Strain Engineering of Graphene on SiC

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In spite of the superior intrinsic characteristics of pristine graphene and its resulting potential for fundamental studies and many applications, the proof of new features on graphene has also generated much interest. Evidence of the modification of electronic properties of graphene by substrate effects has been profusely studied by for example STM, in direct connection to the metal support(s) underneath. Interestingly, graphene nanobubbles exhibit pseudo-magnetic fields [1], as predicted from theory. Additionally, the phenomena arising from crystal distortion of graphene nanobubbles had been comprehended in terms of the shift of the characteristic modes of graphene in Raman spectroscopy [2].
Strained graphene has also been reported on the Si face of 6H-SiC samples and understood on the basis of fundamental theory of Raman scattering [3], as well as related to nanoscaled topographical features on highly deconstructed SiC supports [4]. However, extended modulation of graphene electronic properties by strain on SiC which could be used for testing strained graphene practical performance in electronic devices has never been achieved.
We present microscopic strain engineering of graphene grown on the Si face of 6H-SiC. The controlled synthesis process results from a combination of ex situ and in situ surface conditioning of the SiC crystal. Ex situ conditioning of SiC, prior to graphene deposition, consists in a certain chemical mechanical polishing (CMP) which allows us obtaining SiC atomic step uniformly all over the used wafers (typically 1 cm^2) [5]. In situ processing comprises a selected combination of techniques and process conditions used for the graphene formation during the high temperature treatment, including the use of a graphite cap as reported in [6]. Thermal treatment of Si face 6H-SiC wafers is common for all samples reported here, which provides an extended continuous predominantly graphene single layer.
Figure 1 compiles the processed data of Raman scattering in more than 20 specific positions of single layer graphene grown on the Si face of 6H-SiC 3.5º off axis-cut sample. The plot represents the ratios of G mode shift upon 2D mode shift for each probed location [3], as indicated in the optical images depicted in the right side of Figure 1. Simultaneous shift of both G and 2D modes towards higher frecuencies, which is an indication of strain rather than a charge-related effect [3], is obtained in every position. Relative shift of G and 2D mode in a ~1:2.5 ratio has been attributed to uniform (hydrostatic) compressive strain [2,3]. In purple, the data of probing across different terraces and strategically corresponding to either terraces or SiC steps are shown. It can be observed that localized anisotropic strain tends to be found for certain locations, coincidental specifically at (and towards) steps – e.g. positions 4 and 9. In blue, the data for several points along one wide terrace (T1) and one narrower terrace (T4) are plotted; where higher G:2D tends to be obtained for the wider terrace (T1). Terraces have widths in the 10-30 μm range.
We have corroborated that actually the uniformity of processing-induced strain is higher when CMP-SiC is used as the starting substrate for the graphene deposition. Raman-probed locations of graphene deposited onto on-axis cut 6H-SiC CMP sample have always G:2D of ~ 1:2.5, whereas using conventional mechanical polished (MP) SiC sample under the same in situ conditions leads to larger variations in strain; from increased G:2D ratio (0.83) to relaxed graphene (data not shown).
We show some instances of the remarkable morphological and topographical differences for CMP versus MP SiC, where graphene has been grown, in Figures 2 and 3. Figure 2 (left) shows an optical image of CMP 6H-SiC on axis cut sample. CMP SiC tends to become regularly reconstructed/step bunched. Having typically wide terraces, straight step edges are always obtained, both features in contrast to [4]. MP-SiC, Figure 2 (right), instead, has poor/irregular step edge definition and alternate terraces of smooth as well as patterned SiC are found. The latter aspect can be easily visualized and quantified in terms of terrace width and step height in the AFM image of Figure 3 (right). Additionally, the inset shows the contrast of AFM phase signal, which highlights the existence of wrinkles in graphene - not easily perceived from the topography signal due to the Z scale range (100 nm). AFM images in Figure 3 exemplify the topographies where more or less conformal graphene is laying onto CMP-SiC versus MP-SiC after the thermal treatment in buffer layer-assisted (epitaxial) graphene deposition.
Uniform and uneven microscopic strain can be understood as a combination of factors. On the hand, it is a consequence of aspects related to the processing conditions; the ex situ surface conditioning plus particular in situ techniques, including the thermal treatment conditions [6]. And, on the other hand, it can be understood as based on the interaction of grown graphene with the buffer layer, necessary for graphene formation on the Si face of SiC, as well as including the decomposition dynamics of the SiC

crystal, the SiC reconstruction and difference in the thermal expansion coefficients of graphene and SiC crystal upon cooling. A model on our control upon these phenomena for strained graphene on SiC at room temperature will be provided.

References

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Figures

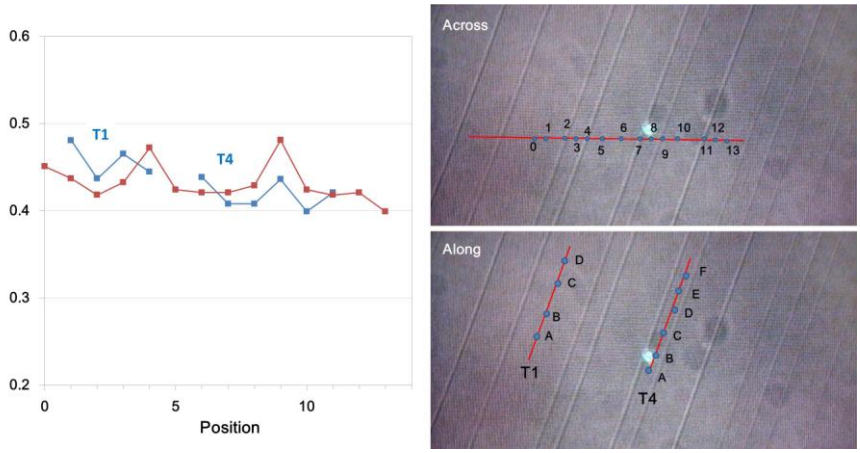

Figure 1. Plot of the ratios for G mode shift upon 2D mode shift, corresponding to each probed location, as indicated in the right side optical images, obtained in graphene grown in the Si face of CMP 6H-SiC 3.5º off axis cut wafer.

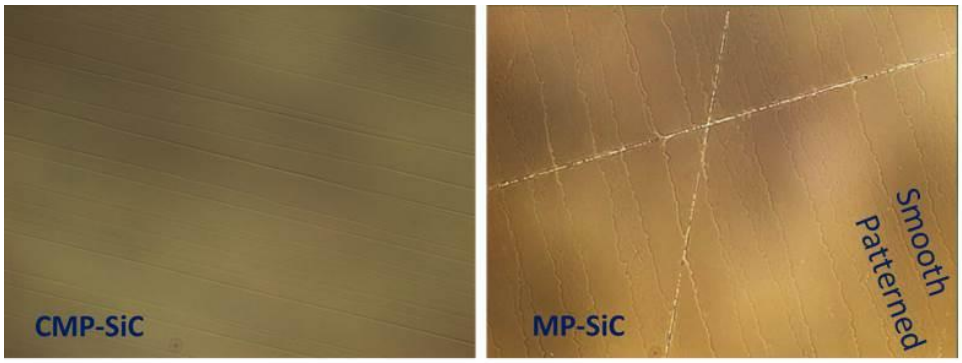

Figure 2. Optical images for CMP (left) and MP (right) on axis cut 6H-SiC wafers after the growth of extended single layer graphene upon the Si face.

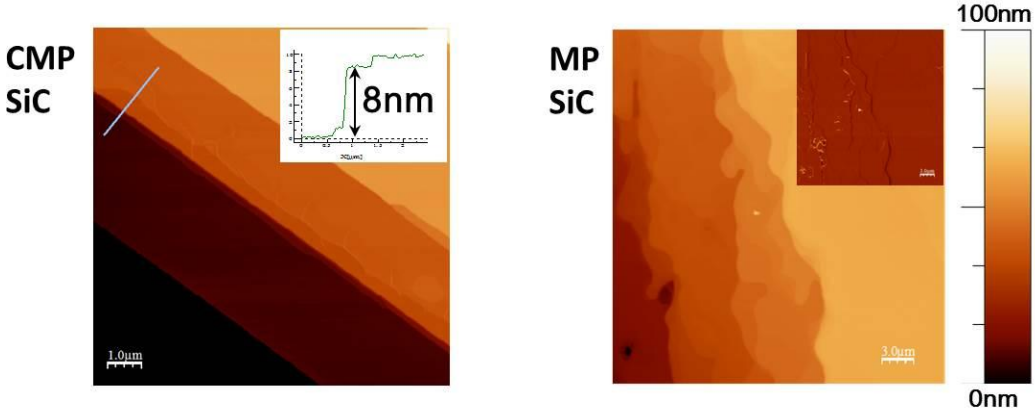

Figure 3. AFM images for CMP (left) (Scan size 10x10 μm^2) and patterned MP (right) (Scan size 30x30 μm^2) on axis cut 6H-SiC wafers after the growth of extended single layer graphene upon the Si face.