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Measurement of Interaction Force Between Droplet and Super-hydrophobic Substrate by Optical Lever Method
--Manuscript Draft--

Dear editor of *JoVE*,

We *submit* a manuscript titled "Measurement of Interaction Force Between Droplet and Super-hydrophobic Substrate by Optical Lever Method" to *JoVE*.

The paper is dedicated to investigating the interaction between droplets and super-hydrophobic substrates in the air. The protocol includes calibrating the measurement system and measuring the interaction force at super-hydrophobic substrates with different grid fractions.

Thanks a lot for considering our manuscript to be published on *JoVE*.

Yours sincerely!

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1 **TITLE:**
2 Measuring the Interaction Force Between a Droplet and a Super-hydrophobic Substrate by the
3 Optical Lever Method
4
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21 **KEYWORDS:**
22 Super-hydrophobic, interaction force, cantilever, optical lever, calibration, electrostatic force
23

24 **SUMMARY:**
25 The protocol aims to investigate the interaction between droplets and super-hydrophobic
26 substrates in the air. This includes calibrating the measurement system and measuring the
27 interaction force at super-hydrophobic substrates with different grid fractions.
28
29 **ABSTRACT:**
30 This goal of the paper is to investigate the interaction force between droplets and super-
31 hydrophobic substrates in the air. A measurement system based on an optical lever method is
32 designed. A millimetric cantilever is used as a force sensitive component in the measurement
33 system. Firstly, the force sensitivity of the optical lever is calibrated using electrostatic force,
34 which is the critical step in measuring interaction force. Secondly, three super-hydrophobic
35 substrates with different grid fractions are prepared with nanoparticles and copper grids. Finally,
36 the interaction forces between droplets and super-hydrophobic substrates with different grid
37 fractions are measured by the system. This method can be used to measure the force on the scale
38 of sub-micronewton with a resolution on the scale of nanonewton. The in-depth study of the
39 contact process of droplets and super-hydrophobic structures can help to improve the
40 production efficiency in coating, film and printing. The force measurement system designed in
41 this paper can also be used in other fields of microforce measurement.
42

43 **INTRODUCTION:**
44 The contact between a droplet and a super-hydrophobic surface is very common in daily life and

45 industrial production: water droplets sliding from the surface of lotus leaf[1,2], and a water strider
46 traveling rapidly over the water[3-6]. A super-hydrophobic coating on the exterior surface of a ship
47 can help reduce the corrosion degree of the ship and reduce the resistance of the navigation[7-10].
48 There is great value for industrial production and bionics research in studying the contact process
49 between a droplet and a super-hydrophobic surface.
50
51 To observe the spreading process of droplets on a solid surface, Biance used a high-speed camera
52 to photograph the contact process and found that the duration of the inertial regime is mainly
53 fixed by the drop size[11]. Eddi photographed the contact process between the droplet and the
54 transparent plate from the bottom and side using a high-speed camera, which comprehensively
55 revealed the variation of the contact radius of the viscous droplet with time[12]. Paulsen combined
56 an electrical method with high-speed camera observation, thus reducing the response time to 10
57 ns[13,14].
58
59 Atomic force microscopy (AFM) has also been used to measure the interaction force between
60 the droplet/bubble and solid surfaces. Vakarelski used an AFM cantilever to measure the
61 interaction forces between two small bubbles (approximately 80-140 μm) in aqueous solution
62 during controlled collisions on the scale of micrometers to nanometers[15]. Shi used a combination
63 of AFM and reflection interference contrast microscopy (RICM) to simultaneously measure the
64 interaction force and the spatiotemporal evolution of the thin water film between an air bubble
65 and mica surfaces of different hydrophobicity[16,17].
66
67 However, since commercial cantilevers used in AFM are too small, the laser spot irradiated on
68 the cantilever would be submerged by droplets or bubbles. The AFM has difficulties in measuring
69 the interaction force between droplets and droplets/substrates in the air.
70
71 In this paper, a measurement system based on an optical lever method is designed to measure
72 the interaction force between droplets and super-hydrophobic substrates. The force sensitivity
73 of the optical lever (S_{OL}) is calibrated by electrostatic force[18], and then the interaction forces
74 between droplets and different super-hydrophobic substrates are measured by the
75 measurement system.
76
77 The schematic diagram of the measurement system is shown in **Figure 1**. The laser and position
78 sensitive detector (PSD) constitute the optical lever system. A millimetric silicon cantilever is used
79 as a sensitive component in the system. The substrate is fixed on the nanopositioning z-stage,
80 which can move in vertical direction. When the substrate approaches the droplet, the interaction
81 force causes the cantilever to bend. Thus, the position of the laser spot on PSD will change, and
82 the output voltage of PSD will change. The output voltage of PSD V_p is proportional to the
83 interaction force F_i, as shown in Eq. (1).

$$F_i = S_{OL}V_P \tag{1}$$

85
86 In order to acquire the interaction force, S_{OL} must be calibrated first. The electrostatic force is
87 used as the standard force in the calibration of S_{OL}. As shown in **Figure 2**, the cantilever and the
88 electrode make up a parallel plate capacitor, which could generate electrostatic force in a vertical

89   direction. The electrostatic force F_{es} is determined by the voltage of the DC power supply V_s, as
90   shown in Eq. (2)[19-21].

$$F_{es} = \frac{1}{2}V_s^2 \frac{\mathrm{d}C}{\mathrm{d}z} \tag{2}$$

92
93   where C is the capacitance of the parallel plate capacitor, z is the displacement of the cantilever
94   free end, and $\mathrm{d}C/\mathrm{d}z$ is called capacitance gradient. The capacitance could be measured by the
95   capacitance bridge. The mathematical relationship between C and z can be fitted by a quadratic
96   polynomial, as shown in Eq. (3).

$$C = Qz^2 + Pz + CT \tag{3}$$

98
99   where Q, P and CT are the coefficients of the quadratic term, the primary term and the constant
100 term respectively. Therefore, the electrostatic force F_{es} can be expressed as Eq. (4).

$$F_{es} = \frac{1}{2}V_s^2(2Qz + P) \tag{4}$$

102
103 Since the overlap area of two plates of the capacitor is very small, the elastic force acted on the
104 cantilever can be expressed as Eq. (5), according to Hooke's law:

$$F_i = kz \tag{5}$$

106
107 where k is the stiffness of the cantilever.

108
109 When the elastic force and electrostatic force applied on the cantilever are equal (i.e., $F_i = F_{es}$),
110 the cantilever is in equilibrium. Eq. (6) can be derived from Eqs. (1), (2) and (5):

$$2Q\frac{S_{OL}}{k}V_P V_s^2 + PV_s^2 = 2S_{OL}V_P \tag{6}$$

112
113 In order to reduce the uncertainty of calibration results, a difference method is used to calculate
114 S_{OL}. The results of two experiments are taken as V_{s1}, V_{p1} and V_{s2}, V_{p2}, and are substituted into Eq.
115 (6):

$$\begin{cases} 2Q\frac{S_{OL}}{k}V_{P1}V_{s1}^2 + PV_{s1}^2 = 2S_{OL}V_{P1} \\ 2Q\frac{S_{OL}}{k}V_{P2}V_{s2}^2 + PV_{s2}^2 = 2S_{OL}V_{P2} \end{cases} \tag{7}$$

117
118 Transforming the equations and subtracting the lower equation from the upper equation in Eq.
119 (7), the parameters Q and k are eliminated. Then the calibration formula of S_{OL} is obtained, as
120 shown in Eq. (8):

$$2S_{OL}\left(\frac{1}{V_{s1}^2} - \frac{1}{V_{s2}^2}\right) = P\left(\frac{1}{V_{P1}} - \frac{1}{V_{P2}}\right) \tag{8}$$

122
123 Performing a series of experiments, the curve is drawn with $P(1/V_{p1}-1/V_{p2})$ as the ordinate and
124 $2(1/V_{s1}^2-1/V_{s2}^2)$ as the abscissa. The slope of the curve is S_{OL}.

125
126 After obtaining S_{OL}, the electrode will be replaced by different super-hydrophobic substrates. The
127 interaction forces between droplets and super-hydrophobic substrates will be measured by the
128 system shown in **Figure 1**.

129

130 **PROTOCOL:**

131

132 **1. Assembly of the S_{OL} calibration system**

133

134 1.1 Assemble the S_{OL} calibration system according to the schematic diagram shown in **Figure**
135 **2**.

136

137 1.2 Fix the laser to a support, making the angle between the laser and the horizontal direction
138 be 45°.

139

140 1.3 Fix the PSD to another support, making the PSD perpendicular to the laser. Connect the
141 PSD to the data acquisition device and the data acquisition device to the computer.

142

143 NOTE: These angles are determined by the experimenter's visual measurement and need not be
144 exactly 45° or 90°.

145

146 1.4 Fix the wider end of the cantilever to a holding device while the other end is suspended.
147 Fix the holding device to a two-dimensional high-precision displacement stage.

148

149 NOTE: The dimensions of the cantilever are shown in **Figure 3**.

150

151 1.5 Fix the plate electrode to the nanopositioning z-stage by a clamping device.

152

153 NOTE: The nanopositioning z-stage can bring the electrode to move along the z-axis with a
154 displacement resolution of 1 nm.

155

156 1.6 Connect the positive pole of the capacitive bridge with the cantilever and the negative
157 pole with the plate electrode.

158

159 1.7 Install a high-speed camera, whose line of sight is perpendicular to the cantilever.

160

161 1.8 Adjust the position of the plate electrode, making the vertical distance between the plate
162 electrode and the cantilever be about 100 μm, and the overlap length about 0.5 mm.

163

164 NOTE: These distances are checked by image processing.

165

166 **2. Measurement of the capacitance gradient**

167

168 2.1 Use the computer to control the capacitance bridge to collect the capacitance changes
169 between the plate electrode and the cantilever in real time. Set the sampling rate to 0.5 Hz.

170

171 2.2 Control the nanopositioning z-stage by computer to drive the plate electrode to step
172 upward with a step of 10 μm and a step number of 6 and stay for 10 s after each movement.

173

174 2.3   Change the movement direction of the plate electrode to downward, and repeat step 2.2.

175

176 2.4   Determine the relationship between the capacitance and displacement of the plate
177 electrode in the measurement result, and obtain the value of P according to the Eq. (3).

178

179 2.5   Repeat steps 2.1–2.4 5x and calculate the average value of P.

180

181 **3. Calibration of the optical lever**

182

183 3.1   Disconnect the connection between the capacitive bridge and the cantilever/plate
184 electrode.

185

186 3.2   Connect the positive pole of the DC power supply with the cantilever and the negative
187 pole with the plate electrode.

188

189 3.3   Adjust the relative position between the laser, PSD and cantilever to make the laser
190 reflected on PSD by cantilever.

191

192 NOTE: The laser spot is a circle about 2 mm in diameter.

193

194 3.4   Control the DC power supply by computer to apply voltage varying with time on the
195 parallel plate capacitor. At the same time, collect the output voltage of PSD in real time by the
196 data acquisition device.

197

198 3.4.1   Set the sampling rate of the data acquisition device to 1,000 Hz.

199

200 3.4.2   Set the initial voltage of the DC power supply to 0 V and hold for 5 s.

201

202 3.4.3   Increase the voltage by 25 V and hold for 5 s.

203

204 3.4.4   Repeat step 3.4.2 4x until the voltage increases to 125 V.

205

206 3.4.5   Decrease the voltage by 25 V and hold for 5 s.

207

208 3.4.6   Repeat step 3.4.4 4x until the voltage decreases to 0 V.

209

210 3.5   Determine the relationship about the output voltage of PSD and the DC supply voltage in
211 the measurement result, and obtain the value of S_{OL} according to Eq. (8).

212

213 3.6   Repeat steps 3.4–3.5 5x and calculate the average value of S_{OL}.

214

215 **4. Preparation of super-hydrophobic substrates**

216

217 4.1   Prepare three circular copper grids with the same diameter of 3 mm and different grid
218 fractions. Their grid fractions are 46.18%, 51.39% and 58.79% respectively.

219

220 NOTE: These copper grids are commercial products that were purchased.

221

222 4.2   Spray the nanoparticles onto three copper grids to obtain super-hydrophobic substrates
223 with micro structure and hydrophobicity.

224

225 4.2.1   Spray the base coat onto the copper grid.

226

227 4.2.2   Spray the top coat onto the copper grid when the first coat is dry.

228

229 NOTE: The nanoparticles are packed in a can with a spray head. The nanoparticles will be sprayed
230 by pressing the spray head when used.

231

232 4.3   Glue the copper grids on the side of cylinders with a diameter of 3 mm to obtain a surface
233 super-hydrophobic structure with a curvature of $1/3$ mm^{-1}.

234

235 **5. Measurement of the interaction force between droplets and super-hydrophobic substrates**

236

237 5.1   Disconnect the connection between the DC power supply and the cantilever/plate
238 electrode. Remove the plate electrode from the nanopositioning z-stage.

239

240 5.2   Fix a plate support to the nanopositioning z-stage.

241

242 5.3   Install a high-speed camera, whose line of sight is perpendicular to the cantilever.

243

244 5.4   Suspend a droplet on the lower surface of the free end of the cantilever.

245

246 5.4.1   Place a super-hydrophobic structure with a contact angle of almost 180° on the plate
247 support.

248

249 5.4.2   Place a 2 µL droplet on the super-hydrophobic structure using a micropipettor.

250

251 5.4.3   Control the nanopositioning z-stage using software (e.g., PIMikroMove) to drive the
252 droplet to move upward.

253

254 5.4.3.1 In the dialog box, set the velocity to 10 µm/s.

255

256 5.4.3.2 Click the **Forward** button and the droplet begins to move upwards.

257

258 5.4.3.3 Click the **Stop** button when the droplet contacts with the free end of the cantilever.

259

260 5.4.4   Stay for 1 or 2 s, and then control the nanopositioning z-stage to drive the slide glass away

261 from the cantilever.

262

263 NOTE: Since the silicon cantilever is hydrophilic, the droplet is suspended on the lower surface of
264 the free end of the cantilever, forming a hemispherical droplet with a diameter of about 0.5 mm.

265

266 5.4.5   Remove the super-hydrophobic structure with a contact angle of almost 180° from the
267 plate support.

268

269 5.5   Place the super-hydrophobic substrate with a grid fraction of 46.18% on the plate
270 support.

271

272 5.6   Adjust the position of the plate support, making the vertical distance between the super-
273 hydrophobic substrate and the hemispherical droplet be about 100 μm.

274

275 NOTE: The distance is checked by image processing.

276

277 5.7   Turn on the PSD, laser, and high-speed camera.

278

279 5.8   Control the data acquisition device by computer to collect the output voltage of PSD in
280 real time. Set the sampling rate to 100 kHz.

281

282 5.9   Set the velocity to 10 μm/s in the software, and then click the **Forward** button, so that
283 the super-hydrophobic substrate moves gradually closer to the droplet.

284

285 5.10   Click the **Stop** button when the super-hydrophobic substrate and the droplet contact.

286

287 5.11   Set the velocity to 10 μm/s in the software, and then click the **Back** button to drive the
288 super-hydrophobic substrate to move downward.

289

290 5.12   Click the **Stop** button when the super-hydrophobic substrate is separated from the
291 droplet.

292

293 5.13   Draw the curve of the output voltage of PSD varying with time.

294

295 5.14   Repeat steps 5.3–5.11 using super-hydrophobic substrates with grid fractions of 51.39%
296 and 58.79%.

297

298 5.15   Analyze the relationship between the interaction force and the grid fraction of super-
299 hydrophobic substrate.

300

301 **REPRESENTATIVE RESULTS:**
302 The displacement of the plate electrode and the corresponding capacitance between the
303 cantilever and the electrode measured in one experiment are shown in **Table 1**. The relationship
304 between capacitance C and displacement z is fitted by quadratic polynomial using the polyfit

305 function in MATLAB, as shown in **Figure 4**. The first order coefficient P can be obtained by the
306 fitting function. The final value of P is 0.2799 pF/mm, which is the average calculated from ten
307 experimental results.

309 The supply voltage and the corresponding output voltage of PSD in one experiment are shown in
310 **Table 2**. The relationship between the output voltage of PSD V_p and the supply voltage V_s is fitted
311 by linear function, as shown in **Figure 5**, where V_{p1} and V_{p2} are the differences between the
312 measured values and V_{p0} (the initial value of the output voltage of PSD at $V_s=0$). S_{OL} can be
313 obtained by the slope of the curve in **Figure 5**. The final value of S_{OL} is 8.847 μN/V, which is the
314 average calculated from twelve experimental results.

316 The curves of measured interaction forces between droplets and super-hydrophobic substrates
317 varying with time are shown in **Figure 6**. The interaction forces are calculated by Eq. (1), where
318 V_p are the differences between the measured output voltages of PSD and initial output voltages
319 of PSD.

321 Before point A, the substrate has not contacted with the droplet, so the interaction force is 0. In
322 stage AB, the distance between the substrate and the droplet is very small. Due to the influence
323 of aerodynamic, there will be a repulsive force between the substrate and the droplet, which
324 shows a rising curve in the figure. Point B is the critical point at which the substrate and droplet
325 begin to contact. After point B, the interaction force between them becomes attractive force. In
326 stage BC, the droplet gradually wets the super-hydrophobic substrate under the action of
327 capillary force. The cantilever will bend downward in this stage, showing a decreasing curve in
328 the figure. At point C, the system reaches equilibrium again, and the cantilever begins to oscillate
329 in the equilibrium position.

331 As shown in **Figure 6**, the interaction force between the droplet and the substrate decreases with
332 the increase of the grid fraction. The reason is that the contact between droplets and super-
333 hydrophobic substrates is a process of releasing energy. The hydrophobicity of the substrate is
334 positively correlated with the grid fraction. The stronger the hydrophobicity is, the less energy
335 released during contact, so the contact force is smaller.

337 During the experiment we found that the repulsive force only exists in the contact process
338 between the droplet and the substrate with a grid fraction of 46.18%. With the increase of
339 hydrophobicity, the surface energy of the substrate decreases. When the repulsive force cannot
340 reach the resolution of the system, it is difficult to measure the repulsive force.

342 The magnitude of the force is in a direct relationship with the droplet volume. A supplementary
343 experiment was conducted to illustrate the relationship between the interaction force and
344 droplet volume. Three droplets of different sizes were used in the contact experiment, as shown
345 in **Figure 7**. The volume of droplet (a), (b), and (c) are 0.0135 μL, 0.0087 μL, and 0.0073 μL,
346 respectively. In the experiment, the volume of droplets is measured by the change of PSD output
347 voltage. The PSD output voltages before and after suspension of the droplet by cantilever are
348 measured, and their difference V_d is multiplied by S_{OL} to obtain the gravity of droplet. The volume

349 value of the droplet is converted by gravity. The substrate with a grid fraction of 51.39% is used
350 in the experiments. The measured interaction force between the three droplets and the
351 substrate are shown in **Figure 8**. It is obvious that the interaction force increases with the increase
352 of droplet volume.
353
354 **FIGURE AND TABLE LEGENDS:**
355 **Figure 1: The interaction force measurement system.** The schematic diagram of the
356 measurement system based on optical lever method for measuring the interaction between
357 droplets and super-hydrophobic substrates.
358
359 **Figure 2: The calibration system of S_{OL}.** The schematic diagram of the system designed for
360 calibrating the force sensitivity of optical lever using electrostatic force.
361
362 **Figure 3: The dimensions of the millimetric cantilever.** Top view and elevation view of the
363 millimetric cantilever.
364
365 **Figure 4: The relationship between capacitance and displacement.** The quadratic polynomial
366 fitting curve of capacitance C and displacement z in the calibration experiment.
367
368 **Figure 5: The relationship between the output voltage of PSD and the supply voltage.** The linear
369 fitting curve of P(1/V_{p1}-V_{p2}) and 2(1/V_{s1}^2-V_{s2}^2) according to Eq. (8).
370
371 **Figure 6: The measurement results of interaction force.** The interaction forces between droplets
372 and super-hydrophobic substrates with different grid fractions in the air. Different colors
373 represent different grid fractions.
374
375 **Figure 7: Images of three drops of different volumes used in the experiment.** The volume of
376 droplets (a), (b), and (c) are 0.0135μL, 0.0087μL, and 0.0073μL respectively.
377
378 **Figure 8: Interaction force between the three droplets of different volumes and the substrate.**
379 Different colors represent different droplets.
380
381 **Table 1: The calibration results of capacitance gradient.** The displacement of the plate electrode
382 and the corresponding capacitance between the cantilever and the electrode in one experiment.
383
384 **Table 2: The calibration results of S_{OL}.** The supply voltage and the corresponding output voltage
385 of PSD in one experiment.
386
387 **DISCUSSION:**
388 In this protocol, a measurement system based on optical lever method is assembled and
389 calibrated, which is designed for measuring the interaction force between the droplets and
390 super-hydrophobic substrates. Among the all steps, it is critical to calibrate S_{OL} using electrostatic
391 force. The results of the calibration experiment verify Eq. (8): P(1/V_{p1}-1/V_{p2}) is proportional to
392 2(1/V_{s1}^2-1/V_{s2}^2) and make it possible to obtain the value of the force to be measured through the

393 output voltage of the PSD. Through the experiment of measuring the interaction force between
394 the droplets and super-hydrophobic substrates of different hydrophobicity, the interaction force
395 decreases with the increase of hydrophobic capacity, which verifies the relationship between
396 hydrophobicity and surface energy of the substrates.
397
398 The force measurement method based on a millimetric silicon cantilever is an important
399 complement to the traditional methods. Compared with the high-speed camera method, the
400 optical lever method can accurately measure the force on the nanonewton scale. AFM is usually
401 used to measure the interaction force between micron-scale objects, while the system designed
402 in this paper can be applied on objects of millimeter-scale in the air. This method can be used to
403 measure the force in the scale of sub-micronewtons, and its resolution can reach the scale of
404 nanonewtons.
405
406 The method proposed for measuring interaction force in this paper is limited to a small
407 measurement range. A large force will lead to plastic deformation or even break of the silicon
408 cantilever, which will cause incorrect results. In addition, because the principle of this experiment
409 is to measure the interaction force between the droplet and the substrate under the balance of
410 the elastic force of the cantilever and the interaction force, the cantilever can only measure the
411 quasi-static force, but not dynamic force.
412
413 The in-depth study of the contact process of droplets and super-hydrophobic structures can help
414 people to improve production efficiency in coating, film, printing and other industrial production.
415 As a generalized adhesion force measurement technique, the substrates in the system can be
416 replaced with substrates made of other materials. For example, a super-hydrophobic substrate
417 with multi-stage microstructures which is made of PDMS (polydimethylsiloxane) can be used. The
418 force measurement system based on optical lever method can also be used in other fields of
419 micro force measurement, such as the interaction force during the coalescence of two droplets
420 and the interaction force between super-hydrophobic substrates and droplets of different
421 surface tension.
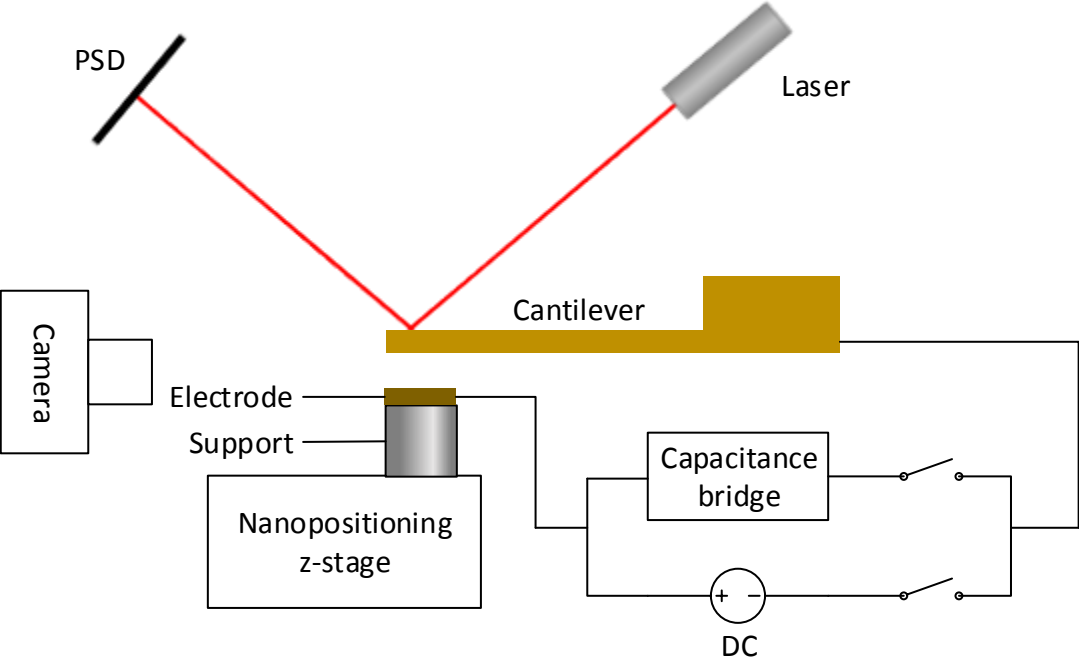422

427
428 **DISCLOSURES:**
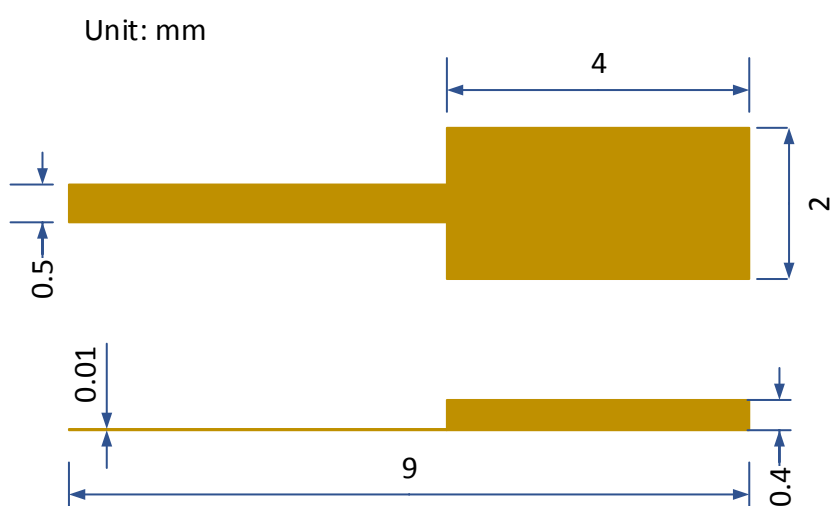429 The author has nothing to disclose.
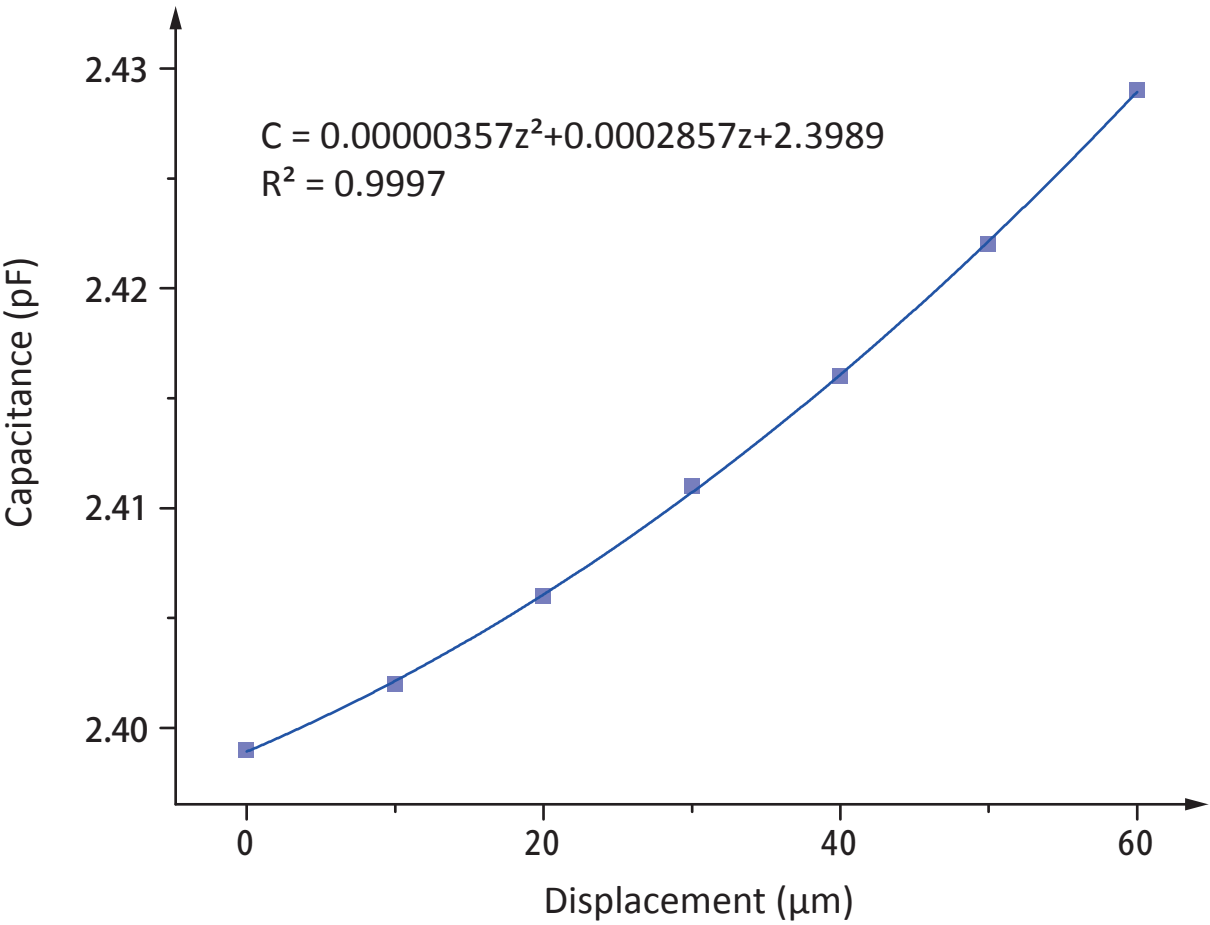430

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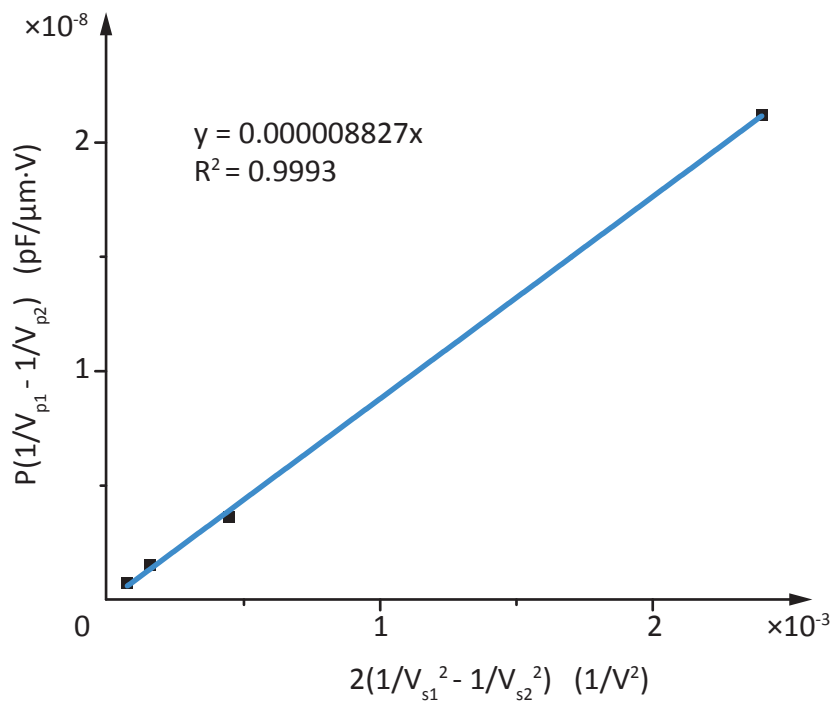435 surfaces. *Soft Matter*. **4** (10), 1943-1963 (2008).

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PSD

Laser

Camera

Cantilever

Droplet

Support

Nanopositioning
z-stage

Super-hydrophobic
substrate

Unit: mm

$C = 0.00000357z^2 + 0.0002857z + 2.3989$

$R^2 = 0.9997$

The plotted figure shows a linear fit with:

$$y = 0.000008827x$$
$$R^2 = 0.9993$$

Y-axis: $P(1/V_{p1} - 1/V_{p2})$ (pF/μm·V), scaled by $\times 10^{-8}$

X-axis: $2(1/V_{s1}^2 - 1/V_{s2}^2)$ (1/V^2), scaled by $\times 10^{-3}$

Table 1
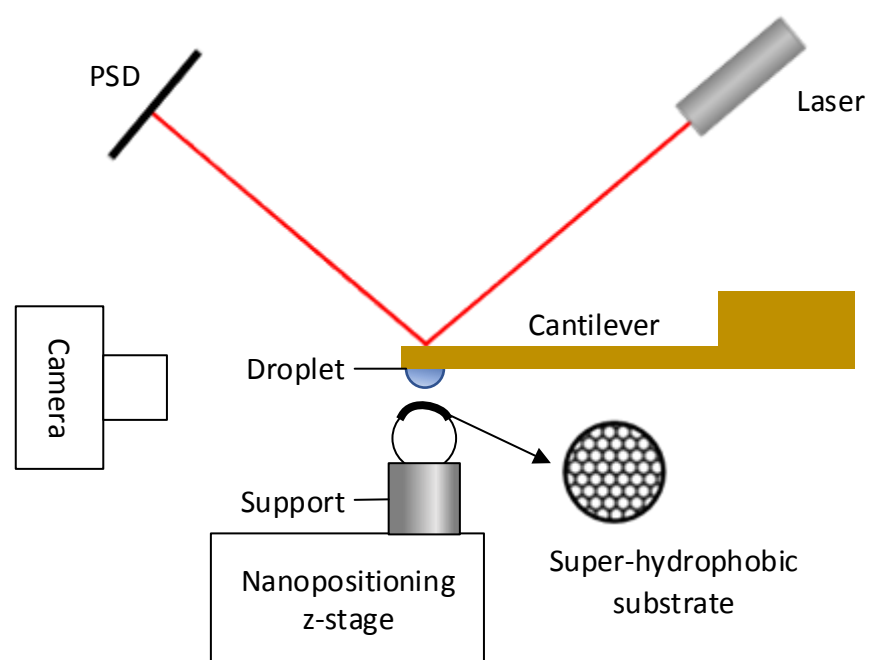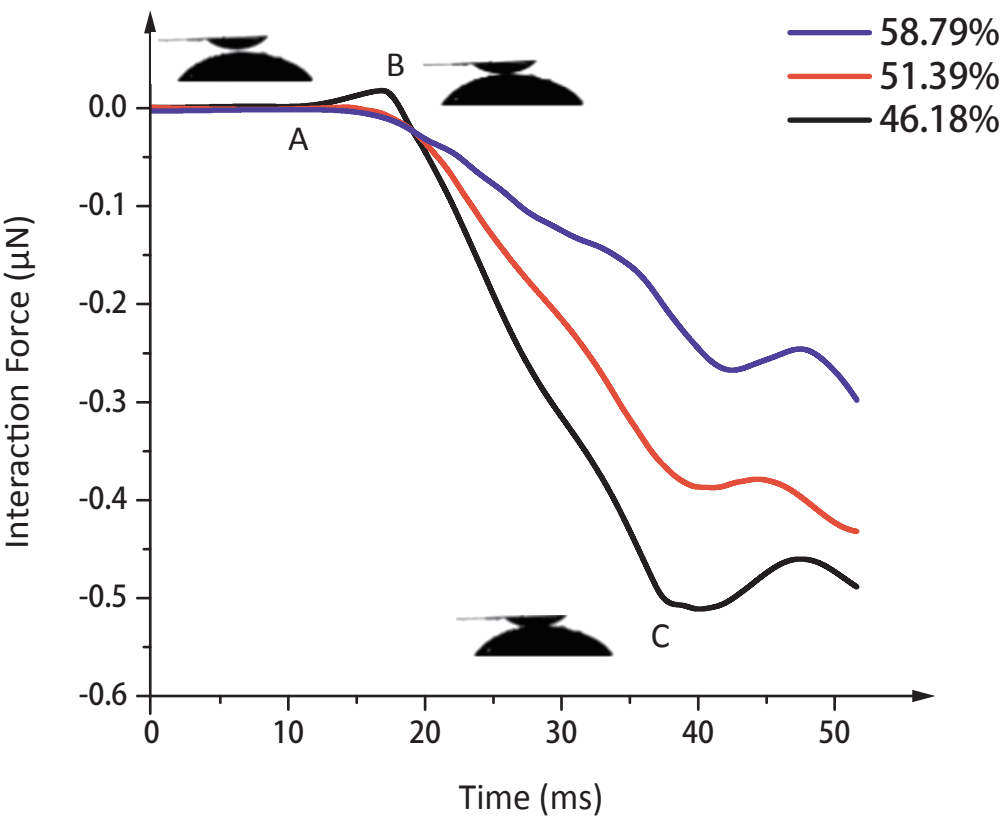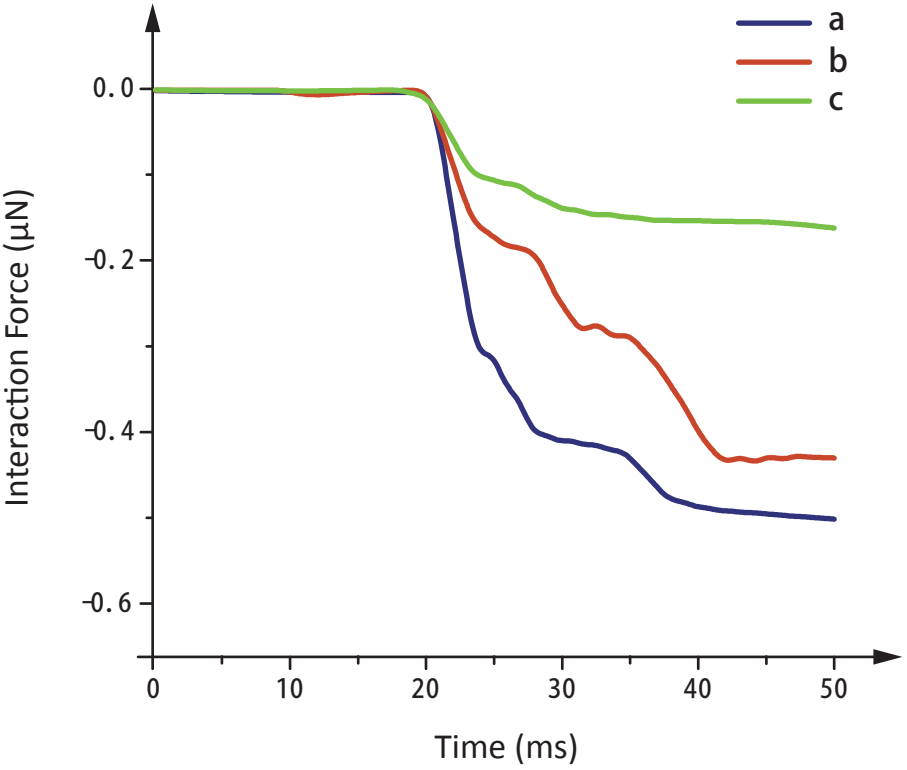
Time(s)	0	10	20	30	40	50	60
Displacement(μm)	0	10	20	30	40	50	60
Capacitance(pF)	2.399	2.402	2.406	2.411	2.416	2.422	2.429
Time(s)	70	80	90	100	110	120	
Displacement(μm)	50	40	30	20	10	0	
Capacitance(pF)	2.422	2.416	2.411	2.407	2.403	2.400	

Table 2

Time(s)	0	5	10	15	20	25
Supply Voltage(V)	0	25	50	75	100	125
Output voltage of PSD(V)	-3.5757	-3.5656	-3.5327	-3.4797	-3.3775	-3.1733
Time(s)	30	35	40	45	50	
Supply Voltage(V)	100	75	50	25	0	
Output voltage of PSD(V)	-3.3765	-3.4786	-3.5321	-3.5644	-3.5755	

Name of Material/ Equipment	Company	Catalog Number	Comments/Description
Camera	Shenzhen Andonstar Tech Co., Ltd	digital microscope A1	Frame rate: 30 frames/sec; Focal distance: 5 mm - 30 mm
Capacitive bridge	Andeen-Hagerling	AH2550A	The capacitive bridge is used to measure the capacitance between the cantilever and the plate electrode.
Data acquisition device	National Instruments	USB-4431	The data acquisition device is used to read the output voltage data.
DC power supply	Keithley	2410	Voltage range: ±5 µV; Accuracy: 0.012%
Grid	Electron Microscopy China	AGH100, AGH150, AGH300	The grid fractions of AGH100, AGH150 and AGH300 are 46.18%, 51.39% and 58.79% respectively
Laser	Shenzhen Infrared Laser Technology Co., Ltd.	HW650AD100-10BD	Laser wavelength: 650 nm
Nanoparticle	Rust-Oleum	274232	NeverWet Multi-Surface Liquid Repelling Treatment is a revolutionary super hydrophobic coating.
Nanopositioning z-stage	Physik Instrumente	P622.ZCD	Travel ranges 50 µm to 250 µm (350 µm open loop); Resolution to 0.1 nm; Linearity error only 0.02%
Position sensitive detector	Hamamatsu Photonics K.K.	S1880	The two-dimensional PSD is used to translate optical signals into electrical signals.

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Author(s): Shuya Zhuang, Meirong Zhao, Zhiyi Wang, Lele Zhang, Yinguo Huang, Yelong Zheng

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