ABSTRACT

Adhesion and stiction are serious problems in microelectromechanical systems (MEMS) fabrication and application. The wettability, surface energies, and nano-scale adhesive forces of commonly used MEMS materials have been examined by contact angle meter and atomic force microscopy. Silicon and silicon compounds have higher surface energy than that of PMMA and SU-8 due to larger polar component of surface energy. The nano-scale adhesive forces of PMMA and SU-8 are 3-4 times smaller than that of as-received silicon with native oxide. It has been shown that the materials with higher surface energy have higher adhesive forces. One efficient way to avoid stiction in silicon microstructures is to deposit a thin fluorocarbon film coating.

Key words: capillary force, stiction/adhesion, MEMS materials, nano-scale adhesive forces.

INTRODUCTION

In MEMS devices, surface forces become dominant forces compared to gravity and inertia. This results in large surface adhesion since restoring force cannot overcome the attractive interfacial forces caused by capillary, van der waals, and electrostatic forces [1, 2]. Among the interfacial forces, capillary force is dominant if MEMS devices are composed of such hydrophilic surfaces as silicon with native oxide, and used in high humidity environment. The surface adhesion strongly affects the reliability and long-term durability of MEMS devices, and is a serious problem in fabrication (release stiction) and application (in-used stiction). Capillary induced stiction is important for both release and in-used stiction. In-use stiction related failure is a major problem and will be increasingly important with miniaturization towards nano-scale structures. Hydrophobization of surfaces to reduce surface energy is the primary technique used to minimize stiction related problems. Both liquid-based and vapor-based processes are investigated in this regard. In order to minimize stiction in MEMS devices, it is quite important to use suitable materials and processes or give proper surface modification for various MEMS devices. Therefore, it was decided to investigate the wettability, surface energies and nano-scale adhesive forces of various commonly used materials in MEMS, such as silicon, poly-silicon, silicon nitride, PMMA, and SU-8, which could give a general idea about materials selection and the methods to minimize stiction. The effect of surface modification and coating on the contact angle are also discussed.

EXPERIMENTAL TECHNIQUES

All the materials investigated have n-(100) silicon wafers as starting materials. The fabrication of the sample relies on the standard cleanroom process. Un-doped poly-silicon was grown on silicon substrate by silane decomposition at 620°C using low-pressure chemical vapor deposition technique. Low stress silicon nitride was deposited onto silicon substrate by plasma enhanced chemical vapor deposition technique using standard recipe for low stress silicon nitride. A 2 μm PMMA layer was prepared by spinning PMMA solution onto silicon substrate and post bake at 150°C for 5 min to remove solvent. A 5 μm SU-8 layer was prepared by spinning SU-8 [3] onto a wafer, followed by pre-baking at 90°C for 3.5 min, flood exposure, post-baking at 105°C for 10 min to cross-link the SU-8 and developing. Fluorocarbon films, which have low surface energy, were deposited by passivation process in deep reactive ion etching, where CF₃ is used as feed gas.

Contact angle measurements were carried out using contact angle meter DSA10 from Krüss GmBH equipped with automatic dispensing system and Frame grabber. Test liquids are deionised (DI) water, diiodomethane and ethylene glycol. Both static and dynamic contact angle were measured. The detailed description of measurement and calculation of surface energy can be found in Ref. 4. The nano-scale adhesive force tests were performed with a commercial AFM system (Dimension 3100, Digital Instrument) operating under ambient conditions of 22°C and 45-50% RH. Square pyramidal Si₃N₄ with a nominal 20-60 nm radius mounted on gold-coated Si₃N₄ cantilevers with a nominal spring constant of 0.32N/m (Digital Instrument) were used in this study. The adhesive force measurements were carried out in force calibration mode [5].

RESULTS AND DISCUSSIONS

The water contact angle and surface energy of commonly used MEMS materials are given in Fig.1. Silicon and silicon compounds have lower water contact angle, and thereby higher
surface energy. The in-use capillary force, $F_{cap}$, is caused by capillary condensation and can be calculated as [2],

$$F_{cap}(d) = \frac{4 \gamma_{lv} r_k (\cos \theta)^2}{d^2}$$  \hspace{1cm} (1)

where $\gamma_{lv}$ is the surface tension of water, $\theta$ is the contact angle of water on the surface and assumed same values for both surfaces, $d$ is the separation distance between the two surfaces, $r_k$ is the Kelvin radius and has value around -0.78 nm at 50% relative humidity [2]. The attractive capillary force decreases with increasing water contact angle. Therefore, as-received silicon wafer has higher tendency for capillary induced stiction, while SU-8 and PMMA might have lower probability to stick. Fig. 2 shows the surface energy and their dispersive and polar components of the as-deposited MEMS materials. It can be seen that silicon and silicon compounds have higher polar components compared to that of PMMA and SU-8.

Fig. 3 gives the surface energies of some MEMS materials and the nano-scale adhesive forces between Si$_3$N$_4$ tip and the materials. The materials with higher surface energies have higher nano-scale adhesive forces. It can be seen that the nano-scale adhesive forces of PMMA and SU-8 are 3-4 times lower than that of as-received silicon wafer, which has native oxide layer, indicating that PMMA and SU-8 have lower tendency for stiction, which is in agreement with the conclusion from the water contact angle and the surface energy. As-received silicon has highest adhesive force. Therefore, it is necessary to minimize stiction of silicon microstructures. Silicon with a buffered hydrofluoric (BHF) acid dip has lower nano-scale adhesive force and surface energy compared to as-received silicon wafer since the BHF dip provides a H-terminated surface. However, the H-terminated surface is not enough for anti-stiction applications. Fluorocarbon films deposited onto silicon substrate by deep reactive ion etching can be an efficient way to minimize stiction of silicon structures by decreasing surface energy. The fluorocarbon films have water contact angle as high as 110 degrees, surface energy as low as 14.3 mJ/m$^2$, and nano-scale adhesive force as low as 33 nN, which is 4.7 times lower than that of as-received silicon. It has been shown that the fluorocarbon films have good anti-stiction behavior in nanoimprinting process [6].

CONCLUSIONS
The wettability, surface energy, and nano-scale adhesive force of MEMS materials have been investigated. It has been shown that silicon and silicon compounds have higher tendency for capillary induced stiction due to their larger polar component of surface energy. The materials with higher surface energies have higher adhesive forces. One efficient way to minimize stiction in silicon microstructures is to deposit a fluorocarbon film coating, which have surface energy as low as 14.3 mJ/m$^2$ and 4.7 times smaller adhesion force than that of as-received silicon wafer.

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REFERENCES

FIGURES

![Fig. 1 Water contact angle and surface energy of five as-deposited MEMS materials.](image1)

![Fig. 2 Surface energy and their dispersive and polar components of five as-deposited MEMS materials.](image2)

![Fig. 3 Nano-scale adhesive force and total surface energy of some MEMS materials.](image3)