Analysis of subsurface atomic structure of 4H-SiC processed by plasma assisted polishing

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Abstract

Scanning white light interferometer (SWLI) observation and cross-sectional transmission electron microscopy (XTEM) observation were conducted to evaluate surface roughness and subsurface damage of the single crystal 4H-SiC surface processed by plasma assisted polishing (PAP) using ceria abrasive. The SWLI image showed that scratch free smooth surface was obtained after PAP process. The XTEM images revealed that there was no oxide layer on the processed surface and well ordered crystal structure of 4H-SiC was clearly observed. This observation result coincides with the result previously obtained by reflection high energy electron diffraction (RHEED) measurement which shows that lattice constant of PAP processed surface is same with that of the ideal SiC crystal.

1 Introduction

Single crystal SiC substrate is a very promising material for power device and high-temperature applications because of its excellent electrical, chemical, and mechanical properties. To make use of SiC as an electronic device, manufacturing of an atomically smooth surface without crystallographic defect is essential. However, SiC have a very high hardness and a chemical inertness. Plasma assisted polishing (PAP) was proposed by the author to achieve the high-efficiency and high-integrity finishing of difficult-to-machine materials such as single crystal SiC, reaction sintered SiC, sapphire, tungsten carbide, and diamond [1]. In the case of PAP finishing of SiC substrate, combination process, which consists of irradiation of atmospheric pressure water vapor plasma and polishing using a soft abrasive such as ceria, is applied. The irradiation of water vapor plasma oxidizes the SiC surface, and the subsequent ceria abrasive polishing preferentially removes the oxidation layer. In our previous research, we have obtained atomically smooth and damage-free 4H-SiC (0001) surface by applying PAP [1, 2]. The rms roughness of the processed surface measured by scanning white light interferometer (SWLI) was decreased to about 0.1 nm and scratch-free surface was obtained. The step and terrace structure, which corresponds to the inclination of the crystal plane, was clearly observed by AFM. Furthermore, reflection high energy electron diffraction (RHEED) measurement revealed that there was no lattice strain on the PAP processed surface. These results indicate that PAP has a good ability to obtain an atomically smooth surface without introduction of subsurface damage. In this paper, we observed the processed surface using XTEM to obtain some direct images of PAP processed surface with atomic resolution.

2 Experimental setup and parameters

The SWLI and XTEM observations were conducted to the surfaces, which were prepared by conventional polishing using diamond abrasive and the PAP using ceria abrasive. The experimental parameters of PAP are shown in Table 1. The schematic of experimental setup for preliminary research is referred [1]. The setup consists of separately installed plasma generation unit and mechanical removal unit. Helium based water vapor is supplied as the process gas. Atmospheric pressure plasma is generated at the tip of an electrode under the open-air condition by applying an RF (f=13.56 MHz) electric power. In the mechanical removal unit, a polishing experiment using a polishing film placed at the tip of a spindle unit is conducted. The diameter of the polishing film is 8 mm. The SiC substrate is placed on a rotary table and plasma irradiation and dry polishing using a polishing film are sequentially conducted. Single crystal n-type 4H-SiC wafers (on axis), manufactured by Cree Inc. were used in this work. The thin specimens for XTEM observations were prepared using focused ion beam (FIB) system (HITACHI FB-2100) and observed by TEM (JEOL JEM-2100).

Table 1: Experimental parameters

Load	30 gf
Abrasive	CeO_2, φ 0.5 µm
Rotation Speed	10500 rpm (Pad), 120 rpm (Subst.)
Process Gas	He+H_2O (1.91%), 1.5 SLM
RF Power	8 W
Processing Time	60 min

3 Results and discussion

Figures 1 (a)(b) show the surfaces observed by SWLI. In the case of the surface processed by diamond abrasive polishing, deep scratches are observed on the surface as shown in Fig. 1(a). In contrast, PAP processed surface shows smooth surface with an rms roughness of 0.17 nm without introducing scratch as shown in Fig. 1(b).

Figures 2(a)(b)(c) show the XTEM images of the surface processed by conventional diamond abrasive (φ5-15 μm) polishing with a load of 1650 gf. Contrast of an atomic image in the vicinity of the top surface region is slightly weak compared with the bulk region as shown in Figs. 2(a)(b). These results indicate the existence of the crystallographical damage. Furthermore, Fig.2 (c) shows that flatness is not perfect due to the lack of surface atoms, which are caused by forced mechanical removal using diamond abrasive.

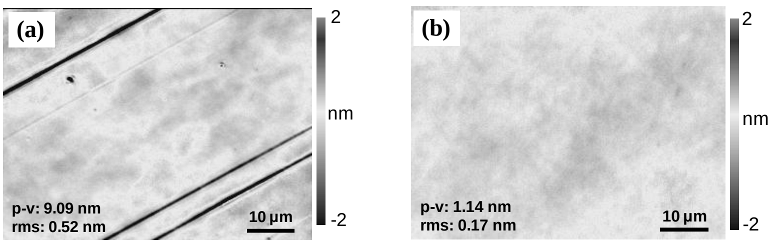
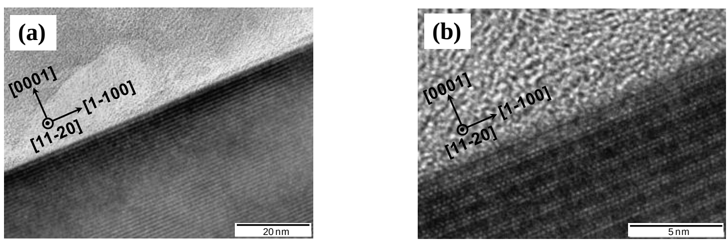


Figure 1: SWLI images of the processed surface (a) Diamond abrasive polishing (b) PAP using ceria abrasive



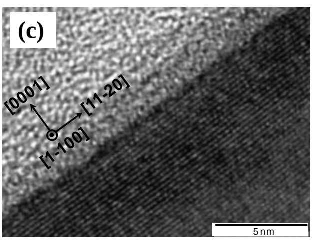


Figure 2: XTEM images of the surface processed by diamond abrasive polishing
(a) Low magnification image
(b) (c) Close-up images

Figures 3(a)(b) show the XTEM images of the surface processed by PAP using ceria abrasive for 1 h. Oxide layer having amorphous structure is not observed on the PAP processed surface. Since the hardness of ceria is almost the same with that of SiO_2 [3], the oxide layer formed by irradiation of water vapor plasma is preferentially removed by soft ceria abrasive as shown in Fig. 3(a). It seems that moderate removal of the oxidized surface atom is very effective to obtain an atomically smooth surface. On the other hand, the deep contrast layer remains on the surface, and this layer is considered as an interface silicon oxicarbide layer ($Si_4C_{4-x}O_2$) [4]. As a product of insufficient oxidation, it is very reasonable to assume that the hardness of $Si_4C_{4-x}O_2$ layer is between that of SiC which is the base material and SiO_2 which is the sufficient oxidation product. As the hardness of ceria is almost the same with that of SiO_2, only the top amorphous SiO_2 layer can be removed, and the silicon oxycarbide layer will remain on the surface. Figure 3(b) shows the close-up image of the PAP processed surface. A periodical well ordered structure, which corresponds to the structure of 4H-SiC, is continuously observed from the bulk region to the top surface. These observation results lead to the conclusion that PAP technique enables us to obtain an atomically smooth surface of single crystal SiC substrate without introducing crystallographical defect in the subsurface region.

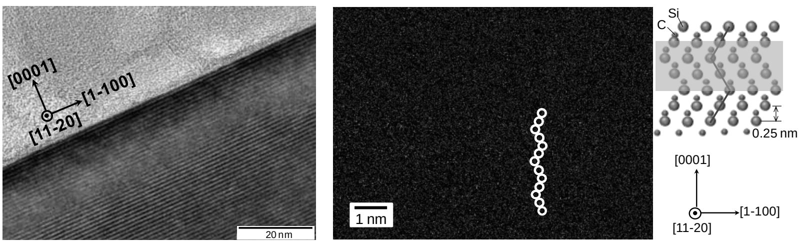


Figure: 3 XTEM images of the surface processed by PAP. (a) Low magnification image. (b) Close-up image and schematic of 4H-SiC structure.

Acknowledgments

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