Computational analysis and chemical mechanical polishing for manufacturing of optical components

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**COMPUTATIONAL ANALYSIS AND
CHEMICAL MECHANICAL POLISHING FOR
MANUFACTURING OF OPTICAL COMPONENTS**

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**SCHOOL OF MECHANICAL & AEROSPACE
ENGINEERING**

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ABSTRACT

High precision optical components are required for modern life and future. To achieve component's surfaces with high quality, chemical mechanical polishing (CMP) is required. It is a unique method to obtain the global uniformity planarization across the surface without scratches. In the polishing of optical components, a new approach has been applied, including two phases: phase one is using the fixed abrasive pad with abrasive-free slurry and phase two is using the soft pad (the fabric cloth pad) with colloidal silica slurry. This process has created a better uniformity surface with lower surface roughness.

The non-uniformity of substrates after polishing is one of the most interesting things in current trends in research. One of the reasons for the non-uniformity is a pad wear profile. Researching on the pad wear profile by improving the pad conditioning process creates a better pad surface, and through that the substrates is polished with better uniformity. Another reason for the non-uniformity is the distribution of abrasive particles in the interface between the wafer and pad surfaces under effects of the pad and wafer rotations.

In this research, an analytical model was established by combining of the kinematic motions and the contact time to investigate the pad wear non-uniformity. The results have indicated that the cutting path density and the contact time at positions near the pad center are more than that near the pad edge. It is a good agreement with experiments. New shapes of the pad and the conditioner have been developed to create a better pad wear profile. The pad after conditioning is convex and more uniform.

In addition, a new computational fluid dynamic model was built. It was a combination of multiphase and discrete phase modelling to investigate the abrasive particles behaviour and the slurry distribution in the interface. The total numbers of particles in the gap were quantified to characterize their mechanical effects under different operating parameters. The simulation results have shown that the particles are non-uniformly distributed below the wafer and provided a deeper insight understanding of the material removal of the CMP mechanism. From the understanding above, a new idea has been developed to explain the mechanism of the CMP processes.

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LIST OF PUBLICATIONS

- [1] N. Y. Nguyen, Z. W. Zhong, and Y. B. Tian, "Analysis and improvement of the pad wear profile in fixed abrasive polishing," *The International Journal of Advanced Manufacturing Technology*, vol. 85, pp. 1159-1165, 2016.
- [2] N. Y. Nguyen, Z. W. Zhong, and Y. Tian, "An analytical investigation of pad wear caused by the conditioner in fixed abrasive chemical-mechanical polishing," *International Journal of Advanced Manufacturing Technology*, vol. 77, pp. 897-905, 2015.
- [3] N. Y. Nguyen, Y. B. Tian, and Z. W. Zhong, "Modeling and simulation for the distribution of slurry particles in chemical mechanical polishing," *International Journal of Advanced Manufacturing Technology*, vol. 75, pp. 97-106, 2014.
- [4] N. Y. Nguyen, Y. B. Tian, and Z. W. Zhong, "Improvement of the pad wear shape in fixed abrasive chemical-mechanical polishing for manufacturing optical components," presented at the International Conference on Optical and Photonic Engineering, Singapore, 2015.

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LIST OF SYMBOLS

ω_p	Angular velocity of a pad
ω_c	Angular velocity of a conditioner
ω_o	Oscillating velocity of a conditioner
n_o	Frequency of the conditioner
n_p	The pad's speed
n_c	The conditioner's speed
r_M	Distance from a point M to the conditioner center
L_t	Distance between the conditioner and pad centers
f	Feed rate of a grain on the conditioner
t	Time
A	A matrix expressing the rotation around a origin
D	A matrix expressing the rotation around the conditioner center and the translation from the conditioner center to the pad center
θ_M	An initial angle of the point M
θ_p	An initial angle of the pad

$r_{\min}$	The smallest distance between grains and the center on the conditioner
$r_{\max}$	The largest distance between grains and the center on the conditioner
D_p, D_c, D_w, D_{ca}	Diameter of the pad, the conditioner, the wafer, and the carrier, respectively
L	Distance between the pad center and the wafer center
V, H	Distance between the pad center and a inlet (x and y direction, respectively)
h_c	Distance between the pad and carrier surfaces
h	Distance between the pad and wafer surfaces
$\dot{m}_{aw}$	Mass transfer from phase air to phase water
$\dot{m}_{wa}$	Mass transfer from phase water to phase air
ρ_w	Water density
α_w	Water volume fraction in a cell
ρ_a	Air density
μ_w	Water viscosity
μ_a	Air viscosity

$\vec{v}_w$	Water velocity
$\vec{F}$	Force/unit particle mass
$\vec{u}$	Fluid phase velocity
$\vec{u}_p$	Particle velocity
μ	Molecular viscosity of a fluid
ρ	Fluid density
ρ_p	Particle density
d_p	Particle diameter
C	Cunningham correction to Stokes drag law
λ	Molecular mean free path
$\vec{v}$	A frame's absolute velocity
$\vec{v}_r$	A frame's relative velocity
ω	A frame's angular velocity
$\vec{r}$	A frame's position vector
x, y, z	A particle position
F_u	Shearing force

$\mathcal{U}_u$	Shearing stress
F_n	Head load
P	Pressure
L_s	Length of surface roughness
w_s	Width of surface roughness
E	Young modulus
k	Particle concentration
R_s	Surface roughness

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CHAPTER 1 INTRODUCTION

1.1 Background

High precision optical components are required for modern life and future. Optical components are often made of silicon or glass [1]. Glass has excellent properties like heat resistance, shockproof, high density storage. They can be used to replace aluminium in a production of hard disk drivers [2]. Because of their brittleness and extreme hardness, these materials are more difficult to produce parts with a high level of quality.

Several methods have been used to achieve surfaces with a higher level of quality: chemical mechanical polishing (CMP), laser reflow, coating with spin-on glasses, polymer and resists, thermally reflowing materials, dielectric deposition, and flow-able oxides [3]. However, CMP is a unique method to obtain the global uniformity planarization across the surface without scratches. The current surface finishing process for glass and silicon substrate is loose abrasive lapping following by mechanical polishing and then CMP.

CMP was used in micro-electric the first time in 1983 at IBM Based Technology Lab in East Fishkill, New York [4]. Before that, CMP was looked at as a dirty process used for glass polishing for several centuries. By demanding of higher speed and smaller size of the integrated circuit manufacturing, more and more layers are added to the wafer surface with more accuracy. The global planarization is required on the whole surface. It makes the CMP process replace the traditional planarization process such as reactive

ion etching [5]. With the development of the planarization process, chip sizes become smaller and smaller, from 0.8 μm (1990) to 45 nm (2007) [4].

The basic idea of a CMP process is quite simple. A wafer is held by a carrier. The carrier rotates around its center. The wafer surface is pressed against a pad surface. The pad is placed on a plate. The plate rotates around its center. Slurry flows on the pad surface and enters the interface between the wafer and the pad (Figure 1.1). Many researchers have proposed that effects of the rotating pad, the rotating wafer, chemical actions of slurry and mechanical abrasions of abrasive particles produce surfaces with high quality and planarization. In fact, there are so many input and output variables in the CMP process. The input variables include the head load, the wafer and pad speeds, the chemical additives in the slurry, the abrasive particle type, the materials of the wafer, pad and abrasive particles, the particle shape and diameter, etc. The effects of these parameters are discussed on next chapter. The output variables include material removal rate, non-uniformity, surface roughness, and so on.

Figure 1.1. Chemical mechanical polishing model.

Applications of CMP are from Si wafers for integrated circuits productions, to copper, tungsten [6-10]. It is used for polishing of quartz, diamond films, MgO single-crystal substrates, ultrathin dielectric substrates, and deposited surfaces during nickel electrodepositing as well as polishing of microbores for microfluidics and optical applications and feldspathic ceramics and other materials for medical applications [11].

Some researchers have proposed that there is a thin layer of fluid between the wafer and pad surfaces [12-20]. They have used a lubrication theory to explain the CMP process and calculate MRR [12, 17]. Others have used Navier-Stokes equations to calculate the layer thickness [14-16].

Some others have proposed that the pad and wafer surfaces are direct contacts or semi-direct contacts [21-24]. In the direct contacts, the wafer surface comes to contact with the pad surface entirely. The particles are trapped between them and drag the wafer material away when the pad rotates. In the semi-direct contacts, the wafer surface and the pad surface are partly contacted. The fluid, the pad and abrasive particles support the head load. The particles, therefore, slide and rotate on the wafer surface and remove its material.

There are some new types of polishing. Many “noncontact” polishing processes have been developed “using magnetic fluids, electrorheological fluids, and abrasive flow for polishing of complicated geometries or difficult-to approach regions.” Automatic polishing is conducted by robots and CNC machines [11]. Polishing with vibrations, beams, or polymer particles have been investigated.

About polishing for manufacturing of optical components, there are two types of pads. They are a soft pad with loose abrasives, and a hard pad with abrasives embedded on the pad's surface, which is called the fixed abrasive pad [25]. Many researchers have shown that the hard pad gives better uniformity but worse roughness surfaces, compared to the soft pad. CMP with the soft pad is usually employed to eliminate subsurface damages induced by previous steps. The polished product meet high quality requirements, such as defect-free surface with sub-nanometer surface roughness, nanometer waviness, micrometric flatness and tens of micrometric thickness variation [2]. However, the non-uniformity of the substrates needs to be improved in order to get better global planarization. Therefore, the CMP processes for the optical components include two phases: phase one is using the fixed abrasive pad with abrasive-free slurry (called a fixed abrasive polishing or FAP) and phase two is using the soft pad (the fabric cloth pad) with colloidal silica slurry (called a conventional or traditional CMP). Using the fixed abrasive pad creates better uniformity surface and higher material removal rate (MRR). After that, the soft pad is used to get better surface roughness.

1.2 Motivation

The motivation of the research is based on the higher requirement in planarization of the CMP processes, especially in optical components. The development of ultra-precision and nanotechnologies require high quality surface after polishing. However, the mechanism of the CMP process is not fully understood. It is difficult to be controlled due to the lack of physical

understanding. The process, therefore, is a trial and error procedure. It needs to be further investigated to improve quality of the polished substrates.

Non-uniformity of the wafer surface is a primary problem. There have been experiments which show that the wafer non-uniformity decreases when down force pressure increases, slurry flow rate decreases, and the pad speed decreases [26]. However, some experiment results have shown that reducing of the pad speed increases the non-uniformity. Wafer size also affects the non-uniformity, but the trend is not clearly understood [27].

The pad wear profile is another reason causing the non-uniformity of the wafer surface, especially in FAP. After long polishing periods, the pad is almost concave which results in the non-uniformity of polished surfaces. The pad wear rate is affected by many factors [28, 29], such as soaking time, conditioning pressure, the pad's and conditioner's properties. Many investigations have shown that the conditioner effect is the most significant factor for the pad wear profile. It has been challenging to create an improved pad surface [30]. Therefore, it is important to develop a model in order to create a better pad wear profile and as a result, better work piece surfaces.

For conventional CMP, non-uniformity is complicated. The abrasive particles are trapped in the interface between the surfaces. They mechanically remove the passive layer on the wafer surface. No direct observation has been made in the gap to prove those mechanisms. Therefore, computational fluid dynamics (CFD) simulation seems to be a solution. It can be used to model the flow of the slurry and abrasive particles in the interface. It is especially

significant to integrate the particles in a three dimensional CFD model which there has not been investigated before. From the simulation process, the distribution of the particles will be visualized. It can be used to explain the non-uniformity of the surfaces.

In addition, material removal rate (MRR) which cannot be precisely predicted is another reason for generating the non-uniformity. Preston and many researchers have shown a linear relationship between MRR and pressure on the back surface of the wafer [26, 31, 32]. Some others have shown a nonlinear relationship between them [33, 34]. MRR increases when particle size increases [6, 35]. However, some researchers have found out that MRR increasing comes with reducing in particle size [34] or changing the size of particles [36]. The dependence of MRR on temperature, slurry's pH, flow rate, abrasive concentration also needs to be further investigated. The mechanisms of both FAP and conventional CMP need to be clarified and compared to get better understanding of CMP.

1.3 Research objectives

The main objectives of this research are to study the mechanism of the CMP processes and improve the uniformity of polished surfaces. Since the CMP processes have been widely used for many applications, the focus is on the polishing process of optical components. The process includes two phases which are different in the mechanism. The detail objectives for each phase are presented below:

- In phase one, FAP, the pad wear profile is important for the uniformity of the polished surface. Therefore, the objectives are to develop an analytical model to predict the pad wear profile and propose new shapes of the conditioner and pad to improve the pad wear profile.
- In phase two, conventional CMP, the effect of abrasive particles of the slurry is one of the reasons which cause the non-uniformity of the polished surfaces. Therefore, the objective is to investigate the distribution of the particles below the surfaces in the CMP processes.

Finally, in order to gain a deeper understanding of the CMP mechanism, the research objective is to investigate the difference between FAP and conventional CMP.

1.4 Research scope

The scope of the research consists of developing a model to predict the pad wear profile in FAP. The analytical model is then used to investigate effects of operation parameters, conditioner patterns and sizes, and its positions on the pad wear profile. Based on the model, a new pad and a new conditioner are proposed to create a better pad wear profile.

In addition, a multiphase computational fluid dynamics model is built to investigate the distribution of abrasive particles in the CMP process. It was the combination of VOF and DPM in the CFD model. The distribution is then used to explain the non-uniformity of the surfaces after polishing.

From the above study about CMP and FAP, comparisons between them are conducted. There are analytical explanations for the non-uniformity and surface roughness in FAP and conventional CMP.

1.5 Organization of the thesis

Chapter 2 will include literature review. It is about the traditional CMP and fixed abrasive polishing (FAP), mainly focusing on non-uniformity of the work piece surface in the processes. Chapter 3 will present a model which has been established to investigate the pad wear profile. New shapes of pad and conditioner are proposed to achieve a better pad wear profile. Chapter 4 will describe and discuss a computational model which has been built to investigate the flow of slurry and the distribution of abrasive particles in the traditional polishing process. Experiments have been conducted to testing the effects of the combination of the fixed abrasive and traditional polishing in Chapter 5. Then, the wafer non-uniformity in fixed abrasive polishing is analysed by using kinematic. Finally, a new idea is proposed for traditional polishing in the same chapter. Chapter 6 will include conclusions, major contributions, limitations and future work.

CHAPTER 2 LITERATURE REVIEW

In this chapter, traditional CMP and fixed abrasive polishing (FAP) are reviewed. This research is mainly focused on NU of the work piece surface in the processes and ways to improved it. Especially, the using of computational analysis has been done in CMP.

2.1 Traditional CMP

There are three main components in the CMP process [37]: the wafer, the polishing pad, and the slurry. Banerjee and Rhoades [4] have conducted a review which compared sizes of components in CMP process: slurry particles in the slurry as sands, pads as small cities, pad asperities as basketballs, and wafers as airports. The softness of the pad and the hardness of the wafer can be approximated as follow: the pad is soft with the hardness of 22.9×10^5 (N/m²) and a density of 260 (kg/m³) [38], the wafer is hard with the hardness of 19.3×10^{10} (N/m²) and a density of 8030 (kg/m³) [38]. There are many types of pads: Suba IV, Suba-500, IC-1000 [21], IC-1400, XHGM1158 [39], Embossed Politex pad [40]. It has been using for quartz, diamond films, MgO single-crystal, ceramics, tungsten, copper, low-k films, etc. Polymers are also being polished by CMP [11].

Optical components are hard and brittle materials. In their polishing process, pad speeds and polishing pressures are the most important factors that affected MRR. However, the non-uniformity cannot be predicted. It can be increased when the pressure increases, and it can be reduced when the pressure increases [41].

The process usually has five steps. The first step is starting the rotation of the pad and the wafer, and spreading the slurry onto the pad. The second step is bringing down the polishing head to a low down force. The third step is increasing the down force to the desired value. The fourth step is the main polish step where the back pressure is set to the desired value. The fifth and last step is a buffing step where water is used to give a final planarization to the wafer. In some cases, the pressure is set one time at the beginning and the down force or the back pressure is automatically controlled. In some other cases, there is an additional step which is called post CMP. It is a cleaning process where a brush and the water are used to clean the polished surfaces.

The most advantage of the traditional CMP is very low of surface roughness. Typical surface roughness of the wafer surface after polishing processes is approximately in the range of 1 to 5 Å root mean square (RMS) in 1mm x 1mm area [5]. The smallest value of Ra can be achieved at 0.8 Å [42].

2.2 Fixed abrasive polishing (FAP)

FAP has been used in polishing ceramics (Si_3N_4 , SiC), tungsten [43], copper [39], and especially in manufacturing of optical components. Tian et al. [2] have developed a procedure for glass polishing instead of using a traditional surface finishing. The procedure includes a loose abrasive lapping followed by FAP and finished by the conventional chemical mechanical polishing [2].

The structure of the fixed abrasive pad is different from the soft pad. There are usually three main layers of the pad: the soft foam layer at the bottom for global planarization, the hard layer in the middle for pattern selectivity and the abrasive

layer on the top for material removal [44, 45]. As shown in Figure 2.1, the fixed abrasive pad includes the resilient foam sub-layer at the bottom, the rigid polycarbonate layer and the micro-replicated resin layer of pyramids filled with the abrasives on the top [44].

Figure 2.1. 3M fixed abrasive pad construction [44].

FAP produces surfaces with a high material removal rate, better uniformity and acceptable surface roughness [44]. van der Velden has shown that the edge effect is eliminated in FAP, and the uniformity is improved by changing the thicknesses of the two layers. Various kinds of abrasive-free slurry, with different operation parameters and in situ/ex-situ conditioning have been investigated. The optimum values for material removal rate (MRR) and surface roughness were found out by ANOVA method [2, 25, 41, 46]. Zhong et al. [1] have indicated that it shortens the CMP time. Tian et al. [2] have shown better results of glass polishing by using the method instead of traditional surface finishing.

Environment problems when a slurry is disposed and cost are other reasons for using a fixed abrasive chemical mechanical polishing (CMP) [47]. FAP is better than traditional CMP for the environment. In traditional CMP, it must be careful when the slurry is disposed of. Because there are solids from the polishing processes, such as silica, alumina, tungsten, copper, etc. In FAP, only DI water is used and abrasive particles are embedded on the pad surface.

2.3 Non-uniformity in CMP processes

The typical metrics which are used to measure the within wafer non-uniformity are the standard deviation of the post-polish thickness [48]. There are six metrics for within wafer non-uniformity:

- The standard deviation of the post thickness measurements.
- The standard deviation of the post thickness measurements divided by the average post thickness.
- The standard deviation of the AR (the pre-thickness minus the post thickness measurement)
- The standard deviation of the AR divided by the average AR.
- The standard deviation of the RR (the pre-thickness minus the post thickness measurements, divided by the process time).
- The standard deviation of the RR divided by the average RR.

Smith et al. [48] have shown that the standard post metric is ineffective in estimating the within-wafer non-uniformity. “It was suggested that using a single standard method may be insufficient for characterizing a process. Some situations

may require multiple metrics, including surface plots at multiple time steps, in order to fully characterize a process.”

The standard deviation σ is:

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \mu)^2}, \text{ where } \mu = \frac{1}{N} \sum_{i=1}^N x_i. \quad (2.1)$$

Where N is the number of measured points, x_i is the value at a point, and μ is the mean value of N points.

The wafer uniformity is about 0.2 μm across a diameter of 200 mm on global scale [49]. With the increasing of the wafer size, a tighter tolerance is required. Even under a uniform pressure on the wafer, the MRR is not uniform across the entire wafer surface. The MRR in a region 3-5 mm from the wafer edge is 15-35% higher than that at the wafer center [50].

Many factors affect the uniformity of the substrates, such as the polishing pressure, speeds, a retaining ring, the slurry flow rate, abrasive particles, wafer properties, pad properties, and a pad wear profile. Chemical reactions between the substrate and the slurry is another one. They are affected by the pressure, temperature, pH valued, etc. However, chemical reactions are not problems in FAP. Tian et al. [25] have done experiments with fixed abrasive pads and different slurry, and concluded that the flatness of the substrate is nearly not affected by chemical factors. That means chemical factors can be excluded in the investigation of the flatness of wafer if the process parameters are unchanged.

2.3.1 Effects of the head load (or polishing pressure)

Effects of pressure on the non-uniformity and surface roughness have been investigated by many researchers [22, 26, 31, 38, 39, 51-59]. In traditional CMP, when pressure increases, MRR increases linearly, non-uniformity is slightly reduced [26, 31], and the surface roughness increases [54]. The head load also causes the wafer deformation, especially when the wafer becomes thinner in ultra-precision machining [60]. It is suggested that the process should be started at low pressure to reduce the non-uniformity [61].

Fu and Chandra [62] have built a 2D finite element method (FEM) model to verify the analytical model in predicting the pressure distribution on the wafer surface. This model considered the deformation of the wafer surface in the direct contact between the wafer and pad surfaces. They explained that the non-uniformity distribution of the pressure produced the non-uniformity of polished substrates.

Therefore, the non-uniformity is primary caused by the contact pressure. Numerical analysis has been using to investigate the effect of polishing pressure on the wafer non-uniformity. When the pad and the wafer contact directly, the back pressure on the wafer create stress on the wafer and pad surfaces. Some researchers have proposed that the stress, which is von Misses stress, is the primary reason of the non-uniformity, especially the edge effect. In 1997, Srinivasa-Murthy et al. [38] have used ANSYS to describe a static, three-dimensional model which helps to explain the origin of non-uniformity in MRR on the wafer surface during CMP. Simulation results showed that the distribution of the Von Mises stress across the wafer surface correlated with experimental removal rate profiles and it was also similar to the one (not magnitude) obtained by using a 2-D axisymmetric model.

They showed the uniformity of von Mises stress near the wafer center, and then von Mises stress increased towards the edge, decreased as the edge was approached and finally reached a peak at the edge. However, Srinivasa-Murthy et al. have not considered effects of relative motion between the pad and wafer on the Von Mises stress distribution [38]. Lin and Lo [57] have also used a two-dimensional axisymmetric quasi-static model for the chemical-mechanical polishing process to investigate the effects of a pad, a carrier film, and a head load on the von Mises stress and the non-uniformity on the wafer surface. The elastic modulus and thickness of the pad and the carrier load would significantly affect the von Mises stress and non-uniformity. The von Mises stress increases with the increasing of modulus and decreasing of the pad thickness. The larger magnitude of the carrier load is, the larger the von Mises stress is. Following the above results, Lin and Lo [56] have developed a 2D axisymmetric quasi-static finite element model with carrier back pressure compensation for CMP. The result has shown that the planarization of the wafer surface was improved by compensating the different carrier back pressures [56].

There are other aspects of the CMP processes that have been investigated using finite element analysis (FEA). Chiu and Lin [55] have built a three-dimensional finite element model to perform model analysis of CMP process and investigated effects of changing head load and elastic modulus of the pad. The investigation of contact stress was expanded by Chen et al. [58] with five finite element models created for different applications. The thicker of the carrier film is, the larger von Mises stress is [22].

All above researchers were focused on the directly contact between the wafer and the pad and calculated the von Mises stress to explain the wafer uniformity. However, many studies have shown that there is a fluid layer between the wafer and the pad. Therefore, more models need to be developed to investigate the CMP mechanism.

2.3.2 Speeds

There are many researchers have focused on the effects of the speeds on MRR and non-uniformity [8, 14, 27, 46, 51, 53, 63-75]. Kinematic analysis is used to investigate the non-uniformity [51, 70, 74]. When the wafer and pad speeds increased, the non-uniformity increased. However, the best uniformity was achieved when the wafer and pad speeds are equal. The oscillation speed has minor impacts on the non-uniformity.

When the wafer speed increases, the non-uniformity is increased [26, 27, 51]. However, this increasing is less than that when the pad speed increases. Especially, when the pad speed is equal to the wafer speed, the non-uniformity is slightly reduced.

When the pad speed increases, the larger centrifugal force pushes the slurry out of the pad surface and reduced the amount of slurry necessary to create high quality surfaces [26, 41, 75]. The surface roughness decreases [54], and the uniformity is decreased [27, 71], or unchanged [39, 53]. Yuh et al. have shown that the non-uniformity decreases when the pad and head speed increases from 30 rpm to 60 rpm. After the value of 60 rpm, the non-uniformity increases [73].

Lin [26] has also counted the effect of the carrier oscillation speed on the MRR and the non-uniformity. However, their effect is smaller than other factors.

2.3.3 A retaining ring

The retaining ring width, its back pressure and the distance from the wafer edge to the ring can be adjusted to minimize the contact pressure non-uniformity [76]. The effect of the retaining ring of the carrier was investigated by Lin [77] and Lo et al. [78] by using a two-dimensional axisymmetric quasi-static finite element model. When the distance between the wafer and the retaining ring increases, the decreasing trend of the peak value of the von Mises stress slows down, and the wafer's non-uniformity decreases gradually [78]. Castillo-Mejia et al. [79] have also built a 2D finite element model to investigate the effect of the distance between a retaining ring and a wafer, the varying of the retaining ring pressure and the relative velocity of the wafer and the pad on the wafer uniformity. Lee et al. [71] has done the same analysis but using an intelligent pad which was integrated sheet shape pressure sensors. The experiment has shown that MRR and uniformity increase when the pressure on the wafer and the ring increases.

Fukuda et al. investigated wafer roll-off and notch which affected the material removal rate at the wafer periphery [80].

2.3.4 Slurry flow

It includes many factors in the slurry: flow rate, abrasive particle size, shape, and concentration, pH, viscosity [81], temperature, inlet position, chemical additive [82, 83], etc.

Lin [26] has presented that when slurry flow rate increases, MRR increases, and non-uniformity increases in traditional CMP. Yuh et al [73] have shown that non-uniformity is reduced when flow rate increases. These contrast conclusions between researchers need to be further investigated.

In the CMP processes, the slurry is trapped in the pad pores. The slurry will change if it is not replaced by fresh slurry [84]. The slurry has shown the presence of agglomerates which reduce the surface quality [85].

A slurry nozzle has significant on the wafer non-uniformity. The more the slurry is distributed on the pad area, the more contact of the substrate and the slurry is. That creates more even chemical reaction on the whole surface. Consequently, the non-uniformity reduces. It has been proved by Lee et al. [9]. They have done experiments with a new nozzle which was a spray nozzle (Figure 2.2). The spray angle and the nozzle height have been adjusted, and the non-uniformity has sharply reduced at a high nozzle height. This new nozzle has significant on reducing cost and saving the environment.

Abrasive particles are a primary factor of CMP processes. The particle shape is spherical in some researches, and is hexagonal or non-spherical in other researches [24, 54]. The irregularity of the particle shapes has affected the surface roughness and caused a fluctuation of the contact forces between the substrate and the particles. It has been investigated by Han et al. using FEA [54]. Li-Jun et al. [86] have used FEA and smoothed particle hydrodynamics (SPH) coupling to investigate the effects of particle size. Their results have shown that the particle size increasing resulted in the increasing of surface roughness.

Figure 2.2. Schematic of a) a conventional nozzle, b) a new nozzle with a height of 10 mm, c) a new nozzle with a height of 30 mm, and d) a new nozzle with a height of 50 mm [9].

The particle size is not constant in the CMP processes. pH value increasing can make the particle size increases [87]. Surface roughness is proportional to the mean particle size. Coarse particles could be a reason of surface damage in the polishing processes [85].

With difference sizes and difference concentration of particles in slurry, difference surface roughness is created. The dependence of the non-uniformity on the concentration of abrasive particles is not clearly understood. It may be reduced at low concentration and increased when the concentration increases.

Particle materials have effects on the MRR. Although colloidal silica has shown good planarization results, there are toxic chemicals. Alumina (Al_2O_3) and

ceria (CeO_2) particles have shown some advantages such as the surfaces with damage-free or the increasing of MRR [88].

Many researchers have used computational models to simulate the abrasive particles and slurry flow. Three types of software are Molecular dynamics (MD) [89-92], Finite element (FE) simulations, and computational fluid dynamic (CFD). Bastawros et al. [93] used ABAQUS to model the deformation of a pad on particle scale. The 2D model expressed the dependence of MRR on head pressure $P^{0.8}$ and proved that the suitability of the partial direct-contact regime. Han et al. [54] have used finite element method to build models of contacts between wafers and abrasive particles. However, these models have focused on a micro scale. It is difficult to visualize the slurry flow accurately.

There are many simulation processes to describe the slurry flow. One of the best methods is computational fluid dynamics (CFD). The method uses numerical analysis to solve the Navier-Stokes equations which define fluid flows. It is extended to analyse many types of flows such as slurry fluid, from single phase two-dimensional (2D) model [40] to multiphase 2D model which included particles [94, 95]. Some approaches in three-dimensional (3D) CFD models were applied to estimate the non-uniformity and MRR [20]. Moreover, a new single phase 3D CFD model with three wafers polished at the same time was also investigated [96]. The main problem of their 3D models was that the flow of water was without particles. That is a big gap in their research and it affects the calculation of MRR because the MRR was proportional to the number of particles in the gap [97]. Therefore, an investigation of abrasive particles distribution in the slurry between the wafer and pad is important in the contribution of knowledge about planarization processes.

2.3.5 Pad properties

Properties of the soft pad are time dependent. It can be showed by two following reasons. First, the pad which is used to polish a first wafer is changed when it is used to polish the second wafer. Because the pad is worn out and deformed after the first run. Second, when the pad is sunk for a long time, its properties are also changed.

A pad surface has significant impact on the polishing rate. The pad with a random surface roughness has shown a linear relationship between the polishing rate and the external pressure. The pad with a wavy surface roughness has shown a sublinear relationship between the polishing rate and the external pressure [98].

A hardness of the pad has a significant impact on the MRR and non-uniformity of the wafer. When the hardness increases, the MRR increases, and the non-uniformity decreases [39]. Van der Velden has presented that the pad with a thick and rigid polycarbonate layer combined with a thick soft foam layer showed best results for the non-uniformity [44]. This can be explained by using the von Mises stress. The von Mises stress increased when elastic modulus of the pad increased and pad thickness was reduced [22]. The thicker of the pad, the smaller von Mises stress.

The finite element method was used to model the deformation of a pad in direct contact with a wafer. Baisie et al. [99] used a two-dimensional (2-D) axisymmetric quasi-static finite element analysis (FEA) model to present results of pad deformation under the effect of diamond disc conditioning in CMP. The model was used to investigate the effect of three process parameters with three levels of

each on the pad deformation such as pad thickness, pad hardness, and conditioning pressure. Tso and Hsu [100] used a finite element method (FEM) to show the effect of compressibility (K), which is defined as the load that compresses the pad by unit volume. The trends in the K values of the two types of pads are exactly opposite, the single-layer pad will become harder, but the composite pad will become softer. K is also related to the contact pressure and can be used to evaluate whether pads are suitable for polishing. The roughness and uniformity of pads are the most important factors that govern the polishing rate and performance, but neither of them significantly influences K [100].

Sung et al. [95] presented the effect of a polishing pad on micro-scratch formation of a post-chemical mechanical polishing wafer surface. The FEA simulations performed physical interactions among pad, particle and wafer during CMP. The results showed that the pad-particle mixture was responsible for the micro-scratch formation.

The better uniformity of the wafer surface could be also achieved by changing the thickness and stiffness of the sub-pad layer [44].

2.3.6 Pad wear profile

The most important aspect of the conditioning process is the stable of the MRR and the better uniformity. However, it also causes the pad wear with time. The pad wear rate is affected by many factors [28, 29], such as soaking time, conditioning pressure, the pad's and conditioner's properties. Many investigations have shown that the conditioner effect is the most significant factor for the pad wear profile. Without the conditioner, the pad surface becomes ineffective, and the MRR

are very low. The grains on the conditioner tear the pad surface, restoring the pad roughness. It eliminates debris and also removes the pad material which is the main reason of the pad wear profile. It refreshes the slurry on the pad surface, therefore, the chemical reaction happens more evenly and continually, and the non-uniformity is improved.

Some researchers have shown that the concavity of the polishing pad increased with conditioning time [101, 102]. Many researchers have used kinematic analysis to investigate the conditioning process [103-106]. Some other researchers have investigated the CMP process based on the kinematic of the cutting motion [30, 51, 61, 70, 74, 101, 103, 105, 107-109]. Lee et al. [103] have studied a kinematical model of motions of the conditioner in the CMP process; however, the conditioner in their research is handled by a swing arm, not an oscillation motion in the radial direction. Chang et al. [101] have also proposed a mathematical model based on a kinematic motion but they assumed that “the oscillation velocity is neglected”. Feng [108] has established a model based on a kinematical motion to research the pad wear caused by the conditioner in the CMP process with a soft pad. A function of conditioning density was developed based on trajectories generated by the conditioner's grains. However, the difference in speeds of the sweeping motion of the conditioner has not been investigated yet. Li et al. [30] have developed a model for predicting the pad wear shape after conditioning. Their model was based on a kinematic motion but it used a surface element method to predict the pad shape. Yeh and Chen [105] have also developed a model for predicting pad wear based on kinematic motion, but the conditioner in their model was a swing motion, not the oscillation motion. Baisie et al. [109] have built up a

model also based on a kinematic motion of the conditioner to predict the pad wear, but the conditioner in the model did not oscillate. It moved from the pad center to the pad periphery. As it touched the pad periphery, it lifted up and moved back to its initial position to complete a whole cycle. However, almost all the above researches are about the soft pad, not the fixed abrasive pad.

2.3.7 Wafer properties

Young modulus of a silicon wafer is $1.9 \times 10^{11} \text{ Pa}$. Hardness of the wafer is $12 \times 10^9 \text{ Pa}$. The Poisson ratio is about 0.27 - 0.3 [100, 110]. The thickness of the wafer can be smaller than 1 mm while the diameter can be 300 mm [111, 112]. Therefore, the wafer is easily bended under a small head load [113-115]. A small curve of the wafer surface has effect on the pressure distribution in the interface [62].

2.3.8 Improvement of the non-uniformity

One of the reasons that cause the non-uniformity is the wafer deformation. The wafer is easily curved under the head load [60]. Therefore, reducing the head load is a way to improve the uniformity [61]. However, it may decrease the MRR. Fujita and Wantanabe [59] have proposed that the wafer should be placed stable on a plate with the polishing face is up instead of facing down (Figure 2.3). The plate keeps the wafer as flat as it is. The pad is faced down. Therefore, the effect of the wafer surface is eliminated within this new mechanism. However, the edge effect of the wafer edge has not been improved. Tsai et al. [116] have developed a similar method to improve the non-uniformity. They have combined the pad which was

faced down with an online measurement and real-time feedback to achieve a better uniformity and eliminate the edge effects.

Figure 2.3. The new developed CMP in comparing with the traditional CMP [59].

Hu et al. [76] have proposed that the non-uniformity of the substrates can be improved by reducing the contact stress non-uniformity. By doing that, a soft wafer carrier (or a float-type carrier) is suggested. In addition, a multi-zone wafer back pressure is also effective in reducing the contact stress non-uniformity.

Chen et al. [117] have investigated core-shell structured polystyrene-coated silica composite abrasive with homogeneous shells. The composite cores are easily deformed and gently to the wafer surface. Therefore, the surface roughness is reduced. The scratches on the surface are also decreased. Lei and Gu [118] have prepared Cu-doped colloidal SiO₂ abrasives and shown the results with higher MRR and lower surface roughness.

Modifying the pad is another way to improve the uniformity. Feng [74] has proposed a ring-type polishing pad to improve the non-uniformity of both the pad and the wafer. However, the method only gives the expecting results when the pad speed is much slower than the wafer speed. In FAP, the thicknesses of the sub pads could be adjusted to get better uniformity [44].

In CMP processes, pad wear has an important effect on the uniformity of wafer substrates. If the pad wear is not uniform, the cutting effect of the pad on the wafer surface is also not uniform [28, 103]. The pad is almost concave which results in the non-uniformity of polished surfaces. It has been challenging to create a flat pad surface [30]. Therefore, it is important to improve the conditioner to create a better pad wear profile as well as better work piece surfaces. Feng [108] has showed that when the dimension of the conditioner decreased, the uniformity of the pad wear profile increased. In addition, patterns of the grain distributions on the conditioner surfaces had no effect on the pad wear profile generation. Baisie et al. [119] have also investigated different patterns of grain distributions on the conditioner surfaces to optimize the conditioning processes. Their research concluded that the sweeping profile of the conditioner affected the pad profile [109]. It caused the concave shape of the pad wear after a long time of polishing. They suggested reducing the conditioner disc size to minimize the transition regions. However, a small conditioner could cause other problems such as some unconditioned pad area and a large amount of time to finish conditioning the whole pad surface. Kincal and Basim [120] have proposed three types of sweep motions of conditioners including a commonly sinusoidal sweep, a custom sweep 1 in which the sweep was adjusted so that the conditioner disk spends a fixed time in each

zone, and a custom sweep 2 in which the conditioner disk spent an equal amount of time per unit pad area. They concluded a smaller conditioner and the custom sweep 2 improved the pad thickness uniformity. Besides, by extending the sweep of the conditioner beyond the pad edges, the transition regions could be reduced. Although many suggestions have been proposed to create better uniformity of the pad, “there always exist some transition regions in the pad shape near the pad center and the pad periphery” [30]. All the improvements mentioned above are efficient in the CMP processes. However, there is no suggestion in creating a convex pad wear profile.

2.4 Material removal rate

The Preston equation has expressed the linear proportional of MRR and pressure. Solid-solid contact is responsible for the MRR [62]. Many researchers have confirmed the relationship [23, 31, 39, 41, 52, 65, 68, 121-125]. It can be explained that when the pressure increases, the penetration depth of abrasive particles on the wafer surface increases [126, 127]. In addition, the contact area between the pad and wafer surfaces increases linearly with the polishing pressure [34]. Consequently, the MRR is increased. However, other researchers have shown a nonlinear proportional between them [34, 39, 53, 63, 128]. Kondo et al. have shown that the MRR increases nonlinearly when the pressure increase in the FAP [39], and Wang et al. has shown the same thing in the traditional CMP [34].

It is well known that the MRR is increased when the speeds are increased [69]. In FAP, when the pad speed is increased, the MRR is decreased [41].

Slurry flow is important in the CMP processes. When the DI water is used, the MRR was 0.12 $\mu\text{m}/\text{h}$. Otherwise, the colloidal silica is used, the MRR was 2.25 $\mu\text{m}/\text{h}$ [42]. When the slurry changes, there is a significant change in the linear behaviour of MRR on pressure [121, 129]. The MRR increases with the increasing of flow rate [130]. Positions of the slurry nozzle also affect the MRR [131]. When the concentration increases, the MRR increases [65].

The abrasive particle size is one of the most important elements of slurry. There is an ideal size for those particles, a diameter of 80 nm. With this diameter, the MRR is highest [132]. It is also well known that the MRR is changed when the concentration of the particles (%wt) in the slurry is adjusted.

pH value is important to MRR [133]. When the pH is increased from 7 to 11, the MRR is decreased. However, after reaching the minimized MRR at pH of 11, the MRR increases when pH increase from 11 to 12 [87]. For silicon dioxide, the formation of $\text{Si}(\text{OH})_4$, which is the result of the reaction of Si and OH^- in the water, is noticeably enhanced at a pH more than 11. The pH value is changed when chemical additives are added [134].

2.5 Summary

Although there have been so many researches about CMP, its mechanism has not been still fully understood. There are many conflicts in those researches. Therefore, investigating the CMP mechanism needs to be continually conducted.

CHAPTER 3 ANALYSIS AND DEVELOPMENT OF THE FIXED ABRASIVE CHEMICAL MECHANICAL POLISHING PROCESS

3.1 Introduction

There are requirements of predicting the pad wear profile to improve the uniformity of substrates after polishing. Researching the motion of the conditioner and the contact time between the grains and the pad surface plays an important role in predicting the pad wear profile [102, 104]. To our best knowledge, no study has yet reported the effects of a combination of cutting path density and contact time between grains of the conditioner and the pad surface on the pad wear profile, especially in the fixed abrasive CMP process (or FAP).

In this chapter, an analytical model for predicting the pad wear profile was developed. This model was based on a combination of kinematic motions of the conditioner's grains and the contact time between the grains and the pad surface. A program was written by using Fortran95 language. By using this program, the effects of the two factors, the cutting path density and the contact time, on the pad wear non-uniformity can be investigated at the same time.

In addition, the effects of many parameters, including operation parameters, sizes, patterns and positions of the conditioner, on the pad wear profile were investigated. Based on that, a new model of the chemical mechanical polishing was proposed to get a better pad wear profile. This model was a combination of a new design of both the conditioner and the pad.

3.2 Motion of one abrasive grain of the conditioner

This study considered the motion of one grain of the conditioner on the pad surface. Figure 3.1 presents the schematic of motions of the pad and the conditioner in the CMP process. The pad rotates with an angular velocity ω_p around the pad center O_p . The conditioner rotates with an angular velocity ω_c around the conditioner center O_c . The conditioner also oscillates in the X direction with a frequency n_o . The motion of one point M of the conditioner is investigated.

Figure 3.1. Model of motions of the pad and the conditioner.

If the origin of the coordinate system is the conditioner center, the position of one grain is shown as:

$$\begin{cases} x'(t) = r_M \cos(\omega_c t + \theta_M) \\ y'(t) = r_M \sin(\omega_c t + \theta_M) \\ z'(t) = ft \end{cases} \quad (3.1)$$

where $x'(t)$, $y'(t)$, and $z'(t)$ are the position of M in the coordinate system which has the origin at the conditioner center, r_M is the distance from M to the conditioner center, and θ_M is the initial location angle of M on the conditioner.

Actually, the origin is the pad center. Therefore, the position of M in the coordinate system is:

$$\begin{cases} x(t) = x'(t) + L_t = r_M \cos(\omega_c t + \theta_M) + L_t \\ y(t) = y'(t) = r_M \sin(\omega_c t + \theta_M) \\ z(t) = z'(t) = ft \end{cases} \quad (3.2)$$

where $x(t)$, $y(t)$, and $z(t)$ are the position of point M with time t in the coordinate system which has the origin at the pad center, L_t is the distance between the conditioner center and the pad center, and f is the feed rate.

The equation of motion of point M can be described as [135]:

$$\begin{Bmatrix} x(t) \\ y(t) \\ z(t) \end{Bmatrix} = \mathbf{A} \cdot \mathbf{D} \cdot \begin{Bmatrix} r_M \\ L_t \\ f \end{Bmatrix} \quad (3.3)$$

A is the matrix expressing the rotation around the origin. **D** is the matrix expressing the rotation around the conditioner center and the translation from the conditioner center to the pad center.

$$\mathbf{A} = \begin{bmatrix} \cos(\omega_p t + \theta_p) & -\sin(\omega_p t + \theta_p) & 0 \\ \sin(\omega_p t + \theta_p) & \cos(\omega_p t + \theta_p) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3.4)$$

$$\mathbf{D} = \begin{bmatrix} \cos(\omega_c t + \theta_M) & 1 & 0 \\ \sin(\omega_c t + \theta_M) & 0 & 0 \\ 0 & 0 & t \end{bmatrix}, \quad (3.5)$$

where ω_p , ω_c are the angle velocity of conditioner and pad, respectively, and θ_p is the angle of the first contact point on the pad.

The conditioner oscillates in the X direction. Assume L_t is a harmonic oscillation: $L_t = B \cos \omega_o t + C$, where ω_o is the oscillating velocity, B and C are constants which are determined by the distance and the center position of the oscillation conditioner. If the center position is in the middle between the pad center and the pad edge, and the oscillation width is 70 mm, then $L_t = 35 \cos \omega_o t - 150$.

Figure 3.2 presents the cutting path patterns which are created using four grain points M_1 , M_2 , M_3 , and M_4 at different oscillation speeds: n_o . When the conditioner is stable, one grain of the conditioner only draws a simple trajectory path on the pad surface. The trajectory with the small value of the oscillation frequency (2 strokes/min) is smoother than that with a high frequency (15 strokes/min). It means that the pad surface may be conditioned better with a low oscillation frequency of the conditioner.

Figure 3.2. Trajectories of four grain points of the conditioner M_1 , M_2 , M_3 , and M_4 on the pad surface when the oscillation frequency is at 0 strokes/min, 2 strokes/min, 7.5 strokes/min, and 15 strokes/min.

The trajectories of the grains are changed when the pad and conditioner rotation speeds change, as shown in Figure 3.3. The shape of the trajectory depends on the ratio of the conditioner speed and the pad speed, n_c/n_p . If the ratios n_c/n_p are the same, for example, 20/40 and 40/80, the shapes of trajectories are the same but the consistence of those paths is different. Certainly, the consistence of the paths caused by the faster speeds (40/80) is more than that at the slower speeds.

Figure 3.3. Trajectories of four grain points M_1 , M_2 , M_3 , and M_4 with different ratios of the conditioner speed and the pad speed: $1/2$, $2/3$, $3/4$, $4/3$, $3/2$, and 2 .

3.3 Model development

To consider the effect of cutting path on the wearing rate of the pad, the pad surface is divided into small species (Figure 3.4). The values of dx and dy were chosen based on the maximum distance that the grain can move in one time step. For the time step of 0.001 sec, the distance that the grain moved is plotted in Figure 3.5. The frequency of the oscillation and the rotation speeds of the conditioner and the pad were $n_o = 10$ strokes/min, $n_c = 40$ rpm, and $n_p = 40$ rpm, respectively. In each 0.001 sec, the grain moved a small distance in both the X and Y directions. To consider the whole process, 12000 steps of time were considered. As shown in Figure 3.5, the distance that the grain moved in one time step is always smaller than 2 mm. Therefore, $dx = 2$ mm and $dy = 2$ mm were chosen. Also from Figure 3.5, the cycle of the process with $n_o = 10$ strokes/min, $n_c = 40$ rpm, and $n_p = 40$ rpm is 6 seconds.

There are many grains on the conditioner. Therefore, many cutting paths appear on the pad surface. Those grains used in calculating must represent the whole conditioner. The conditioner is divided into 180 parts (Figure 3.4). The first and last grains on each part are chosen. The position of the first grain on each part is calculated based on the grain configuration of the conditioner. The distance between the first and last grains is about 10 mm. There are 21 grains on each part are used to draw their trajectories including the first grain, the last grain and those grains between the first and last grains.

Figure 3.4. The conditioner geometry and the divided pad.

Figure 3.5. Distances that the grain moves in one time step in the X and Y directions.

A program was written using Fortran95. The flowchart of the program is presented in Figure 3.6. The position of one grain is calculated using equation (3.3). The Z coordinate of the pad surface is zero at the beginning. For each time the grain appears in one area, the Z coordinates of the area decreases by one unit. For example, at n^{th} time step, if the position of the grain is at area $A(i, j)$, the Z coordinate of area $A(i, j)$ decreases by one unit. At $(n+1)^{\text{th}}$ time step, if the position of the grain is at area $A(i + 1, j)$, the Z coordinate of area $A(i + 1, j)$ decreases by one unit. However, if the position of the grain is still at area $A(i, j)$ at $(n+1)^{\text{th}}$ time step, the Z coordinate of area $A(i, j)$ decreases by one more unit. To ensure the symmetric of the pattern of the cutting paths of grains, at the beginning of each

process, the pad and the conditioner contact at various positions. The program was run at 16 various positions. The program collected all the Z coordinates of all the areas of the pad surface after the process.

The Z coordinates of all the areas on the pad surface are actually the numbers of passes of the cutting paths of the conditioner grains. In this research, it can be called the Z coordinates of the pad surface. Consequently, the pad surface after the conditioning process can be estimated. However, they are not exactly the values of the pad surface after the conditioning process. Those values can be used to investigate the effects of the cutting path density and the contact time on pad wear at the same time. In some cases, to compare some models together, those values are standardized.

The program was tested at a smaller time steps to check its accuracy. The results at different time steps were standardized. They showed the same curve as at the time step of 0.001 sec.

3.4 Model verification

The pad wear was measured after polishing many times in experiments. The oscillation width and stroke were changed in each experiment. However, the final shape of the pad surface was always concave. The CMP machine used in this research was an Okamoto SPP-600S. The diameters of the pad and the conditioner are 600 mm and 200 mm, respectively. Figure 3.7 presents the positions for measuring the pad height. The pad was divided by six lines and each line had 30 points. The pad height at each point was measured. The distribution of the values of the pad height at those points was standardized using Excel software.

Figure 3.6. Flowchart of the program for calculating the Z coordinate of the pad surface.

Figure 3.7. Measured positions for the pad height on the pad in experiments.

The equation for the standardized value is:

$$Z' = \frac{Z - \mu}{\sigma} \quad (3.6)$$

Where Z' is the standardized value, Z is the value that needs to be standardized, μ is the mean value of the distribution, and σ is the standard deviation of the distribution.

Similarly, the values of the Z coordinates of the pad surface from the model were also standardized. Both of standardizations were plotted as shown in Figure 8a. There is a good agreement in the results from the model and the experiments

(Figure 3.8a). That means that the model is suitable for explaining the pad wear profile.

a)

b)

Figure 3.8. Standardization values of the Z coordinates of the pad surface of the model; a) comparing to the experiment data, and b) comparing to the non-contact time model.

Moreover, the model investigated the effects of both the cutting path density and the contact time between the grains of the conditioner and the pad surface. The model in this study integrates the contact time. It is called the contact time model. The model was compared with a non-contact time model. The non-contact time model was established when only the cutting path density was considered. For example, at n^{th} time step, if the position of the grain is at area $A(i, j)$, the Z coordinate of area $A(i, j)$ decreases by one unit, and at $(n+1)^{\text{th}}$ time step, if the position of the grain is still at area $A(i, j)$ the Z coordinate of area $A(i, j)$ is unchanged. The difference of the standardization values of the Z coordinates of the pad surfaces between the two models is shown in Figure 3.8b. The non-contact time model is symmetric and the lowest value is in the middle between the pad center and the pad edge where the cutting path density is the largest. The pad wear profile that the non-contact time model predicted is different from the experiment results. Therefore, the contact time model is better than the non-contact time model in explaining the pad wear profile.

There is a physical explanation for the difference between the contact time model and the non-contact time model. That is the pad deformation. It is integrated to the contact time model through the contact time. The longer one grain of the conditioner contacts the pad surface, the larger the pad deformation is. It keeps the pad surface from returning to the old shape. Therefore, with this contact time model, the cutting density and the pad deformation are considered in the formation of the pad wear profile. With the non-contact time model, only the cutting density is considered. From the contact time model, one conclusion can be suggested that the

pad wear profile is the results of both the cutting path density and the pad deformation.

3.5 Effects of operation speeds on the pad wear profile

The conditioning process parameters, such as the speeds of the conditioner and the pad, and the oscillation velocity of the conditioner, can affect the pad wear profile. When the oscillation speed increases from 1 to 10 (strokes/min), the shapes of the pad wear are almost unchanged (Figure 3.9). Similarly, the effect of the conditioner speed on the pad wear profile is small. When the conditioner speed increases from 1 to 100, the pad wear profiles are almost the same (Figure 3.10). When the pad speed is small, the change of the speed creates a significant change in the pad wear profile. When the pad speed increases, the pad wear profile tends to be stable (Figure 3.11).

Figure 3.9. Effects of the oscillation speeds on the pad wear profile.

Figure 3.10. Effects of the conditioner rotation speeds on the pad wear profile.

It can be concluded that the pad speed is one important factor affecting the uniformity of the pad wear profile. The more the speed of the pad is, the better the pad surface is after the conditioning process is. However, there are not many differences in the pad wear profile when the pad speed is above 10 rpm.

3.6 Effects of sizes, patterns, and positions of the conditioners on the pad wear profile

The patterns on the conditioners affect the pad wear profile in some ways. Figure 3.12 shows pad wear profiles created by different patterns. The conditioner was static in this analysis. Therefore, the effect of the conditioner only impacted on the pad area below the conditioner, and it did not affect the other area of the pad. If abrasive grains cover the circle surface of the conditioner, the pad wear profile looks like a valley (Figure 3.12c). When the abrasive grains are distributed on the

conditioner from $r_{\min}$ to $r_{\max}$, it creates a convex pad wear profile with deeper cutting near the pad center (Figure 3.12a and 3.12b). The total number of abrasive grains distributed on the conditioner did not influence the pad wear profile but affected the cutting depth on the pad part which is conditioned.

Figure 3.11. Effects of the pad rotation speeds on the pad wear profile.

Figure 3.12. Effects of conditioner's patterns on the pad wear shape when the conditioner placed static (only rotation, not oscillation).

The pad wear profile is sensitive to the conditioner sizes. As shown in Figure 3.13, if the conditioner size decreases, the uniformity of the pad wear profile increases. However, if the conditioner size was too small, the conditioner did not

cover the whole pad surface in the conditioning process. That means the pad is not conditioned completely. The best value of the radius should be above 20 mm. With this size of the conditioner, the pad is refreshed perfectly with acceptable uniformity.

Figure 3.13. Effects of the conditioner size on the pad wear shape.

The position of the conditioner also played a significant role in forming the pad wear profile. Figure 3.14 presents the pad wear profile after conditioning with different positions of a static conditioner. The conditioner only rotated around its axis but not oscillated. The more close to the pad center the conditioner position is, the deeper the concave pad shape is.

Figure 3.14. Effects of conditioner's position on the pad wear shape.

3.7 Developing a new model to improve the pad wear profile

As shown in part 3.5, the conditioner process parameters did not change the concave shape of the pad. Therefore, the pad wear profile cannot be improved by investigating those parameters. On the other hand, the pad size and the conditioner size affect the uniformity of the pad wear profile. The distribution of the grains on the conditioner is also an issue. The pad wear profile depends on the cutting density and the time contact between the pad surface and the conditioner grains [106]. The distribution of the grains on the conditioner surface determines the cutting density on the pad surface. In addition, the pad design also affects the pad wear profile [120]. Therefore, the best way to improve the pad wear profile is changing the conditioner and pad design.

Further investigation is established based on the analysis results in section 3.6. When the grains on the conditioner distribute in the same area, from the radius of r_{min} to r_{max} , the pad wear profiles have the same shape (Figure 3.12a and 3.12b). The larger the number of grains is, the deeper the pad wear profile is. When the conditioner disk size increases, the number of passes increases (Figure 3.13). It means that the depth of the pad wear is proportional to the area of the conditioner grains A_c . The depth of pad wear also depends on the inside radius of the area of the grain distribution r_{min} (Figure 3.12b and 3.12c). When the inside radius increased, the uniformity of the pad wear profile increased. In addition, the uniformity of the pad surface in the conditioning process increases when the distance from the pad center to the conditioner center L_t increases (Figure 3.14). Therefore, to improve the uniformity of the pad wear profile, L_t and r_{min} must be as much as possible and the area of the grain distribution must be as small as possible. However, in the

conditioning process, the conditioner should not move over the pad center to avoid contact with the carrier on the other side, and the balance of the conditioner must be maintained. Therefore, the biggest value of r_{min} should be around 150 mm, and the value of $(r_{max} - r_{min})$ should be around 15 mm.

A new design of the conditioner was proposed to get better uniformity of the pad wear profile. The conditioner is a ring with a width of 15 mm and the inside hole diameter of 290 mm, as shown in Figure 3.15. It is static, with only rotation, no oscillation. The distance between its center and the pad center is about 160 mm. The pad is modified by creating a hole with a diameter of 200 mm at the pad center. The rotation speeds of the conditioner and the pad can be any value above 10 rpm (Figure 3.15).

The profile of the pad wear created by the new model is more uniform than that of the traditional model (Figure 3.16). Instead of the concave shape, the new model created a slightly convex shape. Although the area of the pad surface in the new model is less than the old pad because of the hole at the new pad center, the uniformity of the new pad is much more improved. The flat part in the new pad wear shape is much more than the one in the concave shape. It promises better uniformity of the wafer surface in the CMP process.

Figure 3.15. A new model of the pad and conditioner shapes to improve the pad wear profile.

The convex pad wear profile created by the new model has much meaning in CMP processes. First, it improved the uniformity of the pad surface, and through that, the uniformity of machined surfaces such as wafers, optical components, increased. Second, the pad life is extended because the amount of the pad removed in the conditioning process is smaller than that in the old model (Figure 3.16). Third, the pad surface is fully refreshed because the new conditioner always contacts the pad areas from inside edge to outside edge. Fourth, the conditioning process eliminates effectively debris created on the pad surface because of the hole at the pad center and the over edge cutting. When debris created by the cutting

actions of abrasive grains of the pad on the wafer surfaces and of the conditioner on the pad surface, it is flown away to the pad hole and out of the pad edge. The lesser the debris on the pad surface is, the lesser defects appear on the work piece surface in the polishing process.

Figure 3.16. The improved result of the pad wear shape of the new model compared to the old model.

There are some theories about improving a pad wear profile, including using a smaller size of the conditioner and over edge conditioning. Figure 3.17 shows the effects of the small conditioner with a radius of 30 mm (design 1). The pad shape appears flat from the pad radius of 100 mm to 250 mm. However, from the pad radius of 0 mm to 100 mm, the conditioner creates deepest wear on the pad surface.

For that reason, the pad deforms and consequently affects the rest of the pad wear profile.

As in the new model, there is a suggestion that the part of the pad from the radius of 0 mm to 100 mm should be removed. The purpose is to reduce the deformation of pad since the conditioner moves near the pad center. A hole with a radius of 100 mm was generated at the pad center. At first, a conditioner with a radius of 30 mm was used for the conditioning process. The conditioner oscillated around the middle point of the pad area. Its edge moved over the pad edge by a distance of 10 mm. That means the largest distance between the pad center and the conditioner center is 280 mm, and the smallest one is 120 mm. This model was called design 2. However, the result of design 2 is not efficiently in improving the pad wear profile, as shown in Figure 3.17. The pad area from a radius of 100 mm to a radius of 150 mm in design 2 is worse than that in the conditioning process with design 1. That means, in this case, the generated hole on the pad surface helped nothing in the improvement of the pad wear profile.

Both design 1 and design 2 are compared to the new model, as shown in Figure 3.17. The new model showed the least material removal of the pad and almost no transition regions near the pad edge. Therefore, the new model is the best one in improving the pad wear profile.

Figure 3.17. Comparing effects of the new model, design 1 and design 2.

3.8 Summary & Limitation

The research showed the main reason which causes the non-uniformity pad wear is the distribution of cutting path density in the CMP process. An analytical model based on this was proposed for the fixed abrasive pad. Especially, the motion of the conditioner in this research was a combination of two motions: rotation and oscillation. The study finds the correlation between counting the cutting path density and the pad wear in experiments. The proposed model is applicable to not only this type of conditioning pad but also all types of cutting motions including rotation and oscillation.

CHAPTER 3 ANALYSIS AND DEVELOPMENT OF FAP

The effects of different kinds of speeds, i.e. the rotation speeds of the conditioner and the pad, the oscillation speed of the conditioner, have been investigated, allowing a better understanding of the kinematic aspects of the conditioning process of the polishing with fixed abrasive pad. A new model for the fixed abrasive conditioning process, including a new pad and a new conditioner, was developed. This new model improved the wear shape of the pad caused by the conditioning process. According to the result of the new model, the pad shape after the conditioning process is more uniform than the old one conditioned by the old model.

Limitation of the research is that the new shapes of the conditioner and the pad are theoretically developed. They need to be produced in reality to validate the result.

CHAPTER 4 COMPUTATIONAL FLUID DYNAMIC SIMULATION

OF DISTRIBUTION OF ABRASIVE PARTICLES IN TRADITIONAL

CMP

In this chapter, the concentration of the particles in the gap between the wafer and pad surfaces was investigated primarily by using a multiphase 3D CFD model. There were water and abrasive particles injected at the same time. Motions of abrasive particles of the slurry in the CMP process were visualized and calculated by Fluent in ANSYS Workbench 14, which is a powerful commercial software for analyzing these problems.

4.1 Model

To use the CFD commercial software to simulate the slurry flow, geometry was firstly built. Figure 4.1 presents the geometry model and parameters for the CMP model. Only the region where the slurry could be delivered was developed. Therefore, in the model, only the wafer surface was seen, not the whole solid wafer. It was the same for the pad and the slurry injection. All dimension values in Figure 4.1 are set up as shown in Table 4.1. The wafer and the pad rotated in the same direction, counter-clockwise. The slurry flow from the inlet was spread on the pad surface and the pad rotated to bring the slurry entered the interface between the wafer and the pad surfaces.

Figure 4.1. Modeling of the CMP machine.

The fluid flow with boundary conditions, which helps the flow fully developed, is modelled and meshed as shown in Figure 4.2a. The region where the fluid would be filled was expanded outside the pad surface about 200 mm with a thickness of 30 mm. Therefore, the largest diameter of the model, as shown in Figure 4.2, is 1000 mm and the biggest thickness of the model is 30 mm. The thickness of the region for the slurry flow on the pad surface is 2 mm. The distance between the pad and wafer surfaces is

from 20 μm to 40 μm . The distance between the carrier and the pad surfaces is about 0.3 mm. The inlet and the outlet are shown on the figure. The outlet includes the outside limit, the top limit and the bottom limit.

Table 4.1. Dimension parameters

Name	Parameter	Value
Diameter of the pad	D_p	610 mm
Diameter of the carrier	D_{ca}	200 mm
Diameter of the wafer	D_w	50 mm
Distance from the pad center to the wafer center	L	160 mm
Distance from the pad center to the inlet	V	160 mm
Distance between the wafer and pad surfaces	h	40 μm
Distance between the carrier and pad surfaces	h_c	0.3 mm

Figure 4.2. Boundary condition model for ANSYS Fluent simulation: a) full model, and b) cross sectional view.

Skewness is one of the most important criteria in meshing the model. The finer mesh is, the better skewness is. There are two kinds of mesh: structured mesh and unstructured mesh. Skewness is the indicator of the mesh quality and suitability. Based on equilateral volume, value of skewness is given as (for triangles and tetrahedral only) [136]:

$$skewness = \frac{optimal\ cell\ size - cell\ size}{optimal\ cell\ size} \quad (4.1)$$

Based on the deviation from normalized equilateral triangle (almost used for prisms and pyramids), value of skewness for a quad is expressed as [136]:

$$skewness\ (for\ a\ quad) = \max \left[\frac{\theta_{max} - 90}{90}, \frac{90 - \theta_{min}}{90} \right] \quad (4.2)$$

A sweep method and a multizone method were used to mesh the model. It was difficult to mesh the model with good quality and lower skewness. Because the thickness of the gap between wafer and pad was quite small, about 40 μm and the largest diameter of the model was 1000 mm. In addition, in ANSYS Fluent, the value of skewness must be lower than 0.85. Moreover, to investigate the flow between the pad and wafer surfaces, the distance between them must be vertically divided into at least three layers of mesh. Therefore, the domain was divided into three parts: a wafer part, a carrier part, and the rest. The sweep method was used to mesh the gap between the wafer and pad surfaces. There were four layers of mesh in the gap. The total number of cells in a vertical direction between the carrier surface and the pad surface is ten, as shown in Figure 4.3b. The multizone method was used to mesh the other part of the model to get the good quality mesh and skewness, which was suitable for FLUENT simulation. With new version 14.5 of ANSYS Workbench, the mesh model was created with high skewness: 0.61.

Figure 4.3. (a) Mesh schematic of the whole model and (b) sectional view and detailed mesh of the gap between the wafer, carrier and pad surfaces.

There were two kinds of elements of the mesh: Hex8 and Wed6. The meshed body consisted of 105087 elements. Hex mesh was suitable because: it reduced the total number of mesh elements (it takes approximately 5-6 tetrahedrons to fill a hexahedron). Hexahedron meshes were generally more uniform and more accurate when aligned with the flow direction.

4.2 Method

Following the optional model used in ANSYS Fluent for calculating multiphase problems, the model used in this research was a multiphase flow. It was a combination of free-surface flow (also called open channel) and slurry flow. In the free-surface flow, also called open channel flow, water was injected and came to the pad surface, then spread out on the pad surface. Water flew under air in the atmosphere. Meanwhile, solid particles, which were the discrete phase model, were injected at the same time to create abrasive particles in the slurry flow. The slurry was carried by the pad surface, and then went into the interface between the wafer and pad surfaces. There were totally three phases in the analysis process: air, water, and solid particles.

4.2.1 Volume of fluid (VOF) model

For the free-surface model, we used VOF which is based on Euler-Euler approach [136]. With this model, we can track the flow of liquid in transient and open channel. The governing equations, which describe the VOF model, include a continuity equation and a momentum equation [136].

- A continuity equation for the volume fraction of one (or more) of the phases is [136]:

$$\frac{1}{\rho_w} \left[\frac{\partial}{\partial t} (\alpha_w \rho_w) + \nabla \cdot (\alpha_w \rho_w \vec{v}_w) \right] = (\dot{m}_{aw} - \dot{m}_{wa}) \quad (4.3)$$

Where $\dot{m}_{aw}$ is the mass transfer from phase air to phase water.

$\dot{m}_{wa}$ is the mass transfer from phase water to phase air.

ρ_w is the water density.

α_w is the water volume fraction in the cell ($\alpha_w = 0$: the cell is full of air, $\alpha_w = 1$: the cell is full of water, $0 < \alpha_w < 1$: the cell contains the interface between water and air).

$\vec{v}_w$ is the water velocity.

- Momentum equation is [136]:

$$\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot \left[\mu \left(\nabla \vec{v} + \nabla \vec{v}^T \right) \right] + \rho \vec{g} + \vec{F}, \quad (4.4)$$

where $\rho = \alpha_w \rho_w + (1 - \alpha_w) \rho_a$ and $\mu = \alpha_w \mu_w + (1 - \alpha_w) \mu_a$.

μ_w is the viscosity of water.

ρ_a and μ_a are the density and viscosity of air.

4.2.2 Discrete phase model (DPM)

DPM is a model used to simulate the motion of discrete particles. The abrasive particles in the slurry were treated as discrete particles and their motions were given by the Newton's equation [136]:

$$\frac{du_p}{dt} = F_D(\vec{u} - \vec{u}_p) + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} + \vec{F}. \quad (4.5)$$

Where $\vec{F}$ is an additional acceleration (force/unit particle mass) term, $\vec{u}$ is the fluid phase velocity, $\vec{u}_p$ is the particle velocity, μ is the molecular viscosity of the fluid, ρ is the fluid density, ρ_p is the density of the particle and d_p is the particle diameter.

$F_D(\vec{u} - \vec{u}_p)$ is a drag force. For sub-micron particles, a form of Stokes' drag law is available and defined as [137]:

$$F_D = \frac{18\mu}{d_p^2 \rho_p C_c}. \quad (4.6)$$

The factor C_c is the Cunningham correction to Stokes' drag law, which is computed from [137]:

$$C_c = 1 + \frac{2\lambda}{d_p} \left(1.257 + 0.4e^{-(1.1d_p/2\lambda)} \right) \quad (4.7)$$

where λ is the molecular mean free path.

4.2.3 Multiple moving frame

In the CMP process, both the wafer and the pad rotate around their centers. The motion of frames was integrated in the fluid velocities [136]:

$$\vec{\nabla} \vec{v} = \vec{\nabla} \vec{v}_r + \vec{\nabla} (\vec{\omega} \times \vec{r}) \quad (4.8)$$

Where $\vec{v}$ is the absolute velocity, $\vec{v}_r$ is the relative velocity, $\vec{\omega}$ is the angular velocity of moving frame, $\vec{r}$ is the position vector from the origin of moving frame.

4.3 Simulation conditions

In order to simplify the simulation process, several assumptions were made. The pad surface was assumed flat and hard without surface roughness, the wafer surface was also flat, hard, no tilt and deformation. The water and the abrasive particles were injected from the inlet with the same velocity but there were no interactions between them. Because the software has no colloidal silica particle, the particles used in the simulation was modified from anthracite particles. The density was changed to 2300 kg/m³, and the diameter of particles was set from 20 nm to 80 nm with the mean value of 50 nm. Both the water and particle flow had the same velocity of 100 ml/min and the total flow rate of particles was calculated based on 10% (v/v) of particle concentration in the 100ml/min slurry flow rate.

Other settings for simulation conditions were given by the defaults of the software with little modifications. In the VOF model which was used in the simulation process, the primary phase was air and the phase two was water which was injected from the inlet. The discrete phase model, which was used to model the flow of particles, was injected from the inlet at the same velocity as the water. These submicron particles had their motion based on the Newton equation with the Stokes-Cunningham drag law. The rotation of frames and no-slip boundary condition were applied to the rotation of the pad and wafer surfaces. Solution method used SIMPLE scheme, spatial discretization pressure PRESTO!, Second Order Upwind for momentum, Geo-Reconstruct for Volume Fraction and First Order Implicit for Transient formulation. The flow was transient, time

step size was 0.001 sec, max iterations per time step was 20 and simulation time was from 20 second to 65 second. A smaller time steps were tested to prove the correction of the model and the simulation process. A refinement mesh was also conducted to check the convergence of the process. Table 4.2 presents the simulation settings for the pad and wafer speeds, the slurry flow rate, and the thickness of the gap.

Table 4.2. Simulation conditions

Simulation parameters	Settings
Simulation method	Sweep, Multi-zone
Fluid layer thickness	20 μm , 40 μm
Water density	998 kg/m^3
Particle density	2300 kg/m^3
Mean particle diameter	50 nm
Flow type	Transient
Slurry flow rate	100 ml/min (10%v/v.)
Pressure outlet	Atmospheric
Pad rotation speed	20 rpm, 40 rpm counter-clockwise
Wafer rotation speed	20 rpm, 40 rpm counter-clockwise
Time step size	10^{-3} sec

4.4 Simulation results

4.4.1 Velocity

The velocity contour from Figure 4.4 shows a good agreement with a lubrication model. Because of the no-slip boundary condition, the velocity of the fluid layer near the pad surface was equal to the pad's velocity, e.g. $2\pi\omega_p r_p$. It was similar to the layer of the fluid near the wafer surface, meaning the velocity of the fluid layer near the wafer surface had the same value as wafer's velocity, e.g. $2\pi\omega_w r_w$. With the layer of the fluid in the middle of the gap, the velocity is unable to be expressed by using the relative velocity between the wafer and the pad. It might be described using the lubrication theory [12].

Figure 4.4. Distribution of the fluid velocity in the gap with the simulation conditions: a pad speed of 20rpm, a wafer speed of 40rpm, slurry flow rate of 100ml/min, 10%v/v.

4.4.2 Static pressure

The static pressure is supplied by a sum of the mass of water and the head load per unit area. Figure 4.5 presents the static pressure of the fluid in the interface region between the wafer and pad surfaces at 15 sec, 20 sec, 25 sec and 30 sec. The pressure distribution changed with time. At the first 20 seconds, it was the time for the process to achieve a stable status. The slurry began to fulfill the gap between the wafer and the pad, and abrasive particles in the slurry began to follow the stream without extracting or annoying. The most stable form of the process started at about 23 sec depending on the operation parameters. From this time, the static pressure included two regions of negative and positive values. However, in general, there could be always two regions with negative and positive pressures below the wafer in the whole CMP process. In addition, the average of the fluid pressure in the simulation was quite small, and the head load that the fluid supported was low.

Figure 4.6 presents the hydrostatic pressure that occurs in the radial direction of the wafer and carrier after 25 sec. Although two regions of the static pressure are observed as shown in Figure 4.5, there is also a difference between values of the pressure along the radius direction. The max value of the pressure appeared near the center of the wafer. However, this max value was much smaller than the max value on the total wafer surface. One conclusion can be made that the wafer center supports almost the head load in the CMP process. If the average of the pressure of the edge is smaller than the pressure at the center, the wafer becomes convex. If the average of the pressure of the edge is larger than the pressure at the center, the wafer becomes concave.

Figure 4.5. Static pressure below the wafer versus time at the pad speed of 20 rpm, the wafer speed of 40 rpm, the slurry flow rate of 100ml/min and the film thickness of 40 μm .

Figure 4.6. Static pressure of the fluid below the wafer and the carrier surfaces after 25 sec at the pad speed of 20 rpm, the wafer speed of 40 rpm, the slurry flow rate of 100ml/min and the film thickness of 40 μm .

The static pressure below the carrier surface is quite small, nearly zero, as shown in Figure 4.6. That means the fluid which is between the carrier surface and the pad surface cannot support any head load in CMP process. The main reacting force which is used to balance the press down force of the head might be provided by the layer of the fluid between the wafer and the pad surfaces.

Those results of the static pressure have confirmed some theory and experiments in fluid pressure between the wafer and pad surfaces in the literature. Combining them with the dynamic pressure results could be used to explain more about the mechanism of CMP processes.

4.4.3 Dynamic pressure

Dynamic pressure is supplied by mass combined with the energy of motion. It is a form of kinetic energy and is applied by moving water on its surroundings. Figure 4.7 represents the dynamic pressure under the wafer surface and the carrier surface at 25 sec of the simulation process.

Figure 4.7. Dynamic pressure below the wafer and the carrier surfaces after 25 sec at the pad speed of 20 rpm, the wafer speed of 40 rpm, the slurry flow rate of 100ml/min and the film thickness of 40 μm ..

The blue line in Figure 4.7 is the dynamic pressure below the wafer and the red line is the one below the carrier. Because there was the no-slip condition between the wall and the fluid, the velocity of the fluid below the wafer was smaller than the velocity of the flow below the carrier. Consequently, the maximum value of dynamic pressure, which is proportional to the velocity, below the wafer was smaller than the one below the carrier. However, the nature of the flows of the fluid below the wafer and the carrier are different because the gap thicknesses for their flows are different. There are many problems in the dynamic pressure results and they must be further investigated to explain the non-uniformity of the wafer surface.

4.4.4 Motion of particles

When the flow went into the interface zone between the wafer and pad surfaces, some particles changed their direction. Because of the rotation of the wafer, some particles changed their moving directions when they reached the wafer edge. Some particles moved around the wafer and others went through the gap. Motion and distribution of the particles below the wafer have important meaning in calculating MRR and non-uniformity of the surface after polishing.

The purpose of this research is to investigate the distribution of the particles in the gap between the wafer and pad surfaces. The total number of the particles could be calculated based on their positions. When the results of the particle positions were exported from Ansys Fluent, all particles, of which position conditions are described by equation (4.9), were in the interface between the wafer and the pad surfaces.

$$\begin{cases} -0.025 \leq x \leq 0.025 \\ -0.025 \leq y \leq 0.025 \\ \sqrt{x^2 + y^2} \leq 0.025 \end{cases} \quad (4.9)$$

and $z \leq 40e-6$

The total number of the particles in the interface increased until the process was stable. Figure 4.8 presents the total number of particles below the wafer versus time in the first 60 sec of the simulation process. The steady state of the total number of the particles could be achieved about after 20 sec of the process. It could be used to explain why the friction force in the CMP process was unchanged after 20 seconds.

The total number of the particles between the wafer and pad surfaces is changed when operation parameters are changed. The total number of the particles is calculated at the same pad and wafer speeds and slurry flow rate with different thickness of 40 μm , 30 μm and 20 μm (Figure 4.9). It increases with the increasing of the gap thickness. The total numbers of the particles in the gap has a little difference when the gap thickness increases from 20 μm to 30 μm . But it increases a lot when the gap thickness increases from 30 μm to 40 μm . We can conclude that there is a nonlinear relationship between the gap thickness and diameters of the particles in the slurry.

Figure 4.8. Number of particles in the gap between the wafer and pad surfaces at the slurry flow rate of 200 ml/min, the pad speed of 40 rpm, and the wafer speed of 40 rpm.

Slurry flow rate also affects the total number of the particles in the gap (Figure 4.10). The dependence of the total number of the particles on the slurry flow rate is nonlinear. It increases when the slurry flow rate increases from 100 ml/min to 200 ml/min. After that, the total number of the particles decreases when the slurry flow rate increases from 200 ml/min to 300 ml/min. The reason is that there is more space for particles when the flow rate increases. The slurry area is spread widely on the pad surface. The higher the flow rate is, the larger the area is. It may help increasing the total number of particle at first. After that, when the total number particle has reached the highest value, the inside pressure and outside pressure of the gap are balanced. It keeps

the particles from moving inside the gap. If the flow rate continually increases, there are more and more fluid around the wafer edge. This fluid creates more space for particles move out the gap. It also helps particles which are stopped by the wafer edge move away easily. Therefore, the total number of particles in the gap reduced. In the literature, the dependence of MRR on the slurry flow rate has a similarly trend. Therefore, the simulation process can be used to explain the impact of the slurry flow on the MRR.

Figure 4.9. Number of particles in the gap versus time at the same pad speed of 20 rpm, the wafer speed of 20 rpm and the slurry flow rate of 100 ml/min (10%v/v).

Figure 4.11 presents the effects of the operation parameters on the total number of the particles in the gap. When the slurry flow rate, the pad speed, and the wafer speed are kept constant, the increasing of the polishing pressure (or head load) leads to the

decreasing of the gap thickness. As shown in Figure 4.11a, with the constant slurry flow rate and the pad and wafer speeds of 20 rpm, when the gap thickness increases from 20 μm to 40 μm , there is a gradually increasing in the total number of the particles in the gap. This means the polishing pressure or the head load strongly affected the number of the particles.

Figure 4.10. Number of particles in the gap between the wafer and pad surfaces at the same thickness of 40 μm , the pad speed of 40 rpm, and the wafer speed of 40 rpm.

From Figure 4.11a, with the same pad speed, when we change the wafer speed; the number of the particles is nearly unchanged. The wafer speed increases, the number of particles decreases. However, when the gap thickness decreases, the effect of the wafer speed on the number of the particles is quite small. It can be concluded that the

wafer speed has no influence on the number of particles in the gap if the polishing pressure was high. Moreover, the wafer speed may not be an important factor that affects MRR when compared with other factors like the pad speed or the head load.

Figure 4.11. Total number of particles in the gap at 22 sec with the same slurry flow rate of 100 ml (10%v/v) and (a) the pad speed of 20 rpm, (b) the wafer speed of 20 rpm.

If the wafer speed is still the same, as shown in Figure 4.11b, the total number of particles in the gap is decreased when the pad speed is increased. Because the drag force of the pad on the abrasive particles is larger, it forces more particles out of the gap. In addition, to keep the gap thickness constant when the pad speed is increased, the head load on the carrier must be increased. The increasing of the head load causes the increasing in fluid pressure of the gap. The more fluid pressure the gap has, the less number of the particles go through it. The effect of the pad speed on the number of the particles is quite high, especially when the gap thickness is increased.

The primary result about the distribution of abrasive particle was found in the simulation process. That is the particle distribution in the gap is non-uniformity. Figure 4.12 shows the average number of particles per m^2 below the wafer at the same pad speed of 20 rpm and the slurry flow rate of 100 ml/min (10%v/v). The concentration of the particles near the wafer center is higher than the one near the wafer edge.

This result can be used to explain the difference in MRR between the wafer center and edge. With this non-uniform distribution, the center region of the wafer with more particles could support a larger amount of the carrier force than the edge region. Therefore, the concave shape of the wafer is formed in the CMP process. Moreover, the force per particle in the center region is smaller than that in the edge region because the center region had more particles than the edge region. Besides, the fluid pressure near the edge region is larger than that near the center region (Figure 4.5). The relationship between the force per particle and the fluid pressure creates the difference in the MRR between the center and the edge of the wafer. It may be one of the reasons for causing the non-uniformity of the wafer surface.

Figure 4.12. Average number of particles per m² on the interface between the wafer and the pad at the same pad speed of 20 rpm, slurry flow rate of 100 ml/min (10%v/v).

The flow of the particles and the water from the simulation process is presented in Figure 4.13. With the pad speed of 20 rpm and the wafer speed of 40 rpm, Figure 4.13a shows the particle distribution on the pad surface at the first second. Figure 4.13b and 4.13c present the distribution of the water and the particles on the pad surface after 15 sec of the simulation process. The distribution of the water in Figure 4.13b presents the motion of the water. The water is injected from the inlet and then spreads on the pad surface. When time increases, the water covers the whole pad surface except the pad center. The distribution of the particles is presented separately in Figure 4.13c. When time increases, more and more particles are distributed at the pad center. The distributions of the particles and the water are nearly matching because there were approximations and assumptions for the simulation process. One of them was no

interaction between the water and the particles. Therefore, the model needs to be improved to get the perfectly matching of the distributions of the water and the particles.

Figure 4.13. Slurry distribution on pad surface with a pad speed of 20 rpm, a wafer speed of 40 rpm, slurry flow rate of 100 ml/min, (a) particle flow at the first second from the inlet in the simulation, (b) water distribution after 15 sec and (c) particle distribution on the pad surface after 15 sec.

4.5 Observation of the slurry flows in CMP process

The purpose of this experiment was to visualize the flow of slurry in the CMP process. In this experiment, a high-speed camera was set up to take some pictures of the slurry at the beginning of the process. These observations were used to confirm the forms of slurry flow at the beginning and finishing of polishing in the simulation process. From Figure 4.14a, the slurry flow is recorded at the first second of the process with the pad speed of 20 rpm. After polishing, the slurry distribution on the pad surface is shown in Figure 4.14b. There are similarities between the experiment observations

and the simulation results (Figure 4.13). Those convinced that the flow of particles and water in the simulation process could be applicable to investigate the flow of slurry and the motion of the particles in CMP processes.

Figure 4.14. Observation of slurry flow with high-speed camera, (a) at first second from inlet in experiment at pad speed 20 rpm and (b) after polishing.

4.6 Summary & Limitation

This research is focused on a new approach for simulation method to investigate the CMP process. The combination of VOF and DPM in the CFD model has provided an inside observation of the model. The result from the number of the particles below the wafer surface and their distribution has provided a more step in the process of finding out the mechanism of CMP. The distribution of particles in the interaction between the wafer and pad surfaces is not uniform. It can be used to explain the non-uniformity of the substrates after polishing. The polishing pressure and the pad speed are the most important factors that affect the total number of particles in the gap.

This is a simple CFD model used for simulating motion of particles in CMP process. The model is based on many assumptions including flat and hard pads, no tilt

CHAPTER 4 CFD SIMULATION OF DISTRIBUTION OF ABRASIVE PARTICLES

wafers, and no interaction between the abrasive particles. These assumptions are not suitable in reality and need more improvement in future work, such as adding material for the pad and the wafer or including the tilt angle or deformation of the wafer. In addition, the shape of the abrasive particles is not a sphere in reality. Those factors such as particle shape, hardness, and material are needed to be considered.

CHAPTER 5 INVESTIGATING THE WAFER NON- UNIFORMITY IN FIXED ABRASIVE POLISHING & CHEMICAL MECHANICAL POLISHING

CMP is the best choice for planarization. Because of the high requirement for the wafer surface after polishing, the non-uniformity of the surface must be reduced. The surface which is polished by FAP can achieve better uniformity but higher surface roughness. MRR in the FAP is also higher than conventional CMP. Therefore, the surface is first polished by FAP then by conventional CMP to improve the uniformity and surface roughness and reduce polishing time. In this chapter, some experiments were conducted to measure the surface roughness and the flatness of the wafer surface. The experimental results showed the improved surface roughness. To explain the reasons for the improved surface roughness, mechanisms of FAP and conventional CMP were investigated.

5.1 Experiments

The purpose of these experiments is to investigate the glass polishing process using a fixed abrasive pad and a fabric cloth pad. Three samples were polished with the fixed abrasive pad. After that, the pad was changed to the fabric cloth pad. The weight and surface roughness of the wafers were measured.

5.1.1 Experiment tools

The machine in this research was Okamoto SPP-600S. For polishing optical components, two types of the pad were used: a fixed abrasive pad (3M Trizact TM Diamond Tile 677XA) and a low-cost fabric cloth pad (3M 300LSE). Figure 5.1a shows the fixed abrasive pad and Figure 5.1b shows the low-cost fabric cloth pad.

The samples were weighted by a Weighted Ultra Microbalance before and after polishing and MRR in this experiment was calculated based on the formula:

$$MRR = \frac{\text{weight before polishing} - \text{weight after polishing}}{\text{time polished}} \quad (5.1)$$

After polishing, the samples were cleaned by an Ultrasonic cleaner. The flatness was measured by a Laser interferometer machine. Figure 5.2 presents the flatness result of one sample after polishing. The roughness of these samples was also measured. When measuring roughness, ISO standard must be followed as shown in Table 5.1.

a) Fixed abrasive pad

b) Fabric cloth pad

Figure 5.1. Two types of pads.

Figure 5.2. The flatness of the polished surface measured using the laser interferometer.

Polishing time of three samples was different to check the effect of two types of pads on the material removal and surface roughness of the samples (Table 5.2).

The operation parameters for the polishing process with the fixed abrasive pad and the soft pad are listed as follows:

- Parameters for polishing with the fixed abrasive pad:

- Head load: 70g/cm²

- Table speed: 80rpm
- Spindle speed: 40rpm
- Slurry supply rate: 100ml/min (water)

- Parameters for polishing with fabric cloth pad:

- Head load: 98g/cm²
- Table speed: 20rpm
- Spindle speed: 20rpm
- Slurry supply rate: 100ml/min (a 10: 1 mixture of water with colloidal silica)

Table 5.1. Recommended value for cut-off (ISO4288-1996)

Periodic profile	Non-periodic profile		Cut-offs	Sampling length/ evaluation length
Spacing distance Sm (mm)	Rz (μm)	Ra (μm)	Lc (mm)	Lc/L (mm)
> 0.013 ~ 0.04	(0.025) ~ 0.1	(0.006) ~ 0.02	0.08	0.08/0.4
> 0.04 ~ 0.13	> 0.1 ~ 0.5	> 0.02 ~ 0.1	0.25	0.25/1.25
> 0.13 ~ 0.4	> 0.5 ~ 10	> 0.1 ~ 2	0.8	0.8/4
> 0.4 ~ 1.3	> 10 ~ 50	> 2 ~ 10	2.5	2.5/12.5
> 1.3 ~ 4	> 50 ~ 200	> 10 ~ 80	8	8.0/40

Table 5.2. Time of polishing

Sample	Diameter (mm)	Polishing first time (min)	Polishing second time (min)	Before CMP
				Weight (mg)
1	50.8	1	1	1721.05
2	50.8	2	5	1771.15
3	50.8	5	1	1888.22

5.1.2 Experiment results

Table 5.3 presents the weight and surface roughness of the samples after polishing. The MRRs of three samples after polishing with fixed abrasive pad were 33 mg, 19 mg and 26 mg, respectively. However, the MRR of three samples decreased more than one tenth when they were polished with the soft pad (0.2 mg/min, 0.5 mg/min and 0.49 mg/min, respectively). The surface roughness of the samples becomes much better when they were polished in the second time. Based on that, the research could conclude that with the fixed abrasive pad, MRR is higher but roughness is worse than that with the fabric cloth pad. Therefore, fixed abrasive pads can be used in rough polishing and fabric cloth pads can be used in finish polishing.

In the first polishing, the slurry is water and abrasives are fixed on the surface of the pad. Therefore, the chemical reaction did not happen and only mechanical action happened. In the second polishing, the slurry is a solution of

water and colloidal silica. With this slurry, there were chemical and mechanical actions in the CMP process.

Table 5.3. Weight and surface roughness of three wafers after polishing

After CMP with fixed abrasive pad (first time)			
Weight (mg)	Roughness (Ra) (μm)	Roughness (Rz) (μm)	Roughness (Rt) (μm)
1687.96	0.05	0.378	0.562
1733.06	0.038	0.385	0.659
1758.18	0.029	0.328	0.537
After CMP with fabric cloth pad (second time)			
Weight (mg)	Roughness (Ra) (μm)	Roughness (Rz) (μm)	Roughness (Rt) (μm)
1687.76	0.008	0.095	0.154
1730.41	0.008	0.093	0.134
1757.69	0.009	0.095	0.129

5.2 The non-uniformity of surfaces in FAP and conventional CMP

5.2.1 Non-uniformity of wafer surfaces in FAP

The non-uniformity of the wafer surfaces in FAP can be calculated using kinematic analysis. The slurry is DI water. The abrasive particles, which are embedded on the pad surface, are the main factor for MRR. The pad is flat and hard enough to create the same indentation depth on the wafer surface for each abrasive particle. Therefore, the MRR which is caused by the particle is proportional to the distance that the particle moved on the wafer surface. By analyzing the trajectory of the particles, the non-uniformity of the surface can be accuracy estimated.

The equations which were used for modeling the trajectory paths of the conditioner grains on the pad surface in chapter 3 were modified to apply in this section. The pad surface was reduced to become a wafer surface with a diameter of 50 mm. The conditioner surface was enlarged to become the pad surface. The pad surface is faced up. The wafer surface is faced down (Figure 5.3). It was divided into small areas. When a point on the pad surface moved and passed a small area on the wafer surface, the Z coordinate of the area was increased by 1. It was different from chapter 3 at this point. That means in this case, only the number of passes were counted, and for each pass, the Z coordinate was added 1 unit. The contact time was not considered in this part. Therefore, only the kinematic effects of operation parameters were used to estimate the non-uniformity of the wafer surface in FAP.

Figure 5.3. Schematic of the FAP process.

After counting the number of passes on the small areas, the results showed the polished substrates. These substrates had high Z coordinates. The longer time the simulation was, the higher the Z coordinates were. They used to estimate the non-uniformity of the wafer surface after polishing because it was proportional to the MRR.

Figure 5.4 shows the effects of the pad speeds on the non-uniformity. It is based on counting number of trajectory passes on each small substrate area. When the pad speed is 40 rpm, the substrate is concave. When the pad speed increases, the non-uniformity is reduced. The edge effect appears on the substrate when the pad speed is 100 rpm.

The wafer speed affected the non-uniformity. When the wafer speed increases, the non-uniformity increases (Figure 5.5). However, the edge effect only appears when the wafer speed is high (around 80 rpm). The substrate is concave when it rotates at small velocity. It becomes convex more and more when the velocity increases.

Figure 5.4. The number of passes on the wafer surface at different pad speeds and the same wafer speed of 40 rpm.

Figure 5.5. The number of passes on the wafer surface at different wafer speeds and the same pad speed of 40 rpm.

When the wafer and pad speeds are the same, the concave substrate is achieved when the speeds are small (around 40 rpm). The substrate is convex and the edge effect is strong when the speeds increase (Figure 5.6). That means the non-uniformity is increased when the speeds increase. It is a combination of both the pad and wafer speeds presented in Figures 5.4 and 5.5. Experiments, which have been done by Hocheng et al. [51], have validated the results.

Figure 5.6. The number of passes on the wafer surface when the pad and wafer speeds are equal.

The oscillation speed has insignificant on the non-uniformity. As shown in Figure 5.7, when the oscillation speed increases from 1 to 10, the concave substrates are almost unchanged. This is a good agreement with Hocheng et al. [51]. However, when the speed is 0, the uniformity of the surface is the worst. Therefore, the oscillation has minor impact on generating the wafer surface non-uniformity in FAP.

Figure 5.7. The number of passes on the wafer surface with the same pad and wafer speeds of 40 rpm when the oscillation speed changes.

Those results have shown that the non-uniformity in FAP is primary determined by the operation parameters. The head load creates the depth of cut. The speeds of wafers and pads create the surface profile after polishing. There are no chemical reactions in FAP. Therefore, the non-uniformity of the wafer surfaces can

be predicted and improved in FAP. The mechanism of FAP is simple. It is based on the mechanical action of abrasive particles of the pad only, like the grinding process. Therefore, the best surface roughness of the polished surfaces can be achieved by using grinding theory.

5.2.2 Non-uniformity in conventional CMP

The fundamental mechanism for the MRR of the conventional CMP is totally different from the FAP [97]. The relationship between the pressure and MRR is not linear. It is nonlinear. The MRR is proportional to $(F_n)^{2/3}$, where F_n is the head load [97, 138].

A new idea was developed to explain mechanism of the conventional CMP. It was motivated by two reasons. Firstly, the hardness of the substrate is different when it is polished with different types of slurry. Zhou et al. [42] have compared the substrates before polishing, after polishing with colloidal silica, and after polishing with DI water only. They have concluded that a residual product in polishing with colloidal silica is the easiest one to be removed. Secondly, in the polishing processes with DI water only, there are scratches which are caused by the pad asperities. The pad asperities are compressed and generate adhesion forces on the substrate. That means the force caused by the pad asperities is large enough to remove the material on the wafer surface.

Based on that, a new idea is proposed. The pad is the main reason that caused the MRR. First, the wafer surface reacts with the chemical slurry to form a hydrated layer. The abrasive particles contact the surface and there are chemical reactions between them and the wafer. The chemical reaction speed is increased

when the concentration in the slurry increases. However, when the whole surface has been reacted, the chemical reactions stop. Second, the pad asperities exert forces on the surface peaks and remove them away. When the peaks are removed, the surface becomes smoother than before, and then the MRR is reduced consequently. The particle abrasives are embedded on the wafer surface and create new peaks. The new peaks heights depend on the head load and the particle diameters. If the surface is continually polished, the pad asperities continually remove the new peaks on the wafer surface.

Figure 5.8 shows the schematic of the polishing mechanism. Some of the abrasive particles are trapped in the pad holes. Some of the particles are embedded in the pad asperities. The embedded particles exert larger forces than the trapped particles on the passive layer of the wafer surface. However, the forces of the embedded particles are less or equal the forces from the pad asperities because the pad is soft and compressible. Therefore, the forces from the particles on the wafer surface depend on the forces from the pad asperities. The particles may be pressed on the surface and then rolled or dragged away by the pad asperities when the pad rotates. If the particles are rolled away, that means the forces caused by the pad asperities are smaller than that when the particles are dragged away. In both cases, the forces from the pad asperities are large enough to remove some peaks on the wafer surface. The pad asperities are pressed into the hydrated layer, especially go into the gaps between peaks on the surface. When the pad rotates, the pad asperities drag the layer out of the surface. The wafer surface is then exposed and ready to react with chemical factors in the slurry.

Figure 5.8. The schematic of the conventional CMP mechanism.

The slurry is carried to the wafer by the pad holes. This slurry chemically attacks the wafer surface, forms a hydrated layer which is more easily removed by the pad asperities. The hydrated layer is around 2 - 3 Å. The pressure, pH, and the temperature increasing accelerates the chemical reaction [139]. When the slurry concentration increases, the chemical reaction is faster, and the new peaks created by the abrasive particles are increased in number and becomes thinner, then the MRR increases. However, when the number of particles is too large, they prevent the pad asperities contact the wafer surface, therefore, the MRR reduced. When the particles cover most of the pad surface, the MRR remains unchanged.

The mechanism supports the idea that there is a direct contact or semi-direct contact between the wafer and pad surfaces. Its operation is like a brake. The brake disc is very rugged and strong metal, the pad is much softer, and at the end, the brake disc is worn out.

On a microscopic scale, there are ridges and valleys to the surfaces on both materials. When the two materials have pushed and slide against each other, the ridge of one material will shear off when its shearing resistance is weaker than the ridge of the other material. The shearing force is calculated as the product of the shearing stress and the shearing area. Although the shearing stress of the wafer surface is larger than the one of the pad surface but the shearing area of the pad surface is much larger than that of the wafer surface.

$$F_u = \nu_u * (L_s * w_s) \quad (5.2)$$

Where F_u is the shearing force, ν_u is the shearing stress, L_s is the length of surface roughness, and w_s is the width of the surface roughness.

To find out the total length and width of the surface roughness, the contact area can be used, such as the following formula [97]:

$$A_a = \left[F_n \left(\frac{1}{E_a} + \frac{1}{E_w} \right) \right]^{2/3} \propto P^{2/3} \left(\frac{1}{E_a} + \frac{1}{E_w} \right)^{2/3} \quad (5.3)$$

Where F_n is the total load, P is pressure, and E_a and E_w are the Young's modulus of the pad asperities and the wafer.

When the pad is soaked for a long time or the temperature increases, the pad becomes softer. The pad modulus is between 600 MPa and 100 MPa [98].

Removing the peaks by the pad asperities, the surface roughness of the wafer surface becomes better and better. This is the difference between the conventional CMP and the FAP. All the peaks created in the FAP by cutting action of the abrasive particles are gradually removed by the pad asperities in conventional CMP. The surface roughness, R_s can be calculated as the following formula [140]:

$$R_s = \frac{3}{4} d \left(\frac{P}{2kE} \right)^{2/3} \quad (5.4)$$

Where k is particle concentration, E is Young's modulus, and d is the particle diameter.

The MRR is dependent on the contact area between the pad asperities and the wafer surface roughness. If the embedded particles indent on the hydrated layer, the pad asperity will drag, or roll them. When the pressure increases, the depth of pad asperities indent on the hydrated layer is deeper. Consequently, the MRR increases. When the relative velocity increases, the pad asperities move faster on the

wafer surface, the shearing force is bigger, and the number of peaks, which are removed by the pad asperities, increases. Stein et al. [84] have shown that a rougher pad surface removed more oxide than a smooth pad surface.

Without the conditioning process, the viscoelastic properties of the pad play a primary role in MRR. Fu and Chandra [50] have shown that the pad topography were not the reason for dropping of MRR after one hour unconditioned polishing. Therefore, the primary contribution of the conditioner is refreshing the slurry on the pad surface. Without the conditioner, the chemical reaction rate reduces, and the number of abrasive particles embed the wafer surface is reduced, therefore the MRR is decreased.

5.3 Summary & Limitation

Experiments have conducted to show the benefit of using FAP and CMP in polishing. The experimental results showed the high quality improved wafer surfaces after the processes. However, the benchmark data is weak. Because of some reasons, there is no more experiment conducted.

The non-uniformity of the wafer surface in FAP has been investigated by using kinematic analysis. It proves that the mechanism of FAP is based on mechanical action only. However, a mathematical model needs to be established to predict precisely the material removal rate.

A new idea about the mechanism of the traditional CMP has been proposed. From that, it explains the difference between FAP and conventional CMP. It shows the reason why the surface roughness is improved in the conventional CMP. It needs to be further investigated, especially, the chemical action in the process. A

mathematical model for the conventional CMP might be developed based on this idea.

CHAPTER 6 CONCLUSION AND FUTURE WORK

6.1 Review of objectives and conclusions

In order to get better understanding of CMP processes, the research has investigated the pad wear profile, one of reasons that have caused the non-uniformity of the polished substrates. A way to improve the uniformity of the substrates is improving the pad wear profile. There are two main reasons that caused the non-uniformity pad wear in the CMP process. They are the distribution of cutting path density and the contact time between the conditioner and the pad surface. An analytical model based on the two factors was proposed for the fixed abrasive pad. The results from the analytical model showed a good agreement with the experiment results.

The analytical model is used to investigate effects of operation parameters, conditioner patterns and sizes, and its positions on the pad wear profile. The research has shown that the conditioner sizes and positions have the most impacts on the pad wear profile.

To create a better pad wear profile, a new model for the conditioning process, including a new pad and a new conditioner, was developed. This new model has created a convex pad wear profile instead of a concave one. As the result of the new model, the pad shape after the conditioning process is more uniform than the old one.

In addition, in order to study more about the non-uniformity in the CMP process, the distribution of abrasive particles in the interface is investigated. The

new approach of the simulation method has given better visualization of the particle distribution. It was the combination of VOF and DPM in the CFD model. The simulation results presented the total number of the particles and the distribution of the particles in the gap between the wafer and pad surfaces. The total number of the particles increases when the head load and the pad speed decrease. However, the most important result from the simulation process was that the distribution of the particles in the gap was not uniform. There are more particles presented at the wafer center than that at the wafer edge. It could be a reason for the substrates' non-uniformity.

Experiments were conducted to prove the advantage of using both FAP and conventional CMP in manufacturing optical components. The products have better surface roughness and flatness with the increasing of MRR. It shortens the polishing time, reduces cost. In addition, it reduces the slurry used in the process. That means the combination is more environmentally friendly than the conventional CMP alone.

A kinematic model for investigating the substrates in FAP is developed. The model has predicted the non-uniformity of the substrates. Effects of operation parameters on the non-uniformity are also presented and shown a good agreement with experiments' results in literature.

A new idea about the mechanism of conventional CMP has been proposed. It gives another view point in explaining the processes. However, it needs to be further investigated and validated.

6.2 Major contributions and limitations

The major contributions of the work undertaken by the author are shown as follows:

1. Develop the model for predicting the pad wear profile.
2. Develop the new shapes of the pad and the conditioner to achieve a better pad wear profile.
3. Investigate the abrasive particle distribution, which caused the non-uniformity of polished surfaces.
4. Explain the advantage of the combination between FAP and conventional CMP.
5. Develop a kinematic model for predicting the non-uniformity in FAP.
6. Propose a new idea of the conventional CMP mechanism.

The main limitation of the research is lack of experiments. Although the pad wear profile and the flow of slurry on the pad surface were validated by experiments, others are not. The new shapes of the conditioner and the pad are not fabricated to justify the model. The distribution of abrasive particles under the wafer surface is not observed by experiments.

The second limitation is that there are many assumptions in the analytical model and the simulation process. In both cases, the pad surface was assumed flat and uniform instead of porous and non-uniform. In the simulation process, some of properties of the abrasive particles were ignored, such as shape factors, material, and hardness. Moreover, the pad deformation which is quite important in the simulation process was neglected.

The third limitation is that there are no precisely predicted models. The pad wear profile is predicted but it is only the profile. The pad height was not known. The pad wear profile is improved but the author does not know exactly how much it is better for pad life and pad wear amount. The kinematic motion for the wafer non-uniformity can explain the mechanism of the FAP, but the exactly material removal rate has not been calculated. The new idea for the mechanism of conventional CMP is proposed, but the material removal rate cannot be determined from that. All the models need to be further investigated to achieve mathematical models for the prediction.

6.3 Future work

With high requirement in ultra-precision and reducing cost, the uniformity of the polished surfaces is important. The models, the new pad and conditioner shapes, and the new idea of the mechanism have been developed to reduce the non-uniformity. Although the work have given further understanding about the CMP processes, more work need to be done. The future direction of the present work includes the following.

1. Develop the new shapes of the pad and the conditioner in reality.

The new shapes of the pad and the conditioner have been developed based on the model of predicting the pad wear shape. The model has been validated by experimental results. In spite of many conditions, the new shapes of the pad and the conditioner are still not fabricated in reality. Although the new shapes have proved the advantage in producing better pad wear profile, they need to be validated by experimental results.

2. Integrate the pad material and deformation in the simulation process.

The simulation process has presented the distribution of abrasive particles under some assumptions. Especially, the pad material and deformation have been neglected in the process. The process, therefore, can be further developed by using a fluid structure interaction. It can show effects of the pad material and deformation in the simulation process and give better understanding of the slurry flow and the particle distribution.

3. A mathematical model of the new idea of the CMP mechanism.

The new idea has shown some further understanding of the mechanism. It has been used to explain some conflicts and mysteries of the polishing processes. However, a mathematical model need to be built based on the new idea to provide more understanding about the process. Therefore, the MRR and non-uniformity would be precisely predicted.

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