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Quantitative Analysis of Graphene Folded Edges Using Electron Diffraction

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Graphene, a 2D structure of one atomic layer of carbon, has attracted tremendous research interest since it first became experimentally accessible [1]. One of research foci is to use graphene nanostructures for electronic devices. Graphene edges, analogous to the surface of nanoparticles, can significantly influence the overall electronic and magnetic properties of graphene nanostructures [2]. For example, graphene nanoribbons with zigzag edges exhibit a smaller energy gap than a predominantly armchair edge ribbon of similar width[2]. Thus fabrication of graphene edges and characterization of their atomic structure have become an important issue in graphene research with significant implications for potential electronics applications. Scanning tunneling microscopy was used to investigate the folded edges by scratching the surface layers of graphite [3]. High-resolution transmission electron microscopy (HRTEM) was used to study high temperature annealed graphene edges [4, 5]. However, no quantitative method has been so far provided to resolve the structure of the folded edge, and current there is no unambiguous method to distinguish the folded edge from open edge.

Here, we report an experimental study of folded graphene edges. The graphene edges were fabricated by folding suspended graphene in solution with ultrasound which generates random mechanical forces. We use nanoarea electron diffraction (NBD) in combination of HRTEM for the characterization of graphene edges. This work was performed on a JEOL 2200FS operating at 80 kV. The small electron probe about 15 nm in diameter allows us to record diffraction patterns from folded edges, and an in-column omega energy filter is used to reduce the inelastic background in the recorded diffraction patterns. To extract structure information from the diffraction patterns, we have developed analysis procedures to measure the folding angle and to model the electron diffraction pattern from folded edges. The folded edge is described by the folding angle, which is defined as the angle between graphene basis vector and the direction normal to the folding axis. Similar as the measurement of the chiral angle of carbon nanotube, the graphene folding angle can be determined directly from the diffraction pattern by measuring the ratio between the axial distances of the three principle layer lines away from the equatorial line. Fig. 1 shows three folded edges of two, three and five layered grpahene as observed by HRTEM imaging and electron diffraction. Fig. 1a is a chiral edge with 14.6^o folding angle. Fig. 1c is an armchair edge with 0^o folding angle. Fig. 1e is a zigzag edge with 30^o folding angle. The folding angle is measured from the corresponding diffraction pattern (Fig. 1b, d, f). The strong (0, 0, 2) reflection along the equatorial line is an important feature for multi-layer folded edges, due to the interference between graphene layers at the curved region, and this feature can be used to distinguish folded edge from open edge. This additional structure information obtained by NED removes the ambiguity in the interpretation of HRTEM images of graphene edges [6]. Also the physics of graphene folding will be discussed.

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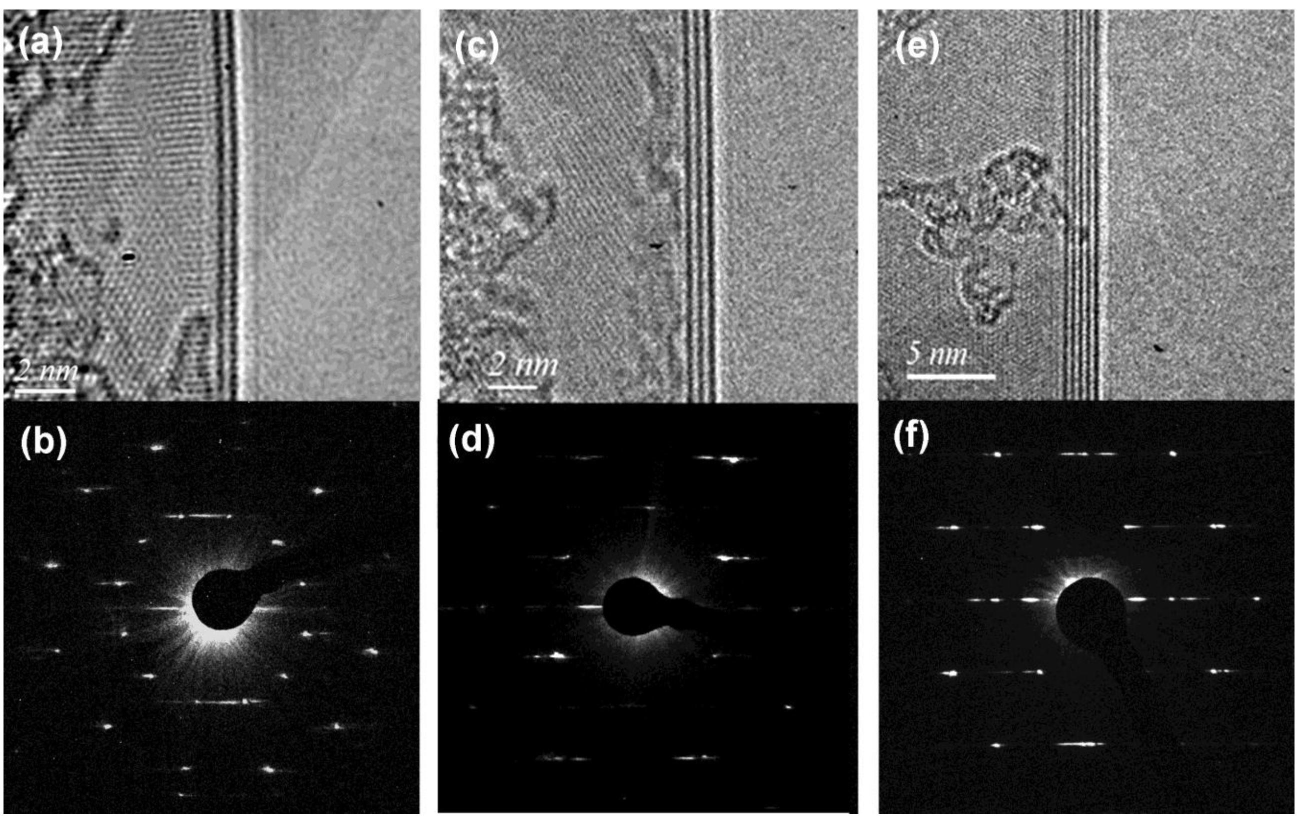

FIG. 1. HRTEM images (a, c, e) and diffraction patterns (b, d, f) of folded edges from two, three and five layered graphene. (a) (b) from a 14.6^{o} chiral folded edge; (c) (d) from armchair; (e) (f) from zigzag.

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