometer scale SiC nanopillars using inductively coupled plasma (ICP) method in SF₆/O₂ based gas mixture.

Experiment

The etching is carried out in a commercial high-density plasma etching chamber from Applied Materials Inc., which was presented elsewhere [6]. The 8° off axis 4H-SiC (0001) wafer used in this study was fabricated by physical vapor transport methods [7]. The doping level of 4H-SiC wafer is 10¹⁷ cm⁻³ with n type. The circular Ni mask patterns with 370 nm diameter were prepared on Si-face of 4H-SiC substrates using electron beam lithography. The etching is carried out in the following conditions of etching gas flow rate, ICP coil power, substrate bias voltage, and chamber pressure at SF₆ : 40 sccm and O₂ : 10 sccm, 1500 W, 150 V, and 6 mTorr, respectively.

Result and discussion

We investigate the effects of etching time during the etching process not only to get longer SiC nanopillars, but also to monitor the effect of the etching characteristic parameters, such as mask size, mask thickness, pillar height, which has direct correlation to describe the profile evolution of SiC nanopillars. Fig. 1 shows the etched SiC nanopillar profiles over etching time.

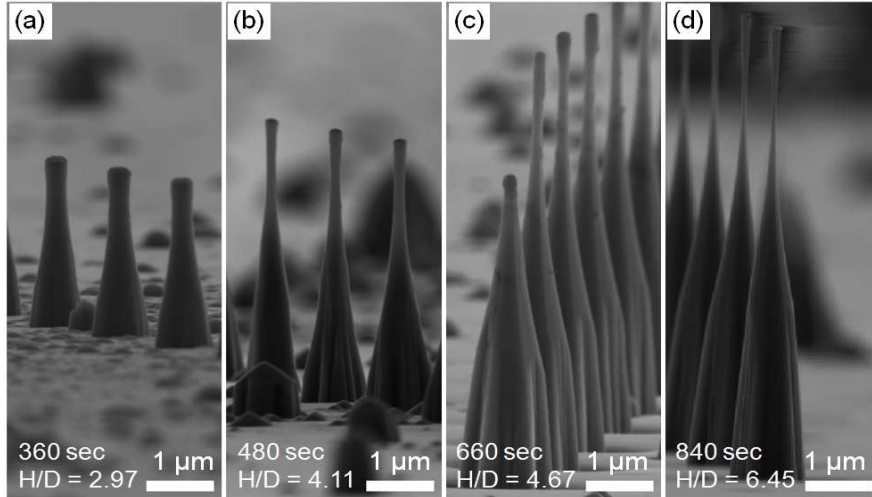


Figure 1. Side-view SEM images of SiC nanopillar with different etching time. (a) 360 sec, (b) 480 sec, (c) 660sec and (d) 840 sec, respectively.

As expected, the height of the SiC nanopillars is increased with increasing the etching time. Anisotropy is simply estimated by mean of aspect ratio (H/D), where H and D represent height and diameter of pillars at the base, respectively. As the aspect ratio of the features increases with etching time, the maximum achieved aspect ratio is around 6.45 at 840 sec, as shown in Fig. 1. For a quantitative analysis, the mask size and thickness, and pillar height were plotted as a function of etching time, as shown in Fig. 2. A linear least squares fit to the curve of pillar height in the linear region yields an etch rate of 550 nm/min. Long etching time lead to high etching depth with high anisotropy but also gives an undercut etching profile at 840 sec (Fig. 1d), probably, due to isotropic chemical etching by direct exposure of F radicals from the plasma.

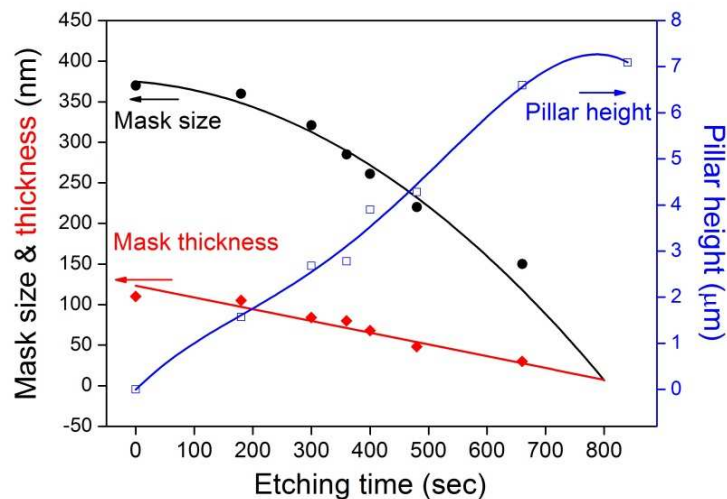


Figure 2. Mask size and thickness, corresponding pillar height as a function of etching time.

The pillar height increases evidently with increasing etching time, and then begins to decrease in the region from 600 sec and 840 sec when metal mask completely removed. The pillar height was approximated by a full fourth-order polynomial fitting in order to estimate the mask removal point. Extracted maximum height of SiC nanopillar from fitted curve is 7.36 μm at 780 sec. The etch selectivity of mask materials (Ni) with respect to the SiC is around 65.

Vertical (thinning) and lateral (narrowing) etch rate of mask fitted linear and a second order polynomial for the experimental data, respectively. Mask thickness at the center of mask is linearly reduced, so vertical etch rate of mask remained constant throughout the etching process, about 8.4 nm/min. Besides, lateral etch rate of mask increases evidently with increasing etching time. It is believed that mask erosion is a little bit faster at the edges due to strong physical sputtering of energetic ions, which is enhanced by the local distortion of the electric field [8].

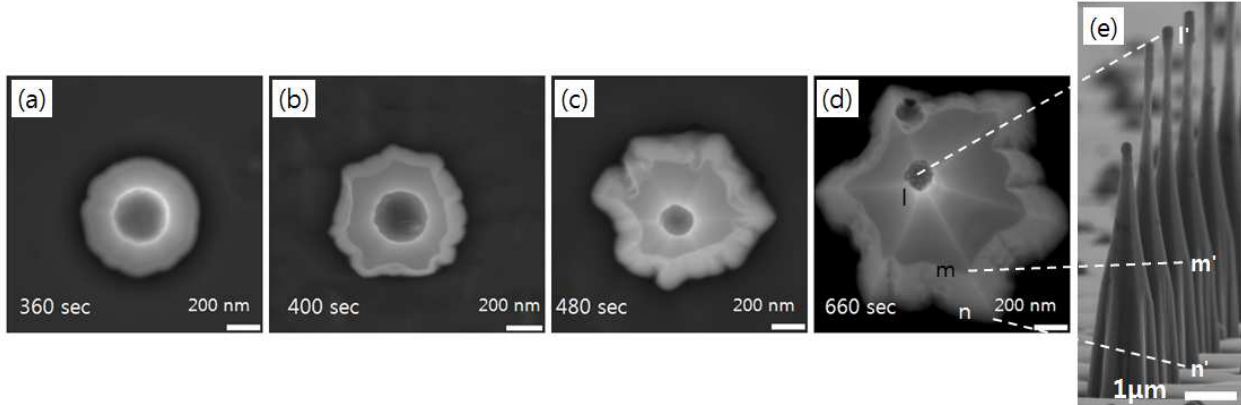


Figure 3. Top-view SEM images of SiC nanopillar after etching for (a) 360 sec, (b) 400 sec, (c) 480 sec, and (d) 660 sec, respectively. (e) Side view SEM images of SiC nanopillar after etching for 660 sec.

Fig. 3(a-d) shows top-view SEM images of a SiC nanopillar with different etching times. It is interesting that etched SiC nanopillars show transition from a circular pillar to a hexagonal pyramid with increasing the etching time. Hexagonal SiC nanowires have been already reported in the literature, using VS method [9] and carbon nanotube confined reaction [10]. Nevertheless, the hexagonal symmetry of SiC nanopillar with etching methods is first presented in this study. This particular feature is generally based on the crystallographic characteristics of the SiC phase. The anisotropy of the surface free energy of SiC along different crystallographic directions leads to the anisotropic chemical and physical properties of SiC, which determine the etching property. As a result of the SiC etching, hexagonal structure is formed since it energetically favored due to the minimum surface free energy of the facets [11].

Unlike circular pillar in Fig. 3a, hexagonal pyramid pillar shows two different contrast modes in Fig. 3d. It reflects the topology of SiC nanopillar. Fig. 3e shows a side-view SEM image of SiC nanopillar after etching for 660 sec. The brighter section ($m - n$) in Fig. 3d is corresponding to SiC nanopillar part ($m' - n'$) near the bottom in Fig. 3e. The sidewalls slope is inclined with increasing the etching depth (from l' to m' on Fig. 3e) along the SiC nanopillar. Above a certain point (m'), the slope is no longer inclined and is close to vertical direction in the range of m' and n' . Etching seems to be faster at the base of the profile. The formation of this feature is typically attributed to the local electric field by non-uniform charge distribution within etching features. The top of the feature charges negatively and the bottom of the feature charges positively, since plasma electrons are more likely to impinge on the top of feature due to isotropic electron angular distribution [12]. Due to local distortion of the electric fields, ions tend to be deflected by negatively charged sidewalls and enhanced ion bombardment at the foot of the sidewall by increased ion flux.

On the other hand, circular pillars show only one contrast mode in Fig. 3a and single tapered profile (Fig 1a), because small height of pillar at the initial stage of etching is not enough to induce the charge nonuniformity.

Summary

We have investigated the etching characteristics of SiC nanopillar in SF₆/O₂ plasma chemistry by using ICP methods. Etching profile and mask evolution over etching time have been monitored. As the etching proceeded, the pillar height and aspect ratio increased until the mask removal point. The hexagonal symmetry feature of SiC nanopillars with etching methods is first presented in this study. It might be attributed to the crystallographic structure of the SiC phase.

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