博士論文（要約）

Electrostatic Instability of Liquid Droplets on MEMS-Based Superlyophobic Surface

(MEMS 超撥液面上液滴の静電場による不安定性に関する研究)

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論文内容の要約

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With the aim for the high efficiency control of the droplet-based microfluidic devices, the vision of the digital microfluidic has been proposed previously. Among the several control mechanism, electrowetting on dielectric (EWOD) and liquid-dielectrophoresis (LDEP) are two of the mostly mentioned technology to realize the design. To further improve the efficiency of these devices, surface friction or contact angle hysteresis (CAH) can be one of the obstacles to be overcome. Applying Cassie state of the super-hydrophobicity can be one prominent solution, and some researches has also reported the increasing of the droplet velocity by utilizing the surper-hydrophobic surface. Recent progress on the Cassie state has made the structure to propel the lowest surface tension liquid to form super-lyophobic surface, which broaden the applicable liquid. Yet as the applying Cassie state to the electric-field-based devices, the Cassie-to-Wenzel transition should be taken into account. Though several investigations have been proposed to explain the mechanism of the instability, the most widely used silicon-based fabricated surfaces have been issues with difficulty in predicting the critical voltage.

Dealing with these issues, we investigated the electrostatic instability of Cassie state with the numerical simulation. The 3-dimentional discrete points are set in the space between the pillar sidewall, liquid-air interface and bottom substrate. The electric potential of each point is calculated with the equation of Gauss's law. The force of acting on the liquid-air interface is calculated to induce the curvature change based on Laplace pressure. With the iterations of calculation for the change of liquid-air interface and the boundary condition of electric potential, the convergent solutions of the liquid-air interface at certain applied voltage can be simulated, and the resulted shape is an exponential curve that dramatically different from the previous knowledge based on the dielectric pillars, which has been studied to be parabolic shape. The simulation shows the conductive pillar will have the deformation of the liquid-air interface about 1.5 times, downward electric force 2 times, and the increase of contact angle at the pinning point about 2.5 times larger than the value under the condition of dielectric

pillar. Eventually the critical voltage of the conductive pillar would be nearly 100 V smaller comparing to the dielectric pillar. Taking the influence of the finite resistivity of materials in to account using Ohm's law, the current materials using Si/SiO2 is about 10 orders of magnitude smaller than the resistance that has the noticeable difference from the ideal conductive pillar.

Taking the Cassie instability to the experimental, the pillar surface has been fabricated with MEMS processes. The conductive Si/SiO_2 pillar is etched through Bosch process with overhanging structure. With the high-resolution displacement meter, we can track the motion of the liquid-air interface under electric field. We scan the surface under electric field, and constructed the 3-D surface profile of the liquid-air interface. The scanned surface and shows little change of the distance between the liquid-air interface and the bottom substrate, which is supported with the simulation that the change of liquid-air interface might be within 0.5 μm in most of the area. Following tracking the motion in the electric field, the critical voltage can be compared with the simulation. The critical voltage predicted in simulation takes the slide-down effect into account. The results of the simulations and experiments of glycerol and water are in good agreement before 200 V. Above the 200 V the instability would be disturbed due to the fluctuation of saturation angle related with the charge injection into the dielectric layer. For hexadecane, the predicted values have mostly 30 ~ 40 deviation from the experiment. The deviation is originated from the deviation in measuring advancing angle, which results the overestimated in the sliding angle in prediction. Due to the stick-slip motion of the advancing behavior, the sliding does not stop at the lower edge of the current overhanging structure. Further lowering the angle of the overhanging such like the double reentrant will prevent this slide-down even with the stick-slip motion. Noted that although the dielectric pillar has a higher critical voltage under applied voltage, in the condition of liquid on electret, the surface potential exists on the sidewall even for dielectric material, so the electric field is the same with the applied voltage in conductive pillar, and the estimation for conductive pillar is inevitable for L-DEPOE.

In order to give an expression for model the critical voltage with geometrical parameter, the shape of the liquid-air interface and also the distribution of the electric field on the conductive pillar surface are fitted with exponential curves using cylindrical coordinate. The parameters of the exponential functions are related with the geometries of the pillar and deformation of the liquid-air interface. Under the balance mechanism of the downward electric force and resisting tension force, the deformation and the shape are related with the applied voltage. The critical voltage of the pillar can then directly calculated from the geometrical parameters, i.e. the pitch, diameter and height of the pillar. With the fitting contact angle changing related with the geometries of pillar, the geometrical boundary of the slide-down, pull-in and touch-down is estimated with a simple relation between the height and the pitch and diameter of the pillar. Note that the slide-down occurs always on the higher pillar region, so that the consideration of slide-down effect for higher critical voltage is crucial for design of high-voltage devices.

Though the current simulation still need some improvements in order to fit the exact condition of the fabricated pillars, the investigation shows the significant differences between the conductive pillar and the dielectric pillar in previous research. The investigation on conductive condition pillar can progress for the better interpretation for the widely used silicon-based fabricated surfaces and the liquid on electret devices. The work will be an important step toward the high efficient droplet-based MEMS devices.