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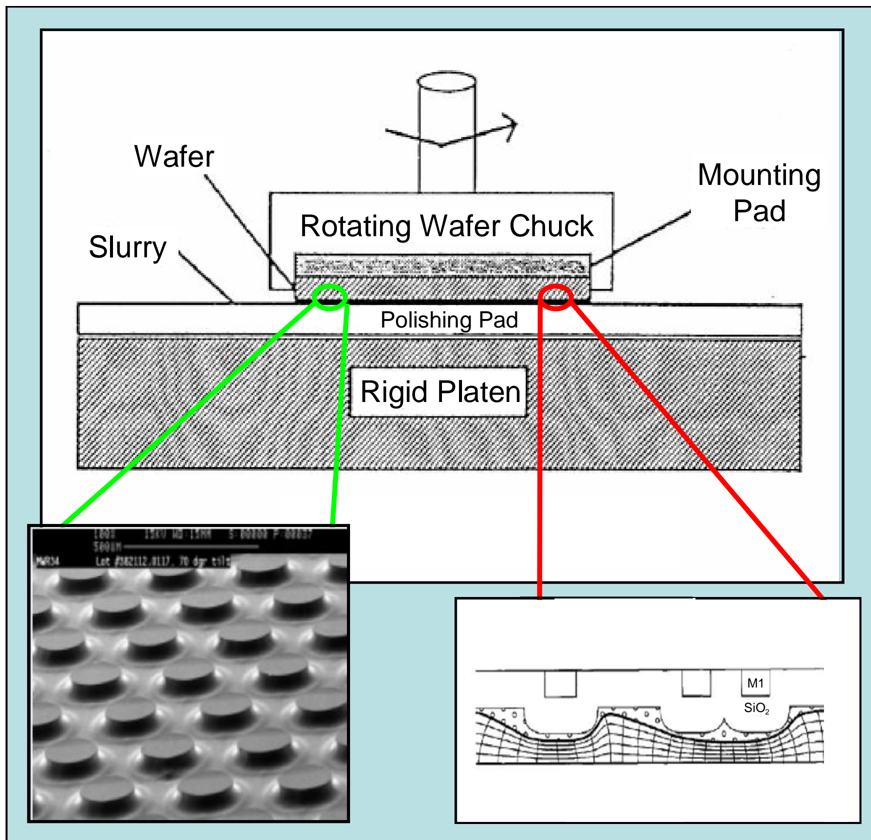

Martin Kulawski

Advanced CMP Processes for Special Substrates and for Device Manufacturing in MEMS Applications

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Advanced CMP Processes for Special Substrates and for Device Manufacturing in MEMS Applications

Martin Kulawski
VTT

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Abstract

The present work reports on studies and process developments to utilize the chemical mechanical planarization (CMP) technology in the field of micro electrical mechanical systems (MEMS). Approaches have been undertaken to enable the manufacturing of thick film SOI (silicon-on-insulator) substrates with a high degree of flatness as well as utilizing CMP for the formation of several novel MEMS devices.

Thick film SOI wafers are of high interest in MEMS manufacturing as they offer obvious benefits as a starting material or foundation for more complex structures. Precise control of the SOI layer thickness as well as the removal uniformity is of critical importance to fully utilize the benefits of this technology. By combining fixed abrasive (FA) pads for polishing and novel grinding techniques it is shown that major improvements can be achieved over the standard manufacturing sequence. Analysis of the material removal rate (MRR) dependency on several process parameters is made. Together with the FA pad vendor a suitable consumable set for SOI is generated, which shows long term stability in the generated process. A comparison with standard methods is undertaken to prove the surface and crystalline quality of the resulting substrate material is equivalent. Analysis is done to understand the microscopic mechanism of removal.

The CMP process is applied to several MEMS structures to smooth deposited oxide films and to enable direct wafer bonding (DWB) at low temperatures. This allows the design of bonded multiple stack layers including heat sensitive materials such as metals.

FA CMP is applied to large pattern MEMS for total planarization but also for smoothing of the surface of single protruding structures while minimizing edge rounding and preserving the original intended pattern shape. With dedicated CMP steps thick film polysilicon smoothing is demonstrated enabling DWB. The chemo-mechanical particularities of the FA pad are investigated in detail.

Preface

It is about 10 years ago, that I was exposed to the newly introduced CMP Technology. As a student I developed first polishing processes at the Fraunhofer Institute for Silicon technology ISiT in Itzehoe, Germany.

The Technology was rather unknown in Europe at that time and only a few people were actively working on CMP in Germany. A lot of development has happen since then. I kept involved with CMP from that time on and was able to follow the rapid evolution of this process and its aggressive introduction into more and more areas of the IC production.

With my re-entry into the world of research and development I was able to contribute myself to the amazing success story of one of the youngest and most widely growing processes. Being exposed to the world of MEMS and responsible to establish the CMP technology at VTT it was a logic consequence to introduce the convenient polishing technology to micromechanical devices.

By connecting the experience of earlier work and having the great opportunity to work together with world leading companies like Okmetic, VTI, 3M and Strasbaugh it was possible to create in short time and with limited amount of work force a new technology platform for the future demands of the growing MEMS world. Finally I have been able to result my experimental work with this dissertation summing up about 3 years of exciting research and development.

Martin Kulawski, Espoo, July 2006

List of Publications

This work is based on the following publications, which are referred to in the text by their alphabetic numerals. Furthermore, unpublished results and results of other own publications [Ref. 74, 78] are included in the text to provide the reader with a most comprehensive view of the status of the overall research.

Paper A: M. Kulawski, K. Henttinen, I. Suni, F. Weimar, J. Mäkinen; *A novel CMP Process on Fixed Abrasive pads for the Manufacturing of highly planar thick film SOI Substrates;* Mat. Res. Soc. Proc. **767**, (2003), pp. 133–139.

Paper B: M. Kulawski, H. Luoto, K. Henttinen, I. Suni, F. Weimar, J. Mäkinen; *Advances in the CMP Process on Fixed Abrasive Pads for the Polishing of SOI-Substrates with High Degree of Flatness;* Mat. Res. Soc. Proc. **816**, (2004), pp. 191–196.

Paper C: M. Kulawski, H. Luoto, T. Suni, F. Weimar, J. Mäkinen; *Integration of CMP Fixed Abrasive polishing into the Manufacturing of Thick film SOI Substrates;* Mat. Res. Soc. Proc. **867**, (2005), pp. 111–116.

Paper D: M. Kulawski, H. Luoto, K. Henttinen, T. Suni, F. Weimar, J. Mäkinen; *Polishing of Bulk Micro-Machined Substrates by Fixed Abrasive Pads for Smoothing and Planarization of MEMS Structures;* Proc. IEEE/SEMI Advanced Semiconductors Manufacturing Conference, Munich 2005.

Paper E: J. Molarius, M. Kulawski, T. Pensala, M. Ylilammi; *New Approach to Improve the Piezoelectric Quality of ZnO Resonator Devices by Chemomechanical Polishing;* The Nano-Micro Interface: Bringing the Micro and Nano Worlds Together; Ed. H. J. Fecht, M. Werner; Wiley-VCH Weinheim 2004; ISBN: 3-527-30978-0.

Paper F: H. Luoto, T. Suni, M. Kulawski, K. Henttinen, H. Kattelus; *Low-temperature bonding of thick-film polysilicon for MEMS;* Journal of Microsystems Technology, Vol. 12, No. 5, pp. 401–405, (2006).

Author’s Contribution

The author Martin Kulawski is the sole writer of the Papers A to D. All direct CMP related experiments, design and analysis were made by the author in the Papers A and B. All design and almost all CMP related experiments and analysis were made by the author contributing to the Papers C and D. Supervising and all of the experimental design concerning CMP as well as the related polishing experiments and their analysis was provided by the author to accomplish the Paper E. Writing was contributed to Paper E relating to CMP and its conclusions. Part of the writing and contribution to the experiments and their design as well as a good portion of the results’ analysis was contributed to Paper F.

Additionally, related results of the Papers A to F and further results of the recent research has been presented by the author at the Semi MEMS Forum in Munich, Germany in 2005, and several CMP User Group Meetings of the VDE in Germany during 2001 trough 2005 as well as the American Vacuum Society’s CMP User Group in Santa Clara, CA in 2005 and the Nordic Semiconductor Meeting in 2005 in Oslo, Norway. The author was invited lecturer at the one-day short course for CMP manufacturing in conjunction with the CMP-MIC 2006 in Fremont CA, as well as invited speaker at the 6th Spring Meeting of the ISE in Singapore in 2006.

Contents

Abstract ... 3

Preface ... 5

List of Publications ... 6

Author's Contribution ... 8

List of Acronyms and Symbols ... 11

1. Introduction ... 14
   - 1.1 History and Background of CMP ... 14
   - 1.2 Scope and Objectives of the Thesis ... 17
   - 1.3 Facilities, Equipment, Methods and Material ... 18
   - 1.4 Summary of the Papers ... 19

2. CMP Technology ... 21
   - 2.1 The CMP Process ... 21
   - 2.2 Oxide CMP ... 24
   - 2.3 Silicon CMP ... 26
   - 2.4 Characteristics of Conventional CMP ... 27
   - 2.5 Characteristics and Technology of Fixed Abrasive Pads ... 33

3. Formation of Thick-Film SOI Substrates ... 38
   - 3.1 The Thick-Film SOI Manufacturing Sequence ... 38
   - 3.2 The Sub-Surface Damage Layer ... 40
   - 3.3 Uniformity of Silicon CMP ... 42
   - 3.4 Surface Quality of CMP ... 50
   - 3.5 Stability of the New Sequence ... 53

4. CMP of MEMS Structures 57
4.1 Surface Smoothing and Planarization 57
4.2 Pattern Conservation 63
4.3 CMP of Polysilicon Films 66

5. Conclusions 69

Acknowledgements 70

References 73

Appendices
Papers A–F

List of Acronyms and Symbols

AFM	Atomic force microscopy
BAW	Bulk acoustic waves
BEOL	Back end of the line; meaning the metallization layer formation on wafer level of IC circuitry after the transistors are ready
BOX	Buried oxide
C	Capacitance
CMOS	Complementary metal oxide silicon field effect transistor technology
CMP	Chemical mechanical planarization
COF	Coefficient of friction
CVD	Chemical vapour deposition
die	Short for one microchip on the wafer during production
DIW	De-ionized Water
DOF	Depth of focus
DSP	Double side polished (Wafers)
DWB	Direct wafer bonding
FA	Fixed abrasive
FBAR	Film bulk acoustic resonators
FEOL	Front end of the line, describing the part of the wafer fab in which the transistors are formed
FTIR	Fourier transform infrared spectroscopy
HSS-Slurry	High selectivity slurry (selective between oxide and nitride for STI processing)
IC	Integrated circuits
ILD, IMD	Inter-layer dielectric, Inter-metal dielectric
IM	Integrated metrology

ITRS	International technology roadmap society
K_P	Preston coefficient
LOCOS	Local oxidation of silicon; older isolation/separation technology
Low-k	Describing dielectric materials with lower dielectric constant than silicon dioxide
LT bonding	Low temperature bonding technique
MEMS	Micro electrical mechanical systems
MOEMS	Micro opto electrical mechanical systems
MRR	Material removal rate
NU	Non-uniformity
OISF	Oxide induced stacking faults
P	Down pressure
PECVD	Plasma enhanced chemical vapour deposition
Q-factor	Quality factor for resonators, filters and oscillators describing energy losses
R	Resistance
RC-delay	Delay created by resistance of conductors and parasitic capacitances inside of a fast microchip
rf	Radio frequency
rf-MEMS	Radio frequency micro electrical mechanical systems
rms	Root mean square (averaging factor)
SAM	Scanning acoustic microscope
SAW	Surface acoustic waves
SEM	Scanning electron microscope
SOG	Spin-on-glass
SOI	Silicon on insulator
SSD	Sub-surface damage

SSP	Single side polished (Wafers)
STI	Shallow trench isolation; current isolation /separation technique
SW-tool	Software-tool, program
TTV	Total thickness variation
v	Velocity
WIWNU	Within wafer non uniformity
WTWNU	Wafer to wafer non uniformity

1. Introduction

1.1 History and Background of CMP

Using polishing materials in order to achieve a smooth and planar surface is a very old method. It was recognized early that the right type of liquid combined with an abrading substance would result in faster removal of material and often provide better surface finish, while each component on its own would maybe have very little or even no effect. In the long run, a huge variety of different combinations of abrasive and chemistry were found to polish almost any material and surface to the desired level. The ancient concept of polishing was the basis for the actual chemical mechanical polishing or chemical mechanical planarization (CMP), which is used in the semiconductor industry today. Either an abrasive particle can remove atomic clusters with the support of chemical active species or, vice versa an abrasive particle mechanically weakens the chemical bond of a crystalline network, enhancing the chemical dissolution during the polishing procedure.

As industrial manufacturing was developing, ever higher accuracy and planarity of surfaces were needed. As early as 1927 Preston made his first attempt to calculate the achievable removal rate of glass, based on the process parameters of the polishing procedure [1]. Glass plate polishing achieved a certain level of quality, but more science was required to further improve the results and to gain better predictions of the outcome of a complicated and uninterruptible procedure. Lessons learned during these investigations were also used to influence the design of new polishing tools.

From these humble beginnings, CMP has evolved to become one of the fastest growing and most important processes used in the IC industry [2] today. Over the past fifteen years the IC industry has further developed the CMP process technology. One of the latest examples is the upgrade of the tool sets with integrated (in-situ) measurement (IM) techniques. CMP is now considered to be ***the*** enabling process for the current technology [3] and it is expected to also guide the chip makers further [4] along Moore's law [5].

In 1961 R. J. Walsh adopted the idea of Monsanto Company to use colloidal silica rather than conventional abrasives for improving the results on raw silicon wafer polishing. The patent over the new wax-less polishing apparatus for thin wafers was issued in 1974 [6]. Together with alkaline chemistry the use of silica particles resulted in very flat and smooth surfaces. Furthermore, a significant reduction in process time was gained, because of well increased removal rates.

CMP was further improved by the efforts of IBM at the end of the 70's and in the early 80's [7, 8]. As the device density was growing under continues down scaling, more than one connecting metallization layer was required. This in turn led to an increased topography which resulted in poor step coverage at the secondary and following metallization layers. Established planarization techniques such as SOG (Spin on glass) were no longer able to provide sufficient flatness. Surface topography became a major issue due to limited depth of focus (DOF) associated with lithography processes. Yield and long term stability were the new issues, so that a more global planarization of the intermetal dielectric (IMD) layers became necessary [9]. By increasing the thickness of each single IMD and planarizing the oxide by CMP prior to next metallization topography was reduced and multiple layers of wiring became possible without suffering from yield problems due to the above mentioned problems.

With further increases in transistor density the LOCOS process (local oxidation of silicon) for transistor isolation, used successfully up to that point, was no longer feasible as it consumed a comparably large amount of chip area (die). Shallow trench isolation technology, STI for short, was developed during the eighties [10, 11]. Also here CMP played the key role as the enabling technology for precise removal of the excess oxide being filled in the pre-etched bulk silicon with accurate stop on top of the thin nitride mask. This marked also the transition of CMP from BEOL (back-end-of-the-line) into the FEOL (front-end-of-the-line) region in the IC (integrated circuit) processing.

Meanwhile CMP has also been introduced to the metallization process itself. The (dual-) damascene technique was developed to form plugs and connecting lines by pre-patterning of the IMD, overfill and CMP for excess metal removal. This was done first with aluminium later with tungsten [12]. Also on device level the first contact formation using highly doped polysilicon was formed by

CMP damascene processing as well as e.g. the novel technique of deep trench capacitor formation [13].

With the increased speed of the IC circuitry the RC-delay (series resistor and parasitic capacitor causing notable switching delay of transistor circuits) had to be considered, which resulted in the implementation of low-k dielectrics and copper metallization [14]. Again, CMP enabled the new approach as no feasible etching process was available for copper so that damascene processing became the mandatory metallization sequence [15]. A lot of continuous research and development is required however, to keep pace with the ever decreasing line widths, which helps to keep CMP up-to-date for the future technology nodes established by the ITRS (International roadmap Society) road map [16].

Besides the conventional method of slurry-based polishing also novel approaches have been developed in order to improve the well known drawbacks of the CMP process. Abrasive free polishing of copper utilizes a well balanced chemistry as lubrication liquid and only the polishing pad acts as the mechanically abrading body for the controlled removal of copper [17]. Fixed abrasive (FA) pads contain the abrading particles embedded in micro-replicated features rather than free floating particles used in the dispensed slurry to gain better planarization results and to avoid the dishing and erosion of the pattern structure [18]. Modified movement by orbital or belt systems try to overcome the problems with non-uniformity of the classic rotary systems as well as using through the pad slurry feeding instead of central dispensing [19, 20].

Outside of the IC industry adjacent technologies have also recognized the apparent benefits of the CMP process. Providing unique possibilities of smoothing surfaces and planarizing patterns CMP is also interesting for the MEMS (Micro electrical mechanical systems) area, where constantly more sophisticated structures are developed. The materials, the scale and pattern densities required for the fabrication of MEMS devices will however necessitate additional process development work and cannot rely on the available processing techniques developed by the IC industry.

1.2 Scope and Objectives of the Thesis

The research work and publications contributing to this thesis are aiming at the improvement of the utilization potential of CMP in the area of MEMS technology and special substrate manufacturing. This is done by applying novel technologies and combining also the knowledge of both the standard silicon polishing and the IC manufacturing processes.

Advanced MEMS device formation often utilizes SOI (silicon on insulator) wafers instead of standard silicon substrates. As these wafers are often made according to the special needs of the latter products, they require individual oxide and device layer thicknesses, which usually can only be achieved by a more mechanical approach than the ion cutting method for the IC SOI-substrates. Grinding and polishing is used to form the device layer to the desired thickness level. This causes problems in terms of repeatability and uniformity with the classic silicon polishing techniques, as requirements in thickness control and uniformity of the SOI layer are often very high and ever increasing. The so-called pad-edge-effect prevents the optimum result and slurry-based silicon polishing requires a large amount of total removal in order to provide suitable surface quality, often at the cost of good flatness.

Therefore significant effort has been dedicated in this work to improve the flatness of thick-film SOI substrates by enabling the use of novel CMP methods and their development towards substrate manufacturing. The work also includes improvements in the preceding thinning process, surface grinding, as substantial benefits can be generated when approaching these two process steps concurrently.

A very practical approach for MEMS formation is the use of engineered substrates, were cavities or other structures are buried below the device layer prior to SOI formation. This process contains a lot of work in enabling the critical LT (Low temperature) bonding after processing the device wafer. CMP processes have been developed to ensure the successful bonding by providing a suitable planarity and surface roughness down to the sub-Å level. Within this development it was possible to utilize the processes also for smoothing and planarization of thick deposited polysilicon films, a novel approach in the functional substrate manufacturing.

Further efforts to improve surface roughness and topography were dedicated to multiple film stacks. The roughness of each single layer is cumulative to the top-level, but a smooth surface is required, e.g. for growth of highly texture dependent active films such as piezo materials or for enabling LT bonding. The maximum allowed removal is often very small and the thickness of the layers as well as the shape of the pattern has to be controlled very precisely because it defines optical and acoustical parameters of the completed device.

The key approach of this thesis was combining the science of IC CMP and silicon processing and introducing novel technologies like the fixed abrasive pads to bring the CMP process closer to the requirements of the MEMS technology. With this development structures beyond today's possibilities are enabled as well as individual substrates, which can be customized for their use and which provide superior uniformity and thickness control.

1.3 Facilities, Equipment, Methods and Material

This work was performed at Micronova, the microelectronic laboratory of VTT. It provides one of the largest clean room facilities available in Northern Europe along with state-of-the-art process equipment for grinding (Strasbaugh 7 AF), polishing (Strasbaugh 6DS-SP), post-CMP cleaning (Contrade Corwet 200) and bonding (Electronic Visions EV801). Furthermore all necessary equipment is available to perform both CMOS (Complementary metal oxide silicon field effect transistor technology) and MEMS manufacturing. VTT Micronova is involved in multiple national Finnish and international research programs as well as in small and medium scale production of different IC and MEMS devices. Furthermore it provides clean room and office space as well as rentable tool time and professional operating services for a group of start-up companies. IC compatible tool sets for CMOS manufacturing down to 0.4 µm are available as well as several processing units including grinding, CMP and post-CMP cleaning are compatible for up to 200 mm wafer size. The work contributing to this thesis however was mainly performed on 100 mm and 150 mm wafers as these are the typical wafer sizes being used for the current MEMS manufacturing.

The laboratory has available all major industrial standard analysis equipment as well as special research tools in-house, including AFM (atomic force microscopy), SAM (Scanning acoustic microscopy), SEM (Scanning electron microscopy), capacitive wafer thickness gage ("ADE"), profilometry ("DEKTAK") and several film thickness measurement tools including reflectometry and ellipsometry.

1.4 Summary of the Papers

Paper A reports the first time use of experimental FA pads for polishing silicon and also thick-film SOI substrates. Material removal rate (MRR) estimation and dependencies on various process parameters are discussed and the general mechanism of FA versus conventional slurry-based CMP is compared.

Paper B continues the research efforts by describing the further development of the process including base line studies and FA pad investigation under long term use. The effective grindline removal is discussed, connecting the FA process to the preceding grinding step for thick-film SOI wafer formation.

Paper C concludes the preceding Papers A and B with the development of a feasible industrial process sequence by use of low sub-surface damage (SSD) grinding and FA CMP. Further base line studies and crystal damage analysis corroborate the full compatibility of the sequence for reaching prime wafer surface quality on thick-film SOI wafers. Along with highly improved surface flatness and thickness control cut in half material removal enhances the throughput.

Paper D describes the chances and challenges of implementing CMP into MEMS processing. With the use of FA pads on patterned MEMS structures close to ideal results are presented, in terms of pattern conservation and surface roughness. The differences between FA and slurry-based CMP are explained.

Paper E describes the benefits for piezoelectric films grown on polished oxides for the formation of FBAR (Film bulk acoustic resonator) filters with high Q-values. Because of conventional CMP processing however, rounding of the acoustic mirrors occurs, which is one of the discussed items as well as the defects in the polished film after CMP, exposed by the wet-chemical cleaning.

Paper F presents CMP as enabling technology for smoothing thick polysilicon layers. By developing a customized process solution, low temperature (LT) bonding is enabled and successfully demonstrated. This in turn opens new capabilities in design and manufacturing of MEMS devices utilizing polysilicon.

2. CMP Technology

In this chapter the technology of chemical mechanical polishing will be briefly explained, mainly presenting the general mechanism and recent developments with emphasis on the fixed abrasive pad technology as it is widely used in the scope of this work. Profound discussion of the CMP process, its mechanics and chemistry can be found in many publications [e.g. 21]. To introduce the FA technology and to connect to the MEMS area the typical characteristics of conventional slurry-based CMP are discussed and related to the actual situation in micromechanical systems. Furthermore, especially the mechanism of removal in oxide and silicon polishing is presented as they have high relevance for this work.

2.1 The CMP Process

The general schematic of a CMP process is shown in Figure 1. The wafer to be polished is held upside down by the rotating carrier chuck. Its backside is protected from damage by a soft insert felt (mounting pad). Polishing occurs usually on a micro-porous cloth made from polyurethane, which is glue-mounted to the polishing table.

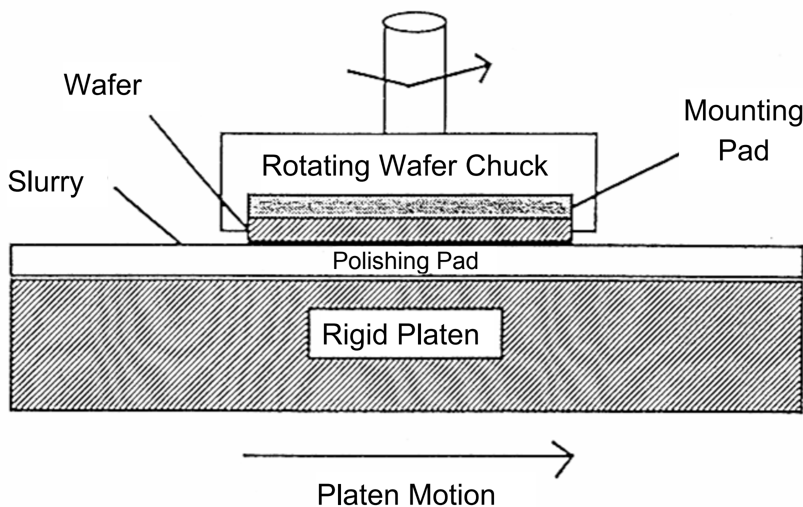


Figure 1. General Schematics of the CMP Process [22]

During processing the polishing liquid (slurry), containing abrasive particles and chemistry in aqueous dilution, is dispensed under particular dosing onto the pad. Rotational speed of the platen and chuck are as well controlled as are the applied downforce of the carrier on the platen and the processing time. Additionally, air back pressure can be present either in zones or at the entire backside of the wafer to enhance the overall uniformity control of the process. Often, the carrier oscillates laterally on the table to maximize the utilization of the polishing pad and to improve the slurry flow under the substrate.

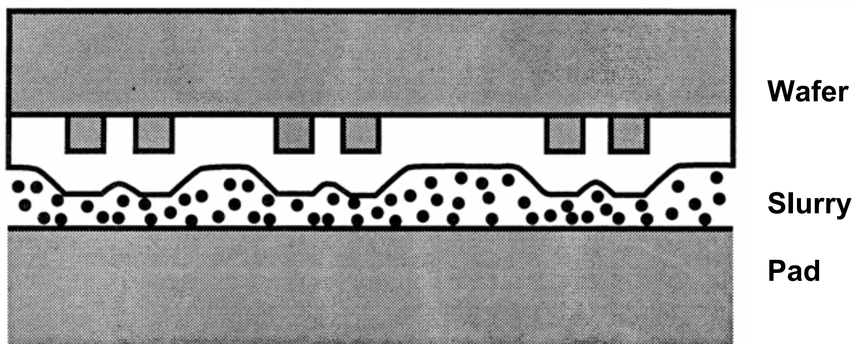


Figure 2. Schematic view of the Pad-Slurry-Wafer Interface [23]

Depending on the above mentioned macroscopic process parameters and other input variables like slurry flow, its viscosity and composition and especially its conjunction with the mechanical properties of the applied polishing pad, different regimes of polishing conditions are present at the pad-slurry-wafer system (Figure 2). The tribological conditions of the CMP process in this aspect have been studied extensively and a variety of modelling work has been done [24, 25, 26, 27, 28]. It is the concerted action of the microscopic asperities of the polishing pad with the nanoscale abrasive particles in the slurry, which defines the removal of material. Being either accelerated by the asperities and impinging the wafers' surface or being dragged between the asperity and wafer the particles act as the weakener of the surface layer or plough away the atomic clusters of the film. This in turn reflects to the material removal rate (MRR) and the created surface quality as well as the uniformity of removal.

Especially Phillipossian et al. have been able to gain fundamental understanding of these different contact modes by investigating the coefficient of friction (COF) directly with a special apparatus, thus enabling its in-situ measurement [29, 30, 33]. The COF is defined by the ratio of the shear force F_{shear} and the normal force F_{normal} being applied to a surface (Eq. 1).

$$COF = \frac{F_{shear}}{F_{normal}} \tag{1}$$

Different pads as well as slurry types have been investigated and the influence of the pattern structure has been included in their studies [31]. To visualize the findings in dependency of CMP-specific parameters the Sommerfeld number So is being introduced:

$$So = \frac{\mu U}{p \delta} \tag{2}$$

In the above equation μ is the slurry viscosity, U the relative pad velocity; p is the applied pressure and δ the effective fluid layer thickness between pad and wafer. The result can be plotted as a so-called Stribeck curve diagram, of which a general version is presented in Figure 3. Based upon the Sommerfeld number and the region of COF one can obtain the different regimes of lubrication, namely the hydrodynamic, partial and boundary lubrication area according to Ludema’s definition [32].

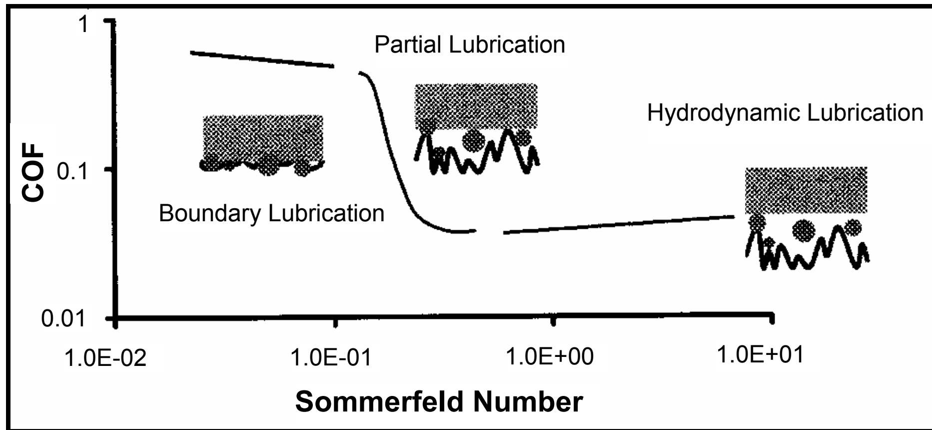


Figure 3. The Stribeck curve based on COF and Sommerfeld number with the indicated three different regimes of lubrication [33]

By this tribological investigation the COF has been re-connected to the Preston's coefficient K_P, (see Eq. (5), p. 25) included in the very first mathematical approach of describing the dependency of MRR to process parameters [1]. Depending on the lubrication regime, predictions can be made about how the polishing process performs in the respect of MRR, non-uniformity (NU) and planarization capability. This approach can be generally utilized in analysing any kind of CMP process based on conventional pads and slurries.

2.2 Oxide CMP

One of the most widely studied processes in the area of CMP is the polishing mechanism of silicon dioxide. Since the roots of this CMP steps are coming from the polishing of glass substrates, some fundamental understanding was available together with a lot of experience, when research started. The details of the studies can be found in [34]. The basic mechanism was adapted from glass polishing, where the softening effect of water as it penetrates into glass was reported already earlier [35]. Landis and Burke et al. developed this idea, when reporting about the integration of CMP into CMOS IC manufacturing in 1992 [36]. The general mechanism is described by the following reaction equation:

$$= \overline{\ } \mathrm{Si} - \mathrm{O} - \mathrm{Si} \overline{\ } + \mathrm{H_2O} \Leftrightarrow 2 - \mathrm{Si} - \mathrm{OH} + 2\,\mathrm{e}^{-} \quad (3)$$

Water penetrates into the oxide network breaking the Si-O bonds to form single Si-OH links. The hydration of the Si-O bond occurs especially near the surface and $Si(OH)_4$ (silanol) is formed:

$$(SiO_2)_X + 2H_2O \Leftrightarrow (SiO_2)_{X-1} + Si(OH)_4 \quad (4)$$

This in turn is soluble in water at elevated pH-values of about 10 and can be dissolved. The compressive stress caused by the presence of the abrasive particles enhances the reaction during the mechanical polishing action [37].

A further enhancement of this mechanism is provided by chemically active abrasive particles. Whereas silica was often used as a suitable abrasive for glass polishing, it was found that using ceria as abrading material the MRR increased drastically. Cook suggests this effect being due to the so-called chemical tooth effect of ceria abrasives. He presents a model giving raise to increased removal based on the gain of free energy during the formation process of ceria-based components under polishing [38].

In general oxide CMP has a very similar mechanism like glass polishing. Thus the MRR can be described by the input variables velocity (V) and downforce (P) in Prestonian type [1]:

$$MRR = K_P PV, \quad \mathrm{K}_P = \text{ the Preston coefficient} \quad (5)$$

This concept is widely used and based on Eq. (5) further and more detailed studies were undertaken to model the process more accurately. This led to more precise forms of Eq. (5) and to the elucidation of the content of the Preston coefficient. A good summary of the evolution of the Preston equation can be found in [39].

2.3 Silicon CMP

In the semiconductor area, the importance of silicon polishing has been growing since the very beginning. After formation of the raw wafers by crystal growth, slicing, lapping and etching, a suitable procedure was needed to improve the surface quality and to remove all remaining crystalline damage. Besides solutions with purely mechanical character, the use of the chemical mechanical concept was adopted quite early as mentioned in Chapter 1.1. Mendel suggested in 1967 the use of colloidal silica in alkaline solution on soft planar pads for the stock removal polish [40]. This has since been the usual approach for this step.

However, only few sources can be found, were the actual mechanism of removal has been discussed. Major work has been done by Pietsch et al. who also developed a model for the mechanism. It took him extensive analysis by IR (infra-red) spectroscopy to find a suitable approach for observing the changes, which are occurring at the silicon surface during polishing. Schnegg et al. had already suggested earlier, that the highly hydrophobic surface after polishing was due to hydrogen termination at the surface [41] and this was finally proved by Pietsch, when applying FTIR (Fourier transform infrared spectroscopy) analysis on Si(111) surfaces directly after polishing [42]. The work was then intensified and also Si(100) was investigated [43]. The results show a strong dependency on both the density of abrasive particles, which in this case were of silica type, and the pH-value of the applied polishing slurry. This in turn led to the conclusion that OH^- molecules are the instrument of the silicon etching process under CMP and that they are also consumed as buffering of hydroxides increased the MRR. The silica abrasives are necessary as transporters and transmitters in this process. Dependent on the pH-regime two different models were suggested. Highest removal rates were achieved at around pH 11. The silicon surface is highly hydrophobic and analysis indicated a predominant surface termination by silicon hydrates. An explanation for this scenario is the direct weakening of the Si-Si backbonds as a result of a strong polarization by the ambient OH^- molecules at exposed areas such as atomic steps or defects (subsurface oxide formation). Then ambient H_2O or O_2 dissolved in the slurry directly break the weakened bonds to form either monohydrates (see Eq. 6) or an internal oxide bridge (Eq. 7).

$$Si - Si + H_2O \Rightarrow Si - H + HO - Si \quad (6)$$

$$Si - Si + O \Rightarrow Si - O - Si \quad (7)$$

Dissolution by mechanical abrasion then occurs depending on the “mix” of neighbouring attacked bonds as monomeric, dimeric or trimeric silica as well as complete silanol. During the complete removal process the hydrogen termination of the attacked surface site stays intact, thus the surface is hydrophobic at all times.

Outside this pH-regime, at a much higher pH but also under acidic conditions, predominate surface termination is represented by direct silanol formation at the surface. The hydrogen is replaced by OH^- molecules as a first step. This in turn leads to a more hydrophilic surface. This now allows the ambient water or dissolved oxygen to enter the surface and the rest of the mechanism is, as described above by Eqs. (6) and (7), leading to the oligomeric dissolution of the silica species. Under the standard polishing conditions this slows down the removal as a quartz-like surface net-work has to be removed by mainly mechanical means of the CMP process as discussed in Chapter 2.2 [41, 44]. The particle concentration however, is usually much lower in silicon processing than it is in standard oxide CMP and therefore this regime is inferior to silicon CMP.

2.4 Characteristics of Conventional CMP

The general aim in using CMP is to remove excess material or to planarize surface films. In case of planarization the mechanism is based on the fact, that elevated structures of a pattern face a locally increased polishing pressure over the lower laying areas of the wafer. Due to the Prestonian dependency described earlier by Eq. (5) the removal rate is higher in those up areas and planarization occurs [45]. Slurry based CMP with polishing pads of different kind show particular characteristics in this respect. Due to those characteristics the process engineers face several challenges concerning the planarization capabilities and uniformity of the process. It is evident, that for aiming at the best possible surface smoothness a softer pad and less chemically aggressive slurry should be used. As optimum planarization is required a hard pad should be considered in order to maximize the removal at the elevated pattern features. For the overall

wafer uniformity of removal however, a soft pad would yield best results. The usual compromise for this conflict is often to use a stacked pad for planarization issues with a hard pad on top performing the planarization and with a soft underlying pad to even out and level the wafer during the process. This however leads to NU, especially at the wafer edge.

Another aspect of the planarization evolution is that it is strongly dependent on the pattern width, its density and the total amount of material removal. To describe the efficiency of the planarization process it is therefore convenient to introduce the step height reduction SHR:

$$SHR = \frac{step\ height_{before\ CMP} - step\ height_{after\ CMP}}{step\ height_{before\ CMP}} \tag{8}$$

Using conventional slurry based CMP solutions it is well known that the SHR is decreasing with increasing line width (LW) and increasing with increased material removal. The below figure describes this effect generally.

The different curves in the diagram of Figure 4 represent the remaining step heights for different pattern widths in dependency of the polishing time. As the pattern width is increasing, it takes much longer to get a full step height reduction or planarity. On die level this results in the necessity of over polishing to make sure that the even the largest pattern is totally planarized. This in turn leads to the fact that small features, which are already planarized, face additional removal and effects like dishing and erosion occur (see also Figure 9 on page 32).

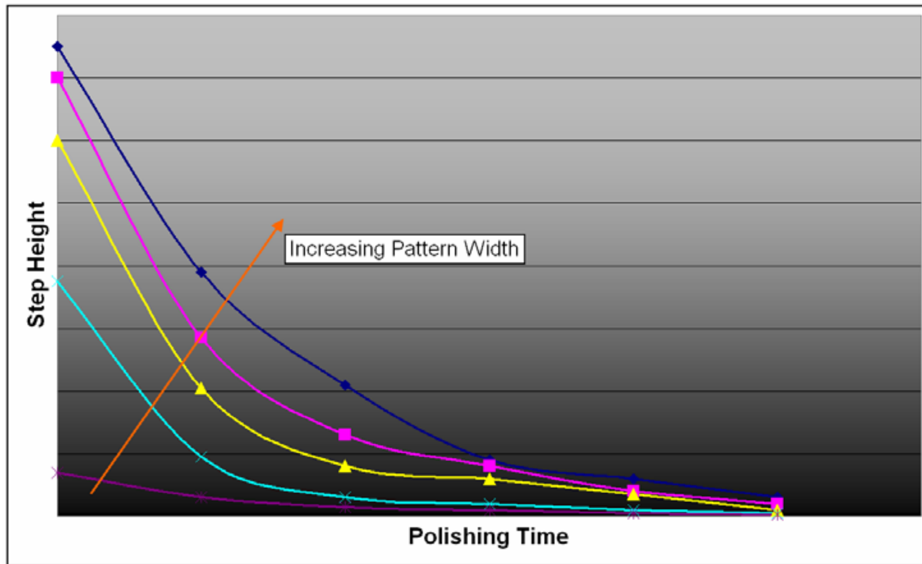


Figure 4. Reduction of the step height with increasing polishing time and material removal. Larger pattern width faces slower SHR

Therefore, planarization by polishing has been from the beginning the object of many modelling trials and investigations in order to understand, improve and overcome the problematic behaviour of this process. The bending of the pad under the presence of topography was modelled by Sivaram [46]. This is one aspect of the problem and has to be considered together with other circumstances like e.g. the presence and properties of a liquid film, which led to the model of Runnels [47], introducing fluid based wear. Warnock directly used the pads' compression to model and predict planarity [48]. Figure 5 depicts the bent polishing pad during process at the presence of a patterned wafer. Due to the pads' relaxation it surrounds the features to be planarized. The very same effect occurs also at the wafer edge, where the pad transits from the substrate to the retainer ring. The gap between ring and wafer as well as the height difference of ring and wafer surface leads to relaxation effects in the pad causing uniformity issues at the outer edge. Further development and understanding of the first models of the early nineties was therefore constantly achieved and they got finer and more accurate. Non ideal conditions are nowadays integrated [49] in comfortable software-tools and the different tribological aspects of the process are included in the considerations [28].

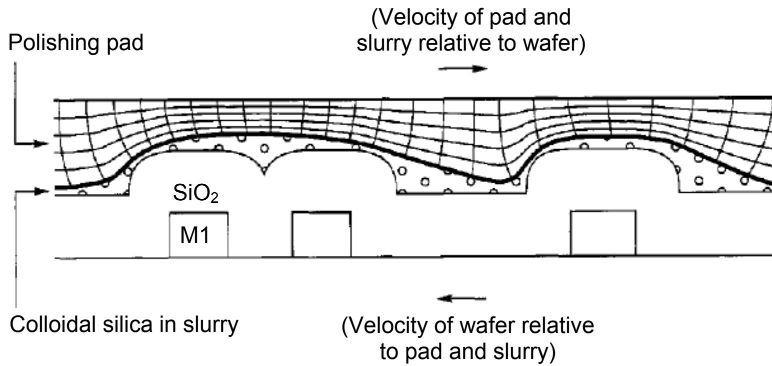


Figure 5. Pad bending under presence of topography. At elevated areas higher pressure is applied through the compression of the pad [9]

One way to prevent high NU due to the pad effect at the wafer edge was followed by the tool vendors, who have been e.g. inventing the pneumatically adjustable retainer ring. An extra force by the retainer ring is applied outside around the wafer and this pre-compresses the pad. The edge effect, caused by the time dependent relaxation of the polishing pad can be minimized by the optimization of this pressure (Figure 6). It has to be considered that the type of pad and the process parameters itself influence the edge effect to large extent and therefore also pad vendors aim at all times towards better pad technology with higher production consistency and process control.

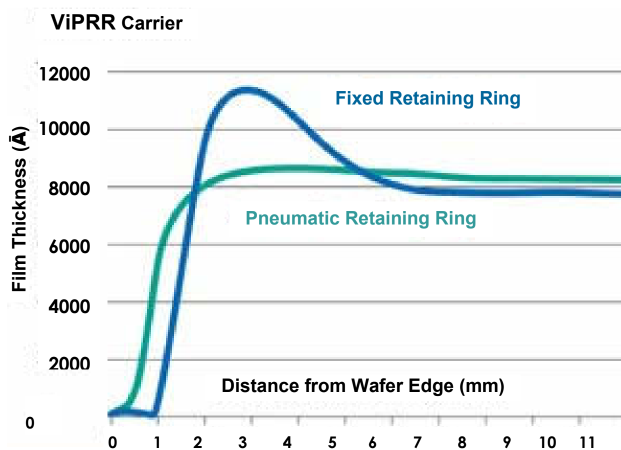


Figure 6. Comparison of the remaining wafer edge profile after CMP. By use of a pneumatically driven retainer ring the edge effect can be minimized [50]

With zoned backpressure at the backside of the wafer, bending can also be applied on the wafer itself to overcome uniformity problems originating from pad and rotation. The more holes are present inside the carrier and the more zones are available the finer a bending can be adjusted to the polished sample (Figure 7) and the better the process can be controlled in terms of non-uniformity.

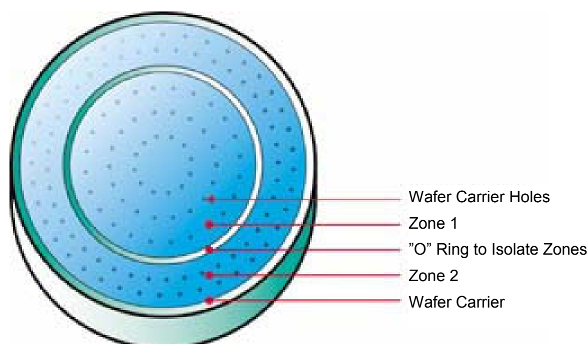


Figure 7. Schematic drawing of a wafer carrier with many backside pressure holes and two independent pressure zones for controlled wafer bending under CMP [50]

The general mechanism of the slurry-based planarizing process however is the attack of the pattern at its corners and its proceeding towards the centre of the elevation as polishing time continues. Thus the pattern is firstly rounded at its corners and then continuously planarized with evolving polishing time. Simultaneously, the down areas of the pattern are also subject to substantial removal, which in turn increases the required thickness of the film to be removed for planarization. The polishing of a single free standing step has been well described by Patrick et al. and is depicted in Figure 8 [45].

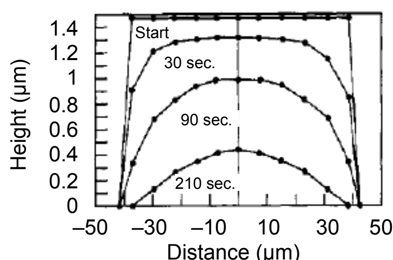


Figure 8. The evolution of the pattern of a wide step under planarization. Attack starts at the edge of the features and proceeds under continuous rounding of the step [45]

Not included in the above figure is the simultaneous removal of material in the open field areas, which would even more clarify the uniformity issue. Due to this behaviour features get ever more flat but never vanish totally, as the removal rate on top of the pattern also erodes with decreasing height difference. Therefore a good amount of total material removal is required in general in order to achieve sufficient planarity, especially with the widely varying pitch of pattern size and density in modern IC circuitry (see also the above Figure 4).

In most of the recent applications however it is the removal of excess material on top of a stop layer that is required, when CMP is used; for example at FEOL processing for STI formation [51] or the dual damascene process for the metallization BEOL [52]. The above discussed mechanical properties of the polishing pad are of especial high importance in these cases. When polishing the deposited metal layer to form interconnects, the process has to be well controlled and stop on the ILD (Inter layer dielectric). As the pattern density and feature shape varies, a certain amount of overpolishing is required in order to clear all the metal and to avoid shorts in the circuitry. Polishing rates are different for the different pattern densities and widths on the die and the process tends to abrade also ILD material by purely mechanical means on small features, which is called erosion. Comparably wide metal lines on the other hand face a removal of material after their clearance during the over polish time and are washed out in the centre, which is called the dishing effect (see Figure 9).

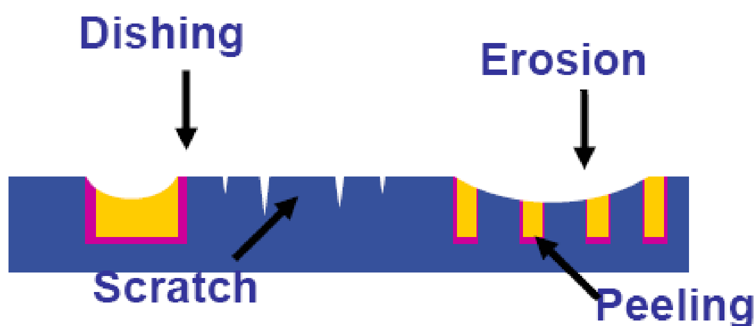


Figure 9. Schematic view of dishing and erosion amongst other defects like scratching [53]

In case of the STI process, shallow trenches have been etched in the bulk silicon and the oxide fills the trenches to isolate the transistors from each others. The CMP process has to remove the excess oxide around the trenches and should stop exactly on top of the masking nitride. It is however difficult to avoid simultaneous nitride removal during planarization due to similar removal behaviour. In order to overcome these problems a lot of different approaches have been undertaken; among others the development of high selectivity (HSS)-slurries [54] or abrasive free slurries [17], but also new design rules have been adopted for better process results. For example by implementing dummy structures [55] or adding additional features by reverse mask processing [56] the maximum step height prior to CMP has been reduced. Also totally new CMP process developments have been undertaken, like for example the development of fixed abrasive (FA) pads.

2.5 Characteristics and Technology of Fixed Abrasive Pads

Especially the STI process requires a well adjusted CMP process, which often has to be monitored by in-situ measurement to prevent oxide and nitride loss [57]. A new approach for this delicate process was introduced by 3M in the mid-end nineties, when they presented their fixed abrasive pads. The polishing pad features a micro-replicated layer of composites with a diameter of some hundred micrometers and height of about 40 micrometers (see also Figure 10). The shape is varying depending on the application and the resin binder holding the abrasive particles (e.g. CeO_2) can be adjusted in its hardness for process purposes as well. The abrading particles are thus bound inside the pad and instead of slurry only pH-value adjusted DIW is necessary as a lubrication liquid, which is fed onto the pad during processing. The composites wear off slowly during polishing and due to the presence of the applied pattern feature fresh abrasives are exposed at all times. The design of the pad allows a good lubrication with the fluid and polishing debris can be swept away easy during the process as wide channels are existing on the pad in between the micro replicated posts. After a slow start FA CMP pads are nowadays well accepted in the industry and further development has brought down starting issues with defects due to scratching to state-of-the-art level and even below. Due to the remarkable benefits of FA pads in terms of Planarization STI processes have been developed at the 65 nm node level [58].

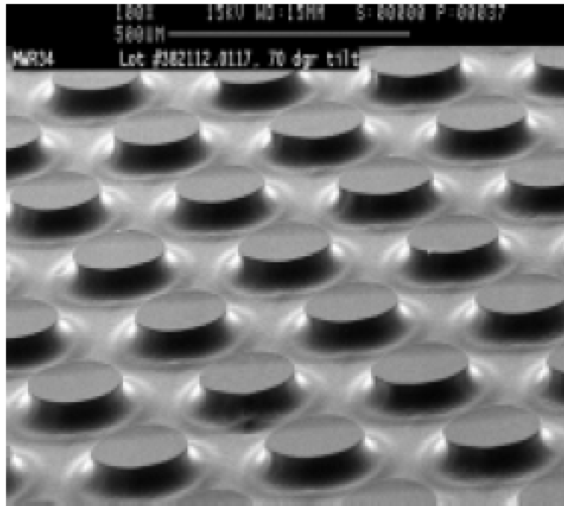


Figure 10. SEM photograph of a 3M fixed abrasive pad. This sample has a micro-replicated composite in cylinder form [59]

In the IC industry the most recent form of using this type pad is in web-roll based polishers. The pad is supplied in rolls and indexed after each run for a certain length, so that each wafer is exposed to an equally used pad surface (Figure 11). With a complete web roll many thousand wafers can be processed without the typically necessary pad change. The FA web rolls are available in different types of pattern according to the specification of the process.

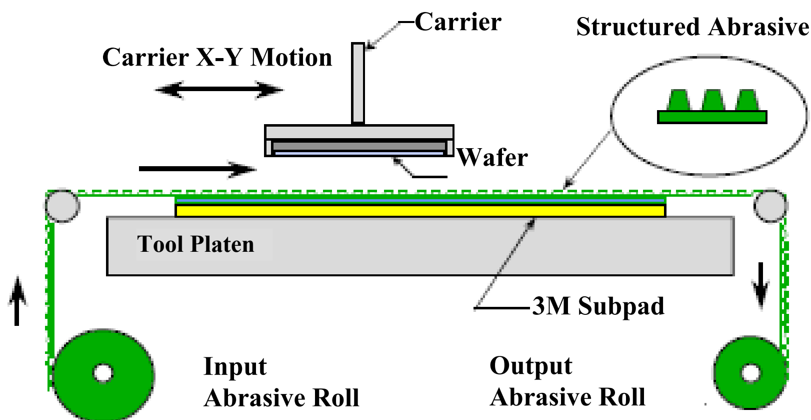


Figure 11. The schematic view of a web-roll based polishing tool [59]

Analysing the mechanism of removal by FA CMP one has to consider the pad-“slurry”-wafer system as done in Chapter 2.1 for slurry-based CMP. The tribology of the fixed abrasive-wafer system is of other nature being depicted in Figure 12, where the conventional, slurry-based CMP and FA pad-slurry-wafer systems are compared. Assuming, that the preferred hydrodynamic lubrication regime for the slurry-based CMP process is present the abrasion mechanism is driven by a 3-body contact mode. In the case of FA pad use however, the surface of the polished substrate is abraded via a 2-body contact mode. The active abrasive particles are fixed in their position inside or on top of the micro-replicated composite respectively.

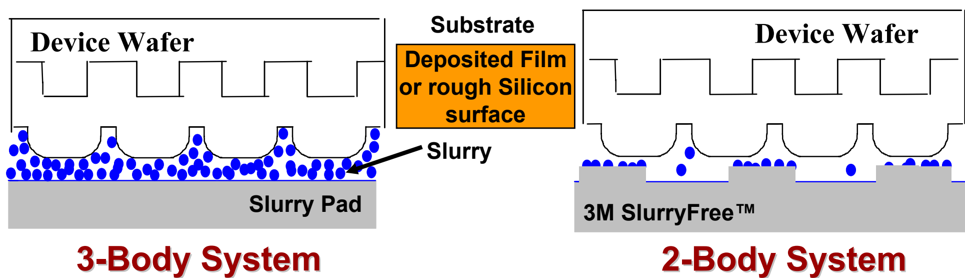


Figure 12. Schematic view of slurry-based and FA CMP, the picture is not to scale [Paper A]

The principle advantage of the FA process is evident; as abrasive particles are positioned at the top of the rather stiff composites of the pad they are mainly active in abrading the elevated parts of the applied wafer surface. The planarization is more efficient than in the case of slurry-based polishing, where the freely moving conventional slurry particles impinging also the lower areas of the die (left in Figure 12).

A sketch of the FA STI polishing is given in Figure 13. The scale does not match all cases of the reality but the figure gives a good idea of the novel CMP step. One composite of the pad is in contact with the top of a large area of the pattern on the wafer surface and does not bend around single features, as in the case of conventional processing with a compressing polishing pad (see Figure 5 in Chapter 2.4).

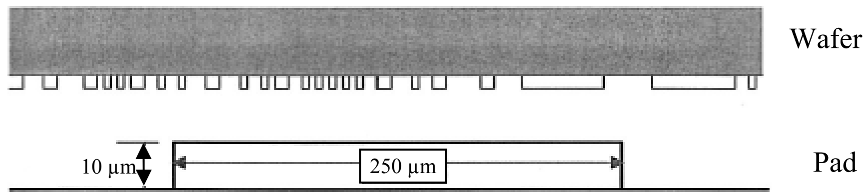


Figure 13. Situation during STI polishing with FA CMP. One composite of the pad is in contact with a large part of the die [60]

The discussion about the evolution of the planarization in Chapter 2.4 does not match in case of FA polishing. The removal is strongly preferential at the top of the pattern and evidently much less rounding of the features is generated due to the shape of the mechanical active posts. Further the removal at the down areas is obviously much lower as the single stiff composites do not approach this area very well and thus erosion is minimized. The planarizing effect of FA CMP is therefore much higher than in case of conventional CMP. Figure 14 shows a comparison for large pattern planarization of STI structures versus field oxide removal.

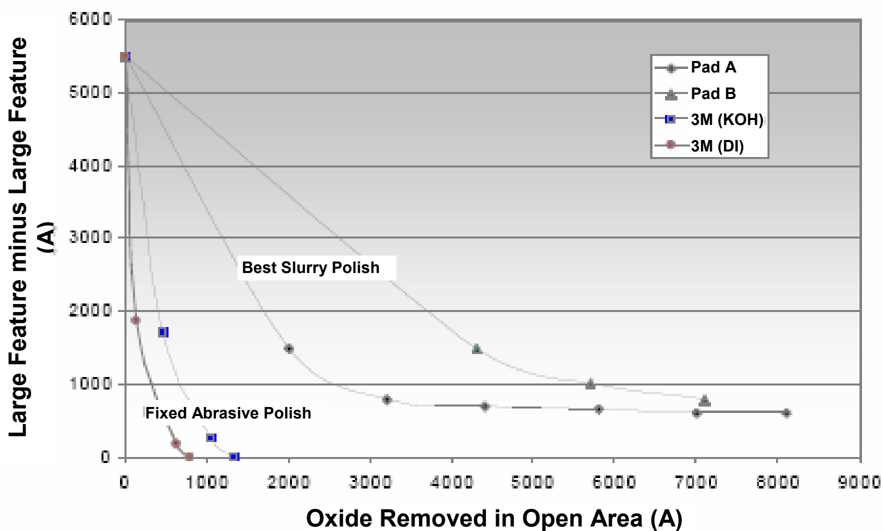


Figure 14. Comparison of large pattern removal efficiency for slurry based and FA CMP. The planarizing effect is strongly enhanced for the fixed abrasive [61]

While the best slurry process leaves a residual step height of about 700Å between small and large features, even when as much as 6000Å of field oxide are removed, the FA is able to remove the pattern completely without thinning the field oxide much more than 1000Å [61].

Another positive effect of the highly reduced bending of FA pads comparing to conventional pads is better overall uniformity around large pattern areas and at the wafer edge. As polishing continues and planarization is achieved, a third positive aspect of the FA technology becomes apparent. As long as there is topography left, the pad will be activated by the pattern and refresh the surface of its composites; the pad is self conditioning. When the pattern however is planarized, no activating topography is left and the pad reacts by reducing the MRR as no fresh abrasive is exposed. The process leads therefore to almost complete planarization when compared to conventional CMP were residual step height remains, this allows substantial overpolish without risking the removal of too much material from the field areas; the FA process is self-tuning [62]. This technology is therefore very interesting for damascene processes involving metals especially copper and some promising results have already been achieved [63]. With the close to ideal planarization capability of the FA pad the necessary compromise using very soft sub pads in the pad stack can be overcome and a better WIWNU can be reached, especially at the wafer edge giving possibility to minimize the edge exclusion. With dedicated two-step processing outstanding results were achieved [64]. As the IC technology moves towards 90 and 65 nm nodes the apparent advantages have been further raising the interest of using the fixed abrasive technology. Due to these results it became apparent that the FA pads could be used also for substrate polishing, especially on thick-film SOI or on large pattern features utilized in several MEMS designs.

3. Formation of Thick-Film SOI Substrates

This chapter is dedicated to the manufacturing process of thick-film SOI wafers. These wafers are of increasing importance for the MEMS industry as they provide convenient processing capabilities. The buried oxide underneath a customized SOI-layer thickness can be used e.g. as sacrificial layer to etch free bulk micromachined features in the top layer [65]. This saves additional process steps and often enables more sophisticated structures. After describing the general approach of the manufacturing sequence, the problems of keeping pace with the increasing demands on the accuracy of the SOI layers will be contrasted to the conventional formation process. With the work presented in the Papers A, B and C a new approach has been developed, which shows highly improved results. Production related issues like throughput are discussed in order to provide a suitable alternative for the current production process.

3.1 The Thick-Film SOI Manufacturing Sequence

For advanced MEMS device formation it is often useful to start with an SOI wafer instead of standard silicon substrate. In contrast to the IC world these SOI wafers do not only require a much thicker SOI film in general but demand also varying thicknesses of both the silicon- and oxide layer. However, the often used Smart-Cut™ technology, invented by Bruel [66, 67] can only be utilized for SOI layers up to about 1,5 µm thickness. The layer cleaving hydrogen implantation cannot be driven deeper inside the bulk silicon of the bonded device wafer. Besides the possibility to grow epitaxially silicon on top of the smart cut layer, which is getting too expensive with increasing thickness often a more mechanical approach is used to manufacture these thick-film SOI wafers, by grinding and polishing the device layer to the desired thickness level.

To gain good results, often two double-side polished (DSP) wafers are used to begin with. The DSP process provides wafers with best possible flatness, often far below 0.5 µm TTV. Then, the oxide layer with customized thickness is grown thermally on the handle wafer. By fusion bonding and annealing the two wafers are connected to form a wafer stack. To avoid chipping during thinning of the device layer, an edge grinding step is introduced to remove the outer edge of the upper wafer, where the bonding is not solid due to the rounded shape of

the substrates. This removes about 2 mm from the device wafers diameter, but leaves a defined edge for the thinning process by mechanical grinding with high speed diamond wheels. Typically a two step process is performed as standard. The coarse step uses wheels with larger diamond particles of around 40 µm and is followed by fine grinding with smaller diamond particles. The abrasives in the wheel can be bond by different ways to form the cutting teeth. The major techniques are the very solid ceramic-like vitrified bond and the softer resin bond, which allows are wide area of adjustment for the cutting teeth strength. Generally the grinding process leaves a very flat surface and a mirror-like finish, however including residual grind lines, which are swirl-shaped from wafer centre to edge (see also Figure 25 on the left in Chapter 3.3). Besides this type of topography, SSD (sub surface damage) is introduced propagating typically some 6 to 8 µm deep into the substrate.

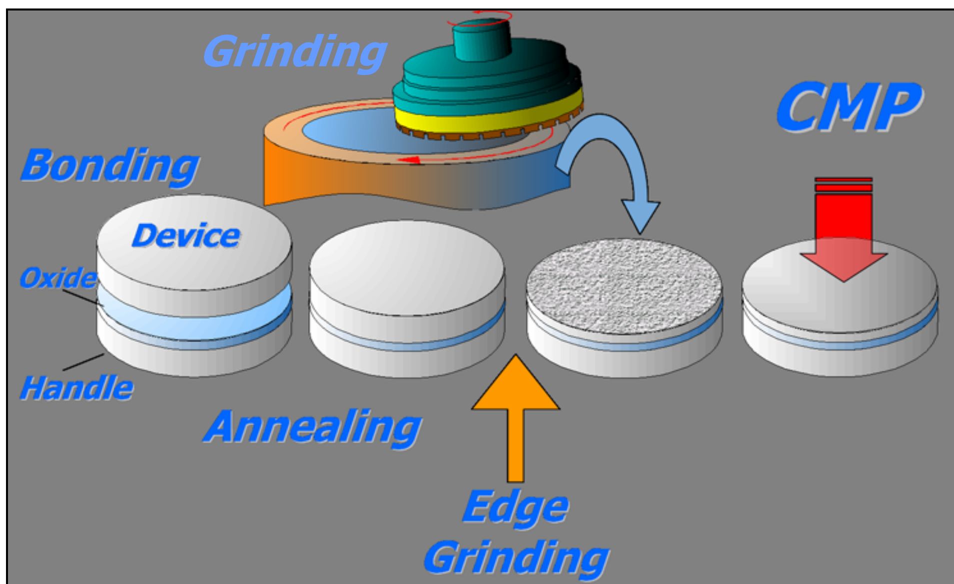


Figure 15. Manufacturing sequence for thick-film SOI Wafers

Removal of this damage layer is done with a sequence of stock removal and fine polishing by CMP. The surface is simultaneously finished to prime wafer quality, removing all grind lines and leaving a planar surface. The entire sequence is shown above in Figure 15.

3.2 The Sub-Surface Damage Layer

The crystalline damage induced by mechanical grinding has been studied by Haapalinna et al. [68]. Figure 16 depicts the different depths of the induced damage, suggested by Hadamovsky [69].

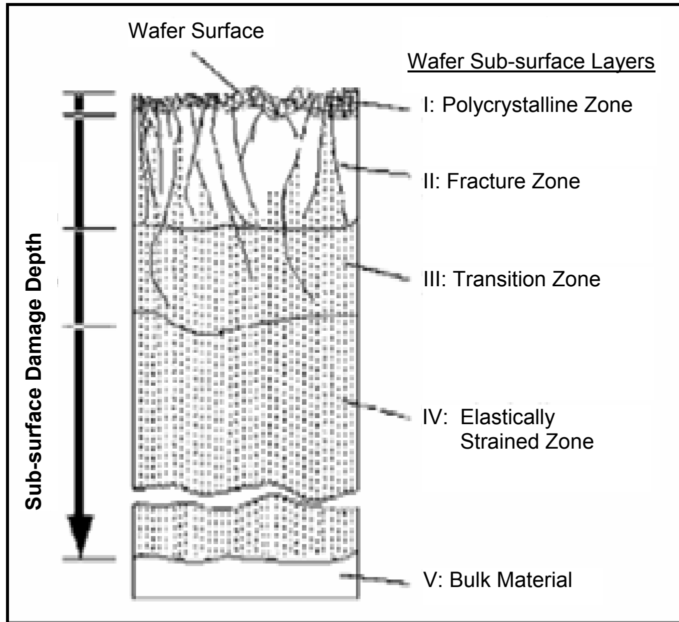


Figure 16. Schematic view of the induced SSD by mechanical grinding [69]

Starting from the wafer surface, which is strongly degenerated, so that Hadamovsky speaks of the polycrystalline zone (I in Figure 16), the big cracks propagate through the fracture zone (II) into the transition zone (III). Still some stress is present in the following elastically strained zone (IV) before finally getting into the bulk material (V) with no further damage. The total depth of the damaged zones and the thickness of each single layer are strongly dependent on the grinding process being applied to the wafer. With state-of-the-art processing, the depth of the total damage stack is about 6 to 8 µm.

Grinding typically results in very flat surfaces but the necessary CMP steps to remove the above characterized damage can often degenerate the flatness. For best performance in terms of uniformity it is evident that one has to minimize

the required polishing removal. Therefore it was very important in this work to investigate the grinding process as well, to achieve best possible flatness for the SOI wafers. Polishing is required as long as damage is left in the ground layer and topography in the form of remaining grind lines is left on the surface. The goal of reducing damage and topography caused by grinding has thus direct impact on the amount of removal required by the CMP process.

Together with the grinding wheel vendor DISCO several approaches were made to improve the SSD performance of the fine grinding step. With the use of smaller diamonds the damage due to the cut would naturally be reduced, but also the applied down force during cutting for maintaining the fixed feed rate of the process is of great importance. Therefore especially the bond of the diamonds within the cutting teeth of the wheel and its porosity are within the scope of the grinding wheel developers. All tested wheels were of resin-type bond and could therefore be adjusted well according to the special needs. On the other hand the lifetime of the wheel is very important for the cost of the process and has to be in balance with a simultaneously soft enough bond to maintain a suitable surface renewal at decent down force for low SSD. For investigating the depth of damage, one has to make it visible at the surface of the wafer, so that it can be detected by inspection either optically or by scanning tools.

One means of detection is the decoration of faults by an oxidation, annealing and etching sequence [70] with the so-called oxidation induced stacking fault (OISF) method. After grinding the wafer, material is removed stepwise by conventional polishing. The OISF are counted after their decoration and drawn up versus the material removal. In Figure 17 the defect counts of standard grinding wheels (right) are compared to those of newly developed grinding wheels (left in Figure 17). As can be seen the new wheels are capable of keeping the SSD at around 3 to 4 μm. These wafers would require much less CMP removal in order to reach the reference level of defects of the compared standard wheels. The polishing time after grinding with the newly developed wheels can therefore be reduced.

The use of improved fine grinding wheels for reduced polishing removal was suggested from the beginning of the investigation [Paper A] and was further studied. The base line studies the Papers B and C showed that the newly introduced process was stable and provided tightly controllable device layer thickness as well as good TTV values of about 0.5 μm.

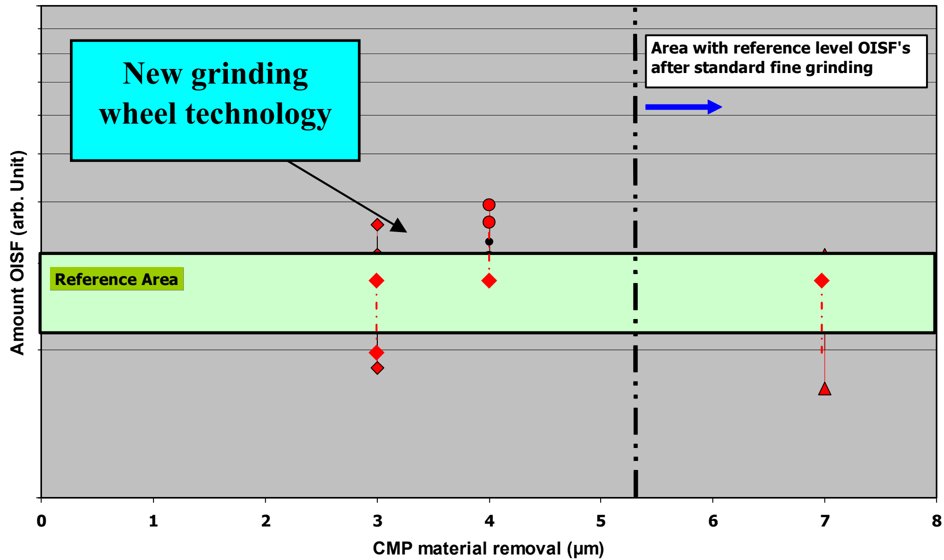


Figure 17. Comparison of OISF counts after CMP polishing on ground wafers with different fine grinding wheels. The wheels on the left show comparable defect level counts after significantly reduced polishing removal

3.3 Uniformity of Silicon CMP

The polishing sequence of the ground wafers is divided into several steps. At first the majority of material is removed by the stock removal polishing. As this step normally removes about 5 to 7 µm it is therefore the most critical in terms of TTV degeneration. The following fine polishing step smoothes the surface down to Å-level and evens out the remaining roughness from the more aggressive stock polish. The typical removal of the fine polishing step is around 0.5 to 1 µm, thus it is not very critical in terms of TTV degeneration. The haze polish then removes the atomic roughness and leads to sub-Å level roughness; this leads to prime wafer surface quality. The removal is very low, usually some tens of nanometres.

With the standard silicon polishing sequence problems arise in achieving the high specifications for the uniformity of the SOI layer, especially the stock polishing step with its large material removal. As the polished device layer features a smaller diameter than the overall substrate (due to the edge grinding)

the earlier mentioned pad-edge-effect (see Chapter 2.4) leads to strong rounding in the stock removal process. The generated edge roll-off by CMP polishing reaches several millimetres inside the device layer as the gap between the carrier's retainer ring and the polished device layer's surface edge is now even larger than with standard substrates. The high importance of the gap between retainer ring and wafer edge for the TTV performance has been recently investigated again and a new model was developed [71]. The strong influence of the gap size on the wafer edge geometry was reconfirmed and it could be shown that uniformity increases strongly with increasing gap size. The resulting edge shape after conventional processing therefore often precludes meeting the stringent specifications of down to 0.5 µm TTV at edge exclusion of 3mm of the total wafer diameter [Paper A]. This means for the SOI wafers' device layer with its smaller diameter an edge exclusion of about 1 mm is required, a value that is even below the tightest specification for IC wafer manufacturing.

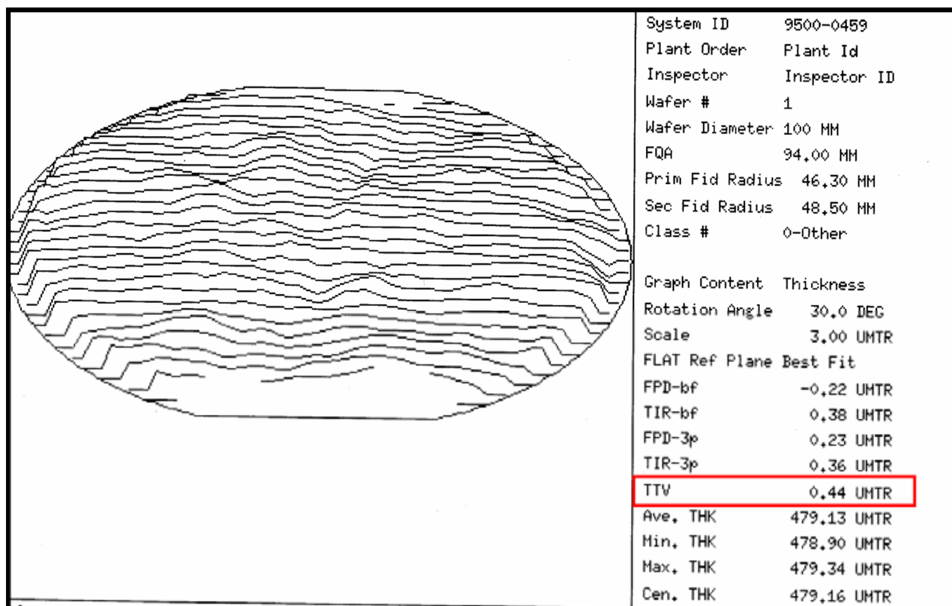


Figure 18. Typical result of a ground SOI wafer. TTV below 0.5 µm indicate very flat surface

Typical results of both states after grinding and after removal of the SSD layer by conventional CMP are shown in Figure 18 and 19 respectively. In this case the total removal by CMP is about 5 µm, which marks the absolute minimum

stock removal needed for taking off all SSD of standard ground SOI wafers. A clear rounding after polishing is visible at the outer wafer edge as well as some additional NU in the centre of the wafer, caused for example by non-optimized backpressure.

The TTV is increased to about 1 µm and the calculated WIWNU (Within-wafer non-uniformity) is about 15 %, based on the k-value, a factor often used in IC-CMP for sensitive evaluation of CMP process non uniformity. The calculation is given by Eq. 9:

$$k\,[\%] = \frac{\Delta - \mathrm{TTV}}{\text{total Removal}}\,\mathrm{X}\,100\,;\;\; \Delta\text{-}\mathrm{TTV} = \mathrm{TTV}_{\mathrm{pre\,CMP}} - \mathrm{TTV}_{\mathrm{post\,CMP}} \tag{9}$$

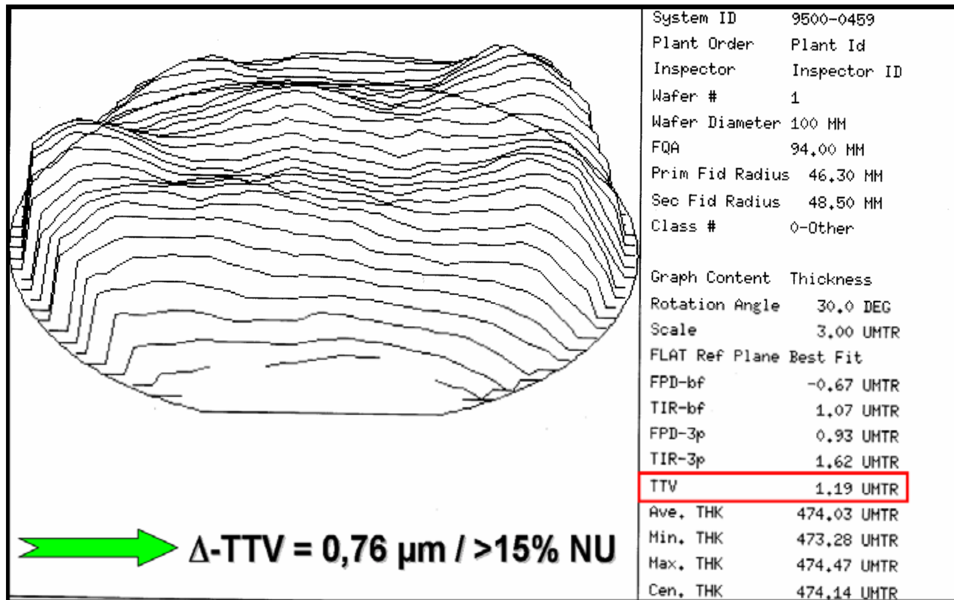


Figure 19. After conventional CMP the rounding of the wafer edge is visible, but also other NU in the wafer centre leads to TTV above 1 µm

Due to its remarkable results in the IC area the idea was born to use FA pads for overcoming the problem with the uniformity at the wafer edge. With a set of prototype FA pads from 3M a new process was set up therefore to investigate its behaviour on silicon.

The first trials of silicon polishing on fixed abrasive pads are depicted in Figure 20. One can see that the TTV change of the process is almost neutral or even improving so that the shape and good flatness of the incoming ground wafer is maintained during FA CMP processing. Even though the total removal of about 1 µm at this early stage was rather small, the calculated WIWNU of the process was around 5% versus about 15% WIWNU with conventional CMP indicating a tremendous advantage for the FA process.

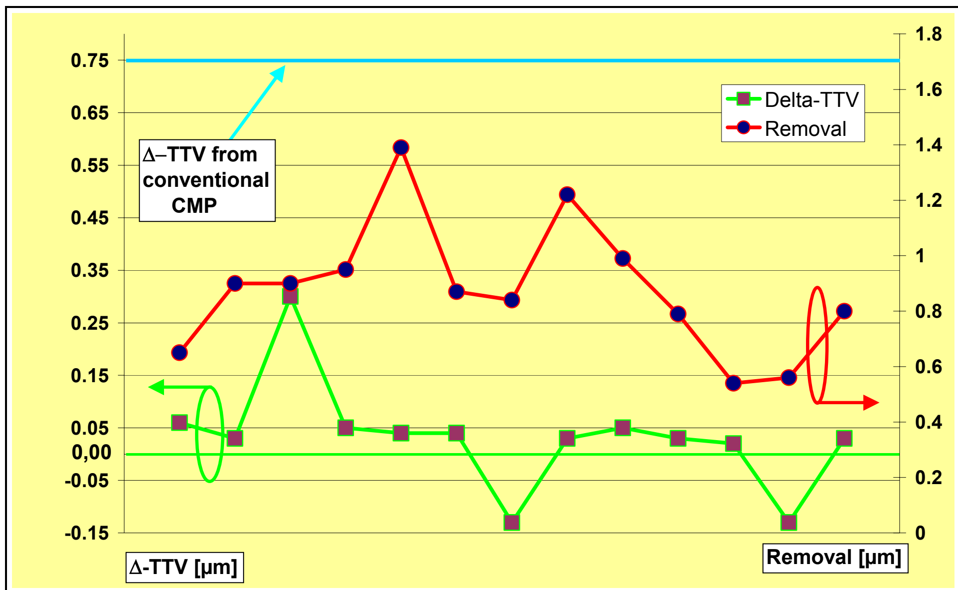


Figure 20. First polishing results of FA CMP on silicon. The TTV behaviour is superior to conventional CMP. The total achieved removal is rather small

To understand more of the mechanism behind the removal, several tests were made, especially with the background of increasing the total achievable removal and improving the MRR. When applying sequential polishing it was discovered that the removal would drop further and also the MRR was going down in the second step, while slightly increasing in the first step [Paper A]. This was connected to the specific removal mechanism of the FA pad, which needs activation of the pattern for its performance. As long as topography is left on the wafers' surface, the abrasive containing posts could get refreshed, but with realized planarization the process stops itself as seen earlier in case of IC device manufacturing [72]. While this effect is highly desired for the STI process, one

would need a pad for SOI polishing that has an effective removal even after topography is no longer present. This so-called zero-rate would ensure the removal of the deeper laying SSD. With this input the vendor supplied a different type of pad to be used with the silicon process. This pad showed an increased MRR with stable uniformity behaviour in the beginning and a higher total removal was achieved. After longer use however, the MRR dropped and could not be recovered. The surface of the pad was analysed by SEM. When inspecting the details of the composites, it was seen that the constant renewal of the surface due to slow wear was working in principle, as the composites' height of the used pad were clearly lower (see Figure 21).

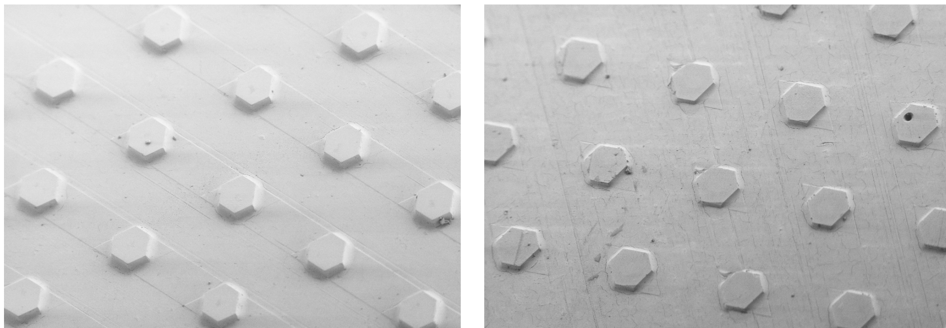


Figure 21. New (left) and used (right) FA pad. The abrasive containing composites are clearly lower after several hours of processing

The used pad however showed a lower density of abrasive particles at the surface of the posts and its topology was smoother. The balance of the abrasive particles wear and their loss with the resin material removal was not well adjusted and led to depletion of particles on the surface. The abrading particles appear as round "balls" in the left picture of Figure 22. Clearly fewer of them are visible on the used pad surface. The overall surface looks clotted (Figure 22 on the right).

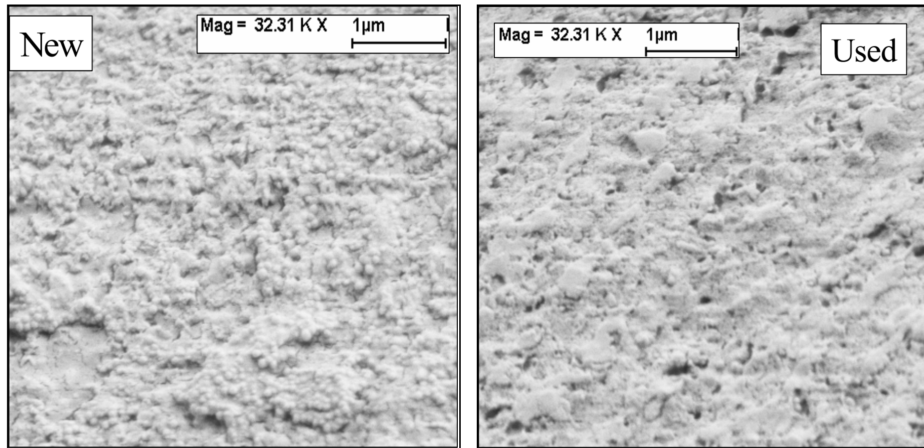


Figure 22. Detailed view on the composites of a new and used FA pad. The unused pad features clearly more abrasive particles (left) than theused one (right) and has a generally higher topology

With another resin-type FA the research was continued and more detailed analysis was done on the influencing parameters of the process. This pad finally showed a stable behaviour on silicon with respect to MRR after grind line topography removal and deeper investigation was enabled.

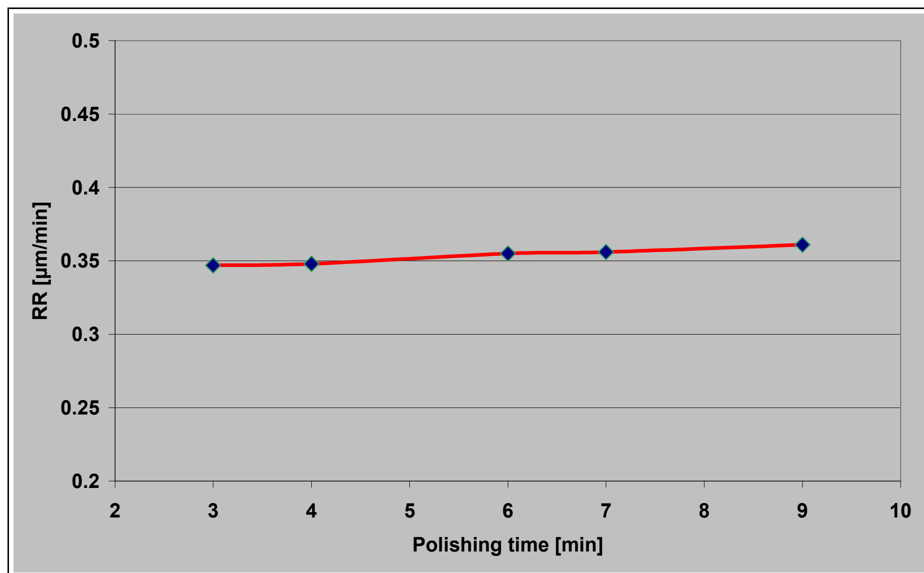


Figure 23. MRR over polishing time. Stable removal of about 0.35 µm/min independent from the applied processing time

The pad continued working after several runs with stable rates and it was possible to adjust the total removal by omly varying the polishing time (Figure 23). Now other influencing parameters were analysed.

Another yet important point to investigate was for example the strong dependence of the MRR on the pH-value of the applied lubrication liquid. With a detailed polishing experiment fine scale pH adjustment was done to the lubrication liquid and the MRR was studied. The removal peaks at pH 11.8, as can be seen from Figure 24. This is very similar to that what has been found in earlier trials on STI oxides [73], rather than on conventional silicon polishing [42, 43]. This finding indicates the special mechanism of removal on the ceria based FA pad for silicon. Ceria is known for its chemical tooth effect when being used for abrading silicon dioxide [38], but no such effect would be expected when removing silicon. According to Pietsch et al. however, a loose quartz-like network is formed on top of the silicon surface, when the polishing takes place at higher pH-regimes. This oxide in turn slows down the conventional polishing process as it is much more difficult to be dissolved by the typically low particle density slurry of the standard silicon CMP. In case of FA CMP however, ceria can act with its chemical activity and enhance the removal as soon as the pH-regime allows the formation of the surface silanol. It is therefore suggested that the removal of silicon by FA pads is supported by the chemically active ceria abrasives, facing an oxide-like surface being formed due to the elevated pH-regime. The silicon removal is thus driven by the surface silanol formation under exchange of the hydrogen by OH^--molecules and the resulting silica dissolution via the Bronsted-base reaction of the chemically active ceria as suggested by Cook [38].

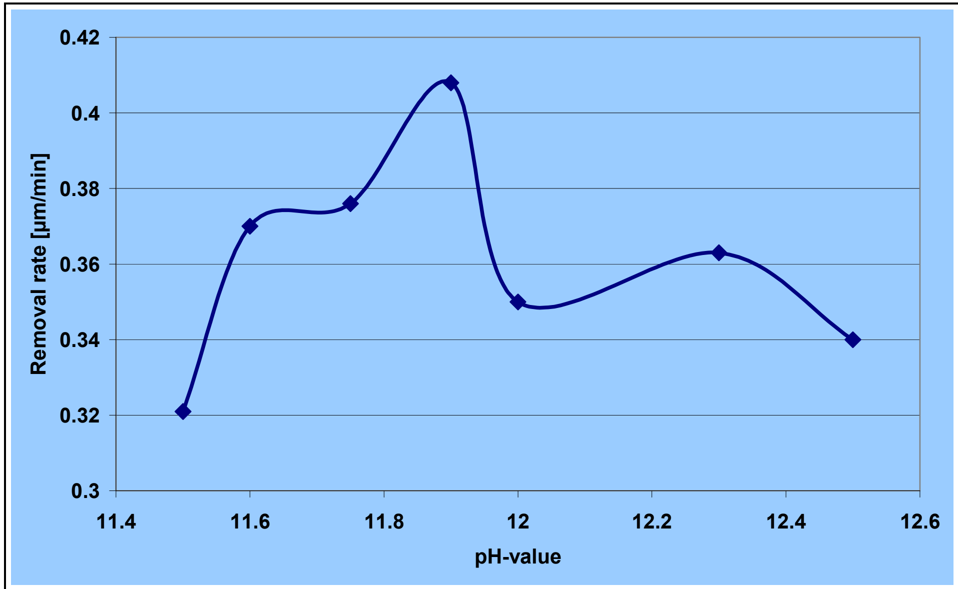


Figure 24. pH-value dependence of the MRR

When compared to conventional CMP it was also interesting to note, that the planarization using an FA pad took place within the first micrometer of material removal, whereas slurry-based CMP would need more than 5 µm to remove all topography from grinding [Paper B]. This in turn was indicated even more of an advantage using highly improved grinding technology as the only limiting factor of reduced removal by using FA CMP now was the SSD (see Figure 25).

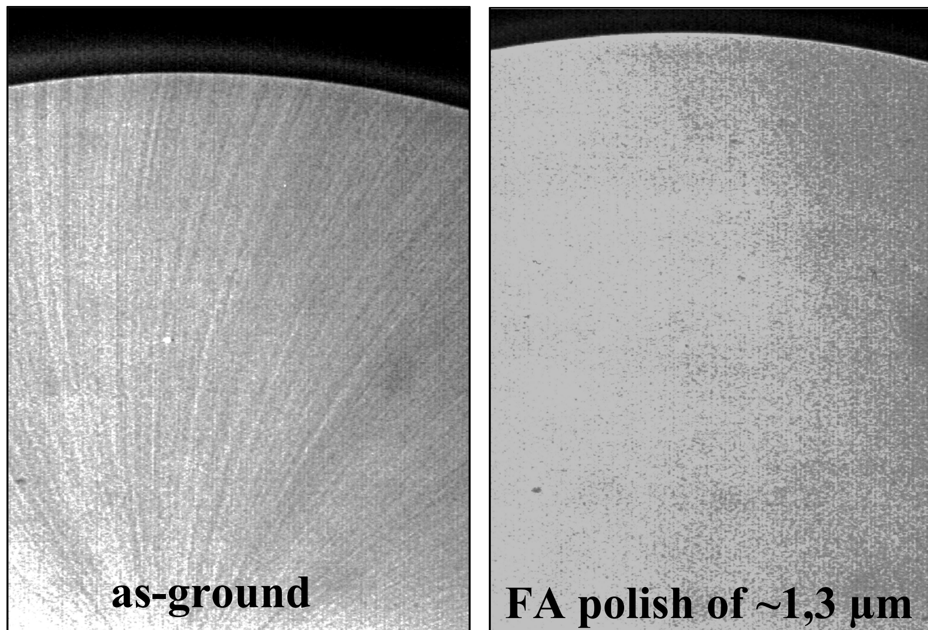


Figure 25. Magic mirror images of ground silicon wafer (left) and FA polished sample (right). Only little more than 1 µm removal is needed to planarize the entire grind line topography

3.4 Surface Quality of CMP

For the successful integration of the FA CMP polishing it was necessary to study the surface quality extensively. In order to replace conventional stock polishing with FA polishing, a similar surface quality after the process needed to be ensured. AFM scans were done for investigating the surface roughness. Figure 26 shows the comparison of an as-ground surface and an FA polished wafer with about 1 µm total removal. The rms roughness is significantly reduced from about 15 nm down to 0.75 nm. This value is as good as or even better than that being typically achieved by standard slurry-based CMP after several micrometers of removal. The subsequent fine polish should therefore require no change, but could maybe even be shorter, while enabling the same quality as is achieved using standard processing [Paper A].

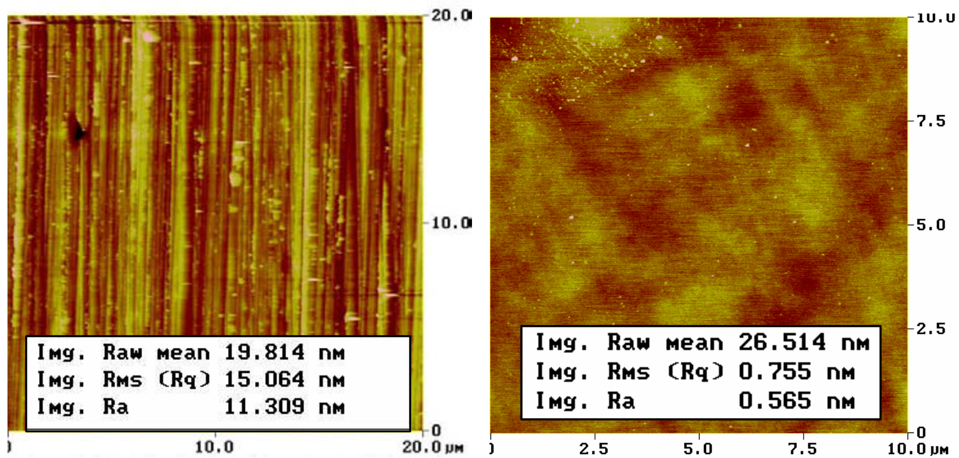


Figure 26. AFM results of as-ground silicon surface (left) and FA polished wafer (right). The Surface quality after 1 µm removal is at least as good as after slurry-based CMP or several µm

As the principle of FA CMP removal is based rather on contact with the stiff resin-type composite pattern than a soft polishing cloth, it was expected to see an influence on the surface defect level after polishing. Even when removing all SSD caused by the grinding step the FA process itself may leave its own damage on the surface to be removed by the subsequent polishing steps. Again the defect decoration method was used to investigate this behaviour. After FA CMP, the wafers were polished with different times by the standard fine polishing process and the decoration etching was done afterwards. The surface was at first inspected at 9 points on the wafer and the defect data were processed and drawn up (Figure 27). Indeed a huge amount of defects was visible directly after FA CMP. A 60 seconds fine polish however removed almost all of them. This indicates that the defects are very shallow and that they can be easily removed by a standard fine polishing process, which is mandatory for the surface quality in any case. Further polishing up to the standard time resulting in about 0.5 to 0.7 µm of removal did not seem to have any greater effect on the OISF count according to the 9-point analysis and the defect level of the wafers stabilized slightly above the compared references (right in Figure 27). To get a more detailed view with better statistics further analysis were necessary, scanning along the entire wafer radius, thus preventing the emphasis on the outer areas of the standard 9-point pattern. The result of the processed data can be seen in Figure 28.

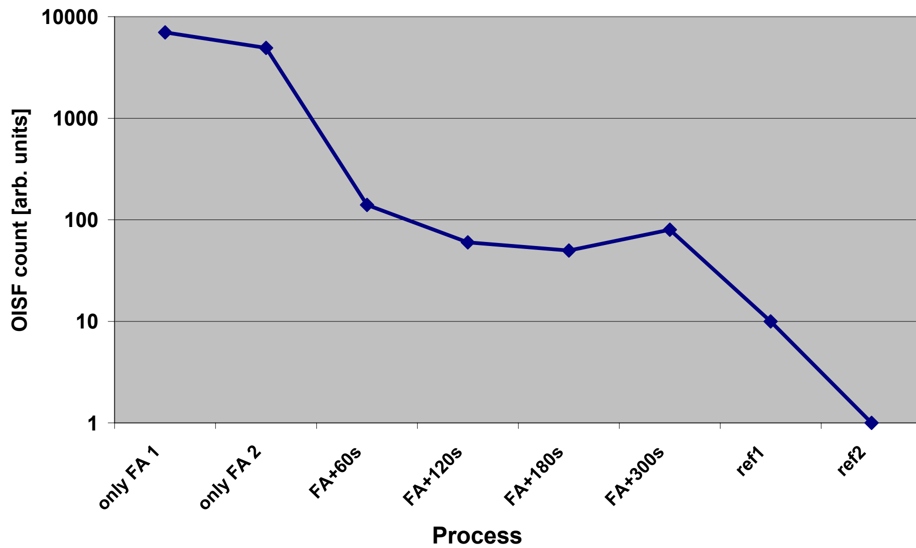


Figure 27. Cumulated OISF data from a 9-point inspection of differently processed wafers after FA CMP. The FA induced SSD is very shallow and is removed almost completely after 60s of fine polishing

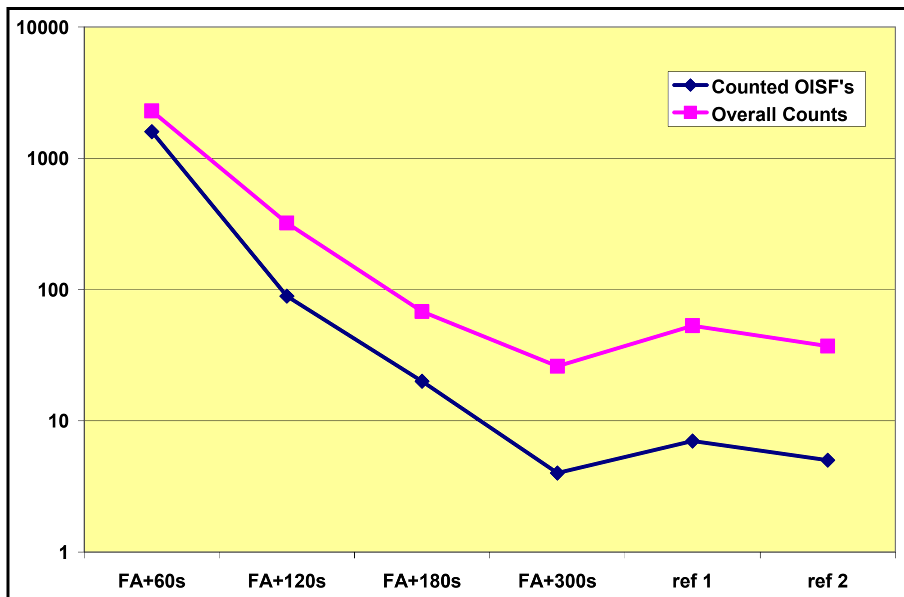


Figure 28. Diameter scans of the defect counts. The more detailed analysis shows a continuous reduction of the defects with increasing fine polish time. After standard polishing time (300s) the defects are at reference level

With the larger inspection area along the wafer radius the continuous reduction of the shallow defects becomes visible. After 300 seconds of polishing or about 0.7 µm removal the defect density reached the reference level of the two parallel analyzed non polished prime monitor wafers.

This result corroborates, that a replacement of the stock removal polishing by FA CMP is highly feasible and easy to integrate into an existing manufacturing sequence as the subsequent processes are facing no need for change. The occurring SSD of the FA process is very shallow as already the first 9-point analysis confirmed and it can be removed by standard fine polishing. The achieved surface roughness as such is at the same level or even slightly better than that of conventional stock polishing. Therefore, a manufacturing sequence with low-SSD grinding and FA CMP is very feasible [Paper C].

3.5 Stability of the New Sequence

From the beginning of the investigation, it was most important for the work to focus also on the stability of the processes with suitable base line studies. Both, the MRR and the TTV have to behave stable over a longer period of time in order to make a process suitable for production. With the adjusted process it was possible to keep the MRR stable over a longer time of processing with more than 80 wafer runs (Figure 29). The process performance of this base line run showed stable results also in terms of NU over the entire sequence as can be seen from Figure 30. Comparing the incoming and post-CMP TTV values as demonstrated by the lower graph, the almost neutral behaviour of the FA CMP step can be obtained. In many cases it was even possible to enhance the flatness of the ground wafers. This is usually not the case with slurry based CMP polishing. The details of the study can be reviewed in Paper B.

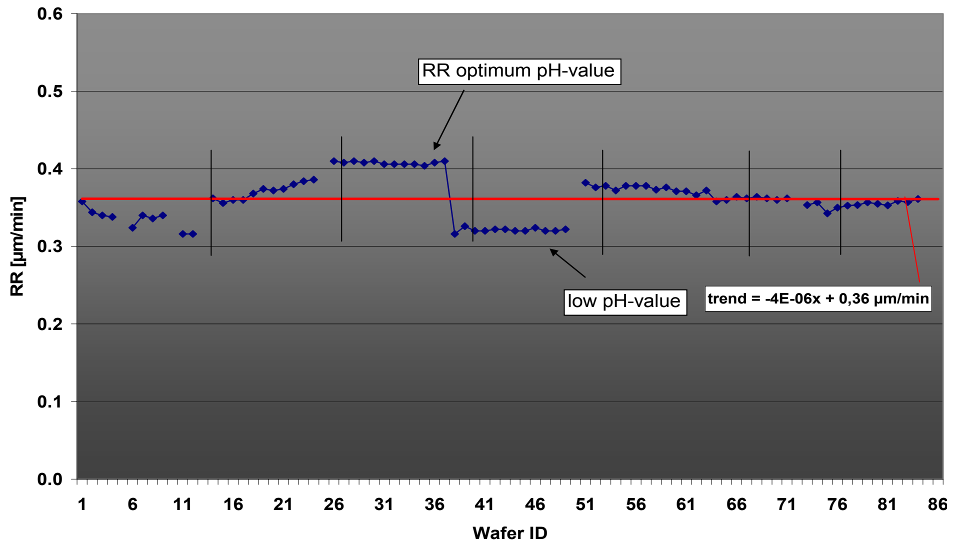


Figure 29. MRR of a base line study. The rate is very stable and shows only influence on the variation of the pH-value of the lubrication liquid

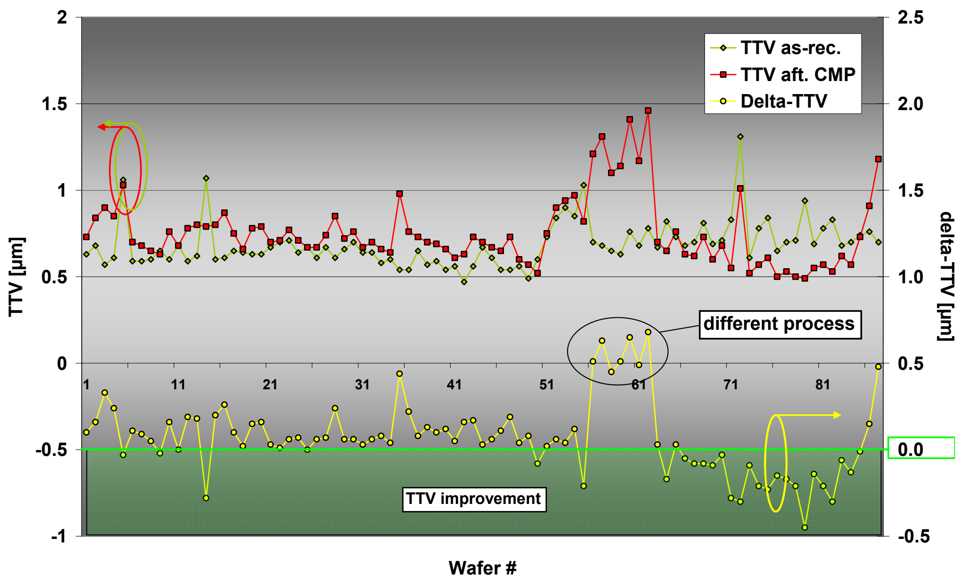
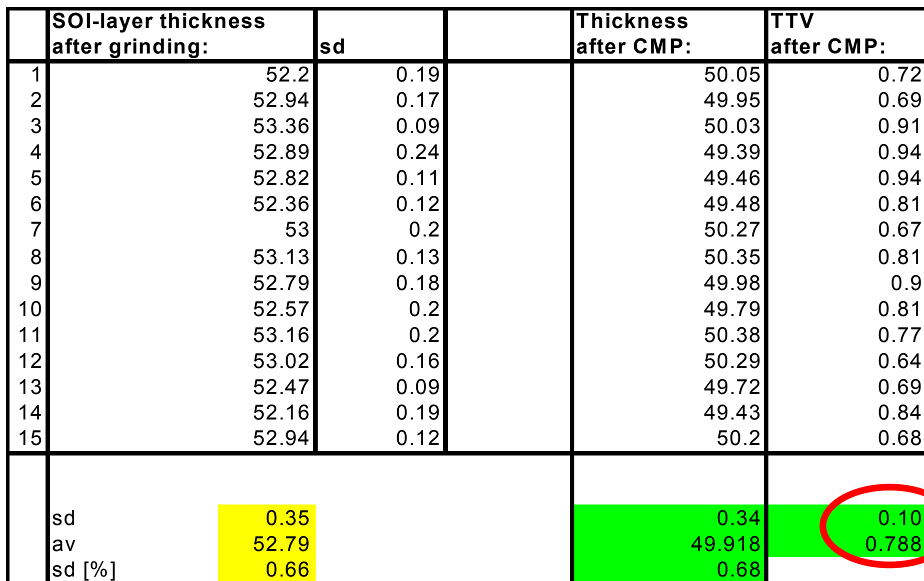


Figure 30. Comparison of incoming and outgoing TTV values of the FA CMP base line study. The lower graph corroborates the almost neutral behaviour of the polishing in terms of TTV

In a final experiment the overall performance of the new sequence was tested including the low SSD grinding, FA CMP and final polishing CMP. The set of 15 wafers with precise thickness control after grinding of 3 µm above target was polished by FA CMP and finished by slurry based polishing. In the final measurement the goal thickness of 50 µm was well targeted, which indicates the stable MRR of the fixed abrasive process. The wafers had an average TTV of clearly below 1 µm with some wafers tending towards 0.6 µm and none of them being above 1 µm. Thus also the TTV was under tight control for the test set with no bigger deviation. The detailed results are depicted in Figure 31.



	SOI-layer thickness after grinding:	sd		Thickness after CMP:	TTV after CMP:
1	52.2	0.19		50.05	0.72
2	52.94	0.17		49.95	0.69
3	53.36	0.09		50.03	0.91
4	52.89	0.24		49.39	0.94
5	52.82	0.11		49.46	0.94
6	52.36	0.12		49.48	0.81
7	53	0.2		50.27	0.67
8	53.13	0.13		50.35	0.81
9	52.79	0.18		49.98	0.9
10	52.57	0.2		49.79	0.81
11	53.16	0.2		50.38	0.77
12	53.02	0.16		50.29	0.64
13	52.47	0.09		49.72	0.69
14	52.16	0.19		49.43	0.84
15	52.94	0.12		50.2	0.68
	sd 0.35			0.34	0.10
	av 52.79			49.918	0.788
	sd [%] 0.66			0.68	

Figure 31. Overall performance of the low-SSD grinding and FA CMP sequence for thick-film SOI wafer formation. Most precise film-thickness and excellent TTV of below 0.8 µm on average (av) with low variation (sd, standard deviation 1σ) was achieved

A final comparison of the performance between the standard method with the use of conventional grinding and polishing and the novel sequence with the use of low-SSD grinding and FA CMP sequence is given in Table 1.

Table 1. Comparison of typical performance values for the standard and novel thick film SOI wafer formation

THICK FILM SOI:	**STANDARD SEQUENCE**	**LOW-SSD GRINDIG AND FIXED ABRASIVE**
Typical Required CMP Removal after Grinding	6.5–8 µm	3–3.5 µm
Achieved TTV	>1.0–2.5 µm	0.5–1.0 µm
Qualified Edge Exclusion (SOI-Layer)	3.0–4.5 mm	1.5–2.5 mm
Typical Removal Rate	0.5–0.8 µm	~0.4 µm
Final Polishing Removal	0.5 µm	0.5 µm

The advantages are evident. Because of the improved grinding process the total required removal was cut in half and the lower MRR of FA CMP compared to slurry driven stock polishing was well acceptable. Much better overall performance is possible in terms of flatness indicated by the TTV at simultaneously much more stringent edge exclusion by the novel sequence. The newly developed process enables thus the production of ultra flat thick-film SOI wafers. This type of performance cannot be achieved using standard manufacturing methods [Paper C].

4. CMP of MEMS Structures

In addition to the outstanding results being achieved by fixed abrasive CMP for the formation of the thick film SOI substrates, chemical mechanical polishing in general has also been able to improve and enable the direct formation of MEMS structures. It is already an established sequence to thin bonded wafer stacks down to dedicated thickness by grinding and do subsequent CMP processing for surface finishing, but also several other applications have been identified, where CMP plays a key role for the success of the entire MEMS process. For SOI substrates with buried cavities uniformity issues of the bonded and mechanically thinned capping silicon layer are in the scope of the researchers. With an attempt to improve the uniformity of large unsupported areas, it has been demonstrated, that using pillars to prop these diaphragm-like areas resulted in better flatness after grinding and polishing [74]. As soon as bonding is required improved surface quality of the pre-processed surfaces has to be ensured for a successful outcome. This chapter summarizes different approaches to use CMP for the smoothing of deposited films as enabler for direct LT bonding as well as developments done with the FA technology in order to preserve the pre-processed pattern of MEMS structures during polishing or to planarize large scale patterns by the CMP process. Furthermore it illustrates the possibility to use alternative materials like thick film polysilicon to be integrated and combined with established MEMS manufacturing methods.

4.1 Surface Smoothing and Planarization

Bonding technology enables the stacking of several substrates on top of each other, upon which a mechanically stable device can be formed. Different bonding techniques are used, depending on the application. The direct wafer bonding by room temperature (RT) pre-bond and subsequent LT annealing is of high interest, as the choice of materials involved in the film stack can be widened and due to its low required process temperatures even include metals. For enabling this process, one has to pay special attention to the surface roughness of the two bonding partners. The formation of SOI wafers often uses a silicon-oxide interface and in other applications in MEMS also silicon-silicon bonds are of principle interest. As long as the used substrates are of prime quality and the silicon surface is having a sub-Å roughness level they are well

suited to meet the requirement of 3 to 5 Å rms roughness, being suggested for successful LT bonding in several publications [e.g. 75, 76]. A thermally grown oxide on top of prime quality silicon usually is also well inside this specification and bonding is no issue, as long as the bonding surfaces are also free of larger particles. In order to meet advanced MEMS process requirements however, customized SOI wafers are needed and thicker oxide films are gaining more interest. With the increased thickness requirements for oxide films longer thermal oxidation times arise and beyond the level of some micrometers the thermal growth process alone is no longer feasible for the insulation layer formation due to process cost and time.

The deposition of oxides by CVD techniques provides a much cheaper, fast and reliable method with good uniformity to obtain thicker layers of the insulating material. The drawback of this method is however, that the resulting surface roughness often exceeds the requirements for a direct LT bonding process. While sputtering would lead to smoother surfaces it offers very slow deposition rates and the roughness is still in the nm-range, thus would need CMP. Therefore, CMP processes have been developed to enhance the roughness level. Combining soft polishing pads used in silicon processing and oxide slurries from the typical IC ILD polishing with suitable process parameters is leading to well controllable removal with good surface quality achieved on unpatterned wafers.

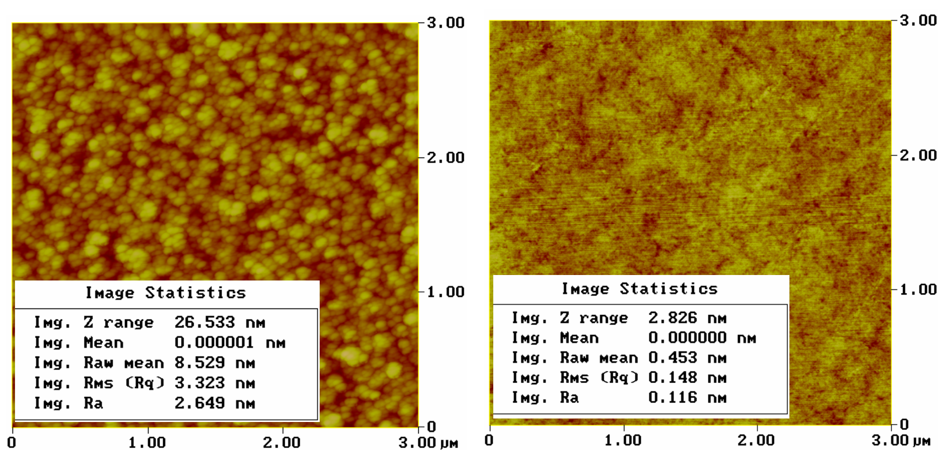


Figure 32. AFM analysis of LTO oxide before (left) and after CMP (right) smoothing. The removal of around 700 Å by the dedicated CMP process reduces the roughness, so that the surface is suitable for direct bonding

The level of roughness can be reduced to Å-level, while as-deposited CVD oxides provide rms roughness values at nanometre range. The required total removal for Å-level surface quality is able to be minimized to about 100 nm and the polished surfaces can be bonded at RT after suitable cleaning. The above Figure 32 shows typical AFM nanographs of an as-deposited CVD oxide (left) and a polished surface (right) respectively.

For encapsulation of patterned structures it is mandatory to simultaneously provide a both plane and smooth surface, which then can be bonded to another substrate. Wafer-level packaging (WLP) technology for example has gained a lot of interest, as the completed components are easy to handle and the packaged devices are completely protected due to the hermetic seal encapsulation of the bond with substantial cost saving comparing to established packaging methods [77]. Using bonding as a manufacturing approach can for example begin with a deposition of a thick CVD or LTO oxide layer on top of the ready device. A suitable CMP process is then applied to planarize the topography of the sacrificial and connecting oxide and to smooth the surface to bondable level. Typical MEMS patterns however are usually much larger than the features used in IC devices and therefore conventional ILD CMP processes would only be able to planarize such a pattern to a certain level leaving a residual step with a rounded shape (see Figure 8, Chapter 2.4). With this insufficient planarization level the required planarity for successful bonding cannot be reached. Therefore FA CMP pads have been used to enable a process for large scale pattern planarization. Figure 33 shows the result of the polishing sequence.

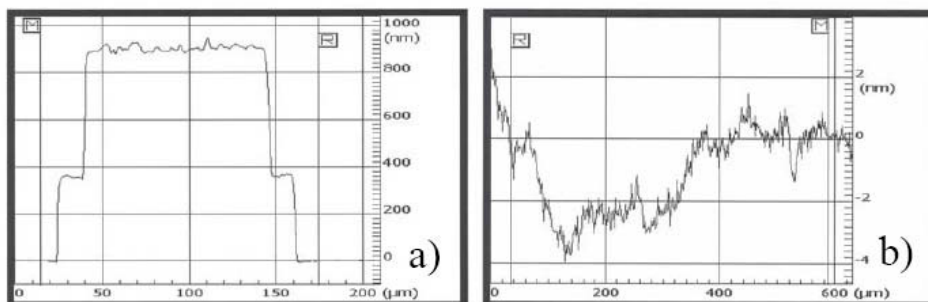


Figure 33. Large scale pattern before (a) and after CMP planarization (b). The pattern is completely removed (note the vertical scale!) and leaves a smooth surface for bonding [78]

CMP by FA is able to remove the large scale pattern totally. The required removal for the total planarization is meanwhile only slightly higher than the initial step height itself. This once again indicates the efficient planarization capability and close to ideal CMP behaviour of the FA pad. The surface quality can be even further enhanced by a short second polishing step on a very soft pad to reduce roughness. This again leads to Å-level roughness, which clearly ensures direct LT bonding capability [78].

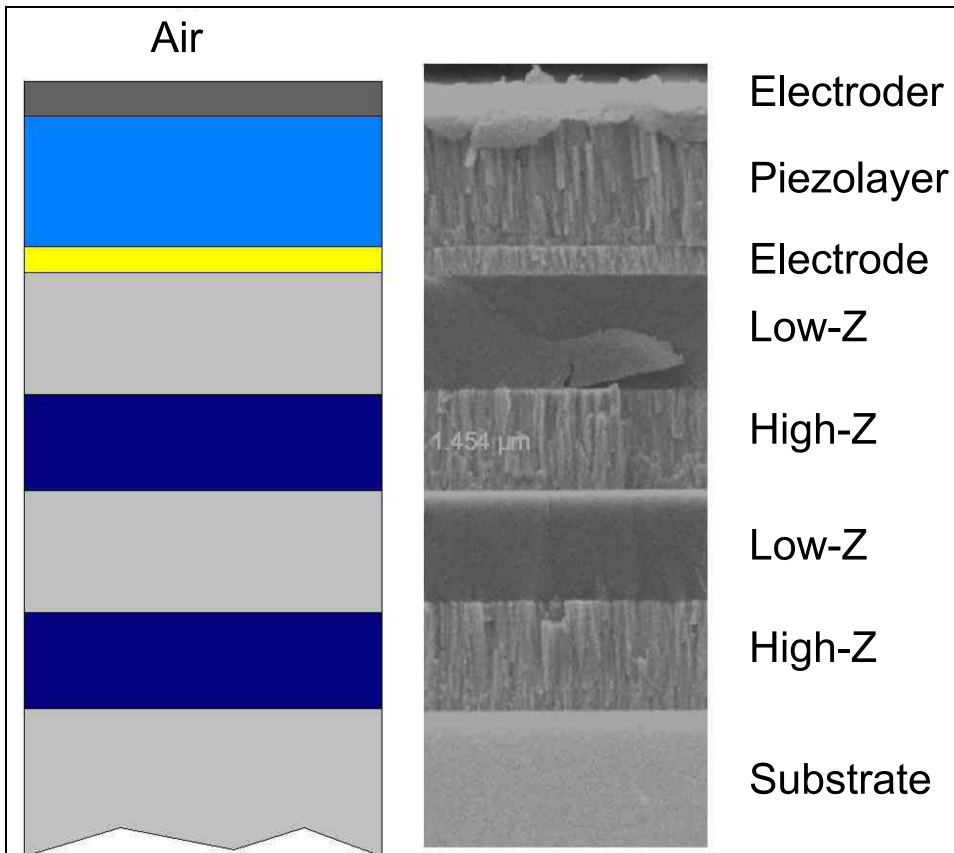


Figure 34. Film stack for the formation of FBAR filters

Aside from bonding there are other MEMS related processes, which benefit from smooth surfaces that result from CMP. For optical and acoustical applications in MOEMS (Micro opto electrical mechanical systems) and rf-MEMS (radio frequency-MEMS) the roughness of the wave conducting layers plays a major role in the losses of the device.

It is known that the surface roughness is cumulative with each deposited layer if no smoothing interlayer such as flow glass is used. As layer deposition starts on a rough surface it can lead to undesired disturbance of the materials integrity and quality. This is especially the case for active layer formation, for example with piezoelectric materials. In Paper E CMP is utilized for the smoothing of an acoustic mirror stack for the formation of FBAR filters.

Figure 34 depicts such an FBAR structure and shows an SEM graph of the filter stack. Starting from the substrate a total of seven films are deposited for filter formation. The most critical part in terms of losses and Q-factor (quality factor) of the filter is the piezolayer between the top and bottom electrode. Below this active part the acoustic mirror stack is formed by alternate deposition of tungsten and PECVD oxide respectively. The mirror stack reflects the acoustic wave and enhances its orientation.

Highest influence on the Q-factor of the device is expected to come from the acoustic coupling of the rf-wave forming piezolayer to the mirror stack. As roughness of the interlaying oxide film increases, energy losses are resulting due to interference phenomena at the interfaces. This in turn reduces the Q-factor of the filter. Furthermore the piezolayer itself has to have a high degree of texture and well orientated crystallites for highest possible piezo-activity.

Therefore the piezo-material carrying up most oxide layer below the bottom electrode of the mirror stack is polished by a slurry-based CMP step and the roughness is reduced down to Å-level. The subsequent sputtering of the piezo-active ZnO shows a drastically reduced surface roughness after CMP, as the film deposition process now starts from the atomically smooth surface (see Figure 35). This in turn may have positive impact on the piezo activity of the ZnO and therefore could lead to higher Q-factors of the resonator structure. It was however not possible within this study to connect the change of the Q-factor to the presence of the CMP process, as other factors of the resonator formation were of great influence too and the polishing process also introduced some other issues [Paper E].

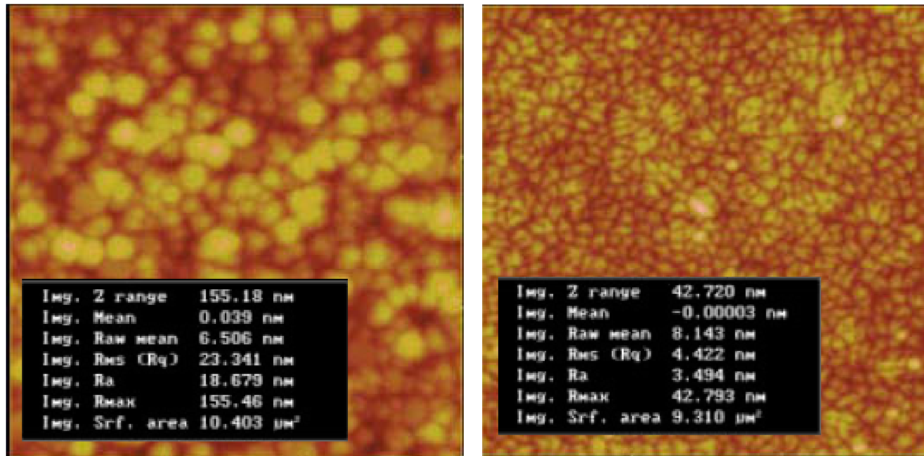


Figure 35. AFM nanographs of the sputtered ZnO film without (left) and with prior CMP smoothing (right) of the underlying oxide film. The roughness and structure of the piezo-active film is greatly improved in the case of polished oxide [Paper E]

The two factors of greatest importance for the successful integration of CMP and the best resulting benefit of the smoothing process are the particle contamination after polishing and the level of rounding of the free standing structures. Due to heavy particle contamination after slurry based CMP an additional SC-1 cleaning was introduced. The particle contamination was removed, but the oxide film showed pin-holes after this cleaning step. The formation of these holes is most probably attributed to defects from the underlying tungsten film, which weakens the deposited oxide. As the wafer is cleaned the weak areas tend to get etched by the ammonia of the required SC-1 bath and this in turn leads to the obtained pin holes [Paper E].

4.2 Pattern Conservation

The rounding of the pattern, its erosion and dishing between single pattern features by conventional CMP is a known fact, especially with the use of soft polishing pads. These are generally utilized for smoothing surfaces. The process leads to a very good surface finish, but for the pattern conservation a more rigid polishing cloth would be required. A hard pad however leads to inferior surface quality but still could not prevent the edge attack totally.

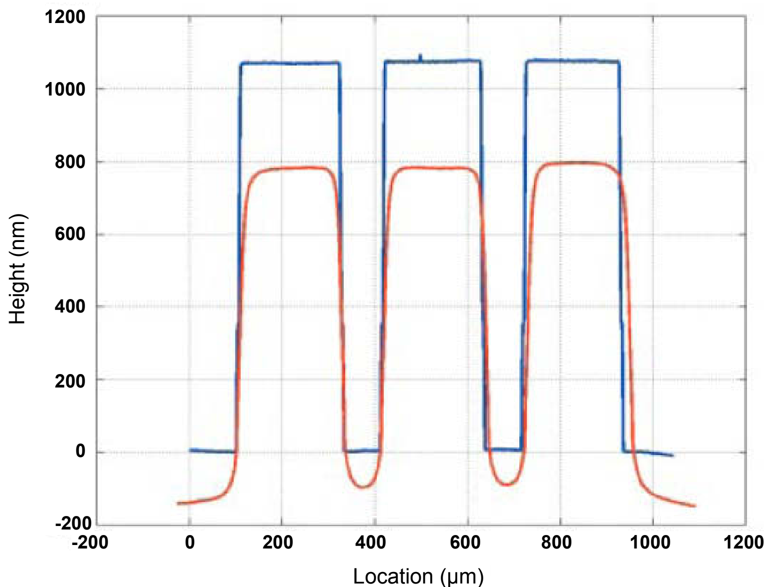


Figure 36. Filter structure before (blue) and after CMP smoothing (red). Despite the desired material removal on top of the pattern, rounding, erosion and dishing of the film stacks occurs with conventional polishing [Paper E]

In Figure 36 the impact of the smoothing process on the structure is visible. The filters experience rounding at the edges, which reduces the active area and could in turn lead to losses in the Q-factor of the resonator. The more detailed picture on the left of Figure 37 depicts the erosion clearly. Furthermore, dishing occurred between the film stacks as the soft polishing pad reaches the down areas of the pattern. This can be observed from the rounded bottom of the polished sample in Figure 36.

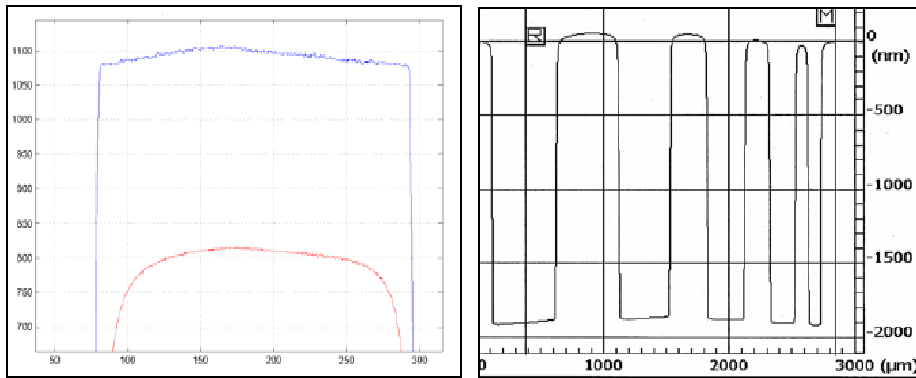


Figure 37. Erosion of the filter structure (left) and improved conventional CMP process with reduced rounding and no visible erosion on the pattern bottom (right) [Paper D]

A lot of development work has been done to overcome this trade-off and improvements have been realized. With the new process another oxide pattern was polished. Now rounding and erosion were greatly reduced and dishing was totally absent (Figure 37 on the right). Still this was not sufficient for the application as major losses would further be expected from still persistent rounding.

Therefore fixed abrasive pads were used to work on the smoothing of elevated patterns. As the abrading composite is rather stiff and decomposes constantly during polishing to expose fresh abrasives rather than to just deform due to the applied load the rounding should be greatly reduced [Paper D]. For ensuring a good surface quality special care was taken that the polishing occurred with sufficient lubrication. As it has already been seen in case of silicon polishing (Chapter 3.3) and with the removal of big oxide patterns (see above), that the required removal for removing the roughness of the deposited film was very low. This in turn was a benefit for the process as the required surface finish would be gained quickly and the film thickness could be adjusted accurately to the needs of the device by adjustment of the polishing time.

Figure 38 compares the details of the critical corner of an elevated oxide structure, polished by conventional CMP (left) and by FA CMP (right). The corner rounding in case of slurry-based CMP reaches several tens of micrometers into the pattern and the slope of the pattern as such is reduced by

the erosion resulting from the process. Applying the FA pad polishing on the same pattern keeps the slope in original shape (besides the systematic error introduced by the finite rounding of the scanning stylus!) and no rounding is visible on top of the oxide structure (note the arrow on the right of Figure 38).

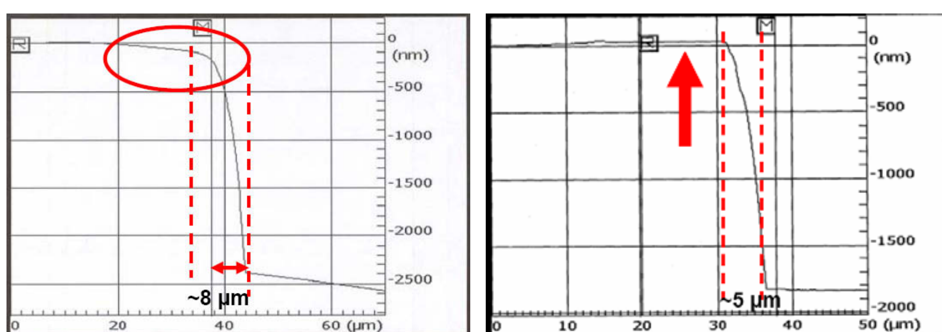


Figure 38. Impact of CMP on the pattern. Conventional CMP (left) tends to strong rounding, while the FA process has very little influence [Paper D]

Besides maintaining the pattern integrity it was of high importance to get a good surface finish as later bonding is used to connect the pre-processed wafer to a cap wafer and therefore an AFM analysis was also made.

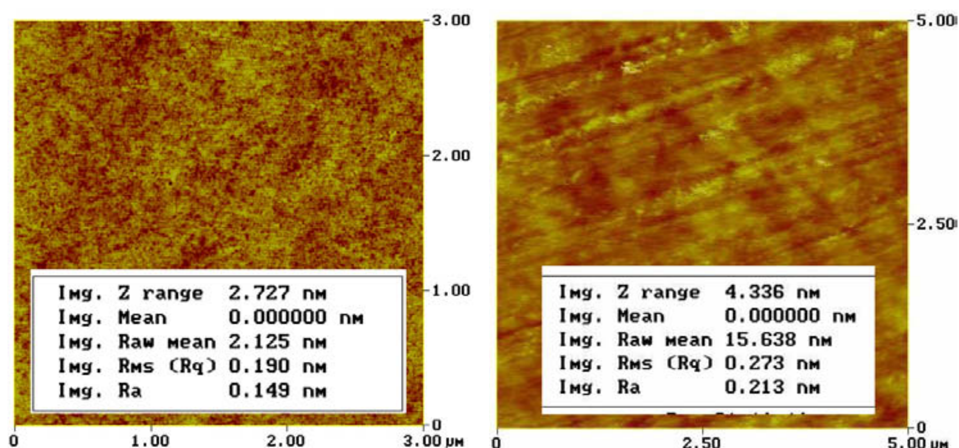


Figure 39. AFM nanographs of slurry-based oxide CMP surface (left) and FA CMP oxide surface (right). While the roughness values are similar the appearance of the surfaces are different. The "wiped" finish of the FA sample is however only about 1 nm in total height difference and of no concern [Paper D]

This made clear another aspect of the novel FA process. The resulting surface roughness was within the range of 2Å like after conventional CMP (Figure 39) and no additional smoothing CMP step was required. The surface however appeared different with a “wiped” finish. A cross-sectional analysis was done to evaluate the topography. A total height variation of less than 1 nanometre was obtained and therefore it was of no concern to use FA, even for the sensitive DWB (direct wafer bonding) process [Paper D].

The bonding test of the FA polished samples resulted in a void-free formation of a wafer stack. A detailed SEM picture of the critical corner after its bonding to the cap wafer can be seen from Figure 40. Bonding occurs to the very edge of the structure providing mechanical stability and the absence of dead pockets. This can be very important for example in the case of using this method for manufacturing micro-fluidic devices.

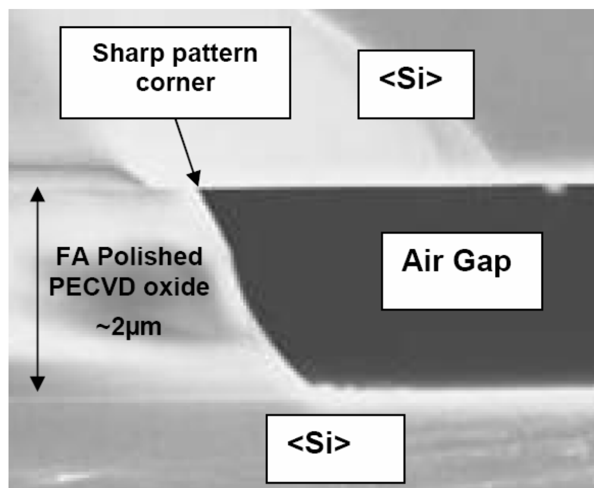


Figure 40. Detailed SEM picture of the bonded corner to the cap wafer. The bonding of the FA polished sample reaches throughout the entire oxide pillar, where the rounding of slurry based CMP would inhibit proper contact

4.3 CMP of Polysilicon Films

The use of polysilicon is very interesting for several MEMS applications, but also for the formation of alternative SOI substrates, when single-crystalline

material is not required. Several people have been reporting on the use of polysilicon in combination with CMP for their MEMS devices [79, 80, 81]. There is often need to bond the polysilicon surface to another substrate. This is usually done by anodic bonding as the surface quality of the deposited polysilicon layer is below the requirements for DWB. Aiming however for high deposition rate thick film polysilicon such as APCVD films with several tens of micrometers thickness, causes severe roughness [82], which would prevent even the most insensitive bonding process. Polishing is therefore needed to implement these films into advanced device formation and alternative substrate manufacturing.

A dedicated two step process has been developed to provide sufficient roughness reduction and surface quality with lowest possible removal [Paper F]. The initial roughness and all other surface disturbances have been removed by a planarizing first step polishing and by a surface finishing second step the roughness was reduced to Å-level (see Figure 41).

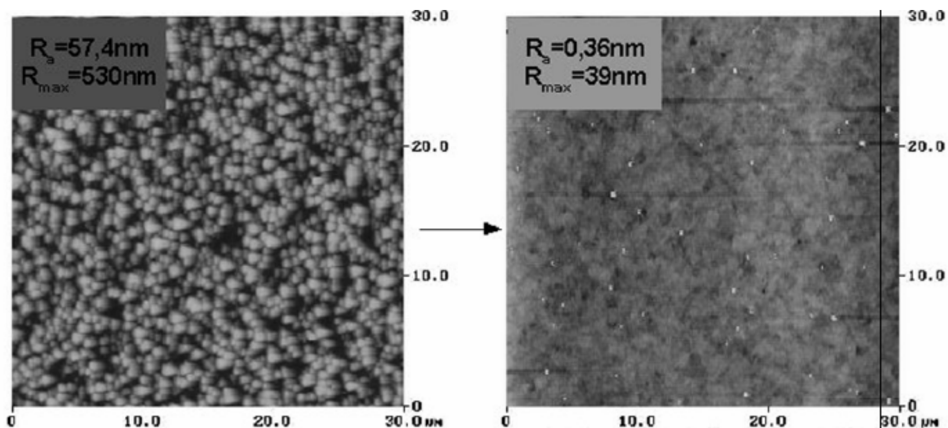


Figure 41. Roughness reduction of thick film polysilicon by dedicated two step CMP process. The resulting surface roughness reaches the quality for enabled low temperature direct wafer bonding

With this CMP sequence it was possible to enable DWB of polysilicon to oxide deposited quartz and glass substrates as well as oxidized silicon wafers at RT and to provide the regular bonding strength of 2000mJ/m^2 as usually seen in silicon wafer bonding.

A SAM picture of a bonded sample can be seen from Figure 42, were only few voids occurred at the outer edge due to wafer handling issues.

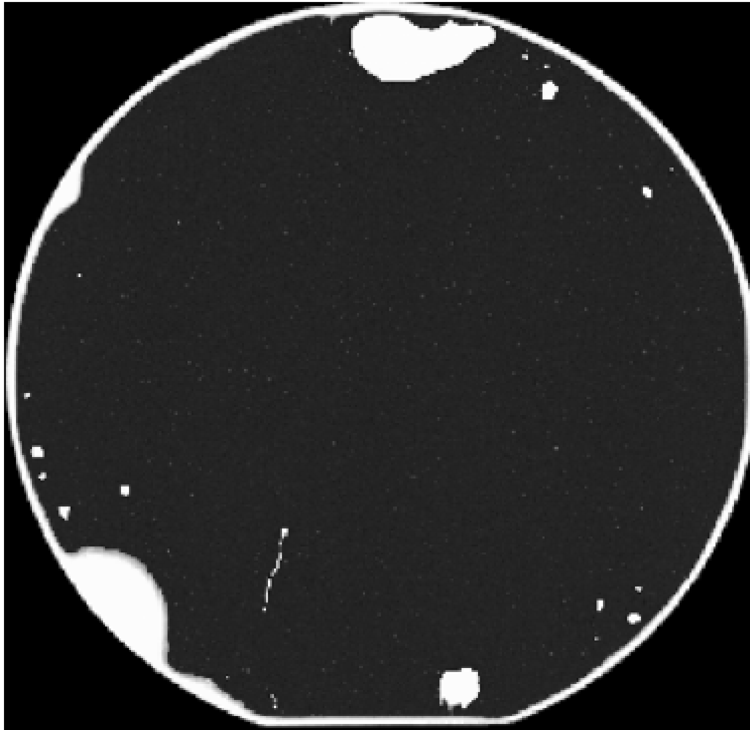


Figure 42. SAM picture of a bonded thick film polysilicon wafer with an oxidized silicon wafer. After applying the developed two step CMP sequence only a few voids caused by wafer handling issues are remaining on the otherwise solid substrate connection

The development of a dedicated CMP process thus enabled the use of polysilicon thick films for the use of WLP or special SOI substrates. With further studies of the polishing process it will be possible to also integrate the simultaneous planarization of the underlying device pattern of a MEMS device and enables the simultaneous capping of a ready device by formation of a double layer SOI wafer. This is an important achievement to manufacture real 3D-MEMS devices, which are a main path for several upcoming developments like smart multi-axis accelerometers for automotive applications.

5. Conclusions

The purpose of this work has been the utilization of CMP in the field of MEMS manufacturing for enabling new capabilities in the area of micromechanical device formation.

Starting from the use of the FA pad technology for thick film SOI wafer processing it was possible to present a new sequence, which results in ultra flat SOI layers. The overall quality of the substrates was examined by utilizing standard metrology techniques of industrial wafer manufacturing. The additional use of low-SSD grinding enabled a greatly reduced polishing removal and led to a highly competitive method ready for industrial production application. The mechanism of removing silicon by FA is studied and a model for abrasion is presented, based on the findings of the intense analysis of the process. The particularities of the FA pad are analyzed and turned into benefits.

CMP was successfully implemented in MEMS structure manufacturing. By polishing of thick deposited oxide films Å-level roughness enabled the DWB at RT and LT annealing, and allows the use of a wide variety of materials in the stack including metals. Planarization of large features often mandatory in MEMS is enabled by the use of a suitable FA CMP step. Conventional CMP processes would lead to inferior results and are compared with the FA sequence.

Smoothing the surface of elevated patterns is demonstrated by FA CMP, resulting in Å-level roughness. No edge rounding or erosion of the features is observed and successful bonding corroborates the beneficial outcome of the process. A comparison with slurry based CMP indicates the tremendous benefits of the novel planarization technique.

With the results of this work it is possible to utilize CMP for several new applications in the field of micromechanical structures as well as significant knowledge on the behaviour of fixed abrasives is generated. A comprehensive overview of CMP technology and its tribology in both conventional and fixed abrasive polishing is given. The removal mechanism of oxide and silicon during polishing is discussed and connected to the actual fabrication challenges being faced in today’s processing.

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Abstract

The present work reports on studies and process developments to utilize the chemical mechanical planarization (CMP) technology in the field of micro electrical mechanical systems (MEMS). Approaches have been undertaken to enable the manufacturing of thick film SOI (silicon-on-insulator) substrates with a high degree of flatness as well as utilizing CMP for the formation of several novel MEMS devices. Thick film SOI wafers are of high interest in MEMS manufacturing as they offer obvious benefits as a starting material or foundation for more complex structures. Precise control of the SOI layer thickness as well as the removal uniformity is of critical importance to fully utilize the benefits of this technology. By combining fixed abrasive (FA) pads for polishing and novel grinding techniques it is shown that major improvements can be achieved over the standard manufacturing sequence. Analysis of the material removal rate (MRR) dependency on several process parameters is made. Together with the FA pad vendor a suitable consumable set for SOI is generated, which shows long term stability in the generated process. A comparison with standard methods is undertaken to prove the surface and crystalline quality of the material is equivalent. Analysis is done to understand the microscopic mechanism of removal. The CMP process is applied to several MEMS structures to smooth deposited oxide films and to enable direct wafer bonding (DWB) at low temperatures. This allows the design of bonded multiple stack layers including heat sensitive materials such as metals. FA CMP is applied to large pattern MEMS for total planarization but also for smoothing of the surface of single protruding structures while minimizing edge rounding and preserving the original intended pattern shape. With dedicated CMP steps thick film polysilicon smoothing is demonstrated enabling DWB. The mechanical particularities of the FA pad are investigated in detail.

Keywords
CMP, micro electro mechanical systems, polishing, fixed abrasive, MEMS, SOI, silicon-on-insulator, direct wafer bonding, DWB, low temperature bonding, FA

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Chemical mechanical planarization (CMP) is a comparably new technology, being introduced in the eighties to overcome problems with increasing topography on the ever shrinking integrated circuits (IC) and the demand of multilayer metallization. The topography is removed by polishing the extent amount of material using an elastic polishing pad and chemically active polishing agent with added abrasive particles. Since then the process has seen a rapid evolution and was introduced into several areas of the IC production.

The present work reports on studies to utilize CMP in the field of micro-electro-mechanical systems (MEMS) to create a new technology platform for the future demands of the growing micromechanical world.

Approaches have been undertaken to enable the manufacturing of thick film SOI (silicon-on-insulator) substrates with a high degree of flatness. These wafers are of high interest in MEMS manufacturing as they offer obvious benefits as a starting material or foundation for complex structures. Precise control of the SOI layer thickness and uniformity is achieved by using novel fixed abrasive (FA) pads.

Standard and FA CMP is applied to several MEMS structures for smoothing of deposited oxide and thick polysilicon films to enable direct wafer bonding (DWB) at low temperatures. This allows the formation of 3-D structures including heat sensitive materials such as metals. FA CMP is further applied to large pattern MEMS for total planarization while avoiding degradation of the pattern shape. The FA pad is investigated in detail, compared with standard CMP and the mechanism of removal is discussed.

This book summarizes about 3 years of exciting research and development to contribute to the success story of one of the youngest and most widely growing processes in the semiconductor industry.

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