Analysis of the meniscus and viscous effects in digital micromirror device

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Abstract. Digital micromirror device (DMD) is the core of digital light processing projected display technology wherein the spring tip-landing site adhesion and wear are the substantial clause leading to failure due to frequent contacts. In an attempt to analyze the adhesive force between the spring tip and the landing site, two main aspects are considered: i.e. the meniscus force and the viscous resistance during separation. The simulation results show that the influences of the surface energy, liquid volume and the separate velocity are prominent. The work will provide some hints for control of adhesive force in DMD components.

1. Introduction
Since researchers in University of California Berkeley exhibited micro electro-mechanical system (MEMS) products \[1\] in the late 80’s of the last century, it has brought enormous changes to our life and will continue to do in the same way. This is similar to the impacts which brought to the information technology by the appearance of integrated circuit (IC). The development of MEMS technology enables it to become the important area in nanotribology research \[2, 3\].

The ratio of area to volume increases continuously along with dimension shrinkage, so the properties related to material surface nature (such as adhesive force, friction, meniscus force, viscosity traction, surface tension and so on) play the decisive role. Moreover, the admissible tolerance of these equipments is so small that physical direct contact is nearly inevitable, which will lead to stronger ratio of adhesive force from adjacent components \[4\]. To find an anti-sticking technology becomes important. Generally, the origin is adhesive force of intervenient liquids or the capillary condensation which forms from the condensed vapor in ambient environment \[5\]. So the hydrophobic/hydrophilic performances of material surface in micro/nano apparatus are very essential.

In order to reduce the adherence in MEMS, it is extremely important to let the material surface at
de-wetting or super-hydrophobic state. Reducing the humidity is better for limiting meniscus’s formation; therefore, it can reduce adherence, friction and wear. Super-hydrophobic surface has large contact angle (>150°) but small contact angle hysteresis (<10°). In order to improve hydrophobic performance of materials, one way is to reduce surface energy of materials to deteriorate the interaction between the material surface and the water \cite{6-8}, another one is to increase the materials surface roughness (Ra), by which forming a multilayered roughness structure in micro/nano scale, specially forming compound surfaces \cite{9, 10}. However, some researches pointed out that this kind of multilayered structure of roughness distribution is unnecessary \cite{11}. Moreover, there is also a need to increase adhesion in certain situation in MEMS. It’s a suitable choice to form micro/nano roughness as “spatula” on gecko’s bristle \cite{12}. Hiratsuka et al. experimentally measured average friction coefficient down to 8.3×10^{-4} when water drop intervened in hydrophobic surfaces \cite{13}.

Normal load is generally small and mutual contact surfaces are relatively smooth in micro/nano device in MEMS. At this time, the coherence which causes by the meniscus force and the viscous force is possibly quite large and becomes the primary cause to affect the equipment works reliably. Adhesive force depends on area, separate distance, surface tension and liquid adhesion of formed meniscus. In the separation process the meniscus force decreases along with the distance increase, while the viscous resistance reacts in opposite \cite{14, 15}.

As a successful commercial exemplification of MEMS, the digital micromirror device (DMD) is one kind of large scale integrated three-dimensional light beam regulator. It mainly applies in the projected display equipment and the electrostatic printer \cite{16}. DMD is composed of rotatable aluminum mirror arrays (figure 1). These aluminum mirrors are processed with one kind of semiconductor processing technology. Processed surface array has hundreds of thousands to 1.3 million micromirrors which can control reflection independently \cite{5, 14, 17, 18}. The size of each micromirror is around 12um × 12um. The adhesion and wear between tip which locates at the end of cantilever spring and landing site below may lead to reset failure.

Figure 1. Schematic view of DMD device \cite{17}.

This paper aims at the contact problem of spring tip- landing site in DMD. The meniscus force and viscous resistance during separation are analyzed, which will shed some lights to the mechanism of the adherence property and lay a feasible foundation for the future application.
2. Summary of lubrication technology in DMD

DMD is the display technology which was developed by Texas Instrument (TI) in 1987 [19]. The DMD beam control function of light switch (figure 1) provided the best compromise of contrast gradient ratio and the entire system’s brightness efficiency [20]. In a DMD system, the micromirror connects tightly on the following yoke piece. Because of the electrostatic attraction, the micromirror can turn in two directions (micromirror and yoke piece connect on deflection/resetting voltage). Each micromirror slewing angle is approximately ±12°, stops slewing until meet with mechanical resist. The yoke piece and electrode surface contact guarantees the real binary digital operation. Each picture element causes to electrode surface impacting energy is approximately 9×10^{15} J [17]. Thus, the yoke piece tip rubs electrode surface back and forth during operating process.

In order to land at another direction, the tip must be released from original position after removing the deflecting voltage, leaves landing position when rebound. The commercial micromirror life request is also getting higher and higher, it requests running surpasses 100,000 hours not to have the picture quality drop. The micromirror modulation frequency is 7 kHz. Thus, each micromirror rotates as many as 2,500 billion times in the average life span [21]. Meniscus force or van der Waals force between contact elements might be too big to overcome by reset pulse, thereby cause flaw such as macula or lightspot and so on. In order to overcome the influence which the contact adherence brings about, a low surface energy self-assembly layer is usually deposited on the tip and the landing site surface. However, high adhesion still possibly exists in certain position. Therefore to raise the manufacture output, it’s necessary to research adhesive problem in DMD, in an attempt to find out its mechanism and to propose a probable plan to reduce adhesion. It’s a significant work for either the industrial community or the academic circles.

3. Analysis of contact between spring tip and landing site

3.1 Analysis of contact angle

In DMD system, the meniscus and the viscous resistance are the main sources to dominant adhesive force performance.

Material wetting ability is related to contact angle \( \theta \). If the contact angle \( \theta \) between solid and liquid varies from 0° to 90°, \( (0° \leq \theta \leq 90°) \), liquid can soak the solid, then the solid surface is called a hydrophilic surface. If the contact angle \( \theta \) varies from 90° to 180°, \( (90° \leq \theta \leq 180°) \), liquid cannot soak the solid, then the solid surface is called a hydrophobic surface. A lot of factors influence contact angle, for example, surface roughness, surface pretreatment ways and cleaning degree and so on. Surface with low surface energy usually is hydrophobic. So we can by means of sputtering a layer of low surface energy self-assembly film on high energy surface to improve hydrophobic performance. In DMD, usually deposit a low surface energy layer of perfluorodecanoic acid on high-energy aluminum mirror surface to make it became hydrophobic surface, (whose contact angle is about 113° [22]). The influence caused by surface roughness to contact angle is given by the Wenzel equation [23]:

\[
\cos \theta = f_r \cos \theta_0
\]

(1)

where \( \theta \) is the contact angle of rough surface, \( \theta_0 \) the contact angle of smooth surface, and \( f_r (\geq 1) \) the
roughness coefficient, respectively. Because of increasing actual contact areas, equation (1) indicates: to the hydrophobic surface, roughness existence increases the surface hydrophobic capability, but to hydrophilic surface, roughness existence increases the surface hydrophilic capability. To design a surface with appropriate roughness, an ideal hydrophobic or hydrophilic surface is crucial \[24, 25\]. If there is bubble between the rough peak gaps, composing a solid-liquid-gas compound interface, it is better for dewetting performance of hydrophobic surface \[26\], but this state usually unstable.

In DMD system, the spring’s surface roughness (Rq) is about 0.8 nm, while the value of landing site’s surface roughness (Rq) is usually about 3.2 nm (figure 2), the interface is a rectangle size of 0.41 um×0.65um. Therefore two surfaces are treated as smooth in the following simplified analysis.

Figure 2. SEM image of contact surface \[17\].

Figure 3. Meniscus shape between smooth surfaces.

When a thin water layer enters into two smooth surfaces, it will form a meniscus due to surface energy. Generally speaking, the hydrophilic surface will form concave surface but the hydrophobic surface will lead to convex surface.

The pressure difference (i.e. the Laplace pressure) caused by the surface tension $\gamma$, is given by the equation below:

$$\Delta p = \gamma \left( \frac{1}{r_1} + \frac{1}{r_2} \right)$$  \hspace{1cm} (2)

In the above equation, $r_1$, $r_2$ are the radius of meniscus in two orthogonal planes respectively, they are related with Kelvin radius as follows:

$$\frac{1}{r_k} = \frac{1}{r_1} + \frac{1}{r_2}$$  \hspace{1cm} (3)

The Kelvin radius $r_k$ can be educed as follows

$$r_k = \frac{\gamma V}{9RT \log \left( \frac{p}{p_0} \right)}$$  \hspace{1cm} (4)

where $V$ is the Moll volume, $R$ the gas constant, $T$ the absolute temperature, $p$ the ambient pressure and $p_0$ the saturation vapor pressure when temperature is $T$, respectively.

Meniscus force is calculated on the basis of the equation listed below (figure 3):
where $\Omega$ is the meniscus area. The expression of meniscus height is:

$$h = r_1 \left( \cos \theta_1 + \cos \theta_2 \right)$$

(6)

The meniscus force equation is:

$$F_m = \frac{\pi r_1^2 \gamma (\cos \theta_1 + \cos \theta_2)}{h} + 2\pi \gamma x_n \sin \theta_2$$

(7)

### 3.2 The calculation of adhesive force

Liquid flow between two surfaces during separating is described by Reynolds equation. Incompressible Reynolds equation reads:

$$\frac{\partial}{\partial t} \left( r h^3 \frac{\partial p}{\partial r} \right) = 12\eta_r \frac{\partial h}{\partial t}$$

(8)

where $\eta$ is the fluid viscosity. We can get:

$$\Delta p = 3\eta \frac{r^2 - x_n^2}{h^3} \frac{\partial h}{\partial t}$$

(9)

The maximal pressure difference and the mean pressure difference are:

$$\Delta p_{\text{max}} = -3\eta \frac{x_n^2}{h^3} \frac{\partial h}{\partial t} \quad \text{and} \quad \Delta p_{\text{avg}} = -\frac{3}{2} \frac{x_n^2}{h^3} \eta \frac{\partial h}{\partial t}$$

(10)

And then, using the above equation the viscous resistance reads

$$F_v = \int_0^x 2\pi \Delta p_r dr = \frac{3\pi \eta x_n^4}{4t_s} \left( \frac{1}{h_s^2} - \frac{1}{h_0^2} \right)$$

(12)

where $h_s$ is the liquid height when meniscus fracture during separation, and $h_s$ and $x_n$ are determined real-timely in the computational process, which is expressed in reference [27]. Parameter $h_0$ is the initial liquid height.

The meniscus force and viscous force during separation will give rise to the following relation:

$$F_a = \frac{\pi r_1^2 \gamma (\cos \theta_1 + \cos \theta_2)}{h} + 2\pi \gamma x_n \sin \theta_2 + \frac{3\pi \eta x_n^4}{4t_s} \left( \frac{1}{h_s^2} - \frac{1}{h_0^2} \right)$$

(13)

### 3.3 Calculation results

Table 1 and 2 show the adhesive force (the sum of meniscus force and viscous force here) variation features with different conditions, where the separation velocity is set to 4 m/s. From table 1, it is shown that the increase in the initial liquid height $h_0$ will lead to a decrease in $F_a$ (absolute value). Table 2 tells that a larger contact angle (which means a more strong hydrophobicity) will give rise to an increase in $F_a$ (also related to absolute value).
Table 1. Adhesive force of different liquid volume on hydrophobic surface.

\[ \theta_1 = \theta_2 = 120^\circ \]

| \( x_{a0} \) (nm) | \( h_0 \) (nm) | \( F_a \) (nN) |
|-------------------|---------------|---------------|
| 100               | 4             | -981.11       |
| 100               | 6             | -743.61       |

Table 2. Adhesive force of different contact angle on hydrophobic surface.

\( x_a = 100\text{nm}, h_0 = 4\text{nm} \)

| \( \theta_1 \) (°) | \( \theta_2 \) (°) | \( F_a \) (nN) |
|-------------------|-------------------|---------------|
| 120               | 120               | -981.11       |
| 120               | 150               | -1156.80      |

The separate velocity effects are shown in table 3. Clearly, the larger of the velocity, the stronger the viscous force is. The variation of parameter \( F_a \) during separation is plotted in figure 4, by which it is abruptly decrease to zero during the separation.

Table 3. Adhesive force of different separate velocity on hydrophobic surface.

\( \theta_1 = \theta_2 = 120^\circ, x_a = 100\text{nm}, h_0 = 4\text{nm} \)

| \( V \) (ms\(^{-1}\)) | \( F_a \) (nN) |
|----------------------|---------------|
| 4                    | -981.11       |
| 6                    | -1169.33      |
| 8                    | -1357.56      |

Figure 4. Adhesive force on hydrophobic surface:

\( x_a = 100\text{nm}, h_0 = 4\text{nm}, \theta_1 = \theta_2 = 120^\circ, V = 4\text{m/s} \).

4. Conclusions

In digital micromirror device (DMD) system, there are many factors affect the adhesive force between the spring tip and the landing site, among which the meniscus and viscous effects usually take a dominant role. The contributions of meniscus force and viscous resistances are analyzed, and the parameters of different liquid volume, contact angle as well as separate velocity are considered. It will provide some feasible candidate solutions to reduce adhesion so as to withstand a longer operation life of DMD components.

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