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Water droplet friction and rolling dynamics on superhydrophobic surfaces

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Superhydrophobicity is a remarkable surface property found in nature and mimicked in many engineering applications, including anti-wetting, anti-fogging, and anti-fouling coatings. As synthetic superhydrophobic coatings approach the extreme non-wetting limit, quantification of their slipperiness becomes increasingly challenging: although contact angle goniometry remains widely used as the gold standard method, it has proven insufficient. Here, micropipette force sensors are used to directly measure the friction force of water droplets moving on super-slippery superhydrophobic surfaces that cannot be quantified with contact angle goniometry. Superhydrophobic etched silicon surfaces with tunable slipperiness are investigated as model samples. Micropipette force sensors render up to three orders of magnitude better force sensitivity than using the indirect contact angle goniometry approach. We directly measure a friction force as low as 7 ± 4 nN for a millimetric water droplet moving on the most slippery surface. Finally, we combine micropipette force sensors with particle image velocimetry and reveal purely rolling water droplets on superhydrophobic surfaces.
While friction is essential in everyday activities, such as walking and driving, it is also responsible for ~23% of the world’s total energy consumption. By introducing new friction-reducing coatings in the fields of transportation and power generation alone, notable economic and environmental savings could be achieved, including a reduction in global CO₂ emissions. One example is a durable superhydrophobic coating, which could greatly enhance the long-term efficiency of solar cells (via self-cleaning surface finish) or reduce the costs of transporting goods on ships.

In order to produce coatings of increasingly high quality, the manufacturing process has to be guided by a sensitive characterization tool of the non-wetting properties. Today, contact angle goniometry (CAG) is the conventional experimental tool for probing water-repellency on various surfaces. In this technique, the profile of a growing and shrinking or moving droplet is observed optically and the resulting advancing and receding contact angles (θₐ and θᵣ, Fig. 1a) are determined through subsequent image analysis. The friction force (also referred to as the lateral adhesion force) is then calculated (assuming a circular contact region) as:

$$F_{LA} = \frac{24}{\pi} \gamma D (\cos \theta_r - \cos \theta_a),$$  
(1)

where $D$ is the diameter of the contact region and $\gamma$ is the surface tension ($\gamma = 0.0728$ N m⁻¹ for water) (Fig. 1b). The challenge is that when surfaces become increasingly slippery, the advancing and receding contact angles approach each other (decreasing contact angle hysteresis, $\theta_a - \theta_r$) and quantification of slipperness by contact angle will be limited by accuracy of image analysis. This is true for various slippery surfaces, such as lubricant-infused and slippery omniphobic covalently attached liquid (SOCAL) surfaces ($\theta \approx 90^\circ$), as well as liquid-like silicone brush surfaces ($\theta \approx 20 - 100^\circ$). Further issues arise on superhydrophobic surfaces (defined by high contact angles $\theta \geq 150^\circ$ and low contact angle hysteresis $\theta_a - \theta_r \leq 10^\circ$) where optical distortions close to the contact region render increasingly high errors ($\theta_{err} \approx \pm 10^\circ$ for $\theta = (150 - 180^\circ)$) in the contact angle analysis. For next-generation slippery surfaces, Eq. (1) suggests that reducing the contact angle hysteresis could lead to significant reduction in the forces holding the droplet on the surface (Fig. 1b). This can, however, only be assessed by measuring the forces directly.

**Fig. 1 Friction force of droplets on slippery surfaces.**

**a** Schematic drawing of a droplet (surface tension $\gamma$) moving on a superhydrophobic surface with a constant speed $v_{drop}$. The motion is opposed by the friction force $F_{LA}$, which is a function of the contact region diameter ($D$) and the advancing and receding contact angles ($\theta_a = 166^\circ$ and $\theta_r = 156^\circ$ in this example).

**b** The dimensionless theoretical friction force calculated using Eq. (1) plotted as a function of advancing contact angle for different contact angle hysteresis ($\theta_a - \theta_r$) values. On super-slippery surfaces, the contact angle hysteresis decreases to unmeasurably low values around $F_{LA}/\gamma D \leq 10^{-3}$.
water droplet. Our experiments reveal the first observation of pure rolling motion of slowly moving water droplets on a superhydrophobic surface, and explore the transition to roll-slip motion as the droplet speed is increased.

Results and discussion

Micropipette force sensor measurements. Micropipette force sensors have recently been extensively used in various biophysical studies (see ref. 42 for a complete review and protocol and ref. 43 for original paper) and consist of a macroscopically thick and robust millimetric, holdable glass capillary and a much thinner microscopic cantilever tip (Methods). The force sensors are easy to prepare using well-established fabrication protocols from inexpensive glass capillaries (Methods). The high elastic modulus of glass enables simultaneously high spring constant $k_p$ with extremely small diameter of the cantilever. Here, we demonstrate this using an 19 – 2.5 cm long MFS with inner/outer radii $\sim 15/20 \mu m$, yielding $k_p = 2.5 - 20 \text{ nN} \cdot \text{m}^{-1}$, that is, comparable to previously used cantilevers but an order of magnitude smaller diameter. A typical MFS friction experiment is shown in Fig. 2b (Supplementary Movie 1), rendering force versus time data (Fig. 2c) from which the experimental kinetic friction force ($F_K$) is determined. The MFSs induce only miniscule deformation to droplets (Fig. 2b and Supplementary Fig. 2), yet achieve a force resolution as low as $\sim 4 \text{ nN}$ (Fig. 2c, see Supplementary Note 1), which is $\sim 2 - 25$ times better than in previous cantilever-based studies. In addition to having exceptional mechanical characteristics, MFS allows for convenient dispensing of the probe liquid, which is also utilized in the calibration of the pipette (Methods).

Friction on superhydrophobic etched silicon substrates. The performance of the MFS technique is demonstrated by measuring friction forces on a set of five different solid superhydrophobic surfaces ranging from slippery to super-slippery. These were prepared by maskless cryogenic deep reactive ion etching of silicon substrates to create a micro/nanostructure, followed by a subsequent coating with fluoropolymer through plasma-enhanced chemical vapor deposition (Methods). Slipperiness was controlled in the etching step by varying the ratio between SF$_6$ and O$_2$ gas flow rates, resulting in different surface topographies ranging gradually from spikes (sample A) to grass (sample E) (Fig. 3a–e, Supplementary Figs. 3–5). To compare our direct MFS force measurements with the existing gold standard method, CAG was used to measure the contact angles of the surfaces (Supplementary Fig. 6 and Supplementary Table 1, Methods).

As predicted by Eq. (1), the friction force increases linearly with increasing apparent contact region diameter (Fig. 3f). It is noteworthy that a millimetric water droplet (weight $\sim 10 \text{ \mu g}$) moving on the most slippery spikes surface (sample A) experiences the remarkably low friction force of only $7 \pm 4 \text{ nN}$ (Supplementary Table 2). The experimental force data are in excellent quantitative agreement with Eq. (1) (Fig. 3g). CAG proves to be too inaccurate to reliably distinguish between the five types of superhydrophobic samples (Supplementary Table 2). However, the differences between all samples can clearly be probed with MFS (Fig. 3f), including distinguishing between the two lowest friction samples with $F_K/D = 0.03 \pm 0.02 \text{ nN} \cdot \text{m}^{-1}$ for sample A and $F_K/D = 0.11 \pm 0.04 \text{ nN} \cdot \text{m}^{-1}$ for sample B. The theoretical $F_{LA}$ relies on the optically determined advancing and receding contact angles from each individual MFS experiment. The resulting relative friction force error ($\delta F = \Delta F/F$, where $\Delta F$ is the absolute error, see Supplementary Note 2 for error analysis) is more than ten times higher for the calculated force ($\delta F_{\text{CAG}}$) than for the force measured with MFS ($\delta F_{\text{MFS}}$). As the samples become increasingly slippery (decreasing $F_K/D$), the direct MFS measurements are as much as three orders of magnitude more precise than using Eq. (1). For smaller droplets on the most slippery spikes sample, the lower limit of MFS is approached with decreasing signal-to-noise ratios and increasing relative force errors (see Supplementary Note 3 and Fig. 7). Our direct force measurements on this sample are, however, still ten times more precise than using Eq. (1), highlighting the exceptional suitability of MFS on such a super-slippery sample.

The friction of our etched silicon samples spans a very wide force range due to their topographical differences, where the most sparse spikes of sample A allow for an ultralow dimensionless friction force $F_K/D = (4 \pm 3) \cdot 10^{-4}$ that overcomes the friction of previously studied superhydrophobic surfaces made of micropillars, SOCAH, and silicone nanofilaments, as well as lubricated surfaces and a “nearly friction- and adhesion-free”
underwater-SOCAL surface\(^{20}\) (Fig. 4). The etched silicon spikes surface thus represents a state-of-the-art, super-slippery superhydrophobic solid coating with the lowest measured dimensionless friction force to this date, challenging and even surpassing the hydrophobic solid coating with the lowest measured dimensionless friction force to this date, challenging and even surpassing the hydrophobic solid coating with the lowest measured dimensionless friction force.

**Rolling droplet dynamics.** To investigate the internal fluid dynamics of the water droplets in our system, PIV experiments (Fig. 5a, b, Supplementary Movie 2 and Fig. 8a, b, Methods) were performed in conjunction with MFS on the spikes (A) and grass (E) samples at different substrate speeds (\(v\)) and droplet radii (\(R\)) (Supplementary Figs. 8c–d). Contrary to previous findings of water droplets sliding on superhydrophobic surfaces\(^{26,27}\), our droplets were, interestingly, found to roll with an angular velocity \(\omega = v/R\) for low \(v/R\) values (Fig. 5c, d), that is, like solid spheres without any slippage. In contrast to a sliplessly rotating solid sphere, however, our fluid droplets experience a velocity-independent, dissipative friction force also in the regime of slipless rolling (Supplementary Fig. 9). As \(v/R\) was increased above a critical value (\(\omega_c\)) in our experiments, the angular droplet velocity remained constant although the substrate speed was further increased or droplet size decreased (Fig. 5c, d). This can be understood through droplet-surface slippage\(^{46,47}\), with a slip speed (\(v_s = R\omega - \omega\)) increasing as a function of \(v/R\) (Supplementary Fig. 10). The transition to roll-slip motion occurred earlier on the spikes sample (\(\omega_c^A = 0.79 \pm 0.15 \text{ s}^{-1}\) vs. \(\omega_c^C = 1.3 \pm 0.3 \text{ s}^{-1}\)), which is reasonable since this has less liquid-solid interface (lower solid fraction, see Methods) to maintain a no-slip motion\(^{29}\).

**Fig. 3 Friction force on superhydrophobic etched silicon substrates—experiment vs. theory.** a–e Scanning electron microscopy images taken at a 45° angle of the A (spikes), B, C, D, and E (grass) samples, respectively. Scale bars 1 \(\mu\)m. f Measured kinetic friction force as a function of contact region diameter. The solid lines are linear fits (through origin) to the data with the slopes \(F_{LA}/D = (2.7 \pm 0.4), (1.6 \pm 0.3), (0.6 \pm 0.2), (0.11 \pm 0.04), (0.03 \pm 0.02)\) nN \(\mu\)m\(^{-1}\) for the E (grass), D, C, B, and A (spikes) samples, respectively. g Measured friction force as a function of the theoretically calculated lateral adhesion force (\(F_{LA} = \mu R v\), Eq. (1)). The solid line (going through origin) has a slope of unity. h The ratio between the relative errors (\(\delta F = \Delta F/F\), where \(\Delta F\) is the absolute error) of the theoretical (CAG) and experimental (MFS) force estimates as a function of \(F_{LA}/D\). Measuring the friction force with MFS renders from 10 (min) to 1000 (max) times more precise results as the surface becomes more slippery. As the lower limit of the micropipette technique is approached for small droplets on the most slippery spikes (A) surface (red crosses), the relative error still remains more than 10 times lower when using MFS instead of Eq. (1). The legend in g also applies to the markers in f and h. The error bars in all graphs are standard deviations or error propagations including these (see Supplementary Note 2).

The ratio between the translational (\(E_t = mv^2/2\), where \(m\) is the droplet mass) and rotational kinetic energy (\(E_r = mR^2\omega^2/5\), assuming the moment of inertia of a solid sphere) of the droplet is \(E_t/E_r = 5(v/R)^2/2\omega^2\) (Fig. 5e). For \(v/R < 0.25 \pm 0.10 \text{ s}^{-1}\),
the rotational kinetic energy of our droplets is larger than their translational counterpart. It can be noted that the transition to roll-slip motion (based on \( \omega_c \)) occurred at \( E_f/E_s \approx 4 \) on both surfaces. Previous to this study, the internal flow in water droplets on superhydrophobic surfaces has been studied only on tilted planes\(^{26,27}\), where \( \nu \approx 10^3 \text{ cm s}^{-1} \) and \( E_f \) a factor of \( \sim 10^4 - 10^5 \) higher than in our slow experiments. For rotational speeds of \( \omega < 10^2 \text{ s}^{-1} \) (i.e., for all water droplets rolling without being strongly deformed by inertial effects), the motion on such tilted planes will remain in the translation-dominated, sliding regime. To the best of our knowledge, our MFS experiments thus allow for the first observation of purely rolling water droplets on superhydrophobic surfaces, as well as for a systematic investigation of the transition to roll-slip motion on these.

A droplet moving on a surface can experience viscous (\( P_v \)), contact line (\( P_d \)) and/or interfacial friction (\( P_I \)) energy dissipation\(^{47}\). In our system, \( P_d \) dominates for purely rolling droplets (\( \nu/R < \omega_c \)), while \( P_d \) and potentially also \( P_I \) become important in the roll-slip regime (\( \nu/R > \omega_c \), see Supplementary Note 4 for more details). For sliplessly rolling droplets, the rate of viscous dissipation in the Hertz volume near the liquid-solid interface is given by\(^{22,29,47}\) \( P_v \sim \eta \phi_s \rho \omega^3 \), where \( l = D/2 \) is the radius of the contact region, \( \eta = 0.001 \text{ Pa s} \) is the viscosity of water, and \( \phi_s \) is the surface solid fraction (Methods). In our MFS PIV experiments (for \( \nu/R < \omega_c \)), the viscous dissipation is balanced by \( P_d \sim F_\mu \nu \), so that \( P_d \sim P_v \). This gives a scaling prediction of the angular droplet velocity in the rolling regime

\[
\omega \sim \left( \frac{F_\mu \nu}{\eta \phi_s \rho} \right)^{1/2} \tag{2}
\]

In Fig. 5f, the experimental angular droplet velocity is plotted as a function of \( F_\mu \nu/\eta \phi_s \rho^2 \). The data collapses in accordance with Eq. (2).

To conclude, we study the friction of a surface that cannot be reliably measured with the gold standard method of contact angle goniometry, but instead needs to be characterized through direct force measurements. The dimensionless friction force of droplets moving on such liquid-repellent materials is suggested as the benchmark standard of the surface slipperiness. Our direct friction force measurements using micropipette force sensors render as much as three orders of magnitude more precise results as compared to using contact angle goniometry, and allow for the distinction between superhydrophobic samples with seemingly identical advancing and receding contact angles. A super-slippery superhydrophobic etched silicon surface is presented with a groundbreaking low dimensionless friction force of \( F_\mu/\gamma D = (4 \pm 3) \cdot 10^{-4} \), corresponding to a miniscule friction force of \( 7 \pm 4 \text{ nN} \) for a millimetric water droplet. This solid surface thus challenges and even surpasses the slipperiness of state-of-the-art, liquid-like coatings. Finally, we combine PIV with our micropipette force sensor measurements and reveal a previously unexplored droplet dynamics regime on superhydrophobic surfaces: slow water droplets are shown to roll without any

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**Fig. 5 Rolling vs. slipping droplets.** a, b Particle image velocimetry experiments showing the rolling flow inside a water droplet (\( R = 1658 \pm 8 \text{ m} \), substrate speed \( \nu = 0.1 \text{ mm s}^{-1} \)) to the left) on the spikes (A) surface. Scale bar in a 0.5 mm. The blue line in b shows the outline of the droplet. c, d Angular droplet velocity as a function of the ratio between sample speed and droplet radius (\( \nu/R, \nu = 0.1 \text{ to } 1.9 \text{ mm s}^{-1} \) and \( R = 0.8 \text{ to } 1.6 \text{ mm} \)) for the spikes (A) and grass (E) samples, respectively. Slowly rotating droplets behave as solid spheres rolling without any slippage (\( \omega = \nu/R \), solid line with a slope of unity). As \( \nu/R \) exceeds a critical value (\( \omega_c \), dashed line), \( \omega \) remains constant and the rolling droplet starts slipping as \( \nu/R \) is further increased. e The ratio between translational and rotational kinetic energy (\( E_t/E_r = 5(\nu/R)^2/2\omega^2 \)) as a function of \( \nu/R \) on the spikes (A) and grass (E) samples. f The angular velocity data for sliplessly rolling droplets (\( \nu/R < \omega_c \)) on the spikes (A) and grass (E) samples collapse when plotted as a function of \( F_\mu \nu/\eta \phi_s \rho^2 \). The solid line in this log-log plot has a slope of \( 1/2 \) as predicted by Eq. (2). The error bars in all graphs are standard deviations or error propagations including these (see Supplementary Note 2).
slippage and transition to roll-slip motion as they start moving faster. The use of micropipette force sensors in droplet friction and dynamics experiments facilitates the search for even more slippery surfaces, and enables a comparison of surfaces with unprecedented sensitivity as the scientific community takes steps towards the extreme limit of slipperiness.

**Methods**

**Micropipette force sensor measurements.** We followed the MFS protocol\(^2\) when manufacturing and calibrating the micropipettes used in this work. In short, the micropipettes were placed out of thick glass capillaries (i.d./o.d. 0.75/1 mm, World Precision Instruments, model no. TW100-6) using a micropipette puller (Narishige, model no. PN-31). The end of the micropipette was cut with a microforge (Narishige, model no. MF-900) to a cantilever length of 1.9–2.5 cm, depending on the desired stiffness. The back end of the pipette was connected to a syringe and the micropipette was filled with MilliQ water. The micropipettes were then calibrated by mounting them horizontally and pushing out a small water droplet (density \(\rho = 1000 \text{ kg/m}^3\)) to rest on the outside of the end of the pipette. The entire setup rested on an antivibration table (Halcyonics iLarge, Accuron). The experiment was recorded with a Phantom Miro M310 camera (with various resolutions, between 768 × 768 pixels and 1280 × 800 pixels) at 24 fps (using a macro lens (Canon MP-E 65 mm f/2.8 1–5x Macro Photo) at its highest magnification (≈3.99 μm/pixel). By varying the droplet size and analyzing its volume (\(V\)) with a home-written Matlab code, the linear relation between the weight (\(W = \rho V\)) of the droplet and the micropipette deflection (\(\Delta x\), analyzed with a home-written Matlab code) rendered the spring constant (\(k = W/\Delta x\)) of the cantilever. The calibration was repeated 3–8 times and the resulting average spring constant value was used together with its standard deviation. Many different micropipettes were manufactured and calibrated to be used for friction measurements on the different surfaces. The spring constants used in this work ranged between \(k_s = 2.5 \pm 40 \text{ nN/μm}\) with relative errors −1–3% (Supplementary Table 3).

In the MFS experiment, the water-filled, force-calibrated micropipette was mounted vertically above the sample resting on a motorized xyz-translational stage (Thorlabs, see photograph of the setup in Supplementary Fig. 1). A drop was pushed out from the micropipette tip until it slid down on the surface, still attached to the micropipette tip. The stage was moved in the \(x\)-direction so that the micropipette end was covered inside the droplet (Fig. 2b). This was done merely to ensure reproducibility between experiments. Since the micropipette diameter (≈20 μm) is significantly smaller than the droplet diameter (≈1 mm), its location in the droplet is irrelevant to the internal fluid dynamics. Before each new measurement, the sample was moved in the \(y\)-direction (away from/towards the camera) to equilibrate the micropipette deflection in the \(x\)-direction (to the side as viewed from the camera) and place the droplet in a new position on the surface. In the experiment, the equilibrium, zero-force position of the micropipette was first recorded for \(t = 5\) s and the substrate was then moved in the \(x\)-direction at a constant speed (\(v = 0.11 \text{ mm s}^{-1}\) with a relative error of 5%) and acceleration (\(a = 4 \text{ mm s}^{-2}\)) for 15 s, depending on the surface. The experiment was recorded at a framerate of 50 fps with the same camera and lens as used in the calibration. The kinetic friction force (\(F_k\)) was determined as the difference between the average zero-force and kinetic friction regime (Fig. 2c). The micropipette deflection on the most slippery surfaces was barely visible by the naked eye, but could still be detected with the sub-pixel image analysis of the micropipette position\(^4\). The kinetic friction force was always analyzed in a regime of continuous droplet sliding, that is, where no pinning events (caused by defects in the coating) occurred. A static friction bump (Supplementary Fig. 11) was observed before the kinetic plateau in around 30% and 50% of the experiments on samples A and B, respectively, and in all experiments on samples C–E. The static jump likely occurred in every experiment also on the most slippery surfaces, but the force resolution of the MFS was not high enough to resolve all of these events. The static jump has been described in detail by others\(^5\), and this feature was not included in any further analysis in our work. The contact region diameter (\(D\)) was measured using Matlab. Supplementary Note 2 for details on the error analysis of all variables used in this work. The same sample was measured repeated 8 times as described in Figs. 3a–3c for each sample were taken at five different locations on the surface. Representative AFM images of all samples are shown in Supplementary Fig. 4.

**Scanning electron microscopy (SEM).** The SEM imaging was carried out with a Zeiss Sigma VP scanning electron microscope. For the top-view imaging, samples were placed on a carbon tape attached to an aluminum stub and coated with 5 nm gold-palladium coating using a LEC Sensors AC600 high vacuum sputter coater before imaging. For the side-view imaging, samples were placed on a glass slide, which was vertically mounted in a sputter coater and coated with 8 nm gold-palladium coating before imaging. The imaging at 45° tilt angle was done after side-view imaging by tilting the sample holder at 45°. The images were taken at low acceleration voltage of 1.0 kV with an in-lens detector. Representative SEM images of all samples are shown in Supplementary Fig. 3.

**Confocal microscopy.** Confocal microscopy was carried out with Zeiss LSM710 confocal scanner attached to Zeiss Examiner upright microscope using ×20/0.1 W water immersion objective lens and 561 nm laser line. Imaging was done in reflection mode through a water droplet placed between the sample and the objective lens (Supplementary Fig. 5a), forming a plasmon between the sample and the water droplet. The locations where the droplet is in direct contact with the substrate appear in the images as dark, whereas those locations with an air gap between the sample and the droplet appear as bright due to strong reflection from the water-air interface. A confocal image of the spikes (A) sample is shown in Supplementary Fig. 5b. The reason for the confocal microscopy was insufficient to image the contact zones on the other samples.

**Contact angle goniometry (CAG).** Conventional, optical contact angle measurements were performed using a contact angle goniometer (Biolin Attension Theta). Advancing and receding contact angles were measured separately (see Supplementary Method 1 for more details). The measurements were repeated 5–6 times at different positions on each surface.

**Determination of the solid fraction.** The solid fraction was difficult to quantify on the etched silicon samples due to the uneven shape of the pillars. Top-view SEM images (Supplementary Fig. 3o) were used to determine the solid fraction of the grass (E) sample, whereas top-view SEM (Supplementary Fig. 3k), AFM (Supplementary Fig. 4a) and confocal microscopy (Supplementary Fig. 3b) images were used to render an average solid fraction on the spikes (A) sample. Images were thresholded in Matlab and the fraction of the top parts of the posts was analyzed. An error of ±0.05 was assigned to the thresholding, rendering average solid fractions of \(\phi_A = 0.06 \pm 0.03\) and \(\phi_B = 0.47 \pm 0.05\).

**Contact angle image analysis in the MFS experiments.** A home-written Matlab code (Supplementary Code 1 video_CA.m) was used to analyze the front and back contact angles as a function of time in the MFS experiment. Each frame was made black and white, the outline of the droplet recognized and the thinnest part around the droplet and the micropipette position was analyzed. A fourth-degree polynomial to the data points was used to determine the solid fraction of the grass (E) sample, whereas top-view SEM (Supplementary Fig. 3k), AFM (Supplementary Fig. 4a) and confocal microscopy (Supplementary Fig. 3b) images were used to render an average solid fraction on the spikes (A) sample. Images were thresholded in Matlab and the fraction of the top parts of the posts was analyzed. An error of ±0.05 was assigned to the thresholding, rendering average solid fractions of \(\phi_A = 0.06 \pm 0.03\) and \(\phi_B = 0.47 \pm 0.05\).

**Synthesis of etched silicon samples.** The etched silicon samples were fabricated by maskless cryogenic deep reactive ion etching (Oxford Plasmalab System 100, Oxford Instruments, Bristol, UK) of silicon (the black silicon method)\(^6\). To obtain different topographies, \(SF_6\) gas flows (in scm) were 40, 37.6, 35.3, 32.9, and 30.3, and the \(O_2\) gas flows (in scm) were 18, 20.4, 22.8, 25.1, and 27.5, and the forward powers (in W) were 6, 5, 4, and 4 for the spikes (A), B, C, D, and E samples, respectively. For all samples, the ICP power was 1000 W, the etching temperature −10°C, the pressure 10 mTorr, and the etching time 7.5 min. After etching, the samples were coated by a plasma-enhanced chemical vapor deposited (PECVD, Oxford Plasmalab 80, Oxford Instruments, Bristol, UK) gold-palladium coating using a scan rate of 1 kHz. ScanAsyst Autocontrol was “on” for samples C–E with PeakForce Amplitude of 300 nm, while it was set to “off” for samples A and B with PeakForce Amplitude of 150 nm. Spring constant and Pixel Frequency were 0.6 and 2 kHz for all samples. Individual scans for each sample were taken at five different locations on the surface. Representative AFM images of all samples are shown in Supplementary Fig. 4.

**Particle image velocimetry (PIV) experiments.** A water droplet containing tracer particles (5 μm polystyrene colloids with density 1.03 g cm\(^{-3}\); micromod Partikeltechnologie GmbH, product code 30-19-503) was placed externally onto the micropipette and the surface. The PIV experiment was performed as in a normal friction force experiment (described above) using a framerate of 50 fps, a stiffer micropipette (length 1.7 cm, \(k_s = 40 \pm 8.0 \text{ nN μm}^{-1}\)) to keep the droplet more in place, and with the light source slightly shifted upwards to maximize the area of the drop where tracer particles could be seen. It should be noted that the edges of the droplet remained non-transparent and no data were used from the PIV experiment from this region. An area with particle trajectories speeds (\(v = 0.1 \text{ to } 1.9 \text{ mm s}^{-1}\)) and droplet sizes (\(R = 0.8 \text{ to } 1.6 \text{ mm}\)) were used (Supplementary Fig. 8c–d) and the results were analyzed with Matlab’s PIVLab code (see Supplementary Method 2).
for more details), rendering the average angular velocity ($\omega$) of the internal rotational motion plotted in Fig. 5. The droplet shape remained unchanged during the experiments.

**Data availability**

The data presented in this paper are available from the corresponding authors upon request.

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**Author contributions**

R.H.A.R. and M.B. conceived the idea of the experiments. M.B. performed the friction force measurements together with D.M. The PIV experiments were performed and analyzed by D.M. under the supervision of M.B. M.V. performed the AFM and SEM measurements as well as the contact angle error analysis. M.H.J. performed the conventional contact angle goniometry measurements, and H.N. wrote the time-resolved contact angle analysis code used in the MFS analysis. V.J. made all etched silicon samples and V.I.T. performed the confined microcopy measurements. M.B. analyzed the final data and developed the theory. M.B. discussed the results with all authors and wrote the manuscript with input from all coauthors.
Competing interests
M.V., J.V.I.T., and R.H.A.R. are inventors of patent applications on wetting characterization techniques, and are together with M.J.H. considering potential commercialization partly supported by Business Finland and ERC. M.B., D.M., H.N., and V.J. declare no competing interests.

Additional information
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