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On the "step bunching" phenomena observed on etched and homoepitaxially grown 4H silicon carbide

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Abstract. Using several types of surface analysis (Optical profilometers (OP), Atomic Force Microscopies (AFM), Scanning Electron Microscopies (SEM) and cross-sectional high-resolution Transmission Electron Microscopies (TEM)) we analyze the surface morphologies of misoriented 4H silicon carbide after pre-growth hydrogen etching and homo-epitaxial growths. We observed the characteristic self-ordering of nano-facets on any analyzed surface. This nano-faceting, which should not be confused with step bunching, can be considered as a close-to-equilibrium instability, for this reason can be hindered .

Introduction

Step-and-terrace structures are widely observed on mis-oriented crystal surfaces after thermal treatment, epitaxial growth or etching under suitable conditions. Various interesting phenomena related to step-and-terrace structures such as faceting[1], step bunching[2,3] and step meandering are known to occur due to a, far to be fully understood, competition between several mechanisms such as step kinetics, surface diffusion, step stiffness, step–step interactions, and so on [4,5]. All these surface instabilities are of great interest from a viewpoint of not only crystal growth but also electronic engineering, because device performance is affected by ''micro-roughness'' at a junction interface or surface. Specifically, this phenomenon, is crucial in high-power devices where the rough junction interface causes electric field crowding, resulting in the reduction of blocking voltages. The surface roughness also negatively impacts the channel mobility or the oxide breakdown characteristics in metal-oxide-semiconductor field effect transistors MOSFETs or will strongly affects the electrical properties of graphene epitaxially grown on SiC. For this reasons a deep understanding of the surface morphologies is necessary to correctly link the nano-and micro-structure of the crystal with the growth quality and post-treatment effects. In this work we have investigated the surface morphology of etched and epitaxially grown misoriented 4H silicon carbide using SEM, optical profilometers, AFM and TEM. We found that what was previously considered as step bunching is rather a nano-faceting of the step-and-terrace morphology that leads to periodic oscillations of the step density and, thus, to nano ondulations of the surface.

Results

Fig.1shows the surface morphology of a CMP polished 4H-SiC substrate after pre-growth hydrogen etching (T>1500°) using an optical profilometer (OP). Long parallel and isolated lines can be easily seen on the surface. These lines, which are several hundreds of micron long, can be recognized, using the height profile (Fig.1), as macro-steps.

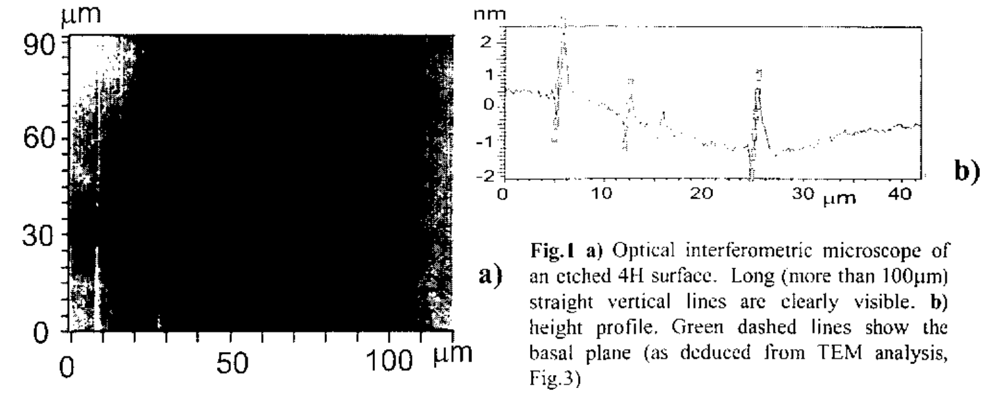


Fig.1 **a)** Optical interferometric microscope of an etched 4H surface. Long (more than 100µm) straight vertical lines are clearly visible. **b)** height profile. Green dashed lines show the basal plane (as deduced from TEM analysis, Fig.3)

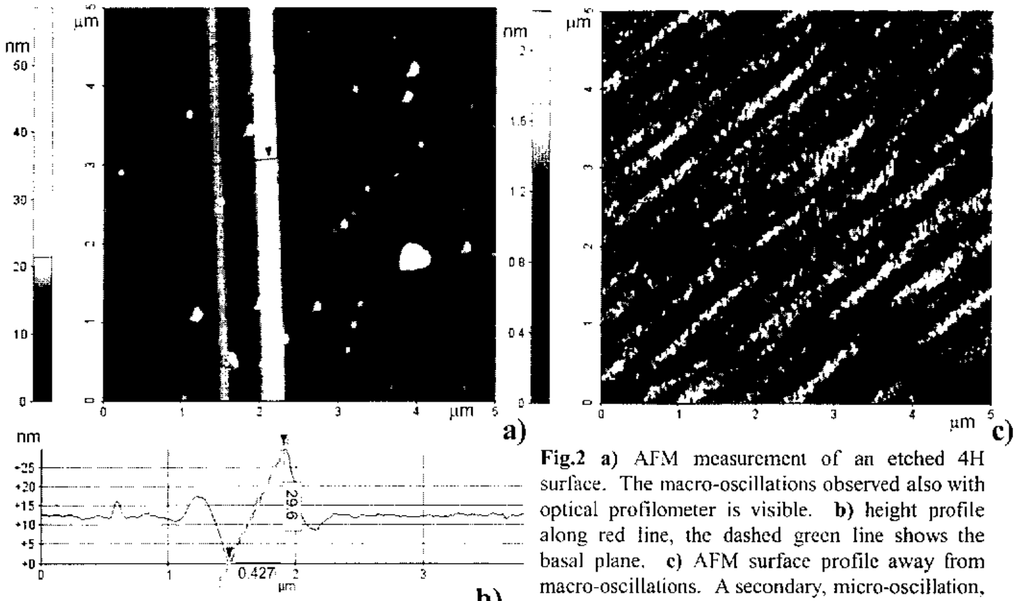
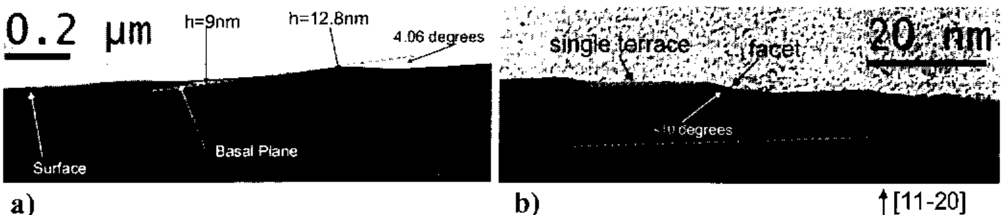


Fig.2 **a)** AFM measurement of an etched 4H surface. The macro-oscillations observed also with optical profilometer is visible. **b)** height profile along red line, the dashed green line shows the basal plane. **c)** AFM surface profile away from macro-oscillations. A secondary, micro-oscillation, is clearly visible.



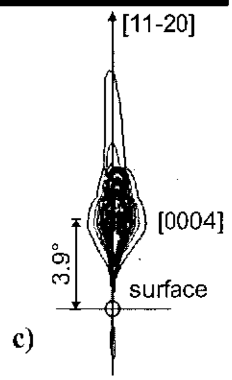


Fig.3 **a)** low resolution cross-sectional TEM analysis of the macro-oscillations observed with OP and AFM. The atomic structure of the macro-oscillations is clearly visible. Specifically it can be identified as a single large terrace (parallel to the basal plane) and a facet. **b)** high resolution cross-sectional TEM analysis of the micro-oscillations observed with AFM. As can be seen, these oscillations are composed by large terraces (several nm wide) and facets. **c)** XRD polar figure showing the miscut angle between the surface and the basal plane [0004].

Given the limited lateral resolution of the optical profilometer we have analyzed the surface with an AFM. In Fig.**2,a** we show the surface morphology of a macrostep, together with its height profile (Fig.**2,c**). As it can be seen, this feature is characterized by (from left to right, that is, along the step flow) a first small peak, then a valley below the surface level, a second pronounced peak, and finally a second, smaller valley. The cross-sectional TEM analysis of the sample (Fig.**3,left**) allows to explain the observed profile. There are two regions of high-step-density separated by a single large terrace, this structure, when planarized by the AFM or OP, will lead to the observed profile. We have double-checked this result by calculating the angle between the surface and the terrace in the AFM height profile (Fig.**2,c**) finding a rising angle of α=arctg(29.6/427)=3.96° which is, indeed, the miscut angle of the substrate, as confirmed by the TEM (Fig.**3,a**) and XRD (Fig.**3,c**). This analysis can be extended to any AFM or OP height profile to identify the presence of large terraces (parallel to the basal plane and with a rising angle equal the miscut one) on the surface. Together with these macro-steps both AFM and high resolution TEM showed a second, smaller, oscillation on the scale of few tens of nanometers, characterized by a highly

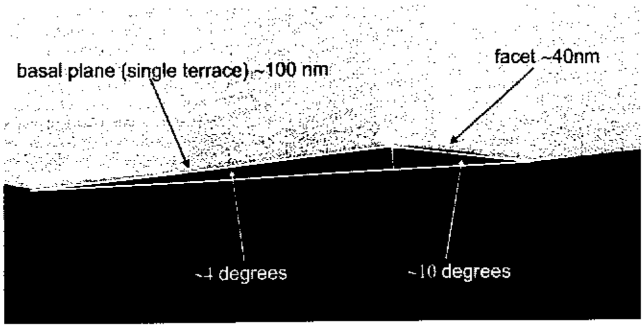


Fig.4 High resolution TEM cross section of a homoepitaxially grown 4H-SiC film. The oscillations are composed by larger terraces and facets compared to the etched surfaces.

periodic sequence of large terraces and facets. Similar morphologies have been also observed on homo-epitaxially grown films (Fig.4). In the later case the oscillations are generally wider and higher, but, it is interesting to note, the falling angle remains constant, indicating that the facets observed in the two processes have the similar miller indices (compare Fig.3 and 4). Furthermore, in the case of the growth process, the oscillations have an higher in-plane order (compare Fig.**2,c** with Fig.**5,a**).

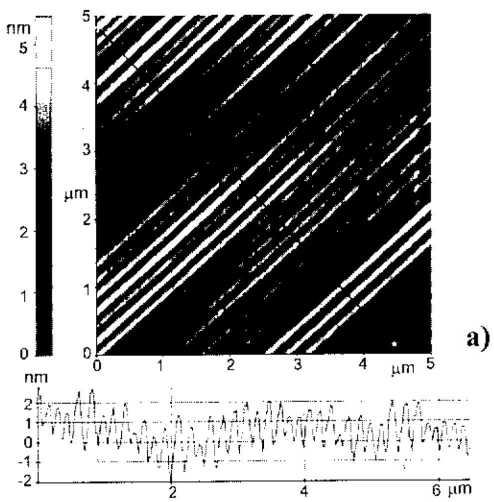


Fig.5. **a)** AFM analysis of a homoepitaxially grown 4H-SiC film. The micro-oscillations, observed also on etched surface, have enlarged and are more clearly visible. **b)** Height profile along the red line.

Discussion

In this work we have investigated the surface morphology of etched and epitaxially grown misoriented 4H silicon carbide using several surface techniques. We observed, for both processes, a self-ordering of the step-and-terrace structures which leads to a nano-faceting of the surface. This nano-faceting have been found over two different length scales, for this reason, to completely analyse the surface morphologies it is necessary to use different techniques to cover both the tens of microns length scale (with OP and SEM) and the micro and nano scale (with AFM and TEM). In all the observed surfaces the angle of the facet with respect to the basal plane was found to be the same ($\beta \sim 10^\circ + 4^\circ = 14^\circ$ degrees) supporting the idea, as suggested also in [6-8], that this self-ordering of the surface is the result of an energy minimization process rather than a kinetic instability. For this reason, it is reasonable to think that an out-of-equibrium process (such as a low temperature or high growth rate one) can hinder this surface reorganization. Finally, it is important to note that the angle between the facet and the basal plane, $\beta \sim 14^\circ$ degrees, is very different from the angle expected in the case of a step-bunched surface, $\beta \sim 90^\circ$ degrees. For this reason the observed surface instability should not be considered as the result of a step bunched phenomena.

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