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Electrically assisted drop sliding on inclined planes

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We demonstrate that electrowetting using alternating current (ac) voltage can be used to overcome pinning of small drops due to omnipresent heterogeneities on solid surfaces. By balancing contact angle hysteresis with gravity on inclined planes, we find that the critical electrowetting number for mobilizing drops is consistent with the voltage-dependent reduction in contact angle hysteresis in ac electrowetting. Moreover, the terminal velocity of sliding drops under ac electrowetting is found to increase linearly with the electrowetting number. Based on this effect, we present a prototype of a wiper-free windscreen. © *2011 American Institute of Physics*. [doi:10.1063/1.3533362]

The chemical and topographic heterogeneities of solid surfaces lead to pinning forces acting along any three phase (solid-liquid-vapor) contact line. The strength of these forces is usually characterized in terms of the macroscopic hysteresis of the contact angle. For drops of finite size, contact angle hysteresis results in a finite pinning force that needs to be overcome to mobilize a drop. This threshold force scales linearly with the radius of the drop. Since gravity scales with the drop volume, surface heterogeneity and pinning become increasingly important the smaller the drop. This statement holds for any driving force that scales stronger than linearly with the drop radius. In applications such as drop-based microfluidic systems contact line pinning leads to an undesirable threshold force for activating drop motion.[1] Once set in motion, drops experience a dynamic friction. At high sliding speeds, these resistive forces are dominated by viscous dissipation and/or molecular scale hopping processes in the vicinity of the contact line.[2] Johnson and Dettre[3] analyzed the energy landscape and the pinning forces arising from a variety of simple wettability patterns on surfaces and described how mechanical "noise" energy can be used to overcome pinning forces. Several experiments demonstrated that this concept allows for effectively eliminating contact angle hysteresis and for mobilizing drops by mechanical shaking.[4,5] Recently, Li and Mugele[1] demonstrated that electrowetting with alternating current (ac) voltage can also be used to effectively eliminate contact angle hysteresis. In this letter, we demonstrate that drops confined between two parallel plates inclined at a variable angle α can be mobilized by applying an ac voltage to electrodes incorporated into the substrates [see Fig. 1(a)]. Moreover, ac electrowetting is shown to speed up already sliding drops. We show as a possible application a windscreen, which is self-cleaning upon applying electrowetting.

The setup consists of two glass substrates (10×3.3 cm^2) covered with thin transparent electrodes of indium tin oxide, which we cover with thin films of high density polyethylene (HDPE), polytetrafluoroethylene (PTFE), or Teflon AF. The two former are $d=10$ μm thick commercial films [Goodfellow Cambridge Ltd. (Huntingdon, UK)] that we "glue" to the substrate using a conductive drop of water/glycerol to guarantee a good electrical connection. Teflon AF 1600 [Dupont (Wilmington, DE)] is applied using a standard dip coating and annealing procedure[1] leading to a thickness $d=0.64\pm0.10$ μm. The advancing and receding contact angles θ_A and θ_R of water on these surfaces are $95°\pm3°$ and $66°\pm3°$ (HDPE), $117°\pm2°$ and $84°\pm2°$ (PTFE), and $120°\pm2°$ and $110°\pm2°$ (Teflon AF), respectively, as determined using contact angle goniometry. The two surfaces are kept at a fixed separation h of 1.2 mm using spacers, and the inclination angle α can be varied continuously between 0° and 90° using a rotary stage. An ac voltage with a fixed frequency (10 kHz) and a variable root mean square amplitude $U_0=0-340$ V is applied to the electrode using a function generator and an amplifier (Trek PZD700). The drop motion is recorded by looking through the transparent samples using a high speed camera.

Each individual substrate is characterized to determine the contact angle hysteresis and to guarantee that the contact angle θ decreases upon applying a voltage following the electrowetting (EW) equation[6] $\cos\theta(U)=\cos\theta_Y+\eta$ within the range of voltage applied. Here, θ_Y is Young's angle and $\eta=\varepsilon_0\varepsilon U^2/d\sigma$ is the electrowetting number measuring the relative strength of electrostatic and surface tension forces in the system. (ε: dielectric constant of insulator, ε_0: vacuum dielectric permittivity, and σ: surface tension.) Note that U in the EW equation is the voltage between the liquid at the contact line and the adjacent electrode. For our experimental geometry, this voltage amounts to $U=U_0/2$. For each sample, we also record the hysteresis $\Delta\theta$ as a function of the applied voltage (see inset of Fig. 2). $\Delta\cos\theta$ is found to decrease linearly with η: $\Delta\cos\theta(U)=\cos\theta_R(U)-\cos\theta_A(U)=\Delta\cos\theta_0-\beta\eta$. Here, $\Delta\cos\theta_0$ is the hysteresis at zero voltage and $\beta\approx1$ is a coefficient characterizing the efficiency of the contact line depinning due to the electric

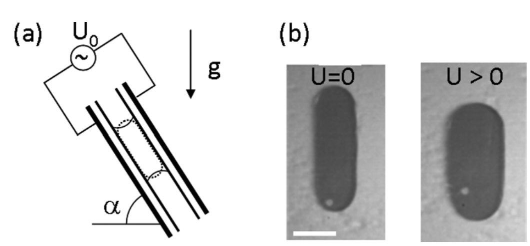

FIG. 1. (a) Experimental setup, consisting of two electrowetting surfaces separated by a gap h. (b) Snapshots of sliding drops. The scale bar is 5 μm.

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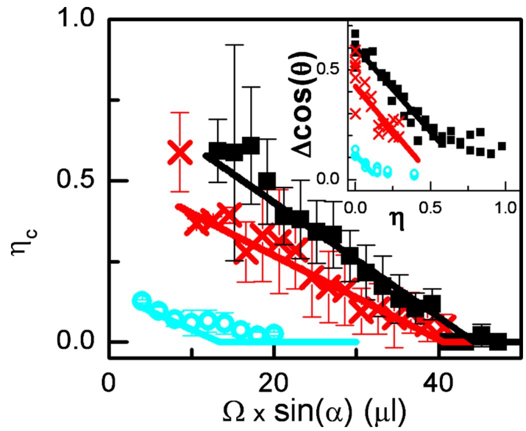

FIG. 2. (Color online) Critical voltage for sliding vs gravity projected along the surface. Symbols: experimental data for HDPE (squares), PTFE (crosses), and Teflon AF (circles). Solid lines: model prediction [Eq. (1)] using experimentally determined contact angle hysteresis. Inset: contact angle hysteresis vs EW number for all three substrates.

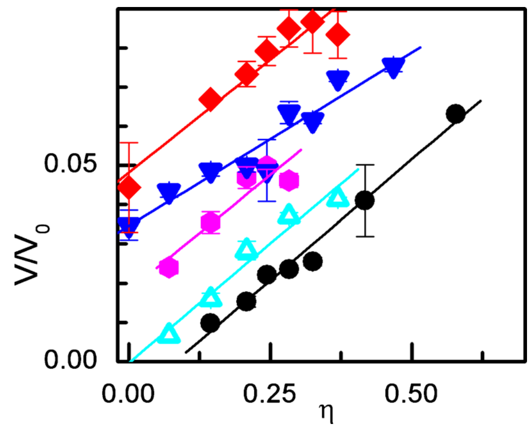

FIG. 3. (Color online) Normalized terminal sliding velocity vs EW number on HDPE for drop volumes of 30 (dot), 40 (open triangle), 50 (octagon), 70 (triangle), and 80 μl (diamond). The lines represent linear fits to the data. (The same qualitative trends were found on Teflon AF surfaces. Data not shown.)

forces.[1] Note that the hysteresis cannot be completely eliminated by ac electrowetting. Rather, the decrease stops at some finite value $\Delta\theta_\infty = 8°$, 7°, and 3° for HDPE, PTFE, and Teflon AF, respectively.

The critical conditions to initiate drop sliding are determined by injecting drops of aqueous solutions of KCl (conductivity 2.5 mS/cm and volume $\Omega = 20-200$ μl) between the two plates at zero voltage. Provided that α and Ω are not too high, the drops remain stuck close to the top of the sample. Subsequently, we increase gradually the applied voltage and record the critical voltage U_c (and the corresponding value of η_c) required to initiate sliding. As qualitatively expected, η_c increases with decreasing drop size for fixed α, and it decreases with increasing α for fixed Ω (see Fig. 2). Since the driving force for drop sliding is given by the projection of the weight of the drop along the surface, we plot in Fig. 2 the critical electrowetting number as a function of $f_g = mg \sin\alpha$, where g is the gravitational acceleration and $m = \rho\Omega = \rho h A$ is the mass of drop ($\rho = 1.0$ g/cm^3: density and A: drop area as seen in top view).

The maximum pinning force f_p experienced by the drop is given by the integral of the imbalanced Young force along the contact line, which leads to[7]

$$f_p = 2w\sigma(\cos\theta_R - \cos\theta_A), \tag{1}$$

where w is the width of the drop. The factor 2 on the right-hand side accounts for the two substrates. The critical condition for the onset of sliding is given by the balance of the projections of both the pinning force and the weight of the drop along the direction of motion

$$\mathrm{mg}\sin\alpha_c = 2\sigma w \Delta\cos\theta(U). \tag{2}$$

(Note that the drop shape can slightly adjust upon increasing the voltage from zero to U_c due to local depinning and relaxation processes that occur preferentially close to its lowest tip, similar to the observations reported in Ref. 8.) The solid lines in Fig. 2 represent Eq. (2) using the experimentally measured voltage-dependent contact angle hysteresis as an input parameter. Notwithstanding the scatter arising from the heterogeneity, the result clearly confirms the effective elimination of the pinning forces by ac electrowetting and the validity of Eq. (2).

Next, we consider the speed of drops beyond the critical conditions for sliding focusing on $\alpha = 90°$. The terminal sliding speed V of the drops is extracted from high speed video recordings close to the bottom of the samples.[9] For any fixed volume, V is found to increase with increasing η (see Fig. 3). Similarly, for fixed η, V is found to increase with increasing Ω. ac electrowetting thus not only reduces the static depinning threshold but also eases the motion of sliding drops.

To understand this behavior, we note that V is determined by the balance of the excess driving force $\Delta f = f_g - f_p = \rho g A h - 2w\sigma\Delta\cos\theta$ and the resistive dissipative forces.[10] We decompose the latter into a bulk contribution $f_{\mathrm{bulk}} = 4A\mu V/h$ ($\mu = 1$ mPa s: viscosity) due to the Poiseuille-like flow profile and into an edge contribution due to the local contact flow patterns close to the contact line. Projecting the drop speed onto the local normal to the contact line and integrating along the edge of the drop, we write the contact line contribution as $f_{\mathrm{CL}} = 4w\xi V$, where ξ is the contact line friction coefficient. The exact expression for ξ depends on the specific model for the contact line dynamics[2] and will not be analyzed here. Solving the nondimensional force balance for the terminal sliding velocity, we find

$$\frac{V}{V_0} = \frac{1 - f_p/f_g}{1 + \tilde{\xi}/\tilde{A}}, \tag{3}$$

where $V_0 = \rho g h^2/4\mu \approx 3.5$ m/s is the sliding velocity expected in the absence of pinning and contact line friction, $\tilde{\xi} = \xi/\mu$, and $\tilde{A} = A/hw$. Given the linear dependence of f_p on η, we recover the experimentally observed linear increase in V with η. Interestingly, the slope is found to be independent of the applied voltage. Fitting the experimental data yields a value of $\xi = 71 \pm 10$ mPa s. Together with the typical values of $\tilde{A} = 5-50$ this demonstrates the dominance of contact line friction over bulk dissipation in our system, which is consistent with the observation that $V/V_0 \ll 1$. In addition to the linear scaling, the absolute value of V/V_0 also agrees with the experiment data for the smallest drops. For the largest drops, the model overestimates the absolute velocity by almost a factor of 2. We tentatively attribute this to the breakdown of the linear approximation for f_{CL} at higher speeds.[2]

FIG. 4. (Color online) Toy car equipped with wiper-free windscreens. The right insets show drop positions before and after activating the voltage. Left inset: illustration of sample with interdigitated electrodes (red and blue; pitch: 240 μm) that are connected to opposite poles of the power supply. (enhanced online). [URL: http://dx.doi.org/10.1063/1.3533362.1]

It is interesting to compare these results to the capillary rise experiments of Wang and Jones[11] for water on Teflon AF. These authors reported comparable values of the contact line friction coefficient (ξ) as we find here. They also found an increased mobility upon applying a voltage, which, since their model does not include pinning, manifests as an overall decrease in ξ with increasing voltage. Neglecting pinning may be justified in their case of surfaces with particularly small contact angle hysteresis. Our measurements on more heterogeneous surfaces can only be described if we explicitly include pinning forces into our analysis. In this case, our data are consistent with a voltage-independent contact line friction coefficient.

Finally, we want to point out that the effect demonstrated here for the case of drops sandwiched between two solid surfaces can also be transferred to the more common situation of sessile drops on a single free surface by using patterned electrodes instead of homogeneous ones on the substrates. Despite the disadvantageous increase in the length on the contact line upon applying a voltage,[12] it is possible to mobilize drops on the inclined windscreen ($\alpha \approx 45°$) of a toy automobile (see Fig. 4 for supplementary video M1) using two combs of interdigitated electrodes. This provides interesting opportunities for wiper-free windscreens, which is particularly attractive for aviation applications.

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