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Tuning the nanotribological behaviors of single silver nanowire through various manipulations

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ABSTRACT

Nanotribological characteristics of silver nanowires (Ag NWs) are of great importance for the reliability of their applications where involving mechanical interactions. The frictional behaviors of the Ag NWs with different lengths on SiO_2/Si substrate have been investigated directly by atomic force microscopy (AFM) nanomanipulation. The relatively short and long Ag NWs behave like the rigid rods and flexible beams, respectively, and the critical aspect ratio of NWs for the two cases is found to be about 20. The relatively short NWs demonstrates three forms of motion with different frictional behaviors. The friction of the relatively long NWs increases with the bend of the NWs. The long Ag NWs display extraordinary flexibility that can be folded to different shapes, and the folded NWs show a similar frictional behavior with the rigid rods. Different simplified mechanical models are established to match the frictional behaviors of the corresponding Ag NWs. The adhesion between the Ag NWs and substrate is calculated by an indirect method based on the van der Waals force equation to assess their adhesive attraction. These findings may provide insight into the frictional characteristics of Ag NWs and contribute to the quantitative interface design and control for their applications.

1. Introduction

Silver nanowires (Ag NWs) have attracted tremendous attention due to their superior characteristics of electrical conductivity, light transmission, flexibility and chemical stability, which are considered to be ideal functional units for the fabrication of transparent conductive films (TCFs), conductive silver adhesive and nanoelectronic devices [1–4]. The interfacial interactions like friction and adhesion between the Ag NWs and the substrate surface, especially for the silicon dioxide (SiO_2) substrate commonly used in microelectronics, have a direct influence on the stability and functionality of nano-devices [5]. In particular, the frictional characteristics of Ag NWs are of great importance for the contact interface containing the mechanical interactions such as contact and relative motion during operation. However, although the frictional characteristics of the Ag NWs are critical for the nano-devices, they are still not clearly understood. This may be partly due to the experimental difficulties in measuring the friction of Ag NWs at the nanoscale, and the other part is because of the frictional characteristics of Ag NWs have not been extensively explored.

Recently, various experimental and numerical methods are applied to investigate the frictional behaviors of nano-structures [6–10]. The methods for investigating the frictional behaviors of one-dimensional nanomaterials included the optical microscopy (OM) nanomanipulation [11], scanning electron microscopy (SEM) nanomanipulation [12,13] and atomic force microscopy (AFM) nanomanipulation [14–16], etc. OM and SEM can be used to directly detect the state of nano-structures, but the quantitative force cannot be obtained directly. Meanwhile, for the case of SEM, the frictional characteristics in vacuum may differ from those under ambient conditions [13]. While AFM nanomanipulation is an intuitive method to evaluate the frictional characteristics of NWs, which can obtain the quantitative force directly and access more motional degrees of freedom (sliding, rotating in-plane, rolling) than regular tip-on-substrate friction studies [16]. Several methods based on AFM nanomanipulation are proposed to assess the frictional properties of different kinds of NWs.

One of them is called the method of the most bent state, which can be used to infer the friction of the NWs on a flat substrate by sequential AFM manipulations [17,18]. This method is based on the fact that an elastically deformed NW is kept in equilibrium by friction of the NW-substrate and restoring elastic forces of the NW. Assuming that the elastic properties of the NW are known, the friction can be deduced from the radius of curvature of the

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deformed NW. In this way, Pettersson et al. studied the frictional characteristics of InAs NWs on Si_3N_4 substrate, and obtained the friction force per unit length for both sliding and static friction over a range of NW diameters [19]. Zhu et al. investigated the static friction between the Si NWs and the ultraviolet/ozone treated polydimethylsiloxane (PDMS) based on "the most-bent state" of the NWs [20]. Huang et al. bent the Al_2O_3 nanowires (NWs) on a Si substrate and developed an analytical model to estimate the kinetic and static frictions [21]. They found the kinetic and static frictions per unit area were in the ranges of 1.16–3.4 MPa and 0.68–2.7 MPa, respectively. Since this friction measurement is indirectly determined based on a theoretical beam model, knowledge of the elastic properties (elastic modulus), geometry (bending angle, moment of inertia), and bending states of the NWs are needed for the analysis, which leads to larger measurement errors. Chung et al. developed a beam theory based model to interpret the lateral force for determination of the elastic modulus and frictional characteristics of NWs [22]. Using this developed model, the elastic modulus and the frictional characteristics of SiO NWs on a Si (100) substrate were obtained simultaneously. Huang et al. characterized the kinetic friction between SiC NWs and Si substrate by the established force-equilibrium and energy-conservation models and combining the optical manipulation [23].

Direct friction measurements of the NWs on a flat substrate have also been conducted, where the kinetic friction is directly determined by the lateral force of AFM tip. Chung et al. investigated the static and kinetic frictional characteristics of oxidized Si NWs sliding against thermally grown SiO_2 and CVD-grown single layer graphene [24]. The kinetic friction was directly measured by the AFM during the translation of the bent NWs, and found the friction of the NWs on the graphene substrate was smaller than that on the SiO_2 substrate. Kim et al. examined the frictional behavior during manipulation of a single ZnO NW on a Si wafer by direct measurement of AFM, and observed the rolling and sliding motions depending on the frictional interaction of the NW–Si substrate [25]. The difference between the frictions of rolling/sliding and pure sliding motions of the NW was not drastic as macroscale systems. Direct friction measurement by AFM was frequently used to characterize the friction behaviors of NWs and nanoparticles [14,25].

Most of the previous AFM manipulation experiments at the nanoscale mainly focused on the NWs of InAs, Si and ZnO and carbon nanotubes. Only a few studies related to the frictional behaviors of Ag NWs have been reported [26,27], due to its applications only recently attracted attentions. Here, the nanotribological behaviors of Ag NWs with different lengths on SiO_2/Si substrate have been investigated by AFM nanomanipulation. The frictional behaviors of the Ag NWs can be controlled by their aspect ratio. Different simplified mechanical models are established to help understand the corresponding frictional behaviors. The adhesion between the Ag NWs and SiO_2/Si substrate is also calculated based on the van der Waals force equation.

2. Experimental

N-doped Si covered with dry oxidation generated 300 nm-thick SiO_2 was used to prepare the substrates. The substrates were sonicated in acetone, ethanol and deionized water successively for 10 min, and then dried with nitrogen. The surface roughness (Ra) values of the substrates were measured by AFM (MFP-3D, Asylum Research) topographies with 1 μm × 1 μm areas to ensure they were cleaned up. Each value of Ra was the average of five measurements on adjacent regions. Ag NWs powders (Xuzhou Jiechuang New Material Technology Co. Ltd., China) were dissolved in alcohol solution using an ultrasonic bath. After resting for half an hour, the supernatant was dripped onto the substrate and then dried with nitrogen.

Scanning Electron Microscope (SEM, HITACHI S-4800) was applied to observe the dispersion of the Ag NWs on the substrate and determine the cross-section shape of NWs. The crystallographic structure of the Ag NW was investigated using X-ray diffraction analysis (XRD, model: XD-5A) at conditions with accelerator voltage of 20 kV and the working current of 30 mA. The morphology of Ag NWs on the substrate was determined by AFM at tapping mode using silicon probes with a nominal normal spring constant of 3 N/m and tip radius less than 10 nm (Multi75Al-G, Budget Sensors). Straight NWs on the substrate were selected for the manipulation. AFM topographic images of the selected NWs were obtained at tapping mode to determine the dimensions (length and radius) of the NWs. The length of the NW was determined directly from the AFM topographic image while the radius of the NW was determined by fitting a circle to the average height profile obtained from the AFM topographic image.

For quantitative force measurement, normal and lateral force calibrations of the AFM tips were performed prior to friction test via noncontact method [28]. Considering the mode shape of cantilever was important for the noncontact lateral force calibration method [29], the first flexural mode with the mode correction factor of 0.971 was applied to calibrate the normal force of AFM tips. Before friction measurement, the NWs were aligned to a direction perpendicular to the fast scan direction of the AFM scanner by continuously multi-step manipulations at Litho PFM mode. The adhesions of tip-substrate and tip-NWs were measured by recording a force-distance curve to determine the pull-off force pulling the AFM tip out of contact with the surface. The error of the adhesions was calculated as the standard deviation of five pull-off force measurements recorded in the near vicinity of the areas. The measured adhesion between the tip and the NW was used to evaluate the adhesion between the NW and the substrate. The adhesions between the tip and substrate were also measured before and after manipulation to exclude the influence of the AFM tip wear on the experimental results.

The Ag NWs were manipulated by AFM at Litho PFM mode and the variations in lateral force were monitored during the manipulation process. The variation in height signal of the AFM tip during manipulation process was also observed to monitor the tip climb over the NW whether or not. The lateral forces were offset to make the friction of the tip-substrate zero, so the lateral forces in the lateral force curves during push processes stood for the friction between the NW and substrate directly. AFM topographic images of the NW before and after each manipulation were obtained at tapping mode to observe the manipulation results. The manipulations were conducted under normal force from 100 nN to 400 nN. The manipulation length was varied from a few hundred nanometers to a few micrometers, and the manipulation speed was set to 100–500 nm/s. All manipulations were performed in ambient conditions (20–25 °C and 30–40% R.H).

3. Results and discussion

3.1. Characterization and manipulation of the Ag NWs

Straight Ag NWs on the substrate were selected for the manipulation. Fig. 1(a) show a typical AFM topographic image of the Ag NW along with the cross-sectional height profile corresponding to the red solid line in the inset. The length of the NW (L_{NW}) is determined from the AFM topographic image directly, and the radius of the NW (R_{NW}) is determined from a circle fitted to the average height profile, considering the effect of the tip convolution. The diameter and length of this Ag NW are about 65 nm and 6 μm,