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Surface engineering for microfabrication

EXECUTIVE OVERVIEW

Richard Feynman predicted the emergence of the nanotechnology field during a now-famous Caltech lecture in 1959 [1]. Today, from cellular phone microphones to stain-resistant fabrics, the products engineered using nanotechnology span many applications and have found their way into mainstream goods. Surface engineering is a versatile technique in which making very small-scale substrate changes can lead to large-scale device performance improvements.

For many applications, nanotechnology is employed as a surface engineering or surface modification tool. One major benefit of nanoscale surface engineering is the ability to impart specific surface characteristics onto a substrate without altering the bulk material traits. For example, a silicon micro or nano-electromechanical system (MEMS/NEMS) can be treated with an anti-stiction material to greatly extend its working lifetime without compromising mechanical durability or otherwise altering device performance. These anti-stiction coatings are self-assembled monolayers (SAMs) that can uniformly coat complex structures including high-aspect-ratio comb drives in MEMS inertial sensors, areas under mirrors in MEMS displays, and membranes of MEMS microphones.

Film applications

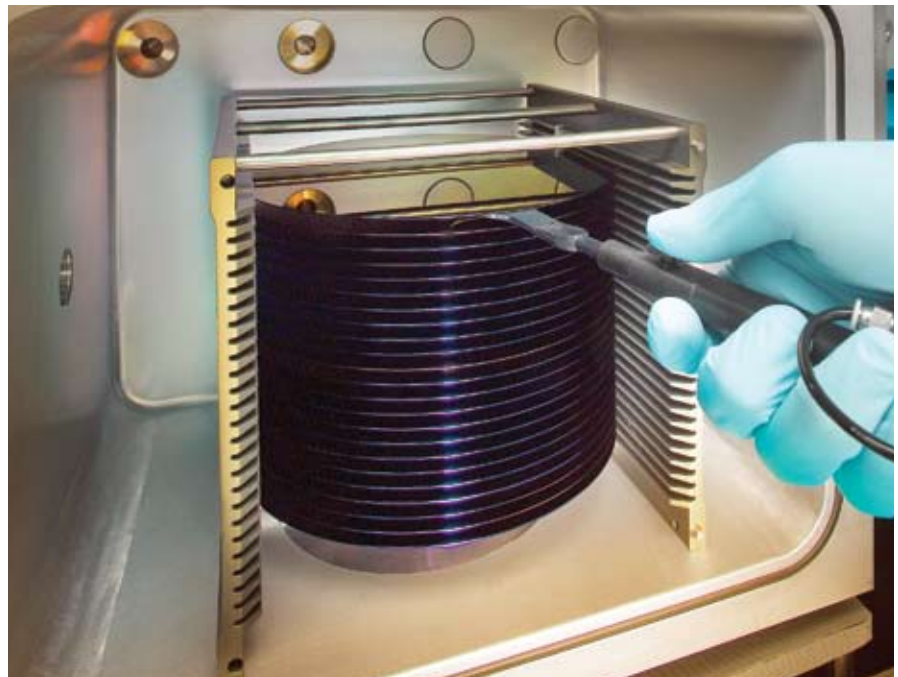
The conventional method of deposition—from a liquid phase—involves a sequence of wet chemical reactions performed in a wet station. It is an expensive and environmentally unfriendly method due to the use (and waste) of expensive solvents, and is unsafe for the operator due to the possibility of direct contact with chemicals. On the other hand, vacuum processing and the vapor-phase deposition of these anti-stiction films, implemented by the Molecular Vapor Deposition (MVD) method, have proven capable of

producing higher quality films, due to tight control of the process environment (moisture), and appear to be an attractive alternative in MEMS manufacturing. Ultrathin hydrophobic coatings repel moisture, which is the main cause of the capillary stiction in MEMS devices.

Some nanofilms can also lubricate surfaces to avoid device failures caused by mechanical impact of movable micromechanical parts. Although silicon is an excellent structural material for MEMS devices, small area contacts (as in contact points between

rough polycrystalline surfaces) can generate sufficiently high contact pressures to create plastic deformations. These in turn lead to significant wear. Recently, we have found that carbon-doped Al_2O_3 deposited by the MVD method provides the highest degree of wear prevention documented to date in sidewall wear test microstructures. These test structures, based on a double comb drive design, were fabricated by the Sandia SUMMiT V process. One set of combs is used to apply a static load on a beam, which is pulled against a fixed post; the other set is used for tangential actuation to rub the beam against the fixed post. MVD-coated microstructures have survived testing without failure for over 7×10^6 cycles (Table 1). This is seven times longer than the SiC-coated structures that were tested in a similar way.

By exploiting the ability of MVD to deposit in situ adhesion layers, functional organic layers (hydrophobic) can be attached



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to a variety of different substrate materials. Moreover, a low temperature MVD process can form high quality metal oxide adhesion layers on materials that can't tolerate high temperatures. Metal oxide layers as thin as 15–20Å effectively promote adhesion of organic layers to plastic materials.

Similar advantages of these layers have been obtained on metals and glass. **Table 2** shows that plasma treatment can generate hydroxyl sites (hydrophilic surfaces) on a majority of materials including polymers, but this does not guarantee successful deposition of organic coatings, as can be seen from the relatively low water contact angles. On the contrary, adhesion layers form a denser network of hydroxyl sites for the attachment of organic molecules, which manifests itself in high values of measured water contact angles. Experiments showed adhesion layers <30Å thick could provide continuous coverage on a majority of surfaces.

One area where MVD has been successfully employed is in the inkjet field. Passivation of the inkjet nozzle face-plates with low surface energy MVD coatings prevents contamination with ink, which reduces printing defects and enhances inkjet nozzle operational lifetime. For inkjet applications, several important performance requirements must be satisfied for the device to function

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properly. The mechanical stability of the coating must be sufficient so that the routine movements of the inkjet device associated with cleaning and use do not destroy the coating.

The durability of MVD coatings has been improved using in situ deposited adhesion layers that enhance the adhesion of the coating to the substrate material and thus increase the density of the bonding sites. The stability of MVD coatings immersed in DI water and different types of inks have been demonstrated to be many weeks. Coatings are stable in thermal treatment up to 400°C in air. The durability of MVD coatings has also been tested using an inkjet dry

Table 2. Contact angle data comparison for MVD hydrophobic coating*

Material	Initial state	Plasma	Adhesion layer	Functional (perfluoro)
				Water contact angle (°C)
Si	27	<5	<5	114
Polycarbonate	98	<5	<5	112
PMMA	71	20	<5	114
Polystyrene	68	<5	<5	113
Si	27	<5	—————>	114
Polycarbonate	98	<5	—————>	23
PMMA	71	20	—————>	52
Polystyrene	68	<5	—————>	36

*deposited on silicon and plastics with and without adhesion layer.

wipe test (HP-990 Maintenance Blades tester), showing stable performance for tens of thousands of wipe cycles (see Fig. 1 on p. 31).

Emerging applications

MVD systems have been used in other microfluidic devices (lab-on-a-chip, biosensors, etc.) for surface modification of microchannels. Passivation of long (up to 6m) buried

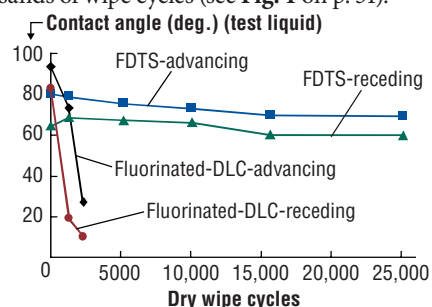


Figure 1. Durability of various MVD coatings as tested using an inkjet dry wipe test (HP-990 Maintenance Blades tester).

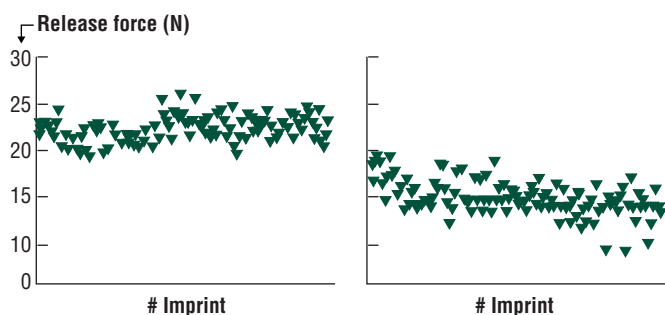
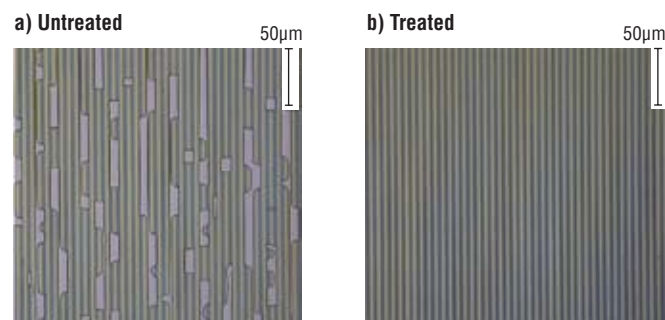


Figure 2. Line imprints and mold release force for **a)** untreated imprint molds, and **b)** molds treated with a low energy surface coating.

Table 1. Summary of cycles-to-failure data for various MVD coatings

Coating	Cycles-to-failure
Native oxide [11]	8×10 ³
Vapor SAM [11]	4×10 ⁵
SiC LPCVD [11]	Testing halted after 10 ⁶
Alumina MVD	Testing halted after 7×10 ⁶

microchannels with controllable wetting coatings has been recently demonstrated using MVD process technology. The capability to coat microchannels in a fully assembled device (buried channels) simplifies the manufacturing process and reduces device cost.

Another emerging MVD application—release layers for nanoimprint lithography (NIL)—has already shown yield improvement and cost reduction advantages and has been used in many development labs worldwide. NIL, as a printing technology, requires mechanical contact between mold and resist (polymer material), thus resist adhesion to the mold is one of its primary challenges.

When intimately contacted, the resist tends to be pulled from the substrate and remain on the mold, creating a defect that affects not only that specific substrate, but all other subsequently printed substrates because of an air gap formed between mold and substrate. The main approach to overcoming this problem is to apply a low surface energy coating to the mold surface that can drastically reduce adhesive forces between the mold and resist materials. Imprint molds coated with a thin and conformal nanolayer perform hundreds of replication cycles without recoating and provide high fidelity of sub-50nm features (Fig. 2).

The surface engineering techniques described above are implemented using an MVD series of tools manufactured by Applied Microstructures (R&D tool MVD-100 and production tool MVD-150). The

MVD-150 enables high volume manufacturing of MEMS devices and facilitates the transfer of MEMS, microfluidic, and NIL technologies from R&D to production.

Conclusion

The use of MVD surface engineering technology has facilitated many new emerging nanoscale applications that have been difficult or impossible using traditional liquid synthetic techniques. It has also demonstrated benefits in a wide variety of fields. These nanoscale vapor surface coatings have shown significant device performance improvements with layers as thin as a few nanometers and are also able to meet the durability requirements in many of these fields. ■

Acknowledgment

MVD is a registered trademark of Applied Microstructures Inc.

Reference

1. R. Feynman, "There's Plenty of Room at the Bottom," *Engineering and Science*, Vol. 23, No. 5, pp. 22–36, 1960.

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High Volume Surface Modification Solution for MEMS, Inkjet Printers and Nanoimprint Lithography

Features

- Designed for High Volume Production
- Advanced Precursor Management (Precision Vapor Delivery)
- Integrated Surface Treatment (RF Downstream Plasma Source)
- 8" Round/Square Substrates/Plates & arbitrary shaped devices
- Multiple Precursors (up to 4)
- Touch-Screen Interface
- Safety Interlocks
- Simple Facilities
- Small Footprint
- Automated Processing Sequence
- Factory Automation (SECS/GEM)
- Robotic Interface (optional)

Substrate Materials

- Semiconductors (Si, Ge, GaAs, etc.)
- Metals (Al, Ni, Ti, Cr, stainless steel, etc.)
- Noble Metals (Au, Ag, Pt, etc.)
- Oxides (SiO₂, Si₃N₄)
- Glass
- Plastics (Acrylics, PC, PP, PMMA, PDMS, etc.)
- Photoresists & SU-8

Form Factor

- Wafers, dies
- Plates
- Packaged Parts & Assemblies
- Boxes of Glass & Plastic Slides
- Plastic & Metal Sheets
- Micro-fluidic components
- Hard drive disks
- Nanoimprint stamps & molds

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