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NANO-SCALE ABRASION STUDIES OF MATERIALS USED IN MEMS DEVICES AND PACKAGES

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ABSTRACT

A number of devices in MEMS introduce frictional contacts between moving surfaces, resulting in particle generation. In this paper, we explore the nano-scale abrasion characteristics of four materials that are commonly encountered in MEMS devices and packages: aluminum (Al), silicon (Si), Pyrex™ glass, and glass-mica ceramic (Macor™). A commercial scribing tool has been adapted to provide controlled velocity and force, and accurate positioning for abrasion utilizing two abrasion heads: a diamond facet edge that provides high-speed serial abrasion, and a custom alumina-grit head that provides parallelism. While Al is easily abraded, it tends to create build-up of material along the edges. Silicon provides triangular clean groves with minimum widths $\approx$ 460 nm. Macor provides scalloped grooves that show some chipping and have minimum widths of $\approx$ 320 nm. Glass provides clean, rounded grooves, with minimum widths of $\approx$ 200 nm. This paper also describes how controlled abrasion can be exploited for the non-lithographic fabrication of nanochannels.

I. INTRODUCTION

The use of abrasives in microfabrication is commonplace. y. For example, a sequence of process is required to turn a silicon ingot into wafers. After they are sliced into the wafers using a diamond saw, lapping and grinding process are performed to achieve a high degree of parallelism and flatness of the wafer. Grinding is performed by feeding the grinding wheel towards the wafer chuck while they rotate about their own rotational axes [1]. Pei et al. have reported that interaction between the wheel speed, chuck speed and feed-rate results in varying degree of grinding force, surface roughness and grinding marks. These process variables can be optimized to reduce grinding marks for a given grinding wheel [2].

In another stage of microfabrication, chemical mechanical polishing (CMP) has become a common process to planarize wafer surface. As layer of interconnect and insulation are successivley are built on the silicon substrate, the lack of planarity causes problems in poor step-coverage of deposited thin films and depth of focus of lithographic tools. During the CMP process, a rotating wafer is pressed down onto a rotating polishing pad while polishing slurry containing abrasive particles and chemical reagents is dispensed onto the pad. The combined action of polishing pad, abrasive particles and chemical reagents result in material removal and polishing of the wafer surface. It is reported that the removal rate is sensitive to the particle concentration in the slurry, more sensitive to the applied load and operating speed and most sensitive to the surface hardness and slurry particle size [3].

In the field of MEMS, as the device size scales down, larger surface-to-volume ratio of the devices results in high adhesion and friction forces that seriously degrade the performance and reliability of these devices. Stiction limits initial yield. Contacting and rubbing surfaces are associated with dominant failure modes in microsystems [4]. Thus, tribological issues in MEMS are the focus of increasing attention, particularly at micro to nanoscales. For example, there are also efforts at developing lubrication methods that are suitable for MEMS application. It has been reported that the bare silicon exhibits poor tribological performance and film coatings (e.g. SiC films) or surface treatments (e.g. oxidation, tungsten coating) can reduce friction and wear [5,6]. Some researchers have explored methods of surface treatment to minimize adhesion [7]. Dichlorodimethylsilane and other coating materials have been explored as anti-stiction monolayer in MEMS [8,9]. Selective tungsten coating has developed to suppress wear in microengine [10].

Another undesirable effect of frictional force is stick-slip phenomenon. This phenomenon is characterized by saw-tooth behavior of the frictional force in time. It arises when the coefficient of static friction is markedly greater than the coefficient of kinetic friction. During the stick phase, the friction force builds up to a certain value, and once the force is large enough to overcome the static friction force, a slip occurs at the interface and friction force decreases dramatically causing saw-tooth pattern in the friction force-time curve. This type of motion should be avoided because it creates vibration, noise, wear, and damage. The characteristic of motion depends on the sliding speed. There exists a critical scan speed below which the uniform sliding transforms into stick-slip motion. For stiffer material the critical speed is lower. Stick-slip process can be minimized by reducing the system compliance or appropriate material selection so that the difference between coefficient of static friction and that of kinetic friction is small. Use of lubricants also helps to reduce the stick-slip process [8].

A number of devices in MEMS introduce frictional contact between moving surfaces. For example, particle can be generated as a by-product of electrothermal actuation, when minor out-of-plane deformation causes dimples on the underside of actuators to rub on the substrate [9]. These dimples are commonly used to reduce stiction of moving parts in a number of electrostatic devices as well. Residual particles are also artifacts of non-ideal fabrication and packaging environments. These particles are known to further accelerate the wear process by abrasion. In this effort, we explore the nano-scale abrasion characteristics of four materials that are commonly encountered in MEMS devices and packages: Al, Si, Pyrex™ glass, and glass-mica ceramic (Macor™).

The question arises, can we exploit controlled abrasion as a fabrication process? It turns out we can, and in section IV of this paper describes how this study on controlled abrasion can be used for non-lithographic fabrication of sub-micron hydraulic diameter channels.

II. PROCESS DESCRIPTION

Nano-scale abrasion of materials has been explored to a limited extent using AFM probes and custom tools [10,11]. However, many questions remain to be addressed in the context of practical MEMS applications. In this work, we have adapted a commercial scribing tool (Karl Suss RA120) to provided controlled abrasion. The schematic of the abrasion tool is shown in Fig. 1. Pressure and speed can be adjusted . In addition, attached microscope assembly permits accurate positioning of the substrate for abrasion. Two abrasion heads are used: a diamond facet edge that provides high-speed serial abrasion, and a custom alumina-grit head that provides parallelism.

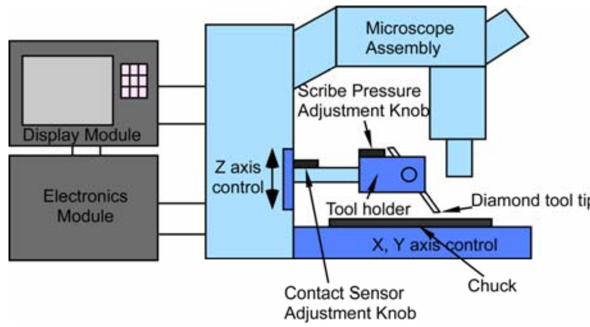

Fig. 1: A schematic of the abrasion tool.

An Al substrate was prepared by evaporating 1500Å of aluminum on a bare silicon wafer. In addition, a bare silicon wafer, a Pyrex glass sheet, and a Macor sheet were used as substrates. (Macor™ is a glass-mica ceramic.) They were abraded with 1500 grit alumina grit head and diamond facet head and examined with SEM. When abraded with alumina grit head, due to the irregularities of grit shapes and orientations, various groove widths were created. The minimum measured minimum width achieved in order to determine the lower limit of the process..

To examine the effect of force on the dimension of grooves created, using Si as a substrate and a diamond head, the hydraulic diameter of the grooves was measured as a function of the applied force.

III. EXPERIMENTAL RESULTS & DISCUSSION

The measurements showed some characteristics that can be correlated to their material properties, while other characteristics were not easily predictable. The material properties of four sample materials used are listed in Table I.

Al is very soft metal and easily abraded. However, the low hardness of Al tends to create build-up of material along the edges of the grooves which cannot be cleaned even ultrasonically. This characteristic makes aluminum unattractive to be used as a packaging material because it yields non-planar surface. The SEM image of Al film abraded by alumina grit head and close up of the built-up edge is shown in Fig. 2. A minimum width of 150 nm was observed.

Contrary to the Al substrate, very high hardness of Si provides triangular shaped clean grooves but the minimum width is approximately 460 nm.

Pyrex glass provides clean, rounded grooves, with minimum width of about 200nm. Close-up of top view and cross-sectional view of created groove is shown in Fig. 4. This particular groove has hydraulic diameter of 138 nm.

Table I: Properties of sample materials.

	Aluminum	Silicon	Glass	Macor
Density (kg/m^3)	2750	2330	2230	2520
Knoop Hardness (kgf/mm^2)	23	1150	418	250
Young's Modulus (Gpa)	73	47	62.75	66.9
Poisson's Ratio	0.33	0.266	0.2	0.29
Shear Modulus (Gpa)	69	79.9	26.1	25.56

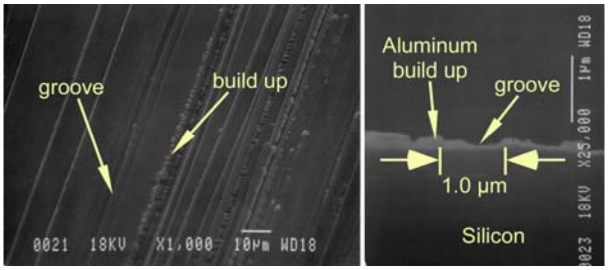

Fig. 2: SEM image of Al film abraded by alumina grit tool.

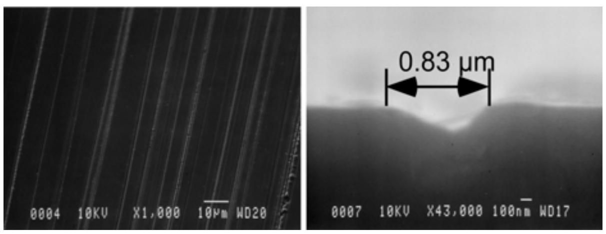

Fig. 3: SEM image of single crystal Si abraded by alumina grit tool.

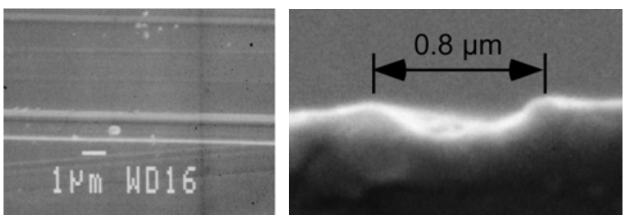

Fig. 4: A #7740 Pyrex^{TM} glass sample abraded by alumina grit tool.

Figure 5 illustrates the minimum widths achieved for each sample material. Smallest dimension is achieved with aluminum, and the next smallest is achieved with glass.

When Macor glass-mica ceramic, a high dielectric strength ceramic, is abraded with diamond tip, it provides scalloped grooves, possibly due to stick-slip motion. The close-up SEM image of such groove is shown in Fig. 6. The triangular shape is characteristic of diamond tool tip.

Figure 7 shows a groove on Si substrate that is abraded with diamond tool head. The characteristic of triangular shape of the groove is clearly visible and build-up of material is not noticeable. Silicon substrates are abraded with diamond tool head by varying the applied force and hydraulic diameter of the grooves were measured to observe the effect of varied force. The graph in Fig. 8 shows the result. As the applied force increases, the hydraulic diameter of the groove increases roughly linearly in the range of interest.

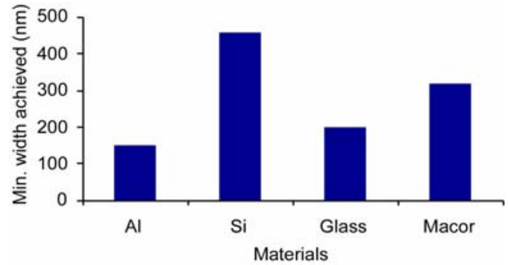

Fig. 5: Minimum width achieved for each substrate by using alumina grit tool.

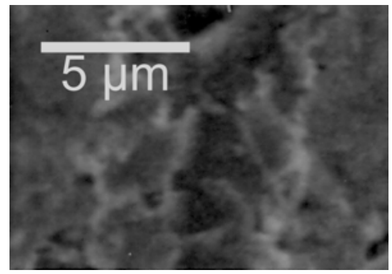

Fig. 6: SEM top view of a triangular groove in Macor^{TM} glass-mica ceramic.

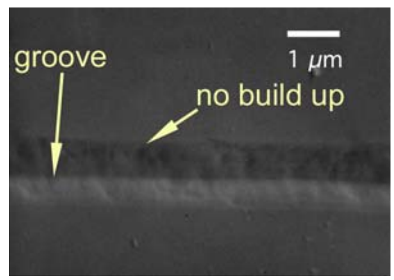

Fig. 7: SEM image of top view of single crystal Si abraded with diamond tool head.

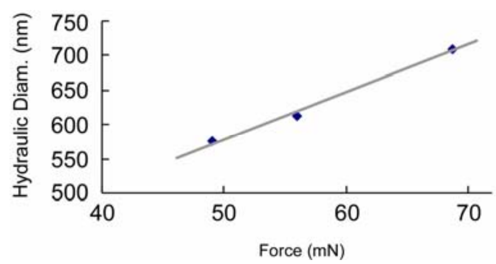

Fig. 8: Hydraulic diameter of Si grooves achieved by varying applied force using diamond tool.

In this set of experiments, it has been observed that for harder material like Si, when abraded, the grooves are clean and build-up is not present. An aluminum layer, being a soft material, is easily abraded and yields smallest width but tends to build-up the material along the edges, which makes the use of Al material unattractive. However, hardness can not always predict achievable minimum width, considering that minimum width obtained for glass is smaller than that for Macor. Roundness of the groove is another factor that is not easy to predict.

IV. APPLICATION TO MICROFLUIDIC CHANNEL FABRICATION

A number of applications call for nano-structured surfaces or channels with sub-micron hydraulic diameter. For example, electro-osmotic pumping favors hydraulic diameter less than 1 μm (depending upon the liquid) because high hydraulic resistance reduces the dominance of unwanted pressure-driven flow [12]. This study on controlled abrasion can be applied to create sub-micron size microfluidic channels. By referring the results in Fig. 8, it is possible to control the channel dimension with corresponding force. We have fabricated a simple microfluidic device using abrasive method, and the process flow is depicted in Fig. 9. First, an SiO_2-Si_3N_4-SiO_2 insulating layer is deposited on silicon wafer by LPCVD method. The top layer is abraded with a diamond abrasion tool. A separate glass wafer is patterned and etched to serve as reservoirs. Then the two substrates are aligned so that small sub-micron channels are connecting the two larger channels and reservoirs in glass, then they are anodically bonded together. After bonding, silicon is dissolved in KOH etch solution leaving insulating layer. Then one can gain access to the reservoir by puncturing holes through the insulating layer.

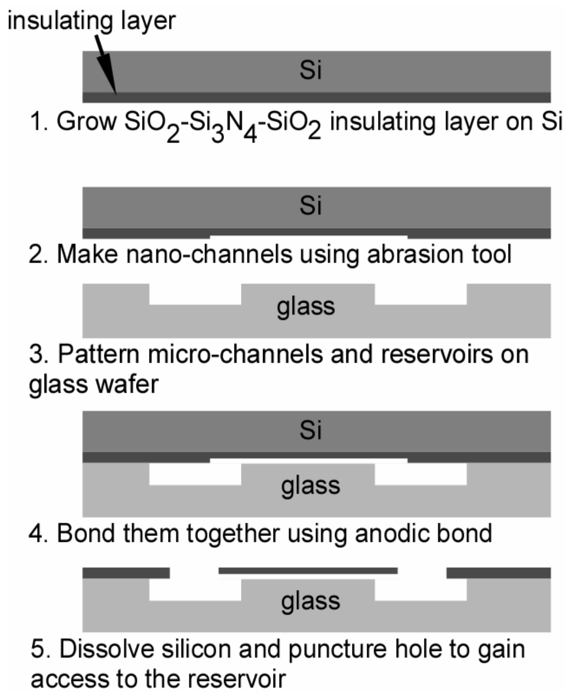

Fig. 9: Process flow diagram for applying the abrasion method for non-lithographic fabrication of channels of sub-micron hydraulic diameter combined with conventionally micro-machined features.

A cross-sectional SEM image of a sealed channel after bonding is shown in Fig. 10. Here, the hydraulic diameter of the channel is 610 nm.

The top view of fabricated device is shown in Fig. 11. Larger micro-channels and reservoirs patterned on glass is on top, and magnified view of micro to nano transition regions is shown at the bottom.

Nano-channels created in this manner pose great advantage in manufacturing cost compared with channels created with advanced lithography such as e-beam or focused ion beam machining. Optical transparency and hydrophilic property of the channel can serve as added benefits in many chemical or biochemical analysis methods.

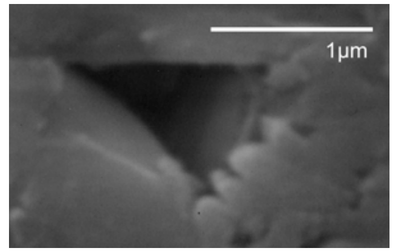

Fig. 10: Cross-sectional SEM image of a sealed channel fabricated as described in Fig. 9.

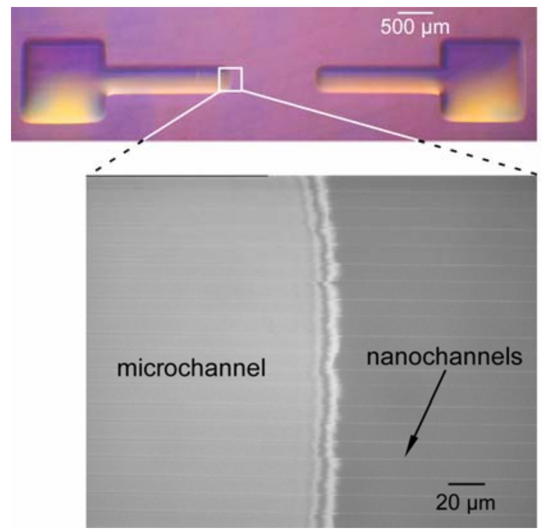

Fig. 11: Top view of the fabricated device.

V. CONCLUSIONS

In this paper, we have explored the nano-scale abrasion characteristics of four materials: Al, Si, Pyrex™ glass, and glass-mica ceramic (Macor™), using two abrasion heads: a diamond tip and a custom alumina-grit head. Minimum width of 150 nm, 460 nm, 200 nm, and 320 nm was achieved for Al, Si, Pyrex glass, and Macor, respectively. With a diamond tool head, increasing hydraulic diameter proportional to the applied force was observed. This result can be applied to control hydraulic diameter when creating sub-micron channels. This potential application has been demonstrated by the fabrication a microfluidic device which contains nanochannels created using abrasion method. Not only is this method suitable for low-cost prototyping of ultra-narrow channels, for some materials such as ceramics, controlled abrasion may be a better alternative than weto or dry chemical etching.

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