Frictional shear stress of ZnO nanowires on natural and pyrolytic graphite substrates

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Abstract: The friction behaviour of ZnO nanowires on natural graphite (NG) and highly oriented pyrolytic graphite (HOPG) substrates was tested in ambient conditions by use of optical microscopy based nanomanipulation. Nanowires on the step-free and waviness-free NG substrate exhibit a diameter-independent nominal frictional shear stress of 0.48 MPa, and this provides a benchmark for studying how the surface topography of graphite influences nanowire friction. Nanowires on the HOPG substrate present a significant diameter-dependent frictional shear stress, increasing from 0.25 to 2.78 MPa with the decrease of nanowire diameter from 485 to 142 nm. The waviness of HOPG has a limited effect on the nanowire friction, as a nanowire can fully conform to the substrate. The surface steps on the HOPG can significantly enhance the nanowire friction and lead to a much higher frictional shear stress than that on NG due to mechanical blocking and the presence of a Schwoebel barrier at step edges. The surface steps, however, can also generate small wedge-shaped gaps between a nanowire and substrate, and thus reduce the nanowire friction. With the decrease in nanowire diameter, the capacity for the nanowire to better conform to the substrate reduces the length of the wedge-shaped gaps, leading to the observed increase in nanowire friction. The results have improved our understanding of the unique friction behaviour of nanowires. Such an improved understanding is expected to benefit the design and operation of nanowire-friction-based devices, including bio-inspired fibrillar adhesives, soft grippers, rotary nanomotors, and triboelectric nanogenerators.

Keywords: frictional shear stress; nanowires; graphite; surface step; waviness

1 Introduction

The friction of nanowires or nanofibers on substrates plays a determinant role on the design and performance of state-of-the-art nanofriction-based devices, such as bio-inspired fibrillar adhesives [1–3], soft grippers [4, 5], rotary nanomotors [6, 7], and triboelectric nanogenerators [8–10]. Furthermore, nanowires have nanoscale lateral dimensions and microscale axial lengths, and therefore the study of their frictional behavior is expected to help fill in the gaps of our fundamental understanding of atomic- and macro-scale friction [11–16].

Numerous nanowire friction tests carried out on smooth substrates have shown that the friction force between a nanowire and substrate is proportional to...
their contact area. This relationship is similar to that exhibited by atomic force microscopy (AFM) tips and nanoparticles on smooth substrates [12, 17–25]. Nanowires on substrates containing surface features, however, exhibit a more complex friction behavior. Segments of a nanowire may bridge over a region of a substrate containing surface features due to the mechanical constraint enforced by its contact with surface steps or asperities, leading to a significant decrease in its real contact area. As a result, the friction force, which is proportional to the real contact area, would decrease on substrates with uneven surface topography [26, 27]. On the other hand, a nanowire may conform to the topography of a substrate and thus exhibit significantly enhanced friction as compared to its bulk counterpart. The later mechanism is generally accepted as being primarily responsible for the high friction/adhesion of gecko-like fiber-based adhesives [3, 28], which was demonstrated experimentally in our recent study [29]. According to the theory of solid mechanics, the lateral flexibility of a nanowire is highly sensitive to its diameter, and so is its frictional shear stress. Such a dependence has not yet been validated experimentally [26, 27, 29]. Moreover, AFM tips and nanoparticles sliding over a rough substrate typically exhibit enhanced friction forces due to mechanical interlocking and the presence of a Schwoebel barrier at steps or asperities [30–35]. Nevertheless, due to the significant experimental challenges associated with testing nanowires, it is not yet known whether they exhibit similar behavior.

This study seeks to understand the effect of surface topography on the frictional behavior of a nanowire. With this goal, we comparatively examine the frictional shear stress of ZnO nanowires on both a natural graphite (NG) substrate and a highly oriented pyrolytic graphite (HOPG) substrate under the ambient atmosphere. It is generally accepted that both NG and HOPG substrates are free of sharp asperities and have the same surface chemistry. Meanwhile, NG substrates are free of surface steps, and have insignificant waviness, while HOPG substrates typically exhibit atomic surface steps and microscale waviness. The selection of NG and HOPG substrates for examination in this comparative study therefore eliminates the possible effect induced by the surface asperity and surface chemistry, and also enable us to clarify how atomic surface steps and microscale waviness influence the friction between nanowires and substrates. This will not only improve our fundamental understanding of the friction behavior of nanowires, but also benefit the design of nanowire-friction-based nanodevices.

2 Experimental details

The ZnO nanowires were synthesized on a Si wafer via chemical vapor deposition (CVD), and the wires exhibit a hexagonal cross-sectional profile with atomically smooth surfaces and a Young’s modulus of $E \approx 140$ GPa [36, 37]. The NG and HOPG substrates were cleaved with the aid of a scotch tape immediately prior to the friction tests and their surface topographies were characterized using an Agilent 5500 AFM.

The friction between a nanowire and substrate was measured using the midpoint push test in an ambient environment (temperature: ~ 25 °C; relative humidity: ~ 50%) [19]. In the test, a nanowire was directly transferred from the Si wafer (i.e. growth substrate) onto the HOPG substrate using an optical microscopy (OM) nanomanipulation technique [19, 38]. The transfer did not use any additional liquids or adhesives, which therefore avoided the absorption of contaminants onto the surface from nanowires or substrates [39, 40]. The nanowire on the HOPG substrate was pushed at its midpoint by using an electrochemically etched W tip with a diameter of ~ 400 nm, to generate a sliding that has a constant speed of ~ 200 nm/s. A W tip with a relatively large tip diameter was used to ensure it was sufficiently robust to apply the required pushing force as well as to avoid damaging the nanowire through contact-induced stress concentrations. In addition, graphite surfaces are generally considered hydrophobic, and therefore capillary necks are not expected to appear when the testing environment is maintained with a moderate humidity of 50% [41, 42]. Capillary forces are therefore considered to have a negligible effect on the friction behavior of the nanowires in this study. The entire testing process was monitored in real time by an OM (Objective lens: Mitutoyo M Plan APO 100× with a resolution of 0.4 μm). The nanowire was formed into an arc shape, sliding on the substrate surface. The sliding remained stable due to a balance between the pushing force of the W
tip at the nanowire’s midpoint and the friction force distributed uniformly along the entire length of the nanowire. During sliding, if the W tip was not in contact at the midpoint of a nanowire, or if the moments about its contact point generated by the frictional forces on each side of the nanowire were not balanced, the nanowire began to rotate. In such cases, the contact point between the tip and nanowire must be adjusted according to the sliding status of the nanowire. Immediately after friction testing on the HOPG substrate, the same nanowire was transferred onto the NG substrate under OM. The midpoint push test was subsequently repeated using the same W tip. The nanowire remained on the NG substrate after testing and was examined using field-emission scanning electron microscopy (SEM, JEOL JSM-7800F and FEI Nova NanoSEM 450, operated at 10 kV).

3 Results and discussion

Figures 1(a)–1(c) show typical AFM micrographs and their corresponding line-scan profiles of the NG substrate. For the scan areas of 50 µm × 50 µm and 2 µm × 2 µm, the measurement at three positions, 1/4, 1/2, and 3/4 of the scan side length (a) gave the same average roughness values of $R_a = 0.10$ and 0.01 nm, and average waviness values (defined by the arithmetic mean waviness) of $W_a = 0.19$ and 0.01 nm, respectively. The NG substrate had an atomically smooth surface without atomic steps over the scale of several tens of µm, and only very shallow waviness could be identified on the surface. The waviness can be approximately described by use of a sinusoidal function, $y(x) = [H \cos(2\pi x/\lambda)]/2$, where $H = 1.0$ nm and $\lambda \approx 10$ µm can be considered as the amplitude and wavelength, respectively. The very small amplitude-to-wavelength ratio, $H/\lambda < 0.1\%$, indicates that the waviness is very shallow, and should not affect the contact behavior between the nanowire and substrate [27, 29]. In contrast, the HOPG substrate, shown in Figs. 1(d)–1(f), exhibits waviness, and also contains many steps with heights corresponding to that of a single or few-layer graphite. For comparison, the values for $R_a$, $W_a$, $\lambda_x$, $H_x$, and $H_x/\lambda_x$ for the three positions,
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\( a/4 \), \( a/2 \), and \( 3a/4 \), are listed in Table 1, where \( i = 1 \) and \( 2 \) correspond to the largest and smallest obtained \( \lambda \) and \( H \) values for the scan area of \( 50 \mu m \times 50 \mu m \), and \( i = 3 \) corresponds to the largest obtained \( \lambda \) and \( H \) for the scan area of \( 2 \mu m \times 2 \mu m \), respectively. The \( R_s \) and \( W_s \) values obtained at each of the three positions can be considered equivalent. The \( H_i \) and \( \lambda_i \) values obtained at each position are different, however the corresponding \( \lambda / \lambda_i \) values, i.e. the slope of the waviness, range from 0.1% to 1.0%, and are therefore can still be considered equivalent.

Figures 2(a) and 2(b) display the initial stress-free state as well as the steady sliding state of the same ZnO nanowire on the HOPG substrate captured by OM. For comparison, the corresponding initial and sliding states of the same nanowire on the NG substrate were presented in Figs. 2(c) and 2(d), respectively. To obtain the deflection and the corresponding projection angle, \( \delta \) and \( \alpha \), of the sliding nanowire, we extracted co-ordinates along the length of the bent nanowire profile using DataThief software, and subsequently implemented a polynomial fit [20, 21]. From the fitting polynomials, we obtained \( \delta_{\text{HOPG}} = 8.0 \pm 0.4 \mu m \) and \( \alpha_{\text{HOPG}} = 43.8(\pm0.2)^\circ \), \( \delta_{\text{NG}} = 5.8 \pm 0.4 \mu m \) and \( \alpha_{\text{NG}} = 31.5(\pm0.2)^\circ \), as labelled in Figs. 2(b) and 2(d). Figure 2(e) provides a SEM image of the same nanowire on the NG substrate after testing, showing that the nanowire has a hexagonal cross-section and a uniform diameter, \( D = 371 \pm 3 \) nm, along its entire length, \( 2L = 29.97 \pm 0.05 \) \mu m. The friction forces exerted on the nanowire are assumed to be distributed uniformly along its length, and are balanced by the elastic restoring force of the nanowire, as illustarted in Fig. 2(f).

\[
-x = s \sin \alpha - \frac{f}{EI} \cos^2 \alpha s^4 - \left( \frac{f}{EI} \right)^2 \frac{\sin \alpha \cos^2 \alpha}{360} s^4 - \left( \frac{f}{EI} \right)^3 \frac{13 \sin^3 \alpha \cos^2 \alpha}{129600} - \frac{\cos^2 \alpha}{10368} s^{10}
\]  

(1)

where \( x \) and \( s \) are the vertical distance and length of an arbitrary point measured on the nanowire.

**Table 1** Average roughness \( (R_s) \), average waviness \( (W_s) \), wavelength \( (\lambda) \), amplitude \( (H) \), and slope \( (\lambda / \lambda_i) \) obtained at three positions, \( a/4, a/2, \) and \( 3a/4 \), in Figs. 1(d) and 1(e). Note that \( R_{s(50)} \) and \( R_{s(2)} \) represent the roughness values for the scan areas of \( 50 \mu m \times 50 \mu m \) and \( 2 \mu m \times 2 \mu m \), respectively.

|       | \( R_s(50) \) | \( R_s(2) \) | \( W_s(50) \) | \( W_s(2) \) | \( \lambda_1 \) | \( \lambda_2 \) | \( \lambda_3 \) | \( H_{1/2} \) | \( H_{2/2} \) | \( H_{3/2} \) | \( H_{1/\lambda_1} \) | \( H_{2/\lambda_2} \) | \( H_{3/\lambda_3} \) |
|-------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| \( a/4 \) | 0.16        | 0.01        | 47.9        | 0.34        | 15.5        | 5.2         | 1.1         | 65.8        | 7.8         | 0.6         | 0.85        | 0.30        | 0.10        |
| \( 2a/4 \) | 0.14        | 0.01        | 29.7        | 0.59        | 17.2        | 6.9         | 1.2         | 46.5        | 9.1         | 1.1         | 0.54        | 0.26        | 0.18        |
| \( 3a/4 \) | 0.17        | 0.01        | 35.8        | 0.45        | 16.1        | 8.9         | 1.2         | 60.3        | 13.1        | 0.7         | 0.75        | 0.29        | 0.11        |

Fig. 2 (a–d) OM micrographs of the initial and stable sliding states of the same ZnO nanowire on the HOPG and NG substrate, respectively. The curves overlayed in (b) and (d) are FEA simulated profiles corresponding to different \( \tau \) values. (e) SEM image of the nanowire on the NG substrate after the midpoint push test. The inset is an enlarged SEM image showing the hexagonal profile of the nanowire. (f) The cantilever model for a nanowire sliding in a stable manner on a substrate at a constant speed.
to its end (Fig. 2(f)), and \( I = 5\sqrt{3}D^4 / 256 \) is the area moment of inertia of the nanowire. Substituting the values of \( s \) and \(-x\) for all the points distributed along the entire nanowire with an interval of 1 \( \mu \)m, as well as the \( E, D, \) and \( \alpha \) values into Eq. (1), we numerically solved Eq. (1) and obtained \( f_{\text{HOPG}} = 0.154 \pm 0.016 \) N/m and \( f_{\text{NG}} = 0.107 \pm 0.021 \) N/m. Here the uncertainties represent the standard errors of the \( f \) values calculated at different points. The values of frictional shear stress, defined as \( \tau = 2f/D \), i.e. the friction force per contact area [44], for the HOPG and NG substrates were calculated to be 0.83 \( \pm \) 0.08 and 0.58 \( \pm \) 0.11 MPa, respectively. To validate the analytical solution, the bent nanowire profiles were simulated by finite element modelling (FEM) using the COMSOL Multiphysics 5.6 software, where the nanowire density of 5.6 g/cm\(^3\) and Poisson's ratio of 0.3 of the bulk ZnO were used. During FEM simulation, the value of the interfacial shear stress was varied until the simulated profile best matched the bent profile recorded during testing. Figures 2(b) and 2(d) show the simulated profiles of the nanowire on both the HOPG and NG substrates, respectively. The simulated profiles that closely match the observed nanowire profile are demarcated by the green curves, and correspond to \( \tau_{\text{HOPG}} = 0.83 \) and \( \tau_{\text{NG}} = 0.58 \) MPa, respectively. ‘Poorly-matched’ simulated profiles that correspond to the shear stress values which under- and over-estimated the best fit value by 10% are demarcated respectively by the yellow and white curves. On both substrates, the poorly-matched profiles clearly deviate from the observed profile.

In this work, 12 ZnO nanowires were tested on both substrates, and their measured frictional shear stress values are plotted in Fig. 3. The frictional shear stress values measured on the NG substrate, \( \tau_{\text{NG}} \), ranged from 0.31 to 0.74 MPa, showing no diameter dependence, providing an average value of 0.48 MPa with a standard deviation of 0.09 MPa. The surface of the NG substrate as well as the nanowire facets are atomically smooth, so that a full contact over the entire facet area of a nanowire can be assumed. The fact that the obtained frictional shear stress values are diameter-independent further supports full conformation of the nanowires occurred [45]. The average frictional shear stress value of 0.48 MPa measured on the ‘smooth’ NG substrate can therefore be used as a benchmark against which the friction behaviour of nanowires on rough or textured substrates can be compared. In contrast, the frictional shear stress value measured on the HOPG substrate, \( \tau_{\text{HOPG}} \), drastically increases from 0.25 to 2.78 MPa with the nanowire diameter decreasing from 485 to 142 nm.

Theoretically, the frictional shear stress of a nanowire can be affected by the presence of surface steps as well as by the waviness of the HOPG substrate. The effect of steps of a substrate surface on the frictional shear stress is complex, due to the existence of competing mechanisms. First, the sliding of a nanowire maybe blocked by the steps on the surface. As a result, a greater force must be applied to the nanowire to overcome the blocking than that on the NG substrate [33]. The contact angle formed between the surface of nanowire and an atomic step can be evaluated by \( D/h \), where \( D \) is the nanowire diameter and \( h \) is the step height. The contact angle will therefore increase for nanowires with smaller diameters. The increase in friction force exhibited by a nanowire due to atomic step-induced mechanical blocking is therefore expected to be more pronounced for nanowires with smaller diameters. Such friction behavior would be considered analogues to that exhibited previously by the micro/ nanoscale contact of spherical balls on stepped surfaces [31, 35]; however, the exact relationship is yet to be explored. Meanwhile, a Schwoebel barrier is present at the steps, and this will further increase the force for the nanowire to pass the steps [34]. Both mechanisms can lead to a significant increase of the friction force exhibited by a nanowire.
surface steps can induce the formation of atomic-scale wedges at the nanowire/substrate interface, as shown in Fig. 4. This in turn may reduce the frictional shear stress exhibited by a nanowire.

When a nanowire lies across a step, the length of the nanowire segment that remains suspended (forming the wedge) is governed by the balance between the adhesion energy of the nanowire-substrate interface and the elastic energy stored in the conforming nanowire. Using the elastic beam theory, the length of a wedge can be estimated by [46]:

$$s_w = \left( \frac{45\sqrt{3}Eh^2D^3}{64\gamma_{ZnO-G}} \right)^{1/4}$$

(2)

where $h$ is the step height which typically corresponds to one or several graphite layers, and $\gamma_{ZnO-G}$ is the ideal adhesion energy between ZnO and graphite, defined as the energy required to separate a smooth ZnO slab from a graphite surface [47]. A $\gamma_{ZnO-G}$ of 0.261 J/m$^2$ is used in this study, and this value was previously measured between a ZnO coated flat AFM nanotip and a HOPG substrate [47]. By evaluating the length of the wedge formed by a nanowire that lies over a step, and then comparing it to the distance between the steps observed on the HOPG substrate, we can estimate what portion of a nanowire’s length remains in contact with the substrate and what portion is suspended. Nanowires with $D = 100, 200, 300, and 400$ nm were selected for evaluation as these diameters are within the range of the nanowires tested. We estimate that a step edge has a height corresponding to a single graphite layer ($h = 0.34$ nm [33, 34]), and this corresponds to wedge lengths of $s_w = 93, 157, 212, and 263$ nm, obtained from Eq. (2). In Fig. 1(f), the distance between steps, or rather, the width of the step terraces, $w_{ter}$, typically ranges from 100–500 nm. The estimated wedge length values should range from $w_{ter}/4$ to $w_{ter}$. This indicates that a large portion of the length of a nanowire is actually suspended above the HOPG substrate. Moreover, Eq. (2) indicates that the real contact length of a nanowire, $s_c = w_{ter} - s_w$, should decrease linearly with the $D^{3/4}$. In our nanowire-HOPG system, the friction force is proportional to the real contact area [48, 49]. Therefore, we can express the friction force as a function of the real contact length of a nanowire, written as $\tau \propto \tau_{max} / (w_{ter} - s_w)$, where $\tau_{max}$ is the maximum measured $\tau$ value. In other words, $\tau_{HOPG}$ exhibits a reciprocal dependence with $D^{3/4}$. To validate this relationship, a curve of the form $\tau = 1/(C_1 + C_2D^{3/4})$ (where $C_1$ and $C_2$ are constants) was fitted to the measured values of $\tau_{HOPG}$ of all the nanowires, and is plotted in Fig. 3. The $R^2$ squared value of 0.8739 indicates that the proposed relationship between $\tau_{HOPG}$ and $D$ is in good agreement with the data.

The surface waviness of the substrate can potentially influence the friction behavior of a nanowire by constraining it in a way that prevents contact at wave valleys or trapping/blocking it at the wave valleys/crests via interlocking [50]. In this study, the nanowires were observed to slide in a stable manner along the substrate surface. This indicates that the friction force is uniformly distributed along the length of the nanowires during sliding. Therefore, it is reasonable to derive that the friction behavior is independent on the waviness of the substrate in our cases. Otherwise, if the friction force was dependent on the substrate waviness, then the nanowire should lose its stability during sliding. In fact, the lack of dependence on waviness observed in our test can be understood by considering how a nanowire conforms to a substrate. For a nanowire that has elastically conformed to a wavy substrate, its bending and tensile energies, $U_b = \int_0^l (EIk^2/2)dx$ and $U_t = \int_0^l (S\sigma^2/2E)dx$, associated with confirmation to each characteristic wavelength should be less than or equal to the corresponding adhesion energy, $U_a = \gamma'_{ZnO-G}\lambda$, where $k$ is the curvature function of the wave surface, $\gamma'_{ZnO-G}$ is the actual adhesion energy between the ZnO nanowires and the HOPG substrate with surface steps and

![Fig. 4](https://mc03.manuscriptcentral.com/friction)  
**Fig. 4** Sketches of a nanowire conforming to a wavy substrate surface and the step-induced gap between the nanowire and substrate surface.
waviness, and $\sigma$ and $S$ are the tensile stress and cross-sectional area of the nanowire, respectively [51, 52]. As $U_i \ll U_s$, the critical diameter $D_c$ for the conform nanowire can be estimated by

$$D_c = \left( \frac{128 \lambda^3 \gamma'_{ZnO-G}}{5 \sqrt{3 \pi^2 EH^2}} \right)^{1/3} \tag{3}$$

Here $\gamma'_{ZnO-G}$ can be estimated by [49]:

$$\gamma'_{ZnO-G} = \frac{\gamma_{ZnO-G}}{(1 + d_{ag} / d_0)^3} \tag{4}$$

where $d_0 = 0.2$ nm is the cut-off distance, and $d_{ag}$ is the average nanowire-substrate distance. For a nanowire on the NG substrate, $d_{ag}$ is taken as 0, as the nanowire is fully adhered to the substrate without surface steps. For a nanowire with $D = 300$ nm over a single graphite layer step of the HOPG substrate with $w_{gr} = 300$ nm, $s_w = 212$ nm can be obtained from Eq. (2); and therefore $d_{ag}$ is estimated to be 0.1 nm, and $\gamma'_{ZnO-G} = \gamma_{ZnO-G} / 2 = 0.13$ J/m$^2$. Considering the characteristic wavelengths and corresponding amplitudes of $(\lambda_1, H_1)$, $(\lambda_2, H_2)$, and $(\lambda_3, H_3)$ measured on our HOPG substrate as shown in Fig. 1(f), we obtain the corresponding critical diameters of $D_{c1} = 820$ nm, $D_{c2} = 740$ nm, and $D_{c3} = 360$ nm. This indicates that all the investigated nanowires can conform well to the broad valleys, $(\lambda_1, H_1)$ and $(\lambda_2, H_2)$, and only the large nanowires are unable to fully conform to the deepest valleys of the wavy HOPG surface, $(\lambda_3, H_3)$. At the same time, the maximum slope presents on the wavy HOPG surface can be roughly evaluated by the ratio $H / \lambda$, and the typically values measured here range from 0.1% to 1.0%. Also, no surface asperities could be detected ($R_s = 0.01$ nm).

Consequently, a waviness-induced interlock effect is expected to insignificantly influence the friction behavior of a nanowire. This is also supported by a previous investigation on the friction behavior of a sharp AFM tip, which found that buried steps had a much smaller contribution on the friction of the tip compared to that of exposed steps. The study also found that the profile of a buried single graphite layer step was equivalent to a surface waviness with a maximum slope of $H / \lambda = 0.17$ [53], within the same range of substrate waviness observed in this study.

The largest diameter of the nanowires investigated here was limited to below 500 nm due the CVD growth process. The shear stress for nanowires with diameters greater than 500 nm is expected to continually decrease with increasing diameter. This can be explained by considering that as the diameter of a nanowire increases, the length of the wedge $S_w$ formed at a step edge on the substrate increases according to Eq. (2), this in turn would lead to a decrease in the real contact length (area) of the nanowire, as hence decrease the frictional force (shear stress). Larger diameter nanowires may also no longer be able to conform to the waviness profile of the substrates, according to the above-estimated $D_c$ values by Eq. (3). Such a non-full conformation would further decrease the contact area and frictional shear stress.

4 Conclusions

In summary, the averaged frictional shear stress of ZnO nanowires on a NG substrate was 0.48 MPa, irrelevant of the nanowire diameter. In contrast, the frictional shear stress generated on the HOPG substrate increased from 0.25 to 2.78 MPa when the nanowire diameter decreased from 485 to 142 nm. The surface waviness of the HOPG substrate showed insignificant influence on the friction behaviour of ZnO nanowires because the nanowires can conform to the substrate surface. In contrast, the surface steps present on the HOPG substrate can significantly influence the frictional shear stress via competing mechanisms. Surface steps can increase the force required by a nanowire to overcome blocking as well as the associated Schwoebel barrier when sliding over the step edges. This mechanism can therefore act to increase the frictional shear stress. Meanwhile, surface steps can generate small wedge-shaped gaps between nanowire and substrate. The length of a gap is dependent on the diameter of the conforming nanowires and dictates the real contact area. This mechanism can therefore act to decrease the frictional shear stress, particularly for larger diameter nanowires. Consequently, the friction shear stress of nanowires on HOPG increases with decreasing nanowire diameter, i.e. $\tau \propto 1 / D^{3/4}$, with values that are typically higher than those observed on NG. This may indicate that the mechanical blocking
and Schwoebel barrier associated with the steps have a stronger influence on friction for the investigated diameter range. Our comparative results clarify how the surface topography of a substrate (waviness and steps) affects the friction generated by a sliding nanowire. These results can be exploited in the design and operation of the high-technology devices based on the friction of nanowires.

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