Materials and Manufacturing Processes, 23: 449–456, 2008
Copyright © Taylor & Francis Group, LLC
ISSN: 1042-6914 print/1532-2475 online
DOI: 10.1080/10426910802103486

Recent Advances in Polishing of Advanced Materials

Z. W. Zhong

*School of Mechanical and Aerospace Engineering, Nanyang Technological University,
Singapore, Singapore*

This article discusses the recent advances in polishing of advanced materials. Ninety-five journal articles published in 2005–2007 are briefly introduced. The topics are advances in chemical mechanical polishing (CMP), fluids for polishing, modeling of polishing, polishing of brittle materials, robotic polishing, polishing with vibrations or beams, and friction in polishing processes. CMP is perhaps the hottest research topic in the articles reviewed. Many "noncontact" processes are developed using magnetic fluids, electrorheological fluids, and abrasive flow for polishing of complicated geometries or difficult-to-approach regions. Modeling of polishing processes helps to understand the polishing mechanisms and is thus increasingly performed worldwide. More research on simulations of polishing processes can be expected in the near future. Polishing of brittle materials is also highly demanded. Automatic polishing of curved surfaces using robots and CNC machines, and polishing with vibrations and beams are promising. Investigations of friction in polishing processes help to understand the polishing mechanisms or control the polishing processes.

Keywords Abrasive flow machining; Advanced materials; Beams; Brittle materials; Chemical mechanical polishing; Curved surfaces; Electrorheological fluid; Friction; Magnetic fluid; Modeling; Polishing mechanisms; Polishing processes; Robotic polishing; Simulation; Vibration-assisted polishing.

1. Introduction

Polishing processes become more important because of the increasing demand for better surface finish. However, the mechanisms of polishing processes are still not fully understood [1]. The parameter settings are often determined by trial and error or expert experience. This may not lead to optimal parameter settings [2]. Therefore, efforts are made worldwide to better understand polishing mechanisms [3–5] and/or optimize polishing processes using various methods such as systemically designed experiments [6], ANOVA and Turkey's honest significant difference multiple comparison tests [7] for various applications such as polishing of quartz [8], diamond films [9], MgO single-crystal substrates [6], ultrathin dielectric substrates [10], and deposited surfaces during nickel electrodepositing [11] as well as polishing of microbores for microfluidics and optical applications [12], and feldspathic ceramics [13] and other materials for medical applications [14]. This general review article attempts to briefly introduce the recently published journal articles. With the reference provided, readers may explore more deeply by reading a particular article for detailed description of a polishing process and its results.

2. Chemical mechanical polishing (cmp)

With the demand for higher-performance in integrated circuits (ICs) and MEMS devices, there is more research on CMP. Besides planarization of Si wafers, CMP is also increasingly performed to planarize and/or smooth various thin films, low-*k* and ultra-low-*k* devices, copper structures, polymer substrates, hard disk substrates, SiC wafers, etc. Research efforts are also made to understand the CMP mechanisms and the effects of slurry and abrasive types, pH values, temperature changes, polishing pads, polishing time, and other process parameters on material removal rates (MRRs), surface quality, and within-wafer nonuniformity.

The pH value of slurry is an important factor in CMP processes. Planarity strongly depends on the pH value [15]. Slurries with the highest removal rate have a high dissolution rate at lower pH [16]. The tantalum oxide films formed during CMP are thinner at pH 2 compared to pH 10 [17]. The pH value change caused by the temperature change affects the surface state of abrasive particles [18]. The pH adjustment and addition of sodium dodecyl sulfate result in a ten-fold increase in selectivity compared to conventional colloidal silica slurry [19]. With an increased temperature, the pH value decreases [20]. Oxalic and malonic acids are most effective at pH 3–4 for abrasive-free removal of Cu [21].

CMP of copper structures is an important operation, and therefore the effects of various parameters during copper CMP have been studied [22, 23]. The use of Scanning Kelvin Probe Force Microscopy can characterize post-CMP copper structures and detect metallic contamination [24].

The polishing pad can significantly affect the process stability. The holes on the pad surface is filled by the reactant, and the pad surface gradually has hard glazing, which reduces the pad ability of absorbing slurry and leads to scratches on the workpiece. The pad must be conditioned regularly [25]. Plowing is the major mechanism if dressing is conducted by a diamond face, while cutting action dominates if dressing is performed by a diamond point [26]. The surface roughness of the pad determines the MRR as the material is removed by direct contact with the pad surface [27]. The surface waviness with a concentric circular

---

Received October 23, 2007; Accepted March 20, 2008

Address correspondence to Z. W. Zhong, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Republic of Singapore; Fax: (65) 6791 1859; E-mail: mzwzhong@ntu.edu.sg

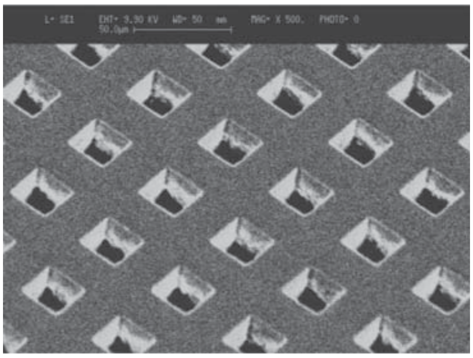

FIGURE 1.—25–25 µm square pattern on SU-8 after chemical mechanical polishing [31].

pattern is generated on highly-boron-doped Si wafers by CMP with amine system slurry [28]. The waviness results from the change of the etching rate in the amine etching system. If CMP of the Si substrate is performed using a hard polishing pad, a smooth surface can be obtained without waviness.

Studies of peeling with respect to the number of ultra low-k dielectric films in interconnect stacking during CMP [29] reveal that delamination during polishing depends on the elastic properties of the interconnect stack. The addition of ultra low-k levels has a major effect on delamination during CMP, due to the effect of the stack residual stress and elasticity.

Polymers are replacing silicon as the major substrates in microfluidic system fabrication because of their outstanding features. CMP is well suited for polishing SU-8 structures (Fig. 1). Polished poly(methyl methacrylate) (Fig. 2), polycarbonate, and SU-8 surfaces have nanometer-order surface roughness [30, 31], acceptable for most MEMS applications.

Studies of CMP of Si and SiC wafers show that the removal rate and surface quality vary greatly with crystal orientations [32]. High-quality surfaces can be obtained by CMP with colloidal silica [33]. Lapping of SiC wafers causes great residual stresses and a deep damage layer. Surfaces machined by mechanical polishing show a large number of scratches with depths of 5–8 nm, which can be removed by CMP and an extremely smooth surface with a low damage layer and roughness $R_a = 0.3$ nm can be obtained [34].

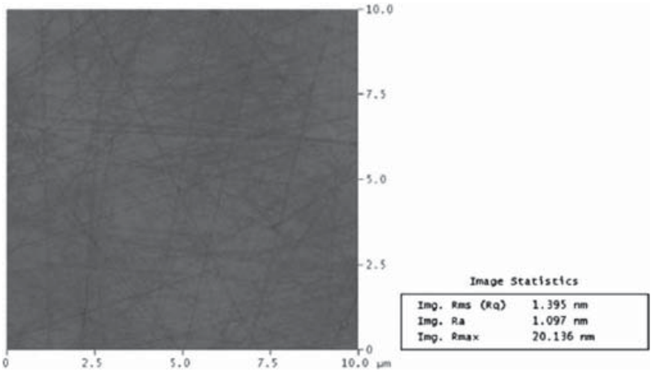

FIGURE 2.—AFM image of poly(methyl methacrylate) after chemical mechanical polishing [30].

Polishing time is an important issue in CMP processes. A neural-Taguchi method can help to reduce the number of experiments without affecting the completeness [35]. With optimal parameters, the desired MRR and within-wafer-nonuniformity can be achieved with the optimal polishing time.

Abrasive is another key factor affecting the CMP quality. α-alumina particles are widely used in CMP slurries, but often result in surface defects due to their high hardness. CMP of hard disk substrates using alumina/silica abrasives [36] reveals that slurries containing these abrasives result in fewer scratches and lower surface roughness, waviness and topographical variations than that containing a pure alumina abrasive.

3. FLOAT POLISHING

A polishing process typically uses a polishing pad and loose abrasives to contact the workpiece, forming a "three-body abrasion" mechanism. However, many "noncontact" polishing processes are also developed using magnetic fluids, electrorheological fluids, and abrasive flow for polishing of complicated geometries or difficult-to-approach regions.

Magnetic compound fluids (MCFs) can be used for noncontact float polishing. The polishing effect depends on the magnetic field strength [37]. The float polishing effect without using a polishing pad is larger than that using a polishing pad. Using a mixed MCF can polish inner capillary walls made of nonmagnetic material. The fluid has the features of a magnetic fluid and a magnetorheological [38] fluid. The polishing involves abrasive particles aggregating at a certain section of the polished wall [39].

Recent research on polishing processes reveals the importance of chemistry, especially slurry pH, for preventing particle agglomeration to achieve smooth surfaces with conventional pads. New sub-aperture polishing processes like magnetorheological finishing (MRF) can shape and smooth spherical, aspherical, flat, and free-form surfaces within a few process iterations. MRF can also finish soft polymer, microstructured polycrystalline zinc sulfide, and water soluble single-crystal potassium dihydrogen phosphate [40]. A mixture of magnetic fluid, magnetorheological fluid, abrasive particles, and cellulose is also proposed [41] for surface finishing.

Optical components of reaction-bonded SiC have attracted research interest because of their high hardness, and low density and thermal expansion coefficient [42]. In one study, a manufacturing system equipped with magnetorheological (MR) finishing technology (Fig. 3 [43]) was adopted to manufacture high-precision parabolic mirrors of reaction-bonded SiC. The final surface roughness (R_a) was reduced from 34.39 nm to 26.74 nm after prepolishing using MR fluids carrying oil with Al_2O_3, and was further reduced to 1.14 nm after fine polishing using the MR fluid with diamond powder. Magnetorheological

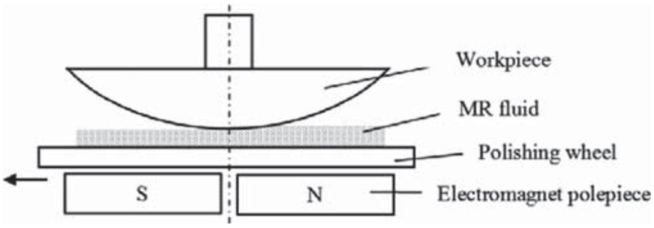

FIGURE 3.—Magnetorheological (MR) finishing [43].

abrasive flow finishing is also developed [44] for complicated geometries using magnetorheological polishing (MRP) fluid, which has carbonyl iron powder and SiC abrasives dispersed in grease and mineral oil. MRP fluid changes its rheological behavior in a magnetic field, which can be used to precisely control finishing forces.

The viscosity of electrorheological (ER) fluid can change with the applied electric field strength. ER-fluid-assisted polishing of WC microdies can be used for mass production of microaspheric glass lenses [45]. An ER-fluid-aided polisher using patterned electrodes is proposed [46], and abrasive grit is condensed on the thick clusters of ER fluid particles formed around the electrodes with increased voltage.

Abrasive flow machining (AFM) is another nontraditional method, which can offer excellent surface finish on difficult-to-approach regions of components and can replace time-consuming deburring and polishing operations [47]. AFM polishes, radiuses and deburrs surfaces and edges by flowing abrasive media over these areas. This process can polish internal shapes that may be difficult to machine using other processes. However, AFM has low MRRs. Therefore, using a rotating rectangular rod inside a hollow workpiece to apply a centrifugal force is explored [48], and this enhances the MRR and improves the surface roughness. In another study [49], abrasive particles and silicone rubber are uniformly mixed to be the flexible media. A chain hole cut by wire electrical discharge machining is polished by AFM using the media. The abrasive medium with high viscosity has excellent deformation and can easily smooth the hole surface. The surface roughness (R_a) decreases from 1.8 μm to 0.28 μm after five machining cycles.

4. MODELING OF POLISHING PROCESSES

Modeling is intensively performed by engineers in the microelectronics manufacturing industry. For example, mobile phone manufacturers have to shorten the development cycle time for their new products to rapidly meet the competing market needs. Modeling and simulations can help them to save the time for full reliability tests, which are very time-consuming. Precision engineering industry may not have such an urgent demand like that in the microelectronics industry. Engineers traditionally can spend time to conduct polishing experiments to achieve their goals. However, modeling and simulations of polishing processes are increasingly performed by researchers, because this approach helps to understand the polishing mechanisms, as discussed in this section. With more engineers obtaining skills of mathematic modeling, molecular dynamics (MD) simulations, and finite element (FE) simulations, more reports on modeling and simulations of polishing processes can be expected in the near future.

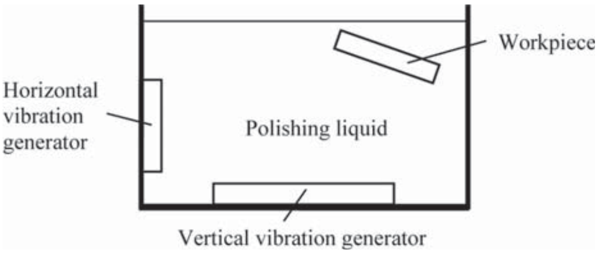

FIGURE 4.—Polishing based on coupling vibrations of liquid [54].

Analytical models [50, 51] and FEA models [52, 53] are increasingly developed to characterize polishing processes. Experimentation is the basis for technology development and science discovery, but there are cases where experiments can hardly be implemented. MD simulations may provide suitable tools, and are powerful in studying ultrafine machining including polishing. The great contributions of MD simulation to the polishing based on coupling vibrations of liquid (Fig. 4) is an example [54]. MD simulations can be run on systems containing millions of particles, and more MD simulations for ultrafine machining can be expected.

For CMP of a thin layer of SiO_2 on a Si wafer, regression models are developed to determine optimum process conditions [55]. The slurry flow beneath the wafer in CMP involves chemical reaction and lubrication, and it is critical to the planarity and surface quality of the large Si wafer. A 3D model based on Brinkman equations and Darcy's law can analyze the effects of pad roughness and key operating parameters on the slurry flow with the suspended abrasives between the wafer and the pad [56]. A model for step height reduction is proposed and the topography evolution on the wafer surface is simulated [57]. The MRR during CMP depends sensitively on pattern geometry and density.

An extension of the density-step height model for pattern effects in oxide CMP [58] reveals that oxide removal rates have a linear dependence on down force and a sublinear dependence on relative velocity. Studies of the compressibility variations of major types of pad with polishing time by modeling and experiments [59] find the compressibility of pads changes because of wear. The compressibility of a pad can be used to judge whether or not the pad is good for polishing. Modeling of pad wear can predict thickness variation of the polishing pad [60]. The polishing pad surface can be deteriorated, reducing the polishing rate and planarity because of pad wear and glazing. Conditioning of polishing pads is one most important process in CMP. Longer conditioning time leads to a higher concavity incidence of the polishing pad. A microcontact model based on the Sneddon's equation is developed [61] for CMP with a soft pad. The large deformation of the pad can significantly affect the microcontact force between a single particle and the pad.

The mechanical response at the interface between the silicon, low-*k*, and copper layer of the wafer is simulated under the loading of the CMP [62]. The results show that the large blanket wafer within high applying pressure would exhibit high stresses possible to delaminate the interface at the periphery of the wafer, and reducing the copper thickness can diminish the possibility of the delamination/failure of the low-*k* material.

5. POLISHING OF HARD AND BRITTLE MATERIALS

Si wafers are the fundamental substrate for most ICs. Over 90% of semiconductor devices are fabricated on Si wafers. Polishing is an important process to obtain the required surface quality. The results of polishing of Si wafers [63] show that the pad speed and the polishing pressure are the most significant factors affecting MRR. A key requirement of Si wafer fabrication processes is extremely flat wafer surfaces with a diameter of up to 350 mm. The surfaces must be smooth and have minimum subsurface damage before the final etching and polishing. Reduced polishing time and improved surface quality can be achieved by increased ductile streaks before polishing [64]. A polishing method using polymer particles is proposed [65] for solving the problems associated with pad deterioration, process inconsistency and poor accuracy, and the results show that appropriate combination of tool plate with polymer particles can greatly improve polishing quality.

SiC is polished using the tribochemical reaction mechanism. Ferrous metal disks effectively polish SiC in water, and the maximum MRR is 0.06 μm/h. The SiC surface is removed tribochemically by the catalytic effect of iron oxide, and no damage on the polished surface is observed. During polishing, ferrous metal disks react with water and form iron oxide, which is a catalyst to assist the tribochemical reaction of water and SiC, leading to hydrolysis of SiC. The reaction mechanism is expressed as follows [66]:

$$SiC + 2H_2O \rightarrow SiO_2 + C + 2H_2. \tag{1}$$

Polishing of Si_3N_4 balls [67] reveals that in rough polishing, high polishing load can lead to rapid reduction of surface roughness. In fine polishing, the erosive process without polishing load dominates the reduction of surface roughness, but cannot remove the high roughness peaks. The diamond particle size should be reduced gradually in the lapping process to avoid generating deep scratches, which are difficult to be removed during the polishing process.

6. ROBOTIC AND CNC POLISHING

Polishing is an important finishing process for die and mold manufacturing. Hand polishing of free form surfaces is widely conducted, but this approach is time and labor consuming. Therefore, automatic polishing of curved and free form surfaces is conducted using robots and CNC machines for various applications. Free form surfaces can be polished using a grinding center by applying the same cutter location (CL) data used in the cutting process to remove only cusp height and maintain the form accuracy generated in the cutting process [68]. A data integration method [69] uses adjacency and feature-data matrices to establish a framework of feature-based data, and enables the storage, retrieval, and operations of geometries, topologies, and machining information for a given ruled mold surface. Molds can be manufactured using a CNC machine and a magnetic polishing tool [70]. Magnetic force produces the polishing pressure and polishing of curved surfaces is possible without tool path control.

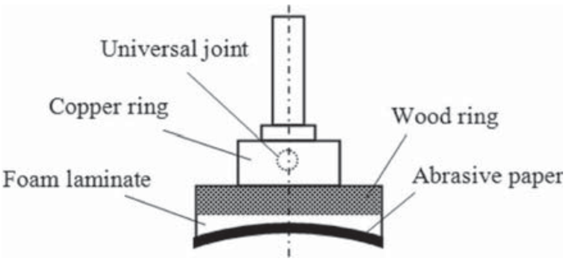

FIGURE 5.—A new compliant polishing tool [74].

The robot polishing path can be generated from the CL data obtained from the postprocessor of a CAD system. The polishing robot does not require the complicated teaching process. A quaternion interpolation algorithm [71] can realize the smooth interpolation of the end-effector positions. CL data can be also used for a desired trajectory of tool translational motion and contact directions, realizing a complete non-taught robotic polishing of molds [72]. Development of new polishing tools is also important for polishing curved mould surfaces [73]. A polishing process is proposed using a new compliant abrasive tool (Fig. 5 [74]) and a force-controllable five-axes robot. Optimal parameters are determined using the Taguchi method. The polishing force dominates the polishing quality.

7. POLISHING WITH VIBRATIONS, BEAMS, EDM, OR POLYMER PARTICLES

Aspherical microglass lenses can be manufactured by a glass press process using ground and polished molds. An ultrasonic vibration-assisted polishing machine is developed [75] to polish aspherical molds with diameters <3 mm. As shown in Fig. 6, a small polishing tool is vibrated by piezoelectric ultrasonic actuators. Form accuracy below 70 nm and surface roughness of 7 nm could be obtained. Polishing of quartz glass can be performed using an ultrasonic vibrating device [76] that produces coupling

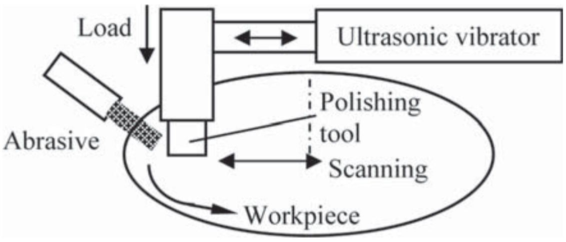

FIGURE 6.—Ultrasonic vibration-assisted polishing [75].

TABLE 1.— Contributions of pulsed current, ultrasonics and the electrode geometry to surface finish improvement [77].

Factor	Contribution (%)
Pulsed current	18
Ultrasonics	24
Electrode geometry	58

vibrations of liquid. Ultrasonic energy is also used to assist the dregs discharge in electrochemical finishing to improve surface finish of large holes. The contributions of pulsed current, ultrasonics and the electrode geometry to surface finish improvement are assessed (Table 1) [77]. The average effect of the ultrasonic energy is advantageous over the pulsed current [77]. Efficient polishing of 3D microcurved surfaces is also possible by a vibration-assisted magnetic abrasive polishing process [78].

One drawback of selective laser sintering is the high surface roughness of resulting parts, which can be polished using laser irradiation beams. The laser beam melts a microscopic layer on the surface, which re-solidifies under shielding gas conditions and leads to a smoother surface. Laser-polishing of sintered parts with R_a roughness of 7.5–7.8 μm resulted in final surface roughness below 1.49 μm [79]. A large-area electron beam (ϕ60 mm) can be used for melting a metal surface in a few microseconds. The surface roughness decreases from 6 μm to <1 μm in a few minutes, and the corrosion resistance of metal mold surfaces can be improved [80].

An EDM machine can be used for a micro-energy discharge process followed by an electrophoretic deposition (EPD) process to coat Al_2O_3 particles on a rotation electrode. The EPD polishing can reduce the R_a roughness of a discharged surface from 0.52 μm to 0.068 μm [81]. Electrochemical polishing of EDM surfaces can be also conducted [82]. A 4-body finishing process is developed using a paste dispersion medium and fine polymer particles as the 4th body to extinguish the microscratches and improve the dispersion stability of the polishing paste. High removal rates and dispersion stability can be obtained using a new paste with low viscosity base agent and fine media particles [83]. Extra-large gas cluster ions can be also used for surface polishing [84].

8. FRICTION IN POLISHING PROCESSES

Copper pits formed after copper CMP are critical defects because they can cause missed or broken interconnections. One important factor affecting the pit formation is the friction force. Studies of polishing friction kinetics [85] help to understand the pit-defect formation mechanism (the magnitude of the friction torque and the location of the edges between the metal line and wafer induce the defect) and significantly reduce the pit formation. Research on the correlation between CMP results and frictional and thermal characteristics of SiO_2 slurry [86] reveals that the effects of mechanical factors in CMP can be expressed as friction force and heat generated by friction. The characteristics of silica slurry such as conductivity, particle size, pH, and zeta potential are changed by the frictional heat during polishing and the remaining heat after a high-temperature pad conditioning process. These changes made the oxide surface removed easily [87]. Research on the relationship between the direction of the frictional force vector and the delamination probability in CMP of Cu/low-*k* damascene structures [88] finds that the directivity of the friction force vector reduces the delamination probability. The delamination probability of a wafer is low when it is polished by the scan-type CMP operating with directional friction force compared to the conventional CMP.

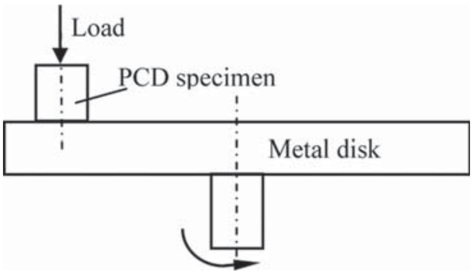

FIGURE 7.—Schematic illustration of dynamic friction polishing [92].

Sensors can be installed in CMP equipment to simultaneously measure frictional behavior during polishing [89]. Monitoring the friction force and temperature of the polishing pad surface can help to reduce the pad conditioning time during polishing [90]. Abrasive grains with blunt edges are easily ablated from the polishing wheel by friction during polishing. The wheel can be continuously refreshed by adding new abrasive grains [91]. Studies using a dynamic friction polishing (Fig. 7) technique [92] reveal that the material removal mechanisms of PCD can be chemomechanical, diffusion, oxidization, evaporation, and their combinations.

Studies of galling properties of tool steel sliding against different work materials [93, 94] reveal that a polished plasma nitrided surface provides improved friction and wear properties of the tool steel and reduces the galling tendency in sliding against austenitic stainless steel. In polishing Cu and Al surfaces, H_2O_2 slurries with friction stimulation can produce an oxide layer [95].

9. CONCLUSIONS

(1) CMP is increasingly performed to planarize and smooth advanced materials and is the hottest research topic in the journal artile reviewed.
(2) Many "noncontact" polishing processes are developed using magnetic fluids, electrorheological fluids, and abrasive flow for complicated geometries.
(3) Modeling of polishing process is also increasingly performed worldwide, helping to understand the polishing mechanisms. With more engineers obtaining the skills of mathematic modeling, MD, and FE simulations, more research on modeling of polishing processes can be expected in the near future.
(4) Polishing with vibrations, beams, EDM, or polymer particles are also promising.
(5) Investigations of friction in polishing processes help to understand the mechanisms or control the processes.

References

1. Dambon, O.; Demmer, A. Surface interactions in steel polishing for the precision tool making. CIRP Annals – Manufacturing Technology **2006**, *55* (1), 609–612.
2. Lo, V.H.Y.; Huang, G.Q.; Cheng, K.C.; Tsang, Y.M. The use of Taguchi methods in polishing for quality optimization. International Journal of Reliability, Quality and Safety Engineering **2007**, *14* (3), 297–309.
3. Sura, E.; Mansori, M.E.; Ghidossi, P.; Deblaise, S.; Negro, T.D.; Khanfir, H. An energy analysis of belt polishing process and its applications to time cycle and tracking effects. Machining Science and Technology **2007**, *11* (2), 217–234.
4. Horng, T.L. A model to simulate surface roughness in the pad dressing process. Journal of Mechanical Science and Technology **2007**, *21* (10), 1599–1604.
5. Zhang, X.Y.; Yang, J.L.; Huang, Y. Research on surface finish of ceramic beads. Rare Metal Materials and Engineering **2005**, *34*, 178–180.
6. Wang, K.; Kang, R.K.; Jin, Z.J.; Wang, N.H. An experimental study of the polishing process for MgO single crystal substrate. Key Engineering Materials **2007**, *329*, 225–230.
7. Reddy, E.S.; Patil, N.P.; Guttal, S.S.; Jagadish, H.G. Effect of different finishing and polishing agents on the surface roughness of cast pure titanium: Basic science research. Journal of Prosthodontics **2007**, *16* (4), 263–268.
8. Vallin, O.; Danielsson, R.; Lindberg, U.; Thornell, G. Polishing of quartz by rapid etching in ammonium bifluoride. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control **2007**, *54* (7), 1454–1462.
9. Chou, W.C.; Chao, C.L.; Chien, H.H.; Ma, K.J.; Lin, H.Y. Investigation of thermo-chemical polishing of CVD diamond film. Key Engineering Materials **2007**, *329*, 195–200.
10. Touge, M.; Watanabe, J. Ultra-thinning processing of dielectric substrates by precision abrasive machining. CIRP Annals – Manufacturing Technology **2006**, *55* (1), 317–320.
11. Zhu, D.; Zhu, Z.W.; Qu, N.S. Abrasive polishing assisted nickel electroforming process. CIRP Annals – Manufacturing Technology **2006**, *55* (1), 193–196.
12. Ramesh, K.; Lewis, W.G.; Yin, L.; Zhou, F.F. Linear grinding of microbores using diamond-adhered wire. Materials and Manufacturing Processes **2007**, *22* (2), 271–276.
13. Sarac, Y.S.; Elekdag-Turk, S.; Sarac, D.; Turk, T. Surface conditioning methods and polishing techniques effect on surface roughness of a feldspar ceramic. Angle Orthodontist **2007**, *77* (4), 723–728.
14. Barbour, M.E.; O'Sullivan, D.J.; Jenkinson, H.F.; Jagger, D.C. The effects of polishing methods on surface morphology, roughness and bacterial colonisation of titanium abutments. Journal of Materials Science: Materials in Medicine **2007**, *18* (7), 1439–1447.
15. Seo, Y.J.; Park, J.S.; Woo-Sun, L. Chemical mechanical polishing of PZT thin films for FRAM applications. Microelectronic Engineering **2006**, *83* (11-12), 2238–2242.
16. Seo, Y.J.; Kim, N.H.; Lee, W.S. Electrochemical corrosion effects and chemical mechanical polishing characteristics of tungsten film using mixed oxidizers. Microelectronic Engineering **2006**, *83* (3), 428–433.
17. Zhang, J.; Li, S.; Carter, P.W. Chemical mechanical polishing of tantalum. Journal of the Electrochemical Society **2007**, *154* (2), H109–H114.
18. Kwon, D.; Kim, H.; Jeong, H. Heat and its effects to chemical mechanical polishing. Journal of Materials Processing Technology **2006**, *178* (1–3), 82–87.
19. Bu, K.H.; Moudgil, B.M. Selective chemical mechanical polishing using surfactants. Journal of the Electrochemical Society **2007**, *154* (7), 631–635.
20. Kim, N.H.; Ko, P.J.; Seo, Y.J.; Lee, W.S. Improvement of TEOS-chemical mechanical polishing performance by control of slurry temperature. Microelectronic Engineering **2006**, *83* (2), 286–292.
21. Ramakrishnan, S.; Janjam, S.V.S.B.; Patri, U.B.; Roy, D.; Babu, S.V. Comparison of dicarboxylic acids as complexing agents for abrasive-free chemical mechanical planarization of copper. Microelectronic Engineering **2007**, *84* (1), 80–86.
22. Kulkarni, M.; Ng, D.; Baker, M.; Liang, H.; Her, R. Electropotential-stimulated wear of copper during chemical mechanical planarization. Wear **2007**, *263* (7-12 SPEC. ISS.), 1470–1476.
23. Kim, N.H.; Choi, M.H.; Kim, S.Y.; Chang, E.G. Design of experiment (DOE) method considering interaction effect of process parameters for optimization of copper chemical mechanical polishing (CMP) process. Microelectronic Engineering **2006**, *83* (3), 506–512.
24. Dominget, A.; Farkas, J.; Szunerits, S. Characterization of post-copper CMP surface with scanning probe microscopy: Part II: Surface potential measurements with scanning Kelvin probe force microscopy. Microelectronic Engineering **2006**, *83* (11–12), 2355–2358.
25. Tso, P.L.; Ho, S.Y. Factors influencing the dressing rate of chemical mechanical polishing pad conditioning. International Journal of Advanced Manufacturing Technology **2007**, *33* (7–8), 720–724.
26. Liao, Y.S.; Tsai, M.Y.; Sung, J.C.; Pai, Y.L. Single diamond dressing characteristics of CMP polyurethane pad. Key Engineering Materials **2007**, *329*, 151–156.
27. Park, K.H.; Kim, H.J.; Chang, O.M.; Jeong, H.D. Effects of pad properties on material removal in chemical mechanical polishing. Journal of Materials Processing Technology **2007**, *187–188*, 73–76.
28. Watanabe, J.; Yu, G.; Eryu, O.; Koshiyama, I.; Izumi, K.; Nakashima, K.; Umeno, M.; Jimbo, T.; Kodama, K. High precision chemical mechanical polishing of highly-boron-doped Si wafer used for epitaxial substrate. Precision Engineering **2005**, *29* (2), 151–156.
29. Leduc, P.; Farjot, T.; Savoye, M.; Demas, A.-C.; Maitrejean, S.; Passemard, G. Dependence of CMP-induced delamination on number of low-*k* dielectric films stacked. Microelectronic Engineering **2006**, *83* (11–12), 2072–2076.
30. Zhong, Z.W.; Wang, Z.F.; Tan, Y.H. Chemical mechanical polishing of polymeric materials for MEMS applications. Microelectronics Journal **2006**, *37* (4), 295–301.
31. Zhong, Z.W.; Wang, Z.F.; Zirajutheen, B.M.P.; Tan, Y.S.; Tan, Y.H. Polishing of poly(methyl methacrylate), polycarbonate, and SU-8 polymers. Materials Science **2007**, *25* (1), 103–112.
32. Chen, X.F.; Xu, X.G.; Hu, X.B.; Li, J.; Jiang, S.Z.; Ning, L.N.; Wang, Y.M.; Jiang, M.H. Anisotropy of chemical mechanical polishing in silicon carbide substrates. Materials Science and Engineering B: Solid-State Materials for Advanced Technology **2007**, *142* (1), 28–30.
33. Chen, X.; Xu, X.; Li, J.; Jiang, S.; Ning, L.; Wang, Y.; Ma, D.; Hu, X.; Jiang, M. Surface polishing of 6H-SiC substrates.

Journal of Materials Science and Technology **2007**, *23* (3), 430–432.

34. Chen, X.; Li, J.; Ma, D.; Hu, X.; Xu, X.; Jiang, M. Fine machining of large-diameter 6H-SiC wafers. Journal of Materials Science and Technology **2006**, *22* (5), 681–684.
35. Wang, G.J.; Chou, M.H. A neural-Taguchi-based quasi time-optimization control strategy for chemical-mechanical polishing processes. International Journal of Advanced Manufacturing Technology **2005**, *26* (7–8), 759–765.
36. Lei, H.; Zhang, P. Preparation of alumina/silica core-shell abrasives and their CMP behavior. Applied Surface Science **2007**, *253* (21), 8754–8761.
37. Shimada, K.; Wu, Y.; Matsuo, Y.; Yamamoto, K. Float polishing technique using new tool consisting of micro magnetic clusters. Journal of Materials Processing Technology **2005**, *162–163* (SPEC. ISS.), 690–695.
38. Di Luzio, S.; Revel, P.; Gagnaire, H.; Feraud, B. An industrial process of high precision aspherical lens surfaces manufacturing. Mecanique et Industries **2007**, *8* (4), 337–348.
39. Nishida, H.; Shimada, K.; Goto, M. Polishing inner capillary walls by a magnetic compound fluid. International Journal of Applied Electromagnetics and Mechanics **2007**, *25* (1–4), 25–29.
40. Jacobs, S.D. Manipulating mechanics and chemistry in precision optics finishing. Science and Technology of Advanced Materials **2007**, *8* (3), 153–157.
41. Wu, Y.; Tetsuka, K.; Kato, M.; Shimada, K.; Wong, Y.C. A new magnetic polishing liquid (MPL) for contact force-free surface finishing II: Detailed performance in metal surface finishing. International Journal of Applied Electromagnetics and Mechanics **2007**, *25* (1–4), 89–94.
42. Tam, H.Y.; Cheng, H.B.; Wang, Y.W. Removal rate and surface roughness in the lapping and polishing of RB-SiC optical components. Journal of Materials Processing Technology **2007**, *192–193*, 276–280.
43. Cheng, H.; Feng, Z.; Wang, Y.; Lei, S. Magnetorheological finishing of SiC aspheric mirrors. Materials and Manufacturing Processes **2005**, *20* (6), 917–931.
44. Jha, S.; Jain, V.K.; Komanduri, R. Effect of extrusion pressure and number of finishing cycles on surface roughness in magnetorheological abrasive flow finishing (MRAFF) process. International Journal of Advanced Manufacturing Technology **2007**, *33* (7–8), 725–729.
45. Zhang, L.; Kuriyagawa, T.; Kaku, T.; Zhao, J. Investigation into electrorheological fluid-assisted polishing. International Journal of Machine Tools and Manufacture **2005**, *45* (12–13), 1461–1467.
46. Tanaka, T. A study of basic characteristics of polishing using particle-type electro-rheological fluid. Key Engineering Materials **2007**, *329*, 201–206.
47. Ali-Tavoli, M.; Nariman-Zadeh, N.; Khakhali, A.; Mehran, M. Multi-objective optimization of abrasive flow machining processes using polynomial neural networks and genetic algorithms. Machining Science and Technology **2006**, *10* (4), 491–510.
48. Walia, R.S.; Shan, H.S.; Kumar, P. Parametric optimization of Centrifugal Force-Assisted Abrasive Flow Machining (CFAAFM) by the Taguchi method. Materials and Manufacturing Processes **2006**, *21* (4), 375–382.
49. Wang, A.C.; Weng, S.H. Developing the polymer abrasive gels in AFM processs. Journal of Materials Processing Technology **2007**, *192–193*, 486–490.
50. Wang, Y.; Zhao, Y.; An, W.; Wang, J. Modeling the effects of cohesive energy for single particle on the material removal in chemical mechanical polishing at atomic scale. Applied Surface Science **2007**, *253* (23), 9137–9141.
51. Lin, T.R. An analytical model of the material removal rate between elastic and elastic-plastic deformation for a polishing process. International Journal of Advanced Manufacturing Technology **2007**, *32* (7–8), 675–681.
52. Lo, S.P.; Lin, Y.Y.; Huang, J.C. Analysis of retaining ring using finite element simulation in chemical mechanical polishing process. International Journal of Advanced Manufacturing Technology **2007**, *34* (5–6), 547–555.
53. Lo, S.P.; Lin, Y.Y. The prediction of wafer surface non-uniformity using FEM and ANFIS in the chemical mechanical polishing process. Journal of Materials Processing Technology **2005**, *168* (2), 250–257.
54. Huang, Z.G.; Guo, Z.N.; Chen, X.; Yue, T.M.; To, S.; Lee, W.B. Molecular dynamics simulation for ultrafine machining. Materials and Manufacturing Processes **2006**, *21* (4), 393–397.
55. Bukkapatnam, S.T.S.; Rao, P.K.; Lih, W.C.; Chandrasekaran, N.; Komanduri, R. Process characterization and statistical analysis of oxide CMP on a silicon wafer with sparse data. Applied Physics A: Materials Science and Processing **2007**, *88* (4), 785–792.
56. Guo, D.; Liu, J.; Kang, R.; Jin, Z. A pad roughness model for the analysis of lubrication in the chemical mechanical polishing of a silicon wafer. Semiconductor Science and Technology **2007**, *22* (7), 793–797.
57. Wu, L.; Yan, C. An analytical model for step height reduction in CMP with different pattern densities. Journal of the Electrochemical Society **2007**, *154* (7), 596–603.
58. Wolf, H.; Streiter, R.; Rzehak, R.; Meyer, F.; Springer, G. Empirical modeling of oxide CMP at chip scale. Microelectronic Engineering **2005**, *82* (3–4), 686–694.
59. Tso, P.L.; Hsu, R. Estimating chemical mechanical polishing pad wear with compressibility. International Journal of Advanced Manufacturing Technology **2007**, *32* (7–8), 682–689.
60. Chang, O.; Kim, H.; Park, K.; Park, B.; Seo, H.; Jeong, H. Mathematical modeling of CMP conditioning process. Microelectronic Engineering **2007**, *84* (4), 577–583.
61. Wang, Y.; Zhao, Y.W.; Gu, J. A new nonlinear-micro-contact model for single particle in the chemical-mechanical polishing with soft pad. Journal of Materials Processing Technology **2007**, *183* (2–3), 374–379.
62. Yuan, C.; van Driel, W.D.; van Silfhout, R.; van der Sluis, O.; Engelen, R.A.B.; Ernst, L.J.; van Keulen, F.; Zhang, G.Q. Delamination analysis of Cu/low-*k* technology subjected to chemical-mechanical polishing process conditions. Microelectronics Reliability **2006**, *46* (9–11), 1679–1684.
63. Zhang, X.H.; Pel, Z.J.; Esayanur, M.; Bowers, G.L.; Fisher, G.R. An experimental investigation of material removal rate in polishing of silicon wafers. Transactions of the North American Manufacturing Research Institute of SME **2007**, *35*, 17–24.
64. Young, H.T.; Liao, H.T.; Huang, H.Y. Surface integrity of silicon wafers in ultra precision machining. International Journal of Advanced Manufacturing Technology **2006**, *29* (3–4), 372–378.
65. Lu, Y.S.; Tani, Y.; Soutome, K.; Kamimur, Y. Applications of polishing technology using polymer particles to silicon wafers and quartz crystal wafers. Key Engineering Materials **2007**, *339*, 263–268.

66. Lin, Y.C.; Kao, C.H. A study on surface polishing of SiC with a tribochemical reaction mechanism. International Journal of Advanced Manufacturing Technology **2005**, *25* (1–2), 33–40.
67. Kang, J.; Hadfield, M. The polishing process of advanced ceramic balls using a novel eccentric lapping machine. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture **2005**, *219* (7), 493–504.
68. Wu, X.; Kita, Y.; Ikoku, K. New polishing technology of free form surface by GC. Journal of Materials Processing Technology **2007**, *187–188*, 81–84.
69. Lai, H.Y.; Huang, C.T. A systematic data integration technique for mold-surface polishing processes planning. International Journal of Advanced Manufacturing Technology **2007**, *31* (11–12), 1109–1126.
70. Kim, J.D.; Noh, I.H. Magnetic polishing of three dimensional die and mold surfaces. International Journal of Advanced Manufacturing Technology **2007**, *33* (1–2), 18–23.
71. Lin, F.-Y.; Lu, T.-S. Development of a robot system for complex surfaces polishing based on CL data. International Journal of Advanced Manufacturing Technology **2005**, *26* (9–10), 1132–1137.
72. Nagata, F.; Hase, T.; Haga, Z.; Omoto, M.; Watanabe, K. CAD/CAM-based position/force controller for a mold polishing robot. Mechatronics **2007**, *17* (4–5), 207–216.
73. Ji, S.M.; Zhang, L.; Zhang, X.; Wan, Y.H.; He, H.P.; Yuan, J.L.; Yuan, Q.L.; Jin, M.S. Spinning- inflated-ballonet polishing tool and its application in curved surface polishing. Key Engineering Materials **2007**, *339*, 21–25.
74. Tsai, M.J.; Huang, J.F. Efficient automatic polishing process with a new compliant abrasive tool. International Journal of Advanced Manufacturing Technology **2006**, *30* (9–10), 817–827.
75. Suzuki, H.; Moriwaki, T.; Okino, T.; Ando, Y. Development of ultrasonic vibration assisted polishing machine for micro aspheric die and mold. CIRP Annals – Manufacturing Technology **2006**, *55* (1), 385–388.
76. Guo, Z.N.; Huang, X.Z.; Huang, Z.G.; Yu, Z.Q.; Yue, T.M.; Lee, W.B. Experimental research on ultra-smooth surface polishing based on two-dimensional vibration of liquid. Key Engineering Materials **2007**, *329*, 219–224.
77. Pa, P.S. Electrode form design of large holes of die material in ultrasonic electrochemical finishing. Journal of Materials Processing Technology **2007**, *192–193*, 470–477.
78. Yin, S.; Shinmura, T. Vibration-assisted magnetic abrasive polishing. Key Engineering Materials **2007**, *329*, 207–212.
79. Lamikiz, A.; Sanchez, J.A.; Lopez de Lacalle, L.N.; Arana, J.L. Laser polishing of parts built up by selective laser sintering. International Journal of Machine Tools and Manufacture **2007**, *47* (12–13), 2040–2050.
80. Uno, Y.; Okada, A.; Uemura, K.; Raharjo, P.; Sano, S.; Yu, Z.; Mishima, S. A new polishing method of metal mold with large-area electron beam irradiation. Journal of Materials Processing Technology **2007**, *187-188*, 77–80.
81. Yan, B.H.; Wu, K.L.; Huang, F.Y.; Hsu, C.C. A study on the mirror surface machining by using a micro-energy EDM and the electrophoretic deposition polishing. International Journal of Advanced Manufacturing Technology **2007**, *34* (1–2), 96–103.
82. Ramasawmy, H.; Blunt, L. Investigation of the effect of electrochemical polishing on EDM surfaces. International Journal of Advanced Manufacturing Technology **2007**, *31* (11–12), 1135–1147.
83. Zhou, W.; Tani, Y. Investigation on 4-body finishing technology with polishing paste. Key Engineering Materials **2007**, *329*, 267–272.
84. Insepov, Z.; Hassanein, A.; Norem, J.; Swenson, D.R. Advanced surface polishing using gas cluster ion beams. Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms **2007**, *261* (1-2 SPEC. ISS.), 664–668.
85. Wang, Y.L.; Chen, K.W. Kinetics of polishing friction for copper pits formation during copper chemical mechanical polishing. Journal of the Electrochemical Society **2007**, *154* (7), 589–595.
86. Lee, H.S.; Park, B.Y.; Park, S.M.; Kim, H.J.; Jeong, H.D. The characteristics of frictional behavior in CMP using an integrated monitoring system. Key Engineering Materials **2007**, *339*, 152–157.
87. Kim, N.H.; Seo, Y.J.; Lee, W.S. Temperature effects of pad conditioning process on oxide CMP: Polishing pad, slurry characteristics, and surface reactions. Microelectronic Engineering **2006**, *83* (2), 362–370.
88. Matsuo, H.; Kondo, S.; Ishikawa, A.; Fukaya, K.; Kobayashi, N.; Kikkawa, T. Effect of frictional force vector on delamination in Cu/low-*k* integration. Microelectronic Engineering **2006**, *83* (11–12), 2146–2149.
89. Jeong, H.; Kim, H.; Lee, S.; Dornfeld, D. Multi-sensor monitoring system in chemical mechanical planarization (CMP) for correlations with process issues. CIRP Annals – Manufacturing Technology **2006**, *55* (1), 325–328.
90. Jeong, H.D.; Park, K.H.; Cho, K.K. CMP pad break-in time reduction in silicon wafer polishing. CIRP Annals – Manufacturing Technology **2007**, *56* (1), 357–360.
91. Tsui, H.P.; Yan, B.H.; Wu, W.T.; Hsu, S.T. A study on stainless steel mirror surface polishing by using the electrophoretic deposition method. International Journal of Machine Tools and Manufacture **2007**, *47* (12–13), 1965–1970.
92. Chen, Y.; Zhang, L.C.; Arsecularatne, J.A. Polishing of polycrystalline diamond by the technique of dynamic friction. Part 2: material removal mechanism. International Journal of Machine Tools and Manufacture **2007**, *47* (10), 1615–1624.
93. Podgornik, B.; Vizintin, J.; Hogmark, S. Improvement in galling performance through surface engineering. Surface Engineering **2006**, *22* (4), 235–238.
94. Podgornik, B.; Hogmark, S. Surface modification to improve friction and galling properties of forming tools. Journal of Materials Processing Technology **2006**, *174* (1–3), 334–341.
95. Ng, D.; Kulkarni, M.; Johnson, J.; Zinovev, A.; Yang, D.; Liang, H. Oxidation and removal mechanisms during chemical-mechanical planarization. Wear **2007**, *263* (7–12 Special Issue), 1477–1483.