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Cutting forces related with lattice orientations of graphene using an atomic force microscopy based nanorobot

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The relationship between cutting forces and lattice orientations of monolayer graphene is investigated by using an atomic force microscopy (AFM) based nanorobot. In the beginning, the atomic resolution image of the graphene lattice is obtained by using an AFM. Then, graphene cutting experiments are performed with sample rotation method, which gets rid of the tip effect completely. The experimental results show that the cutting force along the armchair orientation is larger than the force along the zigzag orientation, and the cutting forces are almost identical every 60°, which corresponds well with the 60° symmetry in graphene honeycomb lattice structure. By using Poisson analysis method, the single cutting force along zigzag orientation is 3.9 nN, and the force along armchair is 20.5 nN. This work lays the experimental foundation to build a close-loop fabrication strategy with real-time force as a feedback sensor to control the cutting direction.

Graphene has shown amazing performance in different kinds of applications, such as solar cell electrodes,1 touch screen,2 highly sensitive sensors,3–5 and the fastest field effect transistor (FET).6 However, a lack of a bandgap in graphene methods such as AFM local oxidation nanolithography, 9,10 proved related with its configurations.7,8 Therefore, many conductor devices. The electrical properties of graphene have proved related with its configurations.7,8 Therefore, many methods such as AFM local oxidation nanolithography,9,10 scanning tunneling microscope (STM) nanolithography,11 catalytic cutting Technique,12–15 AFM scratching method,16 photocatalytic patterning approach,17 e-beam lithography,18 and plasma etching19 have been developed to tailor graphene into ribbons or other shapes for opening a bandgap in graphene. But most of these methods are unable to tailor graphene with desired edge structures in control.

In this letter, after identifying the lattice orientation on the graphene, the cutting forces along different lattice orientation are measured by using an AFM based nanorobot. We found that the cutting forces vary with the lattice orientations and have a good match with the 60° symmetry in graphene honeycomb lattice structure. The single cutting force along different lattice orientation is calculated using Poisson analysis method. The single cutting force along zigzag orientation is 3.9 nN which is smaller than the force along armchair orientation (20.5 nN). This founding lays the experimental foundation to build a close-loop fabrication strategy with real-time force as a feedback sensor to control the cutting direction.

Graphene sample is prepared by chemical vapor deposition (CVD) growth method20 and then transferred to Si/SiO2 marked substrate by using polymethyl methacrylate (PMMA). At last, the PMMA is removed by acetone. The sample is characterized by optical microscope (KH-7700, Hirox Inc.) and AFM (D3100, Veeco Inc.). Fig. 1(a) displays an optical image of the graphene. It can be seen that 90% graphenes have perfect hexagon shapes. One perfect hexagon shape graphene is chosen at random for AFM characterization shown in Fig. 1(b). From the height analysis shown in Fig. 1(c), the thickness of the graphene is around 0.447 nm, indicating it is monolayer graphene.

Atomic imaging is performed in contact mode using a Multimode AFM in air under ambient conditions (30% to 57% relative humidity, 20° C to 50° C). Normal contact tip (DNP-10, Bruker Inc.) is used. The scan size is 5 nm, and scan rate is 59.2 Hz. Fig. 2 shows the lattice orientation on two different graphene sheets. Figs. 2(a-2) and 2(b-2) are the atomic images obtained on the graphene (a-1) and (b-1), respectively. The scan angles are 90° and 60°, respectively. Therefore, Figs. 2(a-3) and 2(b-3) are the real lattice orientations by clockwise rotating the atomic images with their scan angles. It is found that the edges are both zigzags.

The cutting experiments carry out using a diamond tip (PDNISP, Veeco Inc.). The tip radius is 40 nm, and the calibration spring constant is 217 N/m. Graphene is cut by using self-developed manipulation software based on AFM.21 The cutting force can be adjusted by setting different deflection setpoints.22 Many different shapes can be fabricated using this method, such as circles, squares, and ribbons, as shown in Fig. 3. The width of the fabricated nanoribbon is smaller than 10 nm, by considering tip broadening effect especially after cutting many times.

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We then study the relationship between lattice orientations and cutting forces. In the measurement, the sample was rotated to change the lattice orientation and fix the AFM tip cutting along the same direction. In each lattice orientation, three scratches were made on the graphene, and then a scratch with the same load was made on the substrate. Thus, the substrate effect can be removed from the measured lateral forces. Fig. 4 shows the graphene cutting results at rotation angles 0°, 30°, 60°, and 90°, respectively. The cutting speed is 1 μm/s, and applied load is 43.4 μN. Because the edges of the graphene sheet are zigzag orientation, the cutting direction is along the armchair orientation at 0°. We found that the cutting forces along armchair orientation (0° and 60°) are larger than zigzag orientation (30° and 90°), as shown in Fig. 4(e). In addition, the cutting forces nearly the...
same every 60°, which matches the graphene lattice structures. Fig. 5 shows another experimental result. It also displays the same experimental phenomenon.

Many C-C band breaking forces are formed during the cutting forces measurement. Therefore, Poisson analysis is used to calculate single cutting force for each lattice orientation using the following equation:

$$\frac{\delta^2}{\mu} = F,$$

where $\delta^2$ and $\mu$ are variance and mean, respectively. Using this analysis method, a single cutting force along zigzag orientation is 3.9 nN and a single cutting force along armchair orientation is 20.5 nN. This discovery gives experimental evidence that graphene can be tailored along the desired edge structures based on real-time force feedback control by using an AFM.

In conclusion, we demonstrate that the cutting forces are related with the lattice orientations of graphene using an AFM based nanorobot. The experimental results show that the forces cutting along the armchair orientation are larger than the forces along the zigzag orientation and have a good match with graphene lattice structure. The difference of the cutting forces lays the experimental foundation to build a close-loop fabrication strategy with real-time force as a feedback sensor to control the cutting direction.

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