

PAPER D

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of MEMS Structures**

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Polishing of Bulk Micro-Machined Substrates by Fixed Abrasive Pads for Smoothing and Planarization of MEMS Structures

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Abstract

In this work, an approach was made to use chemical mechanical polishing (CMP) by prototype fixed abrasive (FA) pads rather than conventional slurry based polishing for smoothing of bulk micro-machined and oxidized silicon wafers. A comparison is provided to conventional CMP, showing the minimization of edge rounding in case of FA use under the needed polishing step for sub-sequent wafer bonding. Simultaneously the achieved roughness provides a surface quality suitable for direct wafer bonding.

Keywords

CMP, MEMS, Fixed Abrasive, bonding, SOI

INTRODUCTION

Chemical Mechanical Polishing (CMP) has been proving to be the enabling process for state-of-the-art integrated circuit (IC) manufacturing up to the current 300mm technology [1]. While structures are getting ever-smaller [2], the process control has been able to follow the demands of each technology node [3]. Intentionally developed for oxide planarization [4], CMP is used nowadays widely for shallow trench isolation (STI) [5,6], enabling smallest features of today's IC circuitry, for example by use of high selectivity slurries (HSS-STI) [7]. In addition, CMP has entered the metal polishing area by damascene or dual damascene processing of multi metal layer metallization including copper and low-k dielectrics [8].

The benefits of CMP are however not yet widely used in micro electrical mechanical systems (MEMS) as obverse demands are requested [9]. While IC structures are getting smaller, in MEMS area often several micron big structures face the need of not only planarization [9] but also surface smoothing for subsequent bonding processes [10]. Besides oxide and metal, other materials including bulk micro-machined silicon have to be polished. The big structures of highly accurate deep patterning are however object to rounding, when applying the available conventional polishing processes [11]. Standard CMP intends to lead to a

smooth surface, however with non-effective planarization of the big pattern surface, when not aiming for its total removal. Therefore, limits are set by the conventional technology for manufacturing of engineered substrates, such as buried cavity silicon on insulator (SOI) wafers or capped structured silicon wafers.

With fixed abrasive (FA) technology from 3M a new and alternative way of CMP has been introduced recently. Due to its different nature, which is to be explained later, not only the already proven benefits in the IC area of minimized dishing and erosion are expected. Also for the polishing of patterned bulk micro-machined silicon and oxide structures in the MEMS technology this new technique should yield in advantageous results.

EXPERIMENTAL

Avert to the conventional CMP polishing with micro-porous polishing pad and particle containing polishing agent, the so-called slurry, the abrading particles of the polishing process in fixed abrasive pads are residing inside of resin-type posts, which are fixed on the polishing pad (See Figure 1).

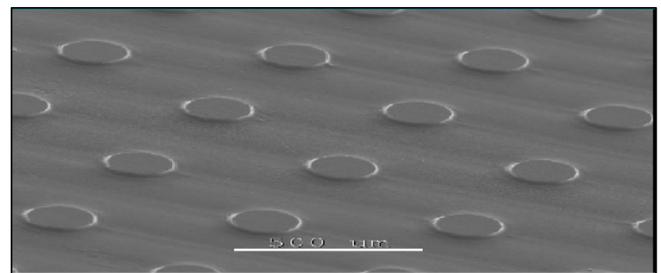


Figure 1 SEM picture of a fixed abrasive pad from 3M. The round shaped posts have a height of around 50 μm and contain the abrasive particles.

Below the micro-replicated layer, a rigid pad and a more resilient pad are stacked in order to adjust for the right mechanical properties of the process like in conventional

CMP. Instead of slurry, a lubrication liquid is provided under polishing, containing mainly water and chemistry to adjust for the appropriate pH-value. Figure 2 shows the schematic of the FA process.

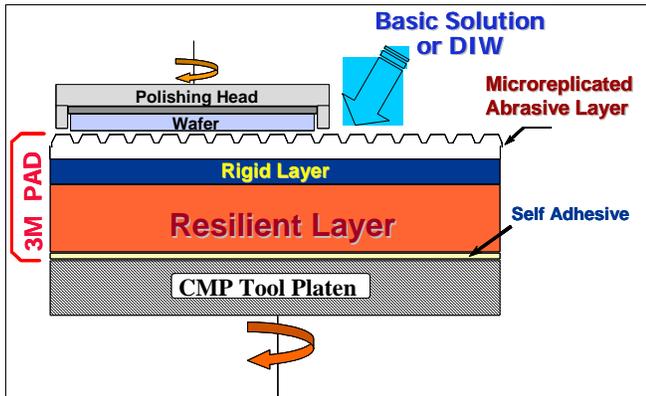


Figure 2. Schematic of the fixed abrasive polishing process.

It is evident, that the abrading particles of the FA process being fixed to the posts have less degree of freedom and thus face mainly the elevated areas of to be polished surface, while the deeper laying fields remain almost untouched. This makes the polishing process a two-body system (Figure 4), while conventional CMP occurs in a three-body system (Figure 3). Here the particles are free to move to all areas of the wafer. Even deeper laying areas are thus attacked by the process, however less than the elevated ones.

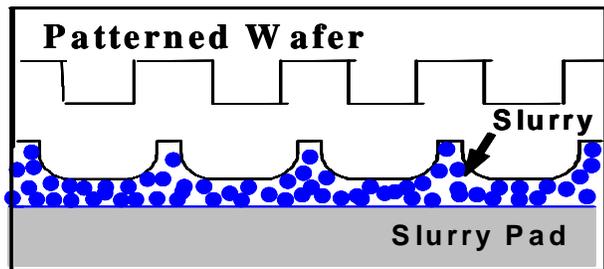


Figure 3 Conventional slurry CMP as 3-body system [12].

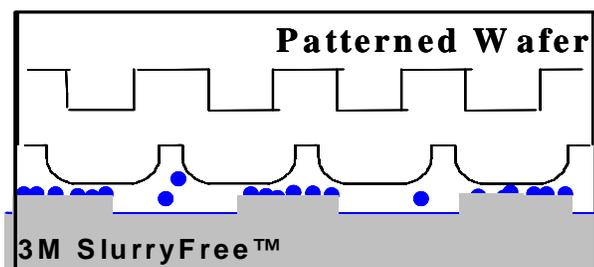


Figure 4 The fixed abrasive CMP from 3M as 2-body system [12].

The aimed planarization occurs therefore slower and under abrasion of material in all areas of the wafer. The process is less effective and sharp corners will round, as the pad can enclose them.

In practice, the fixed abrasive polishing should result in a more effective planarization of the structures and less attack in the lower areas. In addition, another point of interest is to be mentioned; freestanding structures should face less rounding when FA CMP is applied, as the microreplicated area of the fixed abrasive pad cannot surround the features as a conventional pad (See Figure 5).

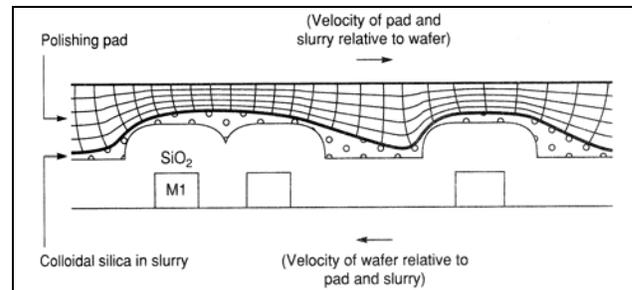


Figure 5. Schematic of conventional CMP. The pad surrounds the pattern features. Highest local pressure at the edges leads to especially high removal and rounds the structure under process [13].

METHODS

Experiments were performed on 4" and 6" standard silicon wafers with bulk micro-machined silicon and oxide pattern respectively. Plasma enhanced chemical vapor deposition (PECVD) was used to deposit films of 1.5 μm to 3 μm thickness. Polishing was done on a Strasbaugh 6DS-SP two-platen polisher. Prototype fixed abrasive pads from 3M were used as well as conventional soft polishing pads with commercially available slurries. Processing was performed based on earlier gained experience and processing time was adjusted to minimum required removal in both cases the conventional and the FA CMP steps to maintain the pattern in original shape as best as possible. This in turn resulted in polishing times in between 60 and 120s and total average removal of in between 70 and 100 nm. Oxide film thickness was measured with Nanoscope 2150, for surface roughness measurements, an atomic force microscope (AFM) from Digital Instruments was used. Step heights and structure geometry was measured by DEKTAK V200.

RESULTS

The designed CMP processes in this investigation are made for smoothing either bulk micro-machined silicon or deposited oxide films in order to enable further processing like direct bonding, which requires a certain level of roughness. Same time the process should be able to remove global height differences of the features, while not changing the features geometry as such. In the first part of the experi-

ment, surface roughness was investigated after polishing while in the second part of the investigation emphasis was put on the pattern geometry after CMP.

Roughness

In Figure 6 the AFM scan of as-deposited PECVD-oxide can be seen. The rms value for the 3 μm thick oxide film is almost 5 nm and a grainy structure is visible. This surface as such is not suitable for direct wafer bonding.

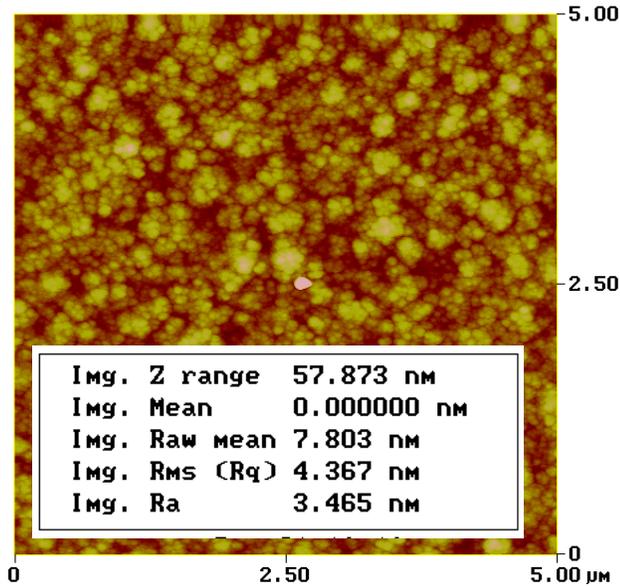


Figure 6. As-deposited PECVD-oxide of 3 μm thickness. The surface has a grainy structure and appears rough.

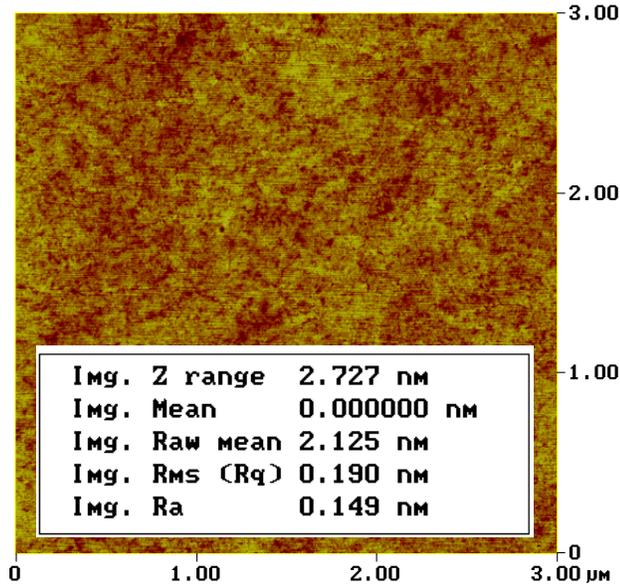


Figure 7. The PECVD-oxide after two minutes of polishing by conventional CMP. The roughness is reduced to Ångström level.

After polishing the film for 120s by conventional CMP, the roughness reduced down to below 2 Å at a 3 μm x 3 μm scan (Figure 7). The total removal was found to be around 100 nm. It has been proven at VTT, that this level of roughness is already able to be bond directly to silicon with low temperature bonding process.

Applying fixed abrasive polishing to as-deposited oxide yield in almost similar result, as can be seen from Figure 8. After 80s polishing time the rms roughness reduces to comparable values of below 3 Å at a 5 μm x 5 μm scan. This is very close to the result of conventional CMP and thus surface quality is at direct bondable level. Also in this case the grainy structure of the deposition process is vanished. Instead, a slightly wiped surface appears which could result from the regular polishing pad features of the micro-replicated layer. However, it is of no bigger concern since the height differences are in the sub-nm area.

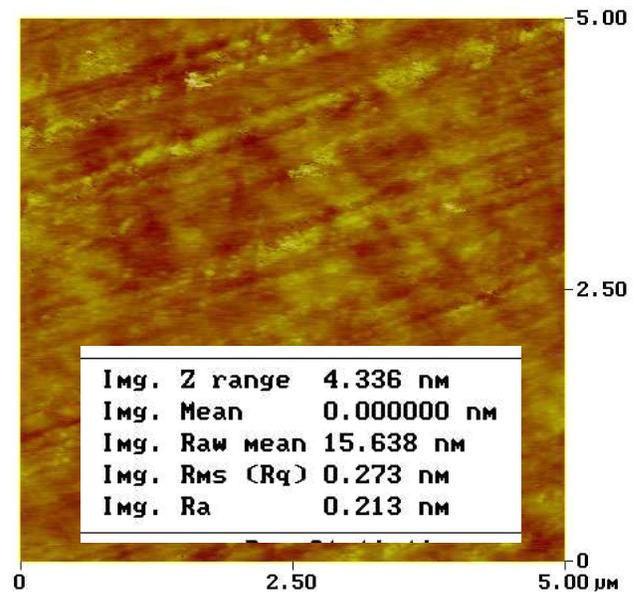


Figure 8. PECVD-oxide after fixed abrasive polishing. The surface is similar smooth as in the case of conventional CMP.

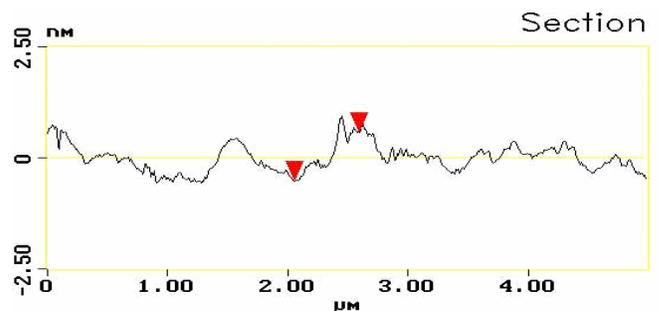


Figure 9. Cross-sectional view of the PECVD-oxide after fixed abrasive polishing. All remaining roughness or structure is at sub-nm area.

Taking a cross section of the AFM scan, one can observe the absolute height differences more distinct (Figure 9) The surface irregularity is within one nanometer and no abrupt height difference is measured, which could lead to voids or unsuccessful bonding.

Pattern Geometry

In terms of roughness, the difference between conventional and fixed abrasive CMP is seen to be small. The FA CMP reaches almost same performance as conventional polishing and can serve as enabling process for direct wafer bonding. The second important issue is to investigate the structure's geometry under the different polishing approaches. The conventional processing does round the features and reduces their width under a polishing time of 120s as can be seen from Figures 10 and 11. This was expected already.

While the removal on top of the structures is already almost 300 nm, Figure 10 shows in addition that dishing occurred in between the pillars at a level of almost 100nm. The total removal on top the structures however is much higher, than in the lower fields, indicating the beginning planarization.

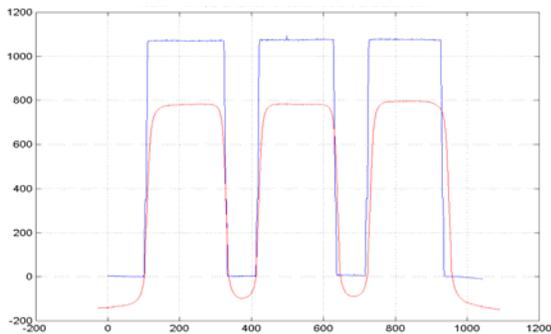


Figure 10 Oxide pattern before and after conventional CMP.

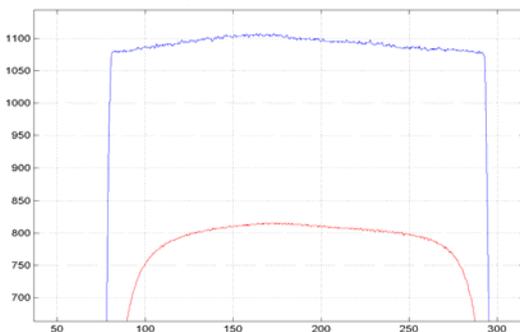


Figure 11 Detail of the oxide pattern before and after conventional CMP. Not only the corners are rounded, but also the feature width is noticeable reduced.

Another set of structures was used to compare directly the behavior of conventional and FA CMP. The total removal was set to be around 100nm in both cases for comparable results. Figures 12 and 13 show the structure before and

after conventional CMP. Also here rounding is visible at the top of the features. However, due to further process development, the overall behavior is much better, than in the first approaches. By limiting the polishing time and reducing the downforce, the total removal was reduced to around 80nm. However, rounding could not be avoided totally.

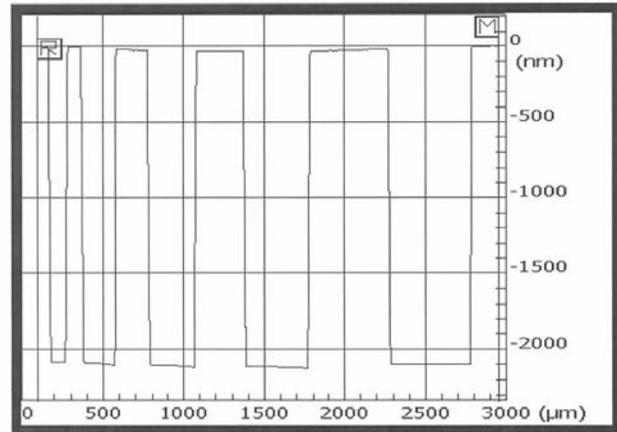


Figure 12 Oxide structure before CMP.

While the top is still facing the rounding, no major dishing occurs at the lower field of the pattern (Figure 13).

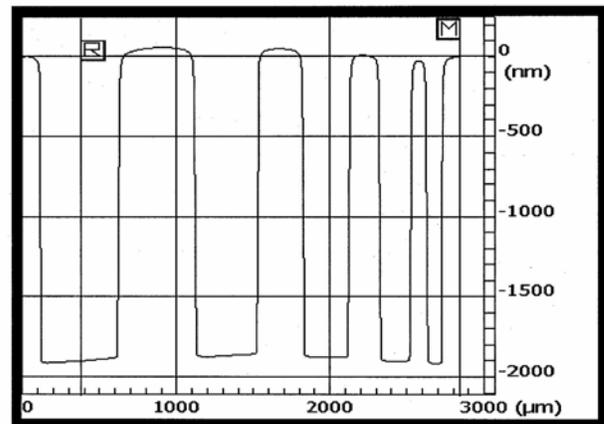


Figure 13 Oxide structure after further developed conventional CMP step. Rounding is still visible at the top but no dishing is seen at the bottom of the structure.

When comparing the details of the pattern when being polished by conventional CMP (Figure 14) and fixed abrasive CMP (Figure 15) the advantage of the new approach becomes evident.

In case of slurry-based CMP the rounding of the pattern top continues almost 20 μm deep into the structure and the slope becomes shallower. The overall pattern widens significantly. When using the FA pad, no rounding is seen in

the detailed picture and the slope remains steeper. Thus, the original shape of the structure is conserved under the advanced CMP process.

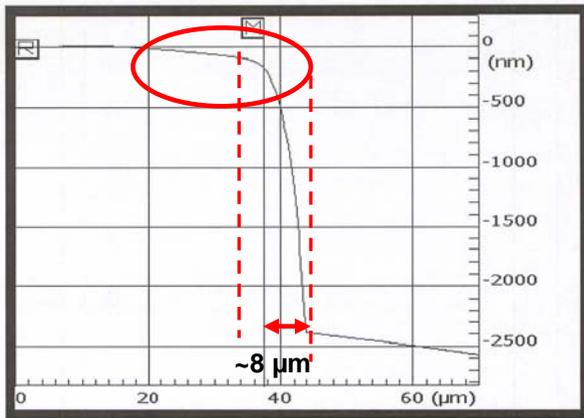


Figure 14 Oxide structure after further developed conventional CMP step at the corner. The rounding of the edge is continuing almost 20 μm into the structure.

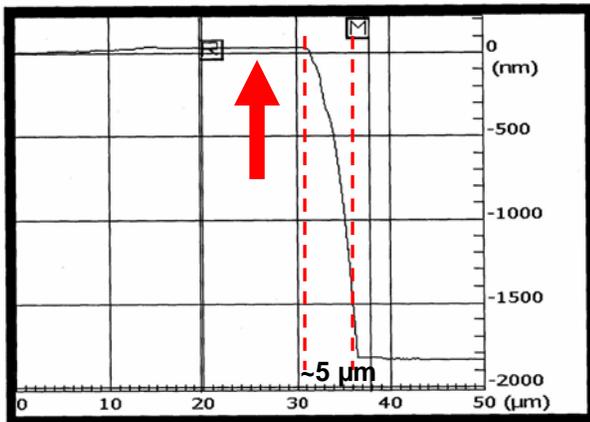


Figure 15 The FA CMP step leaves the corner of the structure untouched. Also the overall slope remains.

The pattern geometry conservation is evidently much better with FA CMP, than with conventional polishing approach. Final confidence in the new process can be gained, when applying the polished samples to the critical direct bonding process.

Bonding

Figure 16 shows an example of the successful direct bonding. At wafer level, no bigger voids were found and the process resulted in a well-connected wafer couple. This indicates that the reached surface roughness is well suiting the needs of direct wafer bonding. In the detailed analysis of the capped pattern by SEM it can be seen, that the bonding occurs well to the edge of the structure due to the conserved geometry under fixed abrasive polishing.

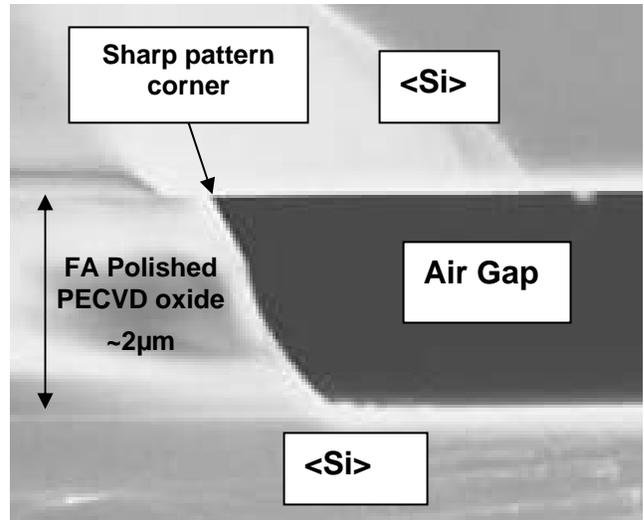


Figure 16 Bonded section of the fixed abrasive polished wafer.

CONCLUSION

The alternative technology of fixed abrasive CMP has been introduced to the area of MEMS manufacturing. The resulting surface roughness is at slurry-based level and enables the critical direct wafer bonding without any additional polishing step. Furthermore, the obstacles of conventional CMP in MEMS processing -the typical rounding of the pattern- can be overcome by FA polishing. The original shape of the pattern can be maintained and CMP can be used, even when structure dimensions are critical. This in turn will enable the capping of bulk micro-machined structures by low temperature bonding processes and the use of bigger variety of materials like PECVD oxides. Further investigation shall stabilize the method and will offer new ways of manufacturing future advanced MEMS design.

ACKNOWLEDGMENTS

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BIOGRAPHY

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