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Correlation between the electrical conductance and the mechanical deformation of a graphite surface

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ABSTRACT

We investigate the correlation between the electrical conductance and the mechanical deformation of a graphite surface by using the scanning tunneling microscope break junction (STM-BJ) technique. During STM-BJ, the Au tip is retracted from contact with the graphite surface as the top layer is lifted away from its rest position, resulting in a decrease of the conductance. We observe a positive correlation between the conductance of the contact and the length to which the top layer of graphite is lifted. We also find that the top layer recovers elastically to its original form after detaching from the layer on the tip. Furthermore, the lift length of the top layer of graphite during tip retraction is shorter than that of a single layer of graphene on a silicon oxide surface. Such a characteristic is probably the result of a weaker attractive force of the graphene with Si oxide, such as the van der Waals force, than that of the interlayer interaction of graphite. Our results thus open a new path to basic research of mechano-electronics with carbon-based materials and their applications.

1. Introduction

Understanding the electronic and mechanical properties of carbon-based materials—including diamond, graphite, graphene and carbon nanotubes—are of critical importance for the basic research of nanoelectromechanical system (NEMS) and for the design of electronic devices using such materials [1–4]. A scanning tunneling microscope (STM) has been widely used to electrically and mechanically characterize single layer graphene or graphite, and an STM-tip induced surface deformation of the graphene or graphite surface at the atomic scale affects the mechanical, electrical, optical and thermal properties of the materials [5–7]. However, it is difficult to obtain an adequate amount of data to statistically analyze the properties of the sample due to the high-vacuum and low temperature conditions of the system [8–10]. The scanning tunneling microscope-based break-junction (STM–BJ) technique is one of the most versatile techniques and it provides deep insight into the structure-conductance relationship of molecular junctions that are formed with a metal or with two-dimensional templates by allowing a statistical interpretation over an ensemble of measurements under ambient conditions [11–13].

In this study, we used the STM-BJ technique to measure the electrical conductance and the mechanical deformation of a graphite surface in order to investigate the correlation of these measurements. The tip-induced deformation of the top layer of the graphite leads to a change in conductance that contains two regimes, contact and tunneling. We observe a positive correlation between the contact conductance and the lift length of the top layer of graphite. Furthermore, we find an elastic recovery of the top layer back to its original form after detaching from the layer during tip retraction. We also obtain a longer lift length for a single layer of graphene than for the top layer of the graphite in the retract-approach measurement.

2. Experimental procedure

We measure the electrical conductance and the mechanical deformation of the graphite surface by using the STM-BJ setup that was previously described in detail [14]. The measurements are carried out using a piece of graphite ($\sim$100 nm in height with an area of $50 \times 30\ \mu m^2$) as the bottom electrode and a cut Au wire (Alfa-Aesar, 99.998% purity) as the tip. The graphite flake is mechanically transferred onto a SiO_2 (300 nm)/Si substrate using the well-known exfoliation process [4,15]. An electrical contact to the edge of this flake is then fabricated by depositing an Au film using thermal evaporation and the shadow mask technique which prevents the surface contamination that occurs during standard lithography. The Au tip is brought into contact with the graphite flake to achieve a conductance of $\sim 10^{-1}\ G_0$ to $10^{-2}\ G_0$. The tip is then retracted from the graphite surface at a speed of 25 nm/s and

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the conductance is recorded at a 40 kHz data acquisition rate while a voltage of −0.5 V is applied to the graphite. For all of the measurements reported here, thousands of curves were collected to allow for detailed statistical analysis.

3. Results and discussions

Fig. 1a shows an illustration of the STM-BJ setup that was used to measure the conductance and the lift length of graphite with an Au tip. Fig. 1b shows a schematic representation of the retraction (i–iv), the approach (v), and the contact (i) of the Au tip to deform the graphite surface. We repeated these processes to have thousands of conductance traces. For a tip-top layer interaction force larger than the interlayer interaction of graphite, the top layer can conform to the tip and will remain attached on retraction. LL is the lift length of the top layer of graphite during retraction of a piezo. To investigate the evolution of the top layer of the graphite, we measure the gap created after tip-graphite contacts ruptures by following a method as previous works. [16,17] We first form a tip-graphite contact (i), and retract the contact until it ruptures (iv). Then, we push the tip back together to determine the gap distance (GD) that the tip needs to move before reaching a conductance of $\sim 10^{-3} G_0$, which is considered to be a touch (v) of the Au tip on the graphite surface with approach. Fig. 1c shows a sample piezo-ramp (black dashed line in the upper panel) and a simultaneously acquired conductance trace (red curve in the lower panel). The GD (iii–v in Fig. 1b) is determined from the difference between the piezo-distances L1 (iii) and L2 (v) as indicated in the figure. The conductance is different at the same piezo-height (i–iii and v–i) resulting in a hysteresis phenomenon in retraction (∼0 to 0.1 s) and approach (∼0.5 to 0.6 s) processes as shown in the conductance traces in the Fig. 1c. It is probably attributed to the different evolution of the contact area for the top layer of graphite with the Au tip in retraction and approach steps. However, the conductance and slope near ∼0.1 s (iii, iv) are almost same to those near ∼0.7 s indicating the top layer of the graphite recovers elastically to its original position. A statistical correlation analysis for the measured conductance traces was performed for the measured conductance traces by constructing a two-dimensional (2D) cross correlation histogram so that the relationship between the LL and GD of the Au tip and the graphite could be better understood [18–20]. Fig. 2a shows a 2D-cross correlation constructed without a data selection according to measurements from more than 5000 individual conductance traces. The dotted black curves are contour plots of the fitted 2D-normal distributions of the data set. To quantify this correlation, the joint distribution between LL and GD was modeled using the generalized 2D Gaussian distribution equation [21–24]:

$$z = A\exp\left[\left(\frac{-1}{2(1-r^2)}\right)\left(\left(\frac{x-\mu_x}{\sigma_x}\right)^2+\left(\frac{y-\mu_y}{\sigma_y}\right)^2 - \left(\frac{2r(x-\mu_x)(y-\mu_y)}{\sigma_x\sigma_y}\right)\right)\right] \quad \text{with } r\in[-1,+1] \qquad (1)$$

where A is the scaling parameter, r is the cross-correlation parameter between −1 and 1, and μ and σ are the mean value and the standard deviation of variables noted in the subscript respectively. Eq. (1) provides a good model of the experimental data in Fig. 2a. The insets show histograms and Gaussian fits for LL and GD, and the calculations produce a mean LL=2.38 nm (μ_x=2.38, σ_x=0.14) and a mean GD=0.59 nm (μ_y=0.59, σ_y=0.09) with a cross-correlation parameter of $r=+0.48$, which is consistent with the positive tilt of constant-z contours.

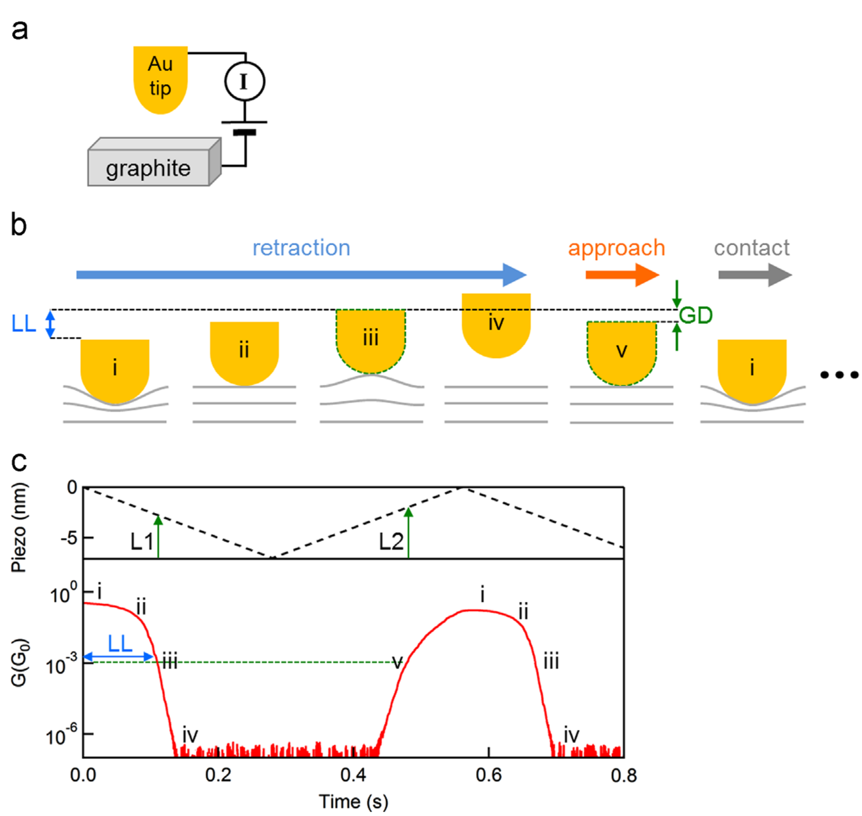

Fig. 1. (a) Illustration of the STM-BJ setup with an Au tip and a graphite surface. (b) Schematic diagram of the retraction (i–iv), approach (v), and contact (i) of the Au tip to the graphite surface. These processes repeated to have thousands of conductance traces. LL represents the lift length of the top layer during tip retraction, and GD is the gap distance during the approach of the tip. (c) Sample piezo-ramp (black dashed line in the upper panel) and conductance trace (red curve in the lower panel). The green dashed line in the lower panel indicates the $10^{-3}G_0$ conductance which is assumed to be rupture (iii) and touch (v) positions of the tip. The GD is determined from the difference between the distances L1 (iii) and L2 (v). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)