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Electrostatic interaction between water droplets coated by cold plasma treated silicone oil. Quantification of cold plasmas charging of liquids

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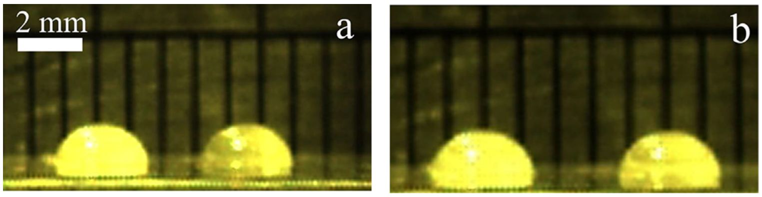
HIGHLIGHTS

- Cold plasma treatment results in the electrical charging of organic oils.
- Water droplets placed on the surface of plasma treated polydimethylsiloxane were used as probes.
- The model of electrostatic interaction between the oil coated charged droplets is reported.
- The specific surface charge was established independently by the electrostatic pendulum.
- The surface charge density was estimated as $\sigma \cong 0.5 \div 3\mu\text{C/m}^2$.

GRAPHICAL ABSTRACT



Two water droplets placed on plasma charged polydimethylsiloxane surface. a) as placed, b) after repulsion.

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ABSTRACT

Cold plasma treatment leads to the electrical charging of liquid organic (polydimethylsiloxane) surfaces. Water droplets placed on the surface of cold radiofrequency plasma treated polydimethylsiloxane oil were used as probes enabling the estimation of the specific surface charge supplied by plasma to polydimethylsiloxane. The specific surface charge was also established independently by the electrostatic pendulum. The surface charge density was estimated as $\sigma \cong 0.5 \div 3\mu\text{C/m}^2$.

1. Introduction

Electrostatic interactions play an important role when colloidal particles or droplets are placed at interfaces [1–3]. Hand in hand with capillary interactions they govern floating and surface arrangement of colloidal particles and droplets [1–3]. Our paper is devoted to the electrostatic interaction of droplets, put on the cold plasma treated polydimethylsiloxane oil surfaces. Plasma treatment leads to electrical charging of solid polymer surfaces [4–6]. The present paper demonstrates that liquid organic surfaces are also charged electrically, when exposed to the cold plasma treatment.

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Plasma treatment (low and atmospheric-pressure) is widely used for the modification of surface properties of solid organic (natural and synthetic) materials [7–17]. The plasma treatment creates a complex set of surface functionalities which influence surface physical and chemical properties; this results in a dramatic change in the wetting behaviour of the surface, usually promoting their hydrophilization [17–23]. It should be emphasized that the modification can be confined to the surface layer without modifying the bulk properties of the polymer. Typically, the depth of modification is several hundreds Angstroms [17].

It was suggested that hydrophilization of organic surfaces by plasmas may be at least partially related to the re-orientation of hydrophilic moieties constituting organic molecules [22,24,25]. Oxidation of plasma-treated surfaces and removal of low-mass weight fragments present on organic surfaces also contribute to hydrophilization [26]. Much effort has been spent in understanding the interaction of plasmas with solid organic surfaces, whereas experimental and theoretical data related to plasma treatment of liquids are scarce [27–32].

An interest in plasma treatment of liquid organic surfaces arose due to various practical reasons, including the possibility of decontamination of liquids by plasmas [28–32] and microfluidics applications of these surfaces, stipulated by their extremely low contact angle hysteresis [33–38]. Quantification of the impact exerted by plasmas on liquid surfaces faces serious experimental challenges. Our paper focuses on the estimation of the electric charge surface density of organic liquids exposed to cold radiofrequency plasma by the measurement of the electrostatic interaction of water droplets coated by plasma treated organic liquids.

2. Experimental

Polypropylene films with a thickness of 25 μm were coated with honeycomb polycarbonate (PC) film with the fast dip-coating process. As a result, typical honeycomb "breath-figures" self-assembly patterns were obtained according to the protocol described in detail in [39,40]. The average radius of pores was about 1.5 μm (for the SEM images of porous structures see Refs. [39,40]). The average depth of pores as established by AFM was about 1 μm. The use of honeycomb surfaces facilitated manufacturing stable silicone oil infused surfaces.

The obtained substrate was covered with polydimethylsiloxane oil (PDMS, supplied by Aldrich) with molecular mass of 580 g/mol. The thickness of PDMS oil layer was established by weighing as 50 ± 2 μm.

The dynamic viscosity of PDMS was measured using the Ostwald type viscometer in thermostatic bath at 25 °C. It was established as $\eta = (2.62 \pm 0.05)\,10^{-3}$ Pa × s.

The abovementioned PC polymer patterns covered with PDMS oil were exposed to a radiofrequency (13.56 MHz) inductive air plasma discharge with the power of 10W under the pressure of 50 Pa and ambient temperature. The time of plasma treatment was 15 s.

Two water droplets with equal volumes of 4, 4.5, 6 and 8 μl were deposited on the above surfaces covered with plasma treated PDMS oil, with the multichannel syringe Discovery Comfort DV8-10 (Poland) with resolution of 0.02 μl, as depicted in Fig. 1. The water droplets were spontaneously encapsulated by PDMS, as depicted in Fig. 2 as discussed in detail in Ref. [41]. When the droplets have been coated by plasma treated PDMS oil layers, they started to repel each other due to the Coulomb repulsion.

The movement of droplets was registered by digital rapid vision camera (Vieworks Co, Ltd, South Korea) and Software CoreViewTM provided by IO Industries (Canada). Starting spacing x_o of 3.5 and 4.5 mm between droplets was used depending on a droplet size (see Fig. 4).

The surface charge density of PDMS was independently established with the electrostatic pendulum, described in detail in Ref. [6]. The measurement of the angle between the threads enabled the estimation of the surface charge density. For this purpose two 25 mm × 25 mm plates of polypropylene film coated with 25 μm in thickness porous PC film were covered with PDMS oil with a

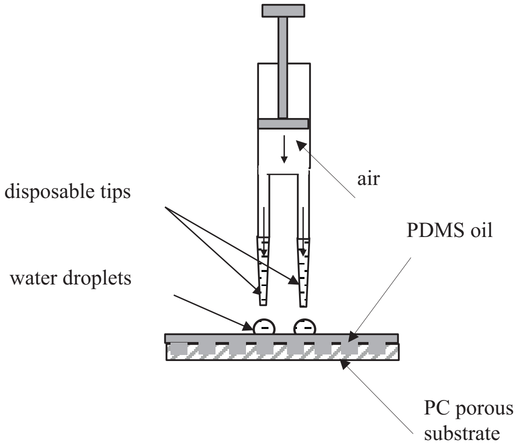

Fig. 1. Principal scheme of work of multichannel syringe pump for simultaneous standing of droplets.

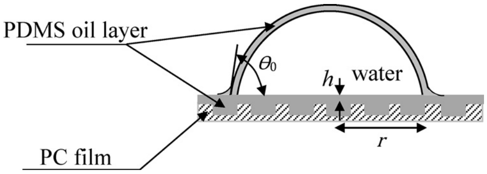

Fig. 2. Water droplet encapsulated with the oil layer. θ_0 is the apparent contact angle, h is the thickness of the oil layer.

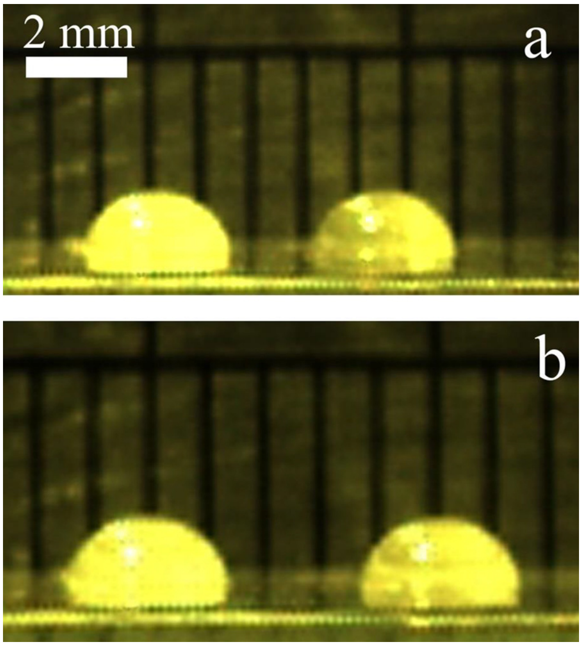

Fig. 3. Two water droplets placed on plasma charged PDMS surface. a) as placed, b) after repulsion.