國立交通大學

機械工程研究所
碩士論文

應用順滑模態理論操作化學機械研磨製程

Dynamic Tuning of Chemical-Mechanical Planarization Operation via Sliding-Mode Theory

研 究 生：紀建宇

指導教授：林家瑞

中華民國九十三年六月

應用順滑模態理論操作化學機械研磨製程

Dynamic Tuning of Chemical-Mechanical Planarization Operation via Sliding-Mode Theory

研究生：紀建宇　　Student: Chien-Yu Chi

指導教授：林家瑞 博士　　Advisor: Dr. Chia-Shui Lin

國立交通大學

機械工程研究所

碩士論文計畫書

A Thesis
Submitted to Institute of Mechanical Engineering
College of Engineering
National Chiao Tung University
in Partial Fulfillment of the Requirement
for the Degree of
Master of Science
in
Mechanical Engineering
June 2004
Hsinchu, Taiwan, Republic of China

中華民國九十三年六月

國立交通大學

論文口試委員會審定書

本校 機械工程 學系碩士班 紀建宇 君

所提論文（中文）應用順滑模態理論操作化學機械研磨製程

（英文）Dynamic Tuning of Chemical-Mechanical Planarization Operation via Sliding-Mode Theory

合於碩士資格水準、業經本委員會評審認可。

口試委員：

林家瑞

陳宗麟 林仁輝

指導教授：林家瑞

系主任：傅武雄 教授

中華民國 93 年 7 月 7 日

應用順滑模態理論操作化學機械研磨製程

學生：紀建宇　　　　　　　　　　指導教授：林家瑞 博士

國立交通大學機械工程學系碩士班

摘要

化學機械研磨製程技術發展至今，多階段研磨的方式普遍被使用在實際製造上以獲得更佳的效能。由於研磨效能與製程操作存在的直接關係，在本研究中，將針對製程動態操作的機制加以探討建立，而實現的方式將採用順滑模態控制。因為現有機台的操作機制無法符合設計要求，用以印證動態調整的實驗仍未進行，這一部分也許需要進一步與設備廠商合作才得以完成。經由數值模擬的方式驗證下，結果顯示在維持相同移除能力的情況下，使用動態調整的方式操作所得之平坦化效果比典型的固定輸入方式操作要來得優異。

Dynamic Tuning of Chemical-Mechanical Planarization Operation via Sliding-Mode Theory

Student: Chien-Yu Chi　　　　　Advisor: Dr. Chia-Shui Lin

Institute of Mechanical Engineering
National Chiao Tung University

ABSTRACT

The development of chemical mechanical planarization (CMP) to date relies on multi-stage polishing for better performance. The straight relationship between performance and operation provides a new method for control of CMP process. The strategy of dynamic tuning is proposed in this paper and one possible operation profile is established via sliding-mode theory. Because of the lack of operation mechanism of the equipment in existence, more elaborate experimental verification of the strategy is yet to follow. We may need to work with some equipment suppliers for future work. Based on the proposed strategy, lower dishing and more efficient copper step height reduction can be verified from some numerical simulations. Simulation results show better performance under the same throughput/removal-rate.

TABLE OF CONTENTS

ABSTRACT (Chinese) Ⅰ

ABSTRACT (English) Ⅱ

TABLE OF CONTENTS Ⅲ

LIST OF FIGURES Ⅵ

LIST OF TABLES Ⅸ

CHAPTER 1 INTRODUCTION 1

- 1.1 Planarization in Integrated Circuits (IC) Fabrication 1
- 1.2 Literature Survey 3
  - 1.2.1 Modeling of CMP Process (Mechanical) 4
  - 1.2.2 Modeling of CMP Process (Chemical) 5
  - 1.2.3 Parameters Characterization 6
  - 1.2.4 Consumables Approach 7
  - 1.2.5 CMP Operation 7
  - 1.2.6 Emerging Approach for Metal(EP/ECP) 8
- 1.3 Objective 9

CHAPTER 2 CHEMICAL MECHANICAL PLANARIZATION (CMP) 11

- 2.1 Chemical Mechanical Polishing System 11

2.1.1 Schematic CMP System 12

2.1.2 Consumables 12

2.1.3 Endpoint Detection System 14

2.2 Chemical Mechanical Planarization Process 15

2.2.1 Process Parameters 15

2.2.2 Performance Indexes 16

2.2.3 CMP Models/Mechanisms 18

2.3 Process Control in Chemical Mechanical Planarization Process 22

CHAPTER 3 OPERATION OF CMP VIA SMC 24

3.1 Variable Structure Control 24

3.2 Sliding Mode Control 26

3.3 Operation Profile Setting 29

3.3.1 Problem Statement 30

3.3.2 Operation Profile Setting 32

3.3.3 Results 35

CHAPTER 4 VERIFICATION BY NUMERICAL SIMULATION 38

4.1 Operation Input Concretization 38

4.2 Verification 41

4.3 Discussion 43

CHAPTER 5 CONCLUSION AND FUTURE WORKS 46

5.1 Conclusion 46

5.2 Future Works 46

REFERENCES 49

APPENDIX Ⅰ 73

APPENDIX Ⅱ 75

LIST OF FIGURES

Fig. 1.1 Various forms of planarization 53

Fig. 1.2 Etchback process 54

Fig. 1.3 Schematic of CMP benefit 54

Fig. 1.4 Illustration of CMP fabrication process 55

Fig. 1.5 Framework of integrated CMP model 55

Fig. 2.1.1 Schematic of CMP polisher (CMP on Rotary Tool) 56

Fig. 2.1.2 Schematic of CMP polisher (CMP on Orbital Tool) 56

Fig. 2.1.3 Schematic of CMP polisher (CMP on Linear Tool) 57

Fig. 2.2 Effects of slurry flow rate on CMP process 57

Fig. 2.3 Pad conditioning 58

Fig. 2.4 Dishing and Erosion 58

Fig. 2.5 Planarization efficiency 59

Fig. 2.6 Copper CMP Defects 59

Fig. 2.7 The Run-to-Run Concept 60

Fig. 3.1.1 All possible situations of system by traditional design 60

Fig. 3.1.2 VSC system response of a simple second order system 61

Fig. 3.2 Generation of sliding-mode 61

Fig. 3.3 The system trajectory in sliding mode 62

Fig. 3.4 Effects of pressure and speed on dishing and erosion 62

Fig. 3.5 Conceptual description of soft landing 63

Fig. 3.6 Simulation results of CMP operation via time optimal control 64

Fig. 3.7 Equilibrium control 65

Fig. 3.8 Simulation result_Sliding Function 65

Fig. 3.9 Simulation result_Phase-Plane Plot 66

Fig. 3.10 Simulation result_Control Input 66

Fig. 3.11 Simulation result_State Variables 67

Fig. 4.1 Removal rate (A/min) as a function of oxidizer concentration for different pressure and speed settings 67

Fig. 4.2 Effect of H_2O_2 concentration on the value of Rc with specific slurries from Rodel 68

Fig. 4.3 Dynamic tuning operation of CMP process 68

Fig. 4.4 (a) Comparison of dishing between dynamic tuning and corresponding constant input (copper removal) 69

(b) Variations of parameters (Kcu, B and Rc are normalized forms) 69

Fig. 4.5 Effect of over polish on the extent of dishing 70

Fig. 4.6 (a) Comparison of step height reduction between dynamic tuning and corresponding constant input (removal rate) 71

(b)Variations of parameters (Kcu, B and Rc are normalized forms) 71

LIST OF TABLES

Table 1.1 Comparison between common planarization techniques 72

CHAPTER 1

INTRODUCTION

As ultra-large scale integration (ULSI) technology progresses, the feature size decreases while the chip size and the number of device increases. Multilevel interconnection technique plays a critical role in Integrated-Circuit (IC) fabrication. The present state of Chemical Mechanical Polishing/Planarization (CMP) is the result of semiconductor industry's needs to fabricate multilevel interconnection for increasingly complex, dense, and miniaturized devices and circuits. This need is related to improving the performance while adding more devices, functions, etc. to a circuit and chip.

Several methods are known to achieve a higher level of planarization: (chemical-mechanical) polishing, laser reflow, coating with spin-on glasses, polymers, and resists, thermally reflowing materials, dielectric deposition, and flowable oxides. In these methods, CMP needs fewer steps compared with the others. Furthermore, CMP uses nontoxic substances, has good removal selectivity, and a good removal rate control [3]. Above all, the main advantage of CMP lies in the global planarization. At the present time, the global planarization can only be achieved by using CMP. Certainly, CMP process becomes a heavy subject of investigation in IC fabrication technology.

1.1 Planarization in Integrated Circuits (IC) Fabrication

To increase factory productivity in semiconductor production, manufacturers are finding way to reduce chip size and add more levels of interconnecting wires. In the fabrication of integrated circuits (IC), the problem of planarity is well known. During IC fabrication, successive deposition and etching of dielectric and conductor layers increasingly modify the substrate topography. Problems caused by variations in relief arise mainly during lithographic processing and metallization and include linewidth variations and step coverage. Therefore, the problem of planarity has been addressed using numerous planarization approaches involving the materials and/or techniques [25].

Over the years many methods have evolved for planarizing wafers. Basically, all of the alternatives to CMP consist of reflow, spin-on film smoothing and etchback techniques. In these methods the wafer is coated with, for example, an oxide. Since the underlying topology is uneven, the wafer is baked at a temperature high enough to enable the oxide to vitrify and flow. To lower the temperature at which flowing can take place, the oxide is typically doped with phosphorous and boron. However, the introduction of these impurities leads to problems such as crystallization and moisture adsorbance. In addition, each time the wafer is subject to high temperatures the thermal budget is consumed, thus affecting the underlying device performance. Unfortunately, even when all of these problems are addressed, the resulting surface morphology is only locally planar, i.e., barely planar enough to meet the needs of today's processing technology. Further reduction in device geometry mandating additional levels of interconnects renders present non-CMP based planarization techniques inadequate. Fig. 1.1 shows various forms of planarization.

Additionally, the common planarization method, etchback, is showed schematically in Fig. 1.2. After metal wirings are formed, deposit thick oxide film and spread photoresist on the surface. Then, the planar surface is derived by dry plasma etching. First, the thinner photoresist will be removed and etching downward continuously. The exposure oxide film and inner photoresist on the caves will be etched. Whole etchback process stops when all the photoresist removed. Moreover, other familiar methods are listed on Table 1.1 in comparison.

Multilevel interconnection keeps playing a critical role in the next generation of ULSI fabrication. Furthermore, global planarization is the key point of realization of multilevel interconnection technique. Employing CMP into the fabrication process is the only way to go. After the discussion on planarization techniques above, it is clear that CMP will play an important role in IC fabrication. Fig. 1.3 shows the difference in planarization between IC with CMP and without CMP. A simple illustration of this part of semiconductor fabrication process is shown in Fig. 1.4. In next chapter, the framework of CMP will be illustrated in detail.

1.2 Literature Survey

CMP is the planarization technique required for meeting stringent photolithography depth of focus requirements for small device multilevel interconnection geometry. At the present time, it appears that the global planarization necessary for establishing reliable multilevel interconnects can only be achieved by using CMP. However, the fundamental physics and chemistry of CMP are not well known, the reason being the difficulty in obtain quantitative information about the pad surface, and what happens to the interface between pad and wafer surface during polishing. In past ten more years, lots of research works are focused on detailed removal mechanism (e.g., chemical and/or mechanical factors) and the influences of process parameters (e.g., slurry components and recipe setting). For improving the performance of CMP process, there exist different ways of modeling or characterization. One of them is operation/control aspects of CMP process. In last decade, much less work has been done on the operational aspect of CMP, especially the process control side of CMP operation.

1.2.1 Modeling of CMP process (Mechanical)

In order to control a system well, it is necessary to understand the objective. To know what happens in a system, the most general way is to establish an explicit mathematical model. Among research of CMP, a lot of works focus on establishing model (or parameters identification). Because of the complexity of whole process (due to the consumables), a model which can describe the entire CMP process is not derived yet. But in last decade, great progresses in CMP modeling have been made.

In modeling of CMP process, the most representative model is that brought up by F. W. Preston [1] for glass planarization in 1927, that is

$$R = k \cdot P \cdot V \tag{1.1}$$

where R represents removal rate of the target material to be removed, P is the pressure applied to the material, V is the relative velocity between the pad and the target material and k is the constant of polishing. This model represents the intuitive mechanism of polishing and the most important mechanical parameters of polishing process, P and V. CMP was first proposed for planarization of large-scale integrated circuit (LSI) features by Kaufman and others [2] in 1991, and since then played a key role in the rapid advance of LSI technologies for multilevel interconnection. Henceforward, there are many people trying to establish the mathematical model (or removal mechanism) of CMP process in various research.

G. Nanz and L. E. Camilletti [3] surveyed CMP process modeling which are established before 1995. It turned out that only a few models exist, and that almost none of them are applicable in general sense. Note that all of the models mentioned in that survey paper are related to mechanical effects. In the same manner, there are some models related to mechanical effects and based on Preston's equation. A model which is a modification to Preston's equation was developed by W.-T. Tseng and Y.-L Wang [4] to re-account the dependence of removal rate on the down force (pressure) and relative rotation speed during the CMP process. F. Zhang and A. Busnaina [5] established a model which is based on the plastic deformation of the polished material and incorporated the important contribution of particle adhesion forces. In the work by B. Zhao and F. G. Shi [6], there can exist a threshold pressure in the CMP process due to tribological interaction among abrasive particles, the polished wafer surface, and the polishing pad. H. Hocheng *et al.* [7] derived an analytical model which contains the effects of the applied pressure and the relative polishing velocity between the wafer surface and the pad surface. In that model, the chemical reaction as well as the mechanical bear-and-shear process is also considered. Moreover, the abrasion mechanism in solid-solid contact mode of the CMP process is investigated by J. Luo and D. A. Dornfeld [8] in detail. In their work, based on assumptions of plastic contact over wafer-abrasive and pad-abrasive interfaces, the normal distribution of abrasive size and an assumed periodic roughness of pad surface, a model is developed for mechanical material removal in CMP. It needs to be mentioned that Preston's equation is effective in describing the average behavior of a process but is ineffective in providing fundamental understanding and locally relevant information regarding a chosen process. Recently, a locally relevant expression for material removal rate based on Preston's equation was presented by D. Castillo-Mejia and S. Beaudoin [9].

1.2.2 Modeling of CMP process (Chemical)

Preston's equation is nonetheless flawed, as it is solely based on concepts derived from mechanical polishing [10]. As the requirement of planarization and the use of copper increases, chemical effect (slurry components) plays a more and more important role in CMP process. Actually, the mechanism presented by Kaufman *et al.* [2] in 1991 contains consideration of chemical effect. Furthermore, a two-step model of copper CMP involving mechanical abrasion of copper surface followed by removal of the abraded material from the vicinity of the surface is established by R. J. Gutmann *et al.* [11] in 1995 through PH value and electrochemical potential of slurry. Q. Luo *et al.* [34] and J. Luo and D. A. Dornfeld [8] included chemical effects in their mathematical model of CMP.

Recently, J. Luo [12] concluded the development of CMP modeling, see Fig. 1.5.

1.2.3 Parameters Characterization

Except for process modeling mentioned above, there are still a lot of researches which are focused on the investigation of consumables (especially in slurry components) or parameters characterization of CMP process. Note that a lot of works are related to copper or barrier layer, e.g. Tantalum (Ta) or Titanium (Ti), because of the employment of copper in IC fabrication. Electrochemical potentiodynamic measurements, obtained under static conditions and during polishing, were used by D. Zeidler *et al.* [13] to explain the CMP performance. In their investigation, an increasing H_2O_2 concentration leads to both lower wet etch rates and polish rates of Cu. V. Nguyen *et al.* [14] investigated the influence of slurry chemistry and thickness of the copper layer on dishing and found that the concentration of the oxidizer and the thickness of copper layer have a strong impact on dishing. Furthermore, surface chemistry studies of CMP of copper were presented by J. Hernandez *et al.* [15] and revealed that the removal of copper during CMP is affected by the presence of copper oxides on the surface. On the other hand, V. S. Chathapuram *et al.* [16] and S. Ramarajan *et al.* [17] investigated the polishing of barrier layer of Ti and Ta, respectively.

1.2.4 Consumables Approach

In recent year, some methods were brought up to improve the performance of CMP process. Instead of investigation of parameters and establishing of model, employing other approaches is researched and developed. The use of slurry with no abrasive and pad with fixed grit are two promising approaches. V.H. Nguyen *et al.* [18] presented the technique of copper CMP using fixed-abrasive pad. S. Kondo *et al.* [19] and Y. Yamada *et al.* [20] worked on development of abrasive-free chemical polishing (AFP) for CMP process. In their experimental study, the method reveals great performances, lower line resistance, lower over-polishing sensitivity and cost reduction.

1.2.5 CMP Operation

However, except investigation of details of CMP process and employment of other approaches, process control/operation is a candidate for solving the uncertainty of the process. Among public research archives, there are less works which are focused on control/operation aspects of CMP process. A. Chen and R.-S. Guo [21] developed a EWMA controller and applied to CMP. L. Da *et al.* [22] analyzed the performance of Run-to-Run control schemes and proposed a self-tuning predictor-corrector controller (PCC) for CMP process. In their development of process control, process statistics plays a key role and the performance within a wafer is not clearly displayed in their result. The experimental data of Wijekoon *et al.* [23] indicates that the important defect, dishing, would vary linearly with operation condition (e.g. down pressure and relative velocity). Therefore, to control the within-wafer performance, taking care of the operation of the process is necessary. J.-B. Chiu *et al.* [24] established an analogy between soft landing of a spacecraft and CMP operation. In that work, the CMP operation was solved as a minimum-time optimal control problem and a two-stage CMP operation procedure was devised to ensure robustness of the controller. Besides, bang-bang control law was employed for preventing measurement uncertainties.

1.2.6 Emerging Approach for Metal(EP/ECP)

Several schemes for dielectric planarization have been developed and obtain good enough performance these years. As the number of metal levels in electric circuits increases, the need for improved planarization also increases at both chip and package levels. An Electrochemical Planarization (EP/ECP) technology involving electroplating followed by electropolishing was proposed by R. J. Contolini *et al.* [44] in 1994. Later in 1995, copper electropolishing is discussed in detail from experimental findings and theoretical interpretation. [45] Recently, this method is further demonstrated by integrating Cu electropolishing (removal of electroplated Cu to barrier layer) with CMP or dry etching (removal of remaining Cu and the barrier metal). [46, 47, 48] The unique advantage of EP/ECP compared with CMP is that no mechanical stress will be applied to the substrate and it might be important especially with the usage of low-k dielectric materials.

1.3 Objective

From the brief survey of CMP research mentioned above, it is clear that major research is focused on modeling, especially in mechanical aspects. Parameters characterization will help to increase knowledge of the complicated process and establish the model. New approach and invention is always taken up in the industry more than in academia because it needs a lot of experiments. The approach of operation aspect of CMP process presented by J.-B. Chiu *et al.* [24] provides a potential way for making a big stride in CMP, i.e. employing more process control in CMP process may be a promising way for deriving better performance. (see section 2.3) Note that there may be also some problems in EP/ECP, like non-uniformity. In the research of D. Padhi *et al.* [48], to gradually increase the electrolyte flow with time is suggested to avoid the inherent flaw of EP/ECP. This suggestion includes the concept of improving process performance by appropriate process operation.

In typical operation, some limitations (due to constant input) will be led into the process. Based on the existing knowledge and the typical operation, some new operation methods are figured out, like two or three stage polishing. The multi-stage method is widely used in real production but it seems not good enough in the growing requirement of planarization. On the basis of the qualitative and quantitative research on CMP, a new operation strategy is proposed in this thesis. In order to increase the degree-of-freedom/flexibility of CMP process and further improve the performance of the process, the method of "Dynamic Tuning" will be tried and the operation profile will be set via sliding mode theory of variable structure control (VSC). The details will be presented in following chapters.

For control system design, a dynamic model which is not too complex and can describe the system behavior reasonably is necessary.[1] Among the research efforts which have been reported on modeling the CMP of copper, ILD, or STI, there is no dynamic model with physical meanings of CMP process except the conceptual description used in the works of J.-B. Chiu *et al.* [24]. Therefore, Chiu’s dynamic model will be employed for setting “dynamic tuning” operation profile via sliding mode theory. Some models/mechanisms with physical meanings will be employed to simulate this “dynamic tuning” operation strategy for CMP process.

---

[1] “Dynamic Tuning” is referred to within-wafer control of process control, so the process must be treated as a dynamic system.

CHAPTER 2

CHEMICAL MECHANICAL PLANARIZATION (CMP)

A novel technique for planarization has drawn more attention, since conventional planarization methods such as reflowing-oxide-layers do not give the required global planarity for advanced processes. Multilevel interconnects and the use of 3-D packaging requires sophisticated methods to planarize the surfaces of wafers for subsequent device processing. (e.g. For multi-layers of a logic device at least one layer should be perfectly planar.) Lack of planarity may lead to severe problems for lithography (insufficient focus depth). Chemical Mechanical Planarization (CMP) evolves as the only way to achieve global planarization in IC fabrication. In this chapter, CMP will be explained from the views of system/configuration and process.

2.1 Chemical-Mechanical Polishing System

As implied by the name, Chemical-Mechanical Polishing, the system must perform mechanical abrasion and chemical erosion to wafer surface of various materials. Mechanical abrasion is mainly provided by contact force of fluid or solid objects, i.e. slurry, abrasive and pad. However, chemical erosion is provided by slurry which is composed of specific chemical agent. These two chief effects are coupled to each other. It is this reason why CMP technique is treated as an engineering 'art' rather than an engineering 'science'.

2.1.1 *Schematic CMP System*

The design goals of all the CMP polishers include high throughput (multi-heads), "dry-in/dry-out", easy control, endpoint detection and high quality of polished surface. The CMP equipments/systems are fabricated by ten more suppliers and all of these equipments have different configurations. However, the main mechanism of these polishers can be separated into three forms. Fig. 2.1.1 shows the most common kind of polisher framework-rotary tool.[2] The wafer is held on a rotating carrier (holder) while the face being polished is pressed against a resilient polishing pad attached to a rotating platen disk. The abrasive contained in slurry and the slurry is carried to the wafer by the porosity of the polishing pad. Another configuration which is different to rotary tool is orbital tool, as shown in Fig. 2.1.2. The major differences between these two frames are slurry supply system and platen motion. The slurry is fed from platen and the platen is oscillating during polishing. The third configuration is announced by Lam Research, Linear Planarization Technology ™ (LPT™), as shown in Fig. 2.1.3. These three equipments have respective advantages and disadvantages.

2.1.2 *Consumables*

CMP combines both chemical action and mechanical forces to planarize wafer surface. The critical components required for CMP are a reactive liquid medium and a polishing pad surface to provide the mechanical control required to achieve planarity. Either the liquid or the polishing surface may contain nano-size inorganic particles to enhance the reactive and mechanical activity of the process. Because of the great quantity of consumables requirement, CMP turns into one of the most expensive steps

---

[2] In this work, the rotary tool will be investigated.

in the IC production. Besides, it is well known that consumables, slurry and pad, play significant roles in CMP. Therefore, consumable suppliers and many researchers are devoted to improve the stability and efficiency of consumables.

Slurry

Typically, slurry consists of two phases, namely, liquid and solid phases. Liquid phase consists of deionized (DI) water with several additives like oxidizers, complexing agents, inhibiting agents, and surfactants (Different components have distinct characteristics and are used to polish different materials). Solid phase is comprised of abrasives, which are usually inorganic oxides, *e.g.*, alumina, silica, ceria, zirconia, titania, magnesia (Different sizes and types of abrasive have different effect on polishing). While recent advances in abrasive-free slurries and fixed abrasive CMP offer great potential, several challenges remain. In CMP process, slurry is dispensed in-between polishing pad and wafer to play a part in planarizing. Slurry flow rate is an important factor in supplying slurry. Fig. 2.2 shows the effects of slurry flow rate on the CMP process. According to that figure, slurry flow rate affects removal rate. In oxide CMP, removal rate will increase with increased slurry flow until saturation effect occurs. In metal CMP, removal rate will increase with increased slurry flow first and then decrease when lubrication effect occurs, i.e. slurry forms hydroplane between wafer and pad.

Pad

All polishing pads used in IC production are polyurethane pads. Based on the structure/composition, a polishing pad can be classified into the following types: solid polyurethane pad, polyurethane with filler or void, fiber felt impregnated with polyurethane, and poromeric pads. Each type of pad uses a unique manufacturing process and therefore has its own unique characteristics. For example, poromeric pads are widely used for buffing and tungsten plug polishing because of their capability to deliver good local uniformity and low cost. For the applications required long range planarity, pads consisting of polyurethane with filler, such as Rodel's IC pads, are the most commonly used pads. Because of lack of long-range planarity and/or excess dishing for large geometry features, older pads made of fiber felt impregnated with polyurethane are limited to sub-pad and tungsten plug polishing applications [27]. According to the same literature [27], pads are investigated for groove effects and there are different influences by different forms of groove. They also mention that pad elasticity is also an important factor in CMP processing.

Conditioner

Pad conditioning, or pad "dressing", is a critical component of the CMP process. It refers to the process of refreshing the polishing pad surface during CMP. In the process, a pad is conditioned by contacting its surface with a diamond abrasive disc or wheel. Generally, the conditioning disc is mounted on a powered rotating chuck that can be lowered onto the pad surface. Well conditioning of a pad can increase pad life and performance of polishing. Fig. 2.3 shows the conditioning effect schematically.

2.1.3 Endpoint Detection System

To date, the design of CMP system is quite different from before, including the design of "dry-in/dry-out", multi-platen and so on. In spite of the advances of configuration setting, robust sensor for end point detection (EPD) of polished material is still a problem for process control of CMP. Endpoint detection is an in-line method of determining the termination point of wafer polishing based on metrological (i.e. film thickness) or physical (i.e. tool hardware) signals obtained during the CMP process. The end of the polishing step is traditionally determined by setting a time limit in the process. Changes in removal rate due to the normal pad life cycle, variation in slurry and pad lots, conditioning issues and a myriad of other potential variables, can result in under- or over-polish[3] errors. Additionally, the incoming initial oxide or metal layer thickness may fluctuate from wafer to wafer. All the possible errors have to be compensated by valid in-line sensors [29]. To control CMP process well, a good and accurate in-line sensor is indispensable.

In past few years, endpoint detection is developed through many methods, optical, thermal, vibration, acoustic, electrochemical and motor current (frictional). Some commercialized transducers were announced, ISRM^{TM} (Applied Materials), Sentinel^{TM} (Novellus) and PRECICE^{TM} (KLA-Tencor) and so on.

2.2 Chemical-Mechanical Planarization Process

After introducing the configuration of CMP system, the CMP process itself will be discussed briefly.

2.2.1 Process Parameters

To improve CMP performance, understanding this process comprehensively is necessary. Finding out what parameters and how they contribute to the mechanical-chemical actions is critical for understanding of CMP. There are so

---

[3] Under-polish and over-polish mean that the process is proceeding before oxide is exposed and until oxide is exposed, respectively.

many parameters related to CMP process. Dozens of parameters are dominant in the process. On the polishing tool side, down pressure/force, platen temperature, slurry flow (supply) rate, platen and carrier speed are all dominant factors in CMP process. On the slurry side, chemical components, PH value, concentration of Oxidizer, kind and size of particles and stability of suspension are all very important factors of the process. On the polishing pad, elasticity, hardness, groove, pore structure, construction, age and conditioning of pad are very critical in CMP process. Finally, materials and structure (pattern) of wafer surface, wafer carrier and endpoint detection system *et al.* all influence CMP process. It is important to note, coupling effects exist among these parameters, between chemical and mechanical factors. It is a very complicated task to investigate CMP.

2.2.2 Performance Indices

Because CMP is a planarization method, it is clear that the most important index of polishing performance must be "how flat" of the polished wafer. The planarity is usually represented by **within-wafer non-uniformity**:

$$\text{Non}-\text{Uniformity}=\frac{\Delta\max-\Delta\min}{2\,\Delta\text{mean}} \tag{2.1}$$

where Δ is removed thickness per minute.

To maintain a high throughput of CMP process, removal of excess material of polished wafer must be accomplished in a specific time, i.e. the removal rate must be sustained on a reasonable level. For Cu CMP[4], thickness of Cu film is calculated by dividing the film resistivity with its measured sheet resistance. The relation between thickness and resistivity is

---

[4] In this thesis, copper material will be considered.

$$\rho \propto R_S \cdot T \tag{2.2}$$

where ρ is the resistivity ($\mu\Omega \cdot \mathrm{cm}/$ unit-area), R_S is the sheet resistance ($\mathrm{m}\Omega/$ unit-area) and T is the copper thickness (kÅ). Sequentially, **CMP removal-rate** can be represented by

$$\text{Removal Rate} = \frac{(\text{Pre - CMP Thickness}) - (\text{Post - CMP Thickness})}{\text{Polish Time}} \tag{2.3}$$

In fabricating Cu damascene interconnects, CMP of Cu and barrier metals is one of the most important techniques. SiO_2 erosion and Cu dishing are serious problems of CMP. This erosion is defined as oxide loss around the patterned Cu area and dishing is defined as Cu thickness loss inside the Cu pattern. Fig. 2.4 shows schematic dishing and erosion. Any dishing and erosion and the resulting decrease in cross section area due to thinning (dishing plus erosion) of the long interconnect line during polish has a significant effect on circuit delays due to the increase in the RC constant. Therefore, to achieve the benefits of the low RC intended with the use of Cu, there is an increased need to minimize and control dishing and erosion across the wafer during Cu CMP process. In the previous literature, Steigerwald *et al.* [28] found that Cu dishing is a strong function of line width, but is only weakly dependent upon pattern density. Moreover, to specify dishing, they defined **planarization efficiency (PE)**

$$\mathrm{PE} = [1 - (\Delta\mathrm{down}/\Delta\mathrm{up})] \times 100\% \tag{2.4.1}$$

where Δdown and Δup are the thickness differences of the inside and outside of the feature after planarization processes, as shown in Fig. 2.5. In other words, planarization efficiency can be expressed as

$$\begin{aligned} \mathrm{PE} &= 1 - \mathrm{R}_{\mathrm{r\_bottom}} / \mathrm{R}_{\mathrm{r\_top}} \\ &= \text{Step Height Reduction} / \mathrm{R}_{\mathrm{r\_top}} \end{aligned} \tag{2.4.2}$$

where $\mathrm{R}_{\mathrm{r\_bottom}}$ and $\mathrm{R}_{\mathrm{r\_top}}$ is removal rate of lower and higher area, respectively.

Wafer roughness which is measured by AFM (Atomic Force Microscope) can be defined by

$$\mathrm{Rq} = \sqrt{\frac{\int_0^L y^2(x)dx}{L}} \tag{2.5}$$

where L is the distance of scanning and y is the difference between probe point and average height. The defects after copper CMP are shown in Fig. 2.6. In that figure, Cu puddle, corrosion and scratch are not caused by CMP, they just might appear as after effect of polishing [39].

2.2.3 CMP Models/Mechanisms

Establishing model/mechanism, much more works are focused on mechanical effects, just like what mentioned at section 1.2.1 and 1.2.2. Based on Preston's equation (1.1), the generalized form

$$R = k \cdot P^{\alpha} \cdot V^{\beta} \tag{2.6}$$

is widely accepted and used [30]. The value α and β are fitted parameters that vary depending on the process and the consumable set (pad, slurry) used. However, the models derived from Preston's equation are ineffective in providing detailed fundamental understanding and locally relevant information regarding a chosen process. To date, there are very few wafer-scale, quantitative models for CMP removal rate and uniformity. This fact, combined with the resiliency of Preston's equation, makes a strong argument for a locally relevant expression for material removal rate [9, 31]

$$R(x,y) = k \cdot P(x,y) \cdot V(x,y) \tag{2.7}$$

where the removal rate R at point (x,y) on the wafer surface is a function of the local pressure $P(x,y)$ and the local pad/wafer relative velocity $V(x,y)$. It has to be mentioned again that Preston equation is nonetheless flawed because of the neglect of chemical effects.

Except for mechanical effect modeling, the chemical effect is also a very important part of CMP process, especially in polishing metal. Early in the works of F. B. Kaufman *et al.* [2] and R. J. Gutmann *et al.* [11], the mechanism related to chemical effects was discussed. The mathematical model including chemical effects was first established by Q. Luo *et al.* [34], that is

$$R = (KP + B)V + R_C \tag{2.8}$$

where B is a modification term of velocity V and R_C represents the purely chemical removal rate. Equation (2.8) was established by linear regression of experimental data and has greater dependence on the velocity compared to the pressure. (It may be different on different polishing tools.) J. Luo and D. A. Dornfeld [8] also derived a model with mechanical and chemical effects of CMP process. In their model, an interface between chemical effect and mechanical effect has been constructed through a fitting parameter H_w, a “dynamical” hardness value of the wafer surface. It reflects the influences of chemicals on the mechanical material removal.

Usually, the model/mechanism in CMP process investigation means material removal mechanism. To further improve the performance of CMP process, e.g. copper dishing, the CMP process model has to be analyzed in more detail, too. Y.

Lin [42] established copper planarization (step height reduction) model and copper-dishing model based on the difference of removal rate between high and low area of wafer surface and that between copper and barrier material, respectively. The copper-dishing model is shown as

$$h_D = \frac{(S-1)PH}{S}\xi \ln\left(\frac{w}{w_0}\right)\left(1-e^{-\frac{K_{Cu}EV}{H}t}\right) \tag{2.9}$$

where h_D is the dishing height; P is applied downward pressure; H is the pad thickness; ξ is a constant defined as the conformity of the pad; K_{Cu} is the Preston constant for copper; E is Young's modules of the pad; V is the relative velocity between the work piece and the pad; t represents the overpolish time; w and w_0 are defined as the trench width and effective minimum width, respectively. (The word "effective" means that pad can contact with the lower feature.) The factor S represents the removal rate selectivity of copper to barrier material, like tantalum, defined as

$$S = \frac{R_{Cu}}{R_{Ta}} = \frac{K_{Cu}}{K_{Ta}} \tag{2.10}$$

The step height reduction model is

$$h_S = h_{S0}e^{-\frac{K_{Cu}EV}{H}t} + \frac{PH}{E}\left[\xi ln\left(\frac{w}{w_0}\right)-1\right]\left(1-e^{-\frac{K_{Cu}EV}{H}t}\right) \tag{2.11}$$

where h_S is the step height of sacrificial copper; h_{S0} is the initial step height; t represents polish time of bulk copper here. Note that (2.9) and (2.11) are derived involving pad conformity. V.H. Nguyen *et al.* [32] also established a physical model for development of dishing during metal CMP. The model is

$$D(LW,t) = R_{Bl}\cdot\int_0^t\left[\int_0^{LW/2}\Phi(r_C)\,dr_C + exp\left(\frac{-t}{LW\cdot K}\right)\cdot\int_{LW/2}^{\infty}\Phi(r_C)\,dr_C\right]dt \tag{2.12}$$

where $D(LW,t)$ is dishing, LW is line width, R_{Bl} is the blanket removal rate, t is over-polish time, $\Phi(r_C)$ is the distribution of contact size, r_C is the average contact radius and K is the only adjustable parameter. Note that this model was derived including pad morphology. G. Fu and A. Chandra [33] also derived an analytical model for dishing and step height reduction in CMP.

These models/mechanisms shown above are established in steady-state. However, one appropriate dynamic model is necessary for setting the operation profile via strategy of dynamic-tuning. The only dynamic model is the conceptual model proposed by J.-B. Chiu *et al.* [24], shown as

$$\frac{d\tilde{h}}{dt} = -R \tag{2.13}$$

$$\frac{dR}{dt} = u \tag{2.14}$$

where $\tilde{h}$ represents the thickness of copper to be removed, R is the removal rate and u is the system input. For convenience, (2.13) and (2.14) are further changed into the following state equation:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{b}u + \boldsymbol{d}(\boldsymbol{x},t) \tag{2.15}$$

where $\boldsymbol{x} = \begin{bmatrix}\tilde{h} & R\end{bmatrix}^{\mathrm{T}} \in R^2$, $\boldsymbol{A} = \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix}$, $\boldsymbol{b} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$ and $\boldsymbol{d} = \begin{bmatrix} -0.1t \\ -0.1 \end{bmatrix}$. Note that the initial value of the system $\boldsymbol{x}(0) = \begin{bmatrix}8000 & 0\end{bmatrix}^T$. The selection of disturbances is based on the investigations of run-to-run controller of CMP, just like the works of L. Da *et al.* [15]. In their research, the removal rate would drift down as the process proceeds because of pad wearing and slurry dilution. Although the problem of pad wearing can be adjusted by conditioning during the CMP process, the slurry concentration can be kept constant by pre-mix before delivering onto platen and they might not be too obvious during a single wafer polishing, the disturbance d is also added into the simulation to model the uncertainties during CMP process processing. Note that the coefficients are assigned small values arbitrarily. This model will be used to design the “dynamic tuning” operation profile via sliding-mode theory in chapter 3.

In following sections, some of these models will be used to verify the ability of dynamic-tuning operation by numerical simulations.

2.3 Process Control in Chemical-Mechanical Planarization Process

Most of people who are devoted to do research on the CMP process focus their works on process improvement, i.e. finding the perfect composition of process parameters, namely, “Golden Recipe”. “Golden recipe” means: through fixed perfect parameters setting the perfect performance will be derived. For example, in the CMP process, the perfect performance is complete flat. Nevertheless, it can not be realized at most case in real world because of existence of a lot of disturbances, noise and uncertainties. The inherent characteristics/flaws of equipments may cause some imperfections in products. (That may be one of the reasons why control theories were developed for.) Continuous control for CMP process seems necessary. Here, one question is raised: Is it more complete if the “Golden Recipe” contains an appropriate operation pattern?

CMP process control covers both consumables and equipments to improve performance of CMP process. Run-to-run control is the only one control method with specific control algorithm/law in the CMP process and is thought to be the only viable scheme in most semiconductor manufacturing processes because of the lack of in-situ measurements of the product quality of interest [22]. The method of run-to-run control is based on statistic data of process performance. Besides, the name “run-to-run” means the control object is a single run, one specific number of wafers (ten, five or less number of wafers). The concept of run-to-run control is shown in Fig. 2.7.

As the requirements of degree of planarization increases, within-wafer CMP process control becomes necessary. Little effort has been tried to move forward to within-wafer control because of the complexity of CMP process. In this thesis, it will be attempted based on the knowledge of CMP process.

CHAPTER 3

OPERATION OF CMP VIA SMC

The theory of sliding-mode control (SMC) has been developed for a long time and has been known as an effective control method for many advantages. One of the most unique aspects of sliding mode is the discontinuous nature of the control action whose primary function of each of the feedback channels is to switch between two distinctively different system structures (or components) such that a new type of system motion, called sliding mode, exists in a manifold. This intriguing system characteristic is claimed to result in superb system performance which includes insensitivity to parameter variables, and complete rejection of disturbances [35]. However, a serious problem is also generated due to this characteristic, namely, chattering. Fortunately, many methods were proposed to reduce the chattering phenomenon. In this paper, the sliding-mode theory is employed to operate CMP process, i.e. to set the removal rate during a single wafer (within wafer) polishing. In this chapter, VSC and SMC will be introduced briefly and the presentation of controller design for the conceptual CMP model will be followed by some simulation results and discussions.

3.1 Variable Structure Control

Variable structure control (VSC) with sliding mode control (SMC) was first proposed and elaborated in the early 1950's in the Soviet Union by Emelyanov and several co-researchers. This method did not catch researchers' attention widely until the publication of the survey paper in 1977. Significant interest on VSC and SMC has been generated in the control community worldwide [35]. To illustrate the advantage of VSC, a concise and acceptable example is generally used, that is, linear second order system [37]. Consider the second order system

$$\ddot{x} + x = u, \qquad x(0) = 1, \dot{x}(0) = 0 \tag{3.1}$$

Let control input $u = -a\dot{x}$, where $a \geq 0$. The control goal is to design parameter 'a' and let system approach zero (get into $x(t) \leq \varepsilon$) in shortest time and not exceeding zero (not across t-axis). Traditionally, the design is to choose a fixed value 'a' for acceptable response. According to VSC theory, the best performance will be derived easily by switching the system between two subspaces. Fig. 3.1.1 is all possible situations in traditional design and Fig. 3.1.2 shows the system response via VSC design. The system which is shown in Fig. 3.1.2 can also be called variable structure system (VSS). The VSS is defined as followed: one system which consists of more than two subsystems (a set of subsystems) together with suitable switching logic. In the example above, the value 'a' which is equal to zero or larger than two form two subspaces. Besides, the switching logic/condition is magnitude of 'x', 'a' is zero or two while 'x' is larger or smaller than ε, respectively.

To date, VSC has developed into a general design method being examined for a wide spectrum of system types including nonlinear system, multi-input/multi-output systems, and stochastic systems. In addition, the objectives of VSC have been greatly extended from stabilization to other control functions. The most distinguished feature of VSC is its ability to result in very robust control systems, in many cases invariant control systems result. Conceptually, the term "invariant" means that the system is completely insensitive to parametric uncertainty and external disturbances [36]. Today, research and development continue to apply VSC to a wide variety of engineering systems.

Recently, the VSC and SMC are almost synonymous nouns, and the key difference between VSC and SMC is the existence of sliding-mode in the system. From the viewpoint of mathematics, sliding-mode is a system behavior in "hyperspace." (The main feature is described in the beginning of this chapter.) It should be mentioned that the system performance will not be influenced by any matched disturbances[5], and the control strategy provides an effective and robust means for certain classes of nonlinear systems subject to modeling uncertainties in the sliding mode. In next section, more detailed descriptions of SMC will be introduced.

3.2 Sliding Mode Control

SMC is a robust nonlinear control algorithm that employs discontinuous control to enforce a system state trajectory on some prescribed sliding surface. The SMC includes several different continuous functions that map plant state to a control surface, and the switching among different functions is determined by plant state which is represented by a switching function. In general, a variable structure system can be described by

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u}(\boldsymbol{x})) \tag{3.2}$$

where $\boldsymbol{x} \in R^n$ is the state variables of the system, $\boldsymbol{u}(\boldsymbol{x})$ is the control input, and the timing of switching is governed by $\boldsymbol{x}$ (a specific form of combination of state variables, namely, switching function). In addition, the equilibrium point of the system is supposed to be $\boldsymbol{x} = 0$, which is the system design target (the control goal). For a single input system, the switching condition of control input is represented by

---

[5] Matched disturbances mean that the disturbances which can be affected by system control input directly.

$$u(\boldsymbol{x}) = \begin{cases} u^{+}(\boldsymbol{x}) & s(\boldsymbol{x}) > 0 \\ u^{-}(\boldsymbol{x}) & s(\boldsymbol{x}) < 0 \end{cases} \tag{3.3}$$

where $u^{+}(\boldsymbol{x}) \neq u^{-}(\boldsymbol{x})$, and $s(\boldsymbol{x})$ is a switching function. The switching function $s(\boldsymbol{x})$ collocate the switching condition, and divides the system state space into three sub-spaces: $s(\boldsymbol{x}) > 0$, $s(\boldsymbol{x}) = 0$, and $s(\boldsymbol{x}) < 0$. It is important that the hyperspace, $s(\boldsymbol{x}) = 0$, must be continuous and contain the equilibrium point $\boldsymbol{x} = 0$, i.e. system in this specified hyperspace must be stabilizable. The main objective of the system design is to generate a sliding mode in the hyperspace $s(\boldsymbol{x}) = 0$. Note that $s(\boldsymbol{x})$ is also called sliding function, and $s(\boldsymbol{x}) = 0$ is the so-called sliding-surface[6].

The most important thing in SMC design is to generate (specify) a sliding-mode (sliding-function). There are two procedures in sliding-mode generation: (1) When system is outside of hyperspace $s(\boldsymbol{x}) = 0$, it must be ensured that the trajectory of system states would reach the hyperspace in a finite time t_h; (2) After the trajectory getting into the hyperspace, the trajectory will never depart from the hyperspace and move toward the equilibrium point $\boldsymbol{x} = 0$. The system behavior of first procedure is called approaching-mode, and the second one is named sliding-mode. Fig. 3.2 illustrates this generation of sliding-mode. In order to ensure the procedures mentioned above being workable, one condition must be satisfied, that is

$$s\dot{s} < -\sigma |s| \tag{3.4}$$

where $s \neq 0$, and σ is a positive constant which can guarantee the system trajectories to hit the sliding surface in a finite time. Note that (3.4) is also called "reaching/approaching and sliding condition." Further looking into the behavior of system in the sliding mode, if the switching condition (3.3) can be realized perfectly,

---

[6] The derivation of "sliding-surface" is due to the existence of sliding-mode in the hyperspace.

i.e. the infinite frequency of switching exists, the ideal sliding mode exists, too. Unfortunately, the system in real world can not provide such a high-frequency switching. To display the situation of system in the sliding mode schematically, a very small layer[7] covering the sliding surface is often employed, as shown in Fig. 3.3.

To design a controller via SMC, the procedure can be concluded into two steps[8], that is: (1) Specify a sliding function $s(\boldsymbol{x})$ which will let the system to move toward control goal while the system is in the sliding mode; (2) Determine the control input u which will force the system to hit the sliding surface and generate the sliding mode in a finite time. For a simple single-input system in controllable canonical form

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= x_3 \\ &\cdot \\ &\cdot \\ \dot{x}_{n-1} &= x_n \\ \dot{x}_n &= a_1 x_1 + a_2 x_2 + \cdots + a_n x_n + u + d(\boldsymbol{x},t) \end{aligned} \tag{3.5}$$

where $\boldsymbol{x} = [x_1 \quad x_2 \quad . \quad . \quad . \quad x_n]^{\mathrm{T}}$ is system states, u is control input, and $d(\boldsymbol{x},t)$ is the disturbance of system. There are several ways to choose sliding function, for the simple case, the easiest way is setting sliding function as

$$s(\boldsymbol{x}) = \boldsymbol{c}\boldsymbol{x} \tag{3.6}$$

where $\boldsymbol{c} = [c_1 \quad c_2 \quad . \quad . \quad . \quad c_n]$. Through some calculation, the value of 'c' will be derived, and then the sliding function is obtained. At the second step, based on the important condition (3.4), the control input can be determined as

---

[7] In SMC design, the setting of layer namely sliding-layer is an important and effective way to reduce so-called chattering phenomenon.

[8] Note that the two steps are concluded based on the procedures of generating sliding-mode mentioned above.

$$u = -a_1 x_1 - (c_1 + a_2)x_2 - \ldots - (c_{n-1} + a_n)x_n - (\delta(\mathbf{x},t) + \sigma)sign(s) \qquad (3.7)$$

where $\delta(\mathbf{x},t)$ is the maximum value of disturbance $d(\mathbf{x},t)$ and σ is the value to be designed. Note that the value of δ is determined by estimating or deciding among the measured data. The control input (3.7) contains an ideal switching function $sign(s)$, which can not be realized in real world. Besides, the ideal switching function $sign(s)$ is the main reason of existence of chattering phenomenon. The easiest and effective way to reduce chattering is to replace $sign(s)$ by saturation function

$$sat(s,\varepsilon) = \begin{cases} 1 & s > \varepsilon \\ s/\varepsilon & |s| \le \varepsilon \\ -1 & s < -\varepsilon \end{cases} \qquad (3.8)$$

where ε is the thickness of sliding-layer mentioned above, and the system trajectory will be limited in $|s| < \varepsilon$. It should be mentioned that employing of sliding-layer would reduce the chattering but it can induce the loss of precision of the controller.

This controller is actually a continuous approximation of the ideal relay control. The consequence of this control scheme is that invariance property of SMC is lost. The system robustness is a function of the width of the boundary/sliding layer. Robustness is decreased as width is increased. Next, dynamic tuning of CMP process based on SMC is presented.

3.3 Operation Profile Setting

Before designing the setting of removal rate of CMP process, some preliminary research results and statement will be recounted first.

3.3.1 Problem Statement

In copper CMP, copper dishing and oxide erosion are critical problems and have to be solved urgently due to the serious influence on RC constant and surface uniformity, especially the copper dishing. (see section 2.2.2.)

From the research by K. Wijekoon *et al.* [23], the operation parameters (applied downward pressure, P, and relative speed between wafer carrier and platen table, V) have direct influence on copper dishing and oxide erosion, as shown in Fig. 3.4. Furthermore, in the investigations by Y.-C. Kao *et al.* [38], a robust operation region is located on the base of copper removal rate curve. Note that the robust operation region means low-sensitivity to parameters change. In their works, some operation-relevant models and an overall strategy of polishing are established, and the strategy setting is subject to the copper dishing (Note that the strategy, soft landing, is related to the work by J.-B. Chiu *et al.* [24]. The conceptual description of the strategy is shown in Fig. 3.5). Based on these results, better operation profile of the process might be a candidate to improve CMP process, especially in reducing the copper dishing. In other words, the copper dishing might be suppressed by accurately tuning the process parameters during a single wafer polishing. Furthermore, the works by V. Nguyen *et al.* [14] [32], G. Fu and A. Chandra [33] and Y. Lin [42] reveal that the copper dishing is a function of over-polish time and process parameters. Consequently, the feasibility of this idea is greatly strengthened. In detail, it is clear that the process parameters, like P and V, play important roles in the forming of dishing besides the feature size, polish time and properties of pad, in reference to equation (2.9). Equation (2.12) reveals that dishing will be also suppressed directly during overpolish stage if the blanket wafer removal rate drops down. From many investigations, the removal rate in CMP process can be related to process parameters including the parameters which can be operated in process.

One of methods of reducing critical problems occurred in CMP process is to optimize the recipe of wafer processing through setting of these process parameters. In this thesis, the other way is considered to improve the performance of CMP process, that is, dynamic tuning of the operation parameters during CMP process run in an appropriate form/scheme.

Generally speaking, to maintain high throughput high removal rate recipe has to be used, but that can cause more damages in most cases. On the other hand, the recipe of low removal rate often cause better surface profile but that will make low throughput, too. Obviously, to achieve balance between high throughput and good surface profile is an important topic. In the discussion in section 2.3, very few works have been done via the strategies of control theory except the work by J.-B. Chiu *et al.* [24].

In the works of J.-B. Chiu *et al.* [24], the control law of time optimal control, is employed, and an analogy between the soft landing of a spacecraft and the CMP process is illustrated for CMP operation. The purposes of citing this analogy is for reducing the copper dishing and handling the uncertainties, the undetermined initial thickness of copper (measurement uncertainties), and the bang-bang control law is used to implement this idea. Fig. 3.6 shows their simulation results. Note that the timing of stopping the process is determined by the endpoint detection. From the first plot of Fig. 3.6, it is clear that the removal rate has to increase to 9000 A/min at once while the process is starting, and drop to 2000 A/min while the process is going for 40 seconds. There are two reasons of setting second step (based on the concept of soft landing), one is for better surface profile and the other is for handling uncertainties. Looking into the ability of uncertainties handling, using lower removal rate can be a “conservative” method. In general, the over-polishing is necessary to remove the barrier layer (in copper CMP) and make sure that copper residue is cleared entirely. However, many damages may occur if the over-polishing is not controlled well. For this reason, to reduce the damages which might occur at the final stage of the process, lower removal rate recipe has to be employed. Additionally, it is known that this strategy is employed in practical production, too.

Even though this method seems to be pretty good, two questions remains: (1) How small is the value of second step (after 40 seconds) will be enough? (2) Do the unstable/discontinuous situations, like the period of rising and dropping the removal rate immediately, will cause any undesired damages?(e.g. vibration of platen or turbulence of slurry) To avoid these two problems, a more continuous/smooth operation strategy will be established via SMC algorithm. Furthermore, the mechanism of operation profile will be proposed to not only solve the above two problems but derive better planarization (dishing and step-height reduction).

Note that it should be not sufficient to improve the performance by adjusting mechanical loads (*P* and *V*) only. From the investigations on CMP process mentioned in section 1.2, the chemical loads should be important factors, like PH value, etcher, inhibitor and oxidizer. In this thesis, only the oxidizer (H_2O_2) concentration will stand for chemical load, i.e. the oxidizer concentration is the only chemical factor which is discussed in this thesis. (see chapter 4)

3.3.2 Operation Profile Setting

There are two steps in SMC design: first, a stable sliding mode/surface/function has to be specified, and the system will move along sliding surface toward equilibrium point (control goal); next, a control input which will force the system to hit sliding surface in a finite time has to be derived. From Chen and Chang [37], there are three methods which are generally used in designing sliding function, Transformation Matrix method, Eigenstructure Assignment method and Lyapunov-based method. Similarly, in establishing control law, there are Hierarchical Sliding-mode Control and Integral Sliding-mode Control and so on. In this work, a convenient and powerful method which is also proposed by Chen and Chang [40], namely, Virtual Eigenvalue method is used in controller design.

In this conceptual model of CMP shown in (2.15), just one sliding-mode eigenvalue and one virtual eigenvalue instead of two set of them have to be selected because of the two by two system matrix. After choosing eigenvalues first, according to linear control theory, a state feedback control input by pole-placement method can be obtained as

$$u = -\boldsymbol{kx} \tag{3.9}$$

where k is the value to be designed. Note that this method can assign the eigenvalues of $\boldsymbol{A}-\boldsymbol{bk}$ to any desired value (Of course, it is always negative for stabilizing systems). Then, $\boldsymbol{A}-\boldsymbol{bk}$ can be diagonized as

$$[\boldsymbol{A}-\boldsymbol{bk}] = \begin{bmatrix} \boldsymbol{v} \\ \boldsymbol{c} \end{bmatrix}^{-1} \begin{bmatrix} J & 0 \\ 0 & \Omega \end{bmatrix} \begin{bmatrix} \boldsymbol{v} \\ \boldsymbol{c} \end{bmatrix} \tag{3.10}$$

where J and Ω represents sliding-mode eigenvalue and virtual eigenvalue, respectively. Consequently, the left eigenvector corresponding to the virtual eigenvalue has to be determined

$$\begin{bmatrix} \boldsymbol{v} \\ \boldsymbol{c} \end{bmatrix} [\boldsymbol{A}-\boldsymbol{bk}] = \begin{bmatrix} J & 0 \\ 0 & \Omega \end{bmatrix} \begin{bmatrix} \boldsymbol{v} \\ \boldsymbol{c} \end{bmatrix} \tag{3.11}$$

where $\boldsymbol{v} = \begin{bmatrix} v_1 & v_2 \end{bmatrix}$ and $\boldsymbol{c} = \begin{bmatrix} c_1 & c_2 \end{bmatrix}$ are the left eigenvector corresponding to J and Ω, respectively. Up to present, the sliding function is derived

$$s = \boldsymbol{cx} \tag{3.12}$$

where $\boldsymbol{c}$ is the left eigenvector corresponding to the virtual eigenvalue Ω in Eq. (3.14). To establish the control input, let the control input be

$$u = -\boldsymbol{kx} + u' \tag{3.13}$$

where u' is the term with switching function. Based on the concept of approaching-mode mentioned before, differentiate Eq. (3.12) and u' will be derived, that is

$$u' = -\left(\|\boldsymbol{c}\|\delta(\boldsymbol{x},t) + \sigma\right)(\boldsymbol{cb})^{-1}\, sat(s,\varepsilon) \tag{3.14}$$

where $\delta(\boldsymbol{x},t)$ represents the maximum value of disturbance $\boldsymbol{d}(\boldsymbol{x},t)$ and $sat(s,\varepsilon)$ is saturation function defined in Eq. (3.8).

Stability

Because the design of SMC is to force the system to hit the specified sliding-mode in a finite time and make it stay there forever, to analyze the stability of the system under SMC control, only the part of system which has entered the sliding mode needs to be considered. In other words, the stability of the system is equal to the stability of the system in specified sliding-mode.

To analyze the stability of the sliding-mode control, an important concept has to be employed, that is, equivalent-control [37]. It is known that the trajectory of the system is continuous even in the sliding-mode. However, the continuous trajectory in the sliding-mode control is made by a discontinous switching condition. The relationship between the continuous trajectory and the discontinuous switching condition is proposed by Filippov in 1988, that is

$$f\left(\boldsymbol{x},u_{eq}\right)=\mu f\left(\boldsymbol{x},u^{+}\right)+\left(1-\mu\right)f\left(\boldsymbol{x},u^{-}\right) \tag{3.15}$$

where the meaning of u^{+} and u^{-} is the same to (3.3). Fig. 3.7 shows a brief but comprehensive explanation. Then, the stability of the sliding-mode can be proved through the concept of equivalent-control. The detailed proof is shown in appendix Ⅰ.

3.3.3 Results

Some simulations are implemented by MATLAB software package. These simulation results are the preliminary demonstration of feasibility of the controller.

Analysis

In SMC design, the first thing which has to be taken care is the convergence to the sliding surface as shown in Fig. 3.8. In Fig. 3.8, it is clear that the system reach the sliding-surface (s=0) in a finite time, about 0.6 minutes. This result represents that the design is successful, i.e. the control law (3.14) works. Additionally, to visualize whole performance of the system, phase-plane analysis is a powerful tool.(Note that the method is restricted to second-order or first-order systems.) Fig. 3.9 shows the phase-plane plot of the system, and it reveals that the thickness (horizontal axis) decreases continuously and the variation of material removal rate (vertical axis) is smooth. Besides, Fig. 3.10 shows the plot of control input (3.13) and it also varies smoothly. The last one is Fig. 3.11, and it shows time history of removed copper thickness and (copper-) material removal rate during CMP process separately. In Fig. 3.11, the more detailed profile of these two important parameters are presented. The CMP process will finish in about 1.7 minutes (102 seconds), and the removal rate will decrease to zero at about the same time.

Discussions

To summarize entire process of CMP under SMC control: Initially, the system starts from an idle situation, the platen speed and the carrier speed increase loading separately , the down pressure is increased gradually, the temperature and the oxidizer concentration of slurry is increased proportionably. After about 0.2 minutes (12 seconds), all parameters tend to decrease their value to lower the removal rate. Note that the rate of change is lower than the period of first stage (increasing removal-rate). The process keeps on going until about 1.7 minutes, and then the platen and the carrier rotation speed go down to a lower value; so do the down pressure and the chemistry of slurry. Finally, all parameters decrease to very low values, and the CMP process is accomplished at the same time.

Certainly, the mechanism mentioned above is just a concept, but the description does contain some possible ways to achieve/realize the mechanism of “dynamic tuning” of operation, i.e. tuning platen and carrier rotation speed, varying down pressure, changing the temperature and oxidizer concentration of slurry and so on. Besides, the distinguishing feature of operation by dynamic tuning comes out from the description, that is, the variations of parameters are all continuous and smooth. In the operation via SMC design, not only the violent switching is avoided but the lower loads of parameters are employed. It will make this method much more applicable in real world. From the parameters variation during the process, the degree-of-freedom/flexibility can be increased. Based on the existing knowledge of CMP process, it is possible to set the process parameters dynamically. The opportunity of further improving the performance of CMP process will be feasible.

Note that detailed mechanism (including the consideration of chemical effects) which tunes the operation profile will be discussed in next chapter.

Additionally, according to the works mentioned in section 3.3.1, some evidences for the capability of the operation profile has been revealed. (Note that the profile means the removal rate curve in Fig. 3.11.) Because the recipe of low removal rate will be employed in the final stage of this operation, it will have better performance in low copper dishing [23, 24, 38]. The “deliberate” (low load on the process) at final stage will reduce the damages caused by over-polish effectively, and the over-polish time will be easier to control. [14, 32, 33, 42] The detailed simulation and verification will be shown in next chapter.

CHAPTER 4

VERIFICATION BY NUMERICAL SIMULATION

To verify the operation strategy of dynamic-tuning, some models/mechanisms which are presented in previous chapters will be employed to simulate in this chapter. Before the numerical simulations, what the operation input has to be clarified first. In last chapter, the operation profile (removal rate curve) is set and shown as Fig. 3.11. However, to realize this operation scheme coordinating the mechanical loads and chemical loads in harmony will be the critical point of "dynamic tuning" operation, i.e. decomposing the operation profile appropriately will be the critical point in forming the strategy of "dynamic tuning" operation. This strategy will be described in detail in this chapter and some verification of ability of the strategy will be followed.

4.1 Operation Input Concretization

To clarify the control/operation input *u*, the mechanism which is presented in section 2.2.3 is repeated here. From the system dynamic equation (2.15) and the material removal model (2.8), the control input is shown by differentiating (2.8), and (2.15) can be formulated as

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{U} + \boldsymbol{d}(\boldsymbol{x}, t) \tag{4.1}$$

where $\boldsymbol{x} = \begin{bmatrix} \tilde{h} & R \end{bmatrix}^{\mathrm{T}} \in R^2$, $\boldsymbol{A} = \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix}$, $\boldsymbol{B} = \begin{bmatrix} 0 & 0 \\ KV & KP + B \end{bmatrix}$, $\boldsymbol{U} = \begin{bmatrix} \dfrac{dP}{dt} & \dfrac{dV}{dt} \end{bmatrix}^{T}$, $\boldsymbol{d} = \begin{bmatrix} -0.1t \\ -0.1 \end{bmatrix}$ and the initial value of the system is $\boldsymbol{x}(0) = \begin{bmatrix} 8000 & 0 \end{bmatrix}^{T}$. The elements of $\boldsymbol{U}$, $\dfrac{dP}{dt}$ and $\dfrac{dV}{dt}$, can be transferred to the design/actuators of equipment. Note that constraints of applied downward pressure and linear relative velocity are not considered in (4.1). Because of the lack of model of chemical factors in CMP process, the detailed equation is difficult to be expressed here. However, from the research by Y.-C. Kao *et al.* [38], some experiments were carried out over wide range of oxidizer concentration. They indicated that the copper removal rate of copper CMP will follow a specific trend as the concentration increases. Coincidentally, the trend, shown in Fig. 4.1, is similar to the operation profile which is shown above (Fig. 3.11). Therefore, the oxidizer concentration can be included into the operation mechanism easily because of this similarity. With the constraints of downward pressure and relative velocity, the chemical factor, R_C can be introduced into the operation mechanism. The control input and input matrix $\boldsymbol{B}$ can be reformed as $\boldsymbol{U} = \begin{bmatrix} \frac{dP}{dt} & \frac{dV}{dt} & \frac{dRc}{dt} \end{bmatrix}^{\boldsymbol{T}}$ and $\boldsymbol{B} = \begin{bmatrix} 0 & 0 & 0 \\ KV & KP+B & 1 \end{bmatrix}$. Note that the relation between oxidizer concentration and R_C (with specific slurry) was proposed by Q. Luo *et al.* [34], as shown in Fig. 4.2. It should be mentioned that reduction of removal rate at higher H_2O_2 concentration in both figures, Fig. 4.1 and 4.2, are due to the formation of passivation layer (copper oxide film).

Because of the important interdependence of chemical and mechanical effects, it has to be mentioned that a phenomenon in changing the process parameters. The phenomenon has been proposed in the works of J. M. Steigerwald *et al.* [43] and Y.-C. Kao *et al.* [38], that is, two polishing regimes, a dissolution rate limited regime (chemical reaction controlled regime) and an abrasion rate limited regime (mechanical abrasion controlled regime), exist in CMP process. Besides, the effects of slurry chemistry on dishing have been proposed by V. Nguyen *et al.* [14]. They revealed that less dishing would be obtained from higher oxidizer concentration in the slurry. These investigations could be great foundations for setting the manner of the chemical factor.

To integrate these research achievements [14, 32, 33, 38, 43], the control inputs integration of control inputs described must be coordinated in harmony with each other. In other words, the objective mentioned in section 1.3 can be implemented with these considerations of chemical effects. The dynamic tuning operation of CMP process is then coordinated, as shown in Fig. 4.3. Fig. 4.1 above is used to illustrate the concept of dynamic tuning operation.

It must be mentioned again that most superior feature of dynamic tuning operation is the higher degree-of-freedom/flexibility of the process parameters. If all of the parameters can be assigned arbitrarily during the process, the possibility of figuring out the optimal operation condition/profile is much larger.

The acceleration stage in Fig. 4.3 means the increasing of removal rate (before about 0.2 minutes of second plot of Fig. 3.11). It is followed by deceleration stage after the peak value of removal rate is achieved. Because all of the operation parameters (means P, V and R_C here) are all changeable, increasing and decreasing of removal rate can be realized by tuning them. Besides, the operation can be designed with more appropriate sequence to obtain better performance. The proposed sequence is to set the system at mechanical abrasion controlled regime in the beginning. At this regime, the passivation layer is formed and the rate of forming is higher than the mechanical abrasion rate. Therefore, it can be expected that lower region of wafer surface is protected by the passivation layer. Continuously, the load is increased (larger values of parameters) to raise the removal rate until the peak value of removal rate. Note that relative velocity will be the major factor in increasing removal rate because of the lower influence on dishing. In the representation of Fig. 4.3, the values of operation parameters, P, V and Rc, can be assigned with 3.5 p.s.i., 93rpm, 300nm/min, respectively. (this set of parameter represents the constraint which is assigned in this thesis) As soon as the peak value is achieved, these parameters can be decreased for suppressing dishing, especially the applied downward pressure P. Moreover, higher oxidizer concentration (causes lower R_C value) will cause less dishing from the results shown by V. Nguyen *et al.* [14] because a more effective passivation layer is formed with higher oxidizer concentration and protects the recess areas.

Because the operation inputs are decomposed directly from the removal rate curve and the bound is the only one constraint for each input, the operation profile can be set in many ways. In other words, there can be infinite solutions because of three variables (P, V and Rc) and only one equation (removal rate curve, Fig. 3.11). Therefore, a new problem will be raised, what is the best tuning/operation profile? It will not be discussed in this work. Here, one possible operation profile will be chosen to verify the effect of dynamic tuning operation of CMP process. To formulate the dynamic-tuning operation profile at first time, the composition of parameters will be obtained by hand based on the trend of Fig. 4.3 and the mechanism of (2.8). Three process parameters, P, V and the oxidizer (H_2O_2) concentration, will be tuned in specific profile dynamically during single wafer polishing. The bounds of P, V and the oxidizer concentration are set by 1.7 p.s.i. to 3.5 p.s.i., 40 rpm to 95 rpm and 2% to 5%, respectively. Note that relative velocity is transferred to platen/carrier rotational speed. The detailed procedure of setting operation profiles is shown in appendix Ⅱ.

4.2 Verification

The dishing model (2.9) is used to verify the ability of dynamic tuning method and the result is shown in Fig. 4.4. It is clear that dishing is suppressed from 1106Å to 950Å in Fig. 4.4(a) while the dynamic tuning is applied to process operation/control. The improvement is more than 14% with maintaining the copper removal (throughput) of constant input. Fig. 4.4(b) displays the sketch of variations of parameters during the over-polish stage.

To complete simulate the dynamic tuning and integrate the whole process, step-height reduction model shown in (2.11) is included here. Before the simulation, the model has to be checked for validity of all of processing time. The results reveal that step height will keep decreasing with time increasing and will be close to zero step height when the polishing endpoint is arrived (not shown here). However, from the work by K. Wijekoon *et al.* [23], as shown in Fig. 4.5, dishing will exist before the end of process and linearly increases with overpolish/time. This experiment data might imply that initial value of dishing will not be zero (i.e. non-zero step height will be transited to dishing) and the step-height reduction model (2.11) may break down for describing/predicting the step height in the back-end stage of bulk copper CMP process. Therefore, the simulation presented below will show the front-end only.

In Fig. 4.6(a), the step-height reduction results of dynamic-tuning and constant input are shown. The better ability of step height reduction (more efficient planarization) of dynamic tuning can provide a weighty evidence for the efficiency of the strategy shown in Fig. 4.3. The variations of parameters during this interval of process are shown in Fig. 4.6(b).

It has to be mentioned again that one of the main goals in this thesis is to maintain acceptable throughput and get better performance. From the operation input concretization, it can be pointed out clearly that the employment of chemical load is the key point in this way of operation profiles setting. In other words, not only increasing the degree-of-freedom/flexibility of CMP process but also deriving better performance (and throughput) with the injection of chemical parameter in operation action could be the key factor.

4.3 Discussion

In CMP process, the chemical and mechanical effects have to be operated in harmony for maintaining acceptable performances and throughput. The procedure is an optimization problem. To optimize the recipe (a set of specific process parameters) becomes a major work of improving the process. For most research on CMP process, the general characteristics of the process are described roughly. However, some limitations (due to constant input) will be led into the process in typical operation. Based on the existing knowledge and the typical operation, some new operation methods are figured out, like two or three stage polishing. The multi-stage method is widely used in real production but it is not good enough in the growing requirement of planarization. In dynamic tuning method the degree-of-freedom/flexibility of process parameters will be increased (while breaking away from the typical operation). That will increase the possibility of formulating the set of process parameters. The opportunity of further improving the performance of CMP process will be feasible. In this thesis, the most striking way to increase the degree-of-freedom/flexibility is the variation of oxidizer concentration (chemical load) based on present knowledge of dishing in CMP process. It is expected that the operation profile can be further modified as the understanding of CMP process increase.

The distinguishing feature of operation by dynamic tuning is the process parameters varying during single wafer polishing. It involves within-wafer control of fabrication process. Although it is not an easy subject in process control of semiconductor production, the tendency of progress of fabrication technique seems to be inevitable. From the simulations shown in last section, the operation of dynamic tuning method reveals outstanding improvement in dishing. The feature of deriving better performance and maintaining throughput simultaneously is the other important advantages of this strategy. Moreover, setting the operation profile via sliding mode theory, not only the violent switching is avoided but the lower loads of parameters are employed. It will make this method much more applicable in real world.

It has to be mentioned again that problem about validity of the step height reduction model and to explain why only the segment simulation result is shown above. The exact definitions of "step-height" and "dishing" are the surface height difference between high and low area of copper and the height difference between oxide and copper line, respectively. During single wafer polishing, the step height of copper may be transited into dishing when endpoint of CMP process is arrived (the oxide is exposed). The dishing exists before zero over-polish in Fig. 4.5 may represent the non-zero step height. However, the step height reduction model predicts that step height in reasonable polishing time will be close to zero. (It may be due to the assumptions in establishing model.) It will conflict with the experiments results shown in Fig. 4.5. Furthermore, the dishing and erosion problems caused by CMP process will not be so serious if the surface is so flat before over-polish stage. Because the problems will be reduced significantly while an appropriate slurry (selectivity Ta to Cu is large) is used in the over-polish stage.

Except the numerical simulations, significant evidences for proving the capability of the operation profile have been revealed. (Note that the profile is the removal rate curve in Fig. 3.11.) Because the recipe of low removal rate will be employed in the final stage of this operation, it will have better performance, low copper dishing. [23, 24, 38] The "deliberate" (low load on the process) operation at final stage will reduce the damages caused by over-polish effectively, and the over-polish time will be easier to control. [14, 32, 33] Additionally, the operation profile of SMC design is closer to the shape on concept of soft-landing because the process almost stops near the endpoint of polishing. In case of the measurement uncertainties, a correct realization of soft-landing should be more effective using SMC approach.

To control the removal rate or the other parameters precisely is a difficult objective because of the existence of uncertainties and disturbances of the prediction model or the working environment. One important point about dynamic tuning method needs to be emphasized here: even though the removal rate can not be performed perfectly with the designed trajectory, the performance can be improved by using the strategy of dynamic tuning (as described in Fig.4.3). (This point is shown in the difference between Fig. 4.4(a) and Fig. 3.11.) In other words, dynamic-tuning operation approach flexibility and degree of freedom for improvement is more important than what is the exact operating profile. It is the future work to determine what the best operation profile is, how to implement the complete control scheme via sliding-mode theory. The dynamic response of the operation of actual CMP tools needs to be looked to ensure proper following of soft landing model in real world.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

5.1 Conclusion

In this work, the concept of dynamic tuning of operating CMP process is presented and one possible operation profile is proposed via sliding-mode theory. This strategy is verified by numerical simulations. The simulation results show 14% reduction in dishing during over-polish stage. Future experiment needs to be designed to confirm this improvement.

However, the simulation verification of step-height reduction needs to be reinforced in future work when there are better models which describes continuous transition from step-height from bulk-polish stage to dishing during over-polish stage. Otherwise, experiments can be designed to compare directly step height reduction between conventional CMP operation and “dynamic tuning” CMP operation.

Dynamic tuning of operation profile provides a new aspect of CMP operation and it might be a candidate for within wafer control in CMP process. This concept provokes thought for the development of within-wafer control to improve CMP performance. It is the hope of this research that dynamic tuning may be considered for improving CMP planarization in the area of step height reduction and dishing reduction.

5.2 Future Works

The requirement of planarization in semiconductor fabrication is growing rapidly with the feature size decreasing. This reveals the importance of process control in semiconductor fabrication process is greater and greater. Advanced process control (APC) becomes a hottest subject in fab production to date. To improve the performance substantially (not only in CMP process), within-wafer control may be a critical method. Once the control subject gets into within-wafer, the system must be treated as a dynamic system. It might be more complex than before but the more improvement can be expected.

Many difficulties in within-wafer control need to be solved, like in-situ sensor and the knowledge of process in the situation of dynamic operation. Except the in-situ sensor, to further research the behavior of process in dynamic state an appropriate dynamic model may be a key point. The tighter within-wafer control will be realized based on the proper dynamic model.

Although the preliminary verification/explanation of dynamic tuning is proposed in this work, more complete simulation and experiments must be done in the future. Some future works are listed below:

1. Further grasp the knowledge of CMP process including mechanical and chemical effects.

2. Establish an appropriate dynamic model for CMP process and performance indexes.

3. Examine the ability and stability of the operation strategy of dynamic-tuning by more theoretical analysis and simulations.

4. Try to overcome the limitation in the design of current CMP equipment and design experiments to verify the concept in real production.

5. To optimize the operation profiles based on more investigations on CMP process and more sophisticated control algorithm.

References

[1] F. W. Preston, "The Theory and Design of Plate Glass Polishing Machines," *J. Soc. Glass Tech.*, Vol.11, pp.214-247, 1927.

[2] F. B. Kaufman, D. B. Thompson, R. E. Broadie, M. A. Jaso, W. L. Guthrie, D. J. Pearson, and M. B. Small, "Chemical-Mechanical Polishing for Fabricating Patterned W Metal Features as Chip Interconnects," *J. Electrochem. Soc.*, Vol.138, No.11, pp.3460-3464, 1991.

[3] G. Nanz and L. E. Camilletti, "Modeling of Chemical-Mechanical Polishing: A Review," *IEEE Trans. Semicond. Manuf.*, Vol.8, No.4, pp.382-389, 1995.

[4] W.-T. Tseng and Y.-L. Wang, "Re-examination of Pressure and Speed Dependences of Removal Rate during Chemical-Mechanical Polishing Processes," *J. Electrochem. Soc.*, Vol.144, No.2, pp.L15-L17, 1997.

[5] F. Zhang and A. Busnaina, "The Role of Particle Adhesion and Surface Deformation in Chemical Mechanical Polishing Processes," *Electrochem. Solid-State Lett.*, Vol.1, No.4, pp.184-187, 1998.

[6] B. Zhao and F. G. Shi, "Chemical Mechanical Polishing: Threshold Pressure and Mechanism," *Electrochem. Solid-State Lett.*, Vol.2, No.3, pp.145-147, 1999.

[7] H. Hocheng, H. Y. Tsai, and Y. T. Su, "Modeling and Experimental Analysis of the Material Removal Rate in the Chemical Mechanical Planarization of Dielectric Films and Bare Silicon Wafers," *J. Electrochem. Soc.*, Vol.148, No.10, pp.G581-G586, 2001.

[8] J. Luo and D. A. Dornfeld, "Material Removal Mechanism in Chemical Mechanical Polishing: Theory and Modeling," *IEEE Trans. Semicond. Manuf.*, Vol.14, No.2, pp.112-133, 2001.

[9] D. Castillo-Mejia and S. Beaudoin, "A Locally Relevant Prestonian Model for Wafer Polishing," *J. Electrochem. Soc.*, Vol.150, No.2, pp.G96-G102, 2003.

[10] R. K. Singh and R. Bajaj, "Advances in Chemical-Mechanical Planarization," MRS Bulletin/October 2002, pp.743-747.

[11] R. J. Gutmann, J. M. Steigerwald, L. You, D. T. Price, J. Neirynck, D. J. Duquette, and S. P. Murarka, "Chemical-Mechanical Polishing of Copper with Oxide and Polymer Interlevel Dielectrics," *Thin Solid Film*, Vol.270, pp.596-600, 1995.

[12] J. Luo, "Review of Chemical-Mechanical Planarization Modeling for Integrated Circuit Fabrication," Research Reports of LMA of UC. Berkley, USA, pp.107-135, 2002-2003.

[13] D. Zeidler, Z. Stavreva, M. Plotner, and K. Drescher, "Characterization of Cu

Chemical Mechanical Polishing by Electrochemical Investigations," *Microelectronic Engineering*, Vol.33, pp.259-265, 1997.

[14] V. Nguyen, H. VanKranenburg, and P. Woerlee, "Dependency of Dishing on Polishing Time and Slurry Chemistry in Cu CMP," *Microelectronic Engineering*, Vol.50, pp.403-410, 2000.

[15] J. Hernandez, P. Wrschka, and G. S. Oehrlein, "Surface Chemistry Studies of Copper Chemical Mechanical Planarization," *J. Electrochem. Soc.*, Vol.148, No.7, pp.G389-G397, 2001.

[16] V. S. Chathapuram, T. Du, K. B. Sundaram, and V. Desai, "Role of Oxidizer in the Chemical Mechanical Planarization of the Ti/TiN Barrier Layer," *Microelectronic Engineering*, Vol.65, pp.478-488, 2003.

[17] S. Ramarajan, Y. Li, M. Hariharaputhiran, Y.-S. Her, and S. V. Babu, "Effect of PH and Ionic Strength on Chemical Mechanical Polishing of Tantalum," *Electrochem. Solid-State Lett.*, Vol.3, No.5, pp.232-234, 2000.

[18] V. H. Nguyen, A. J. Hof, H. van Kranenburg, P. H. Woerlee, and F. Weimar, "Copper Chemical Mechanical Polishing using a Slurry-free Technique," *Microelectronic Engineering*, Vol.55, pp.305-312, 2001.

[19] S. Kondo, N. Sakuma, Y. Homma, Y. Goto, N. Ohashi, H. Yamaguchi, and N. Owada, "Complete-Abrasive-Free Process for Copper Damascene Interconnection," *Interconnect Technology Conference, 2000. Proceedings of the IEEE 2000 International*, pp.253-255, 2000.

[20] Y. Yamada, N. Konishi, N. Ohashi, and T. Kimura, "Improved Cu Abrasive-Free Polishing at 0.13um Manufacturing and Beyond," *Interconnect Technology Conference, 2002. Proceedings of the IEEE 2002 International*, pp.108-110, 2002.

[21] A. Chen and R.-S. Guo, "Age-Based Double EWMA Controller and Its Application to CMP Processes," *IEEE Trans. Semicond. Manuf.*, Vol.14, No.1, pp.11-19, 2001.

[22] L. Da, V. G. Kumar, A. Tay, A. A. Mamun, W. K. Ho, A. See, and L. Chan, "Run-to-Run Process Control for Chemical Mechanical Polishing in Semiconductor Manufacturing," *Proceedings of the 2002 IEEE International Symposium on Intelligent Control, 27-30 Oct.*, pp.740-744, 2002.

[23] K. Wijekoon, S. Tsai, M. Chandrachood, B. Brown, F. Redeker, S. Nanjangud, and G. Amico, "Multi-Step Approach to Copper CMP Development," *SEMI/Japan Technical Symposium*, 1998.

[24] J.-B. Chiu, C.-C. Yu, and S.-H. Shen, "Application of Soft Landing to the Process Control of Chemical Mechanical Polishing," *Microelectronic Engineering*, Vol.65, pp.345-356, 2003.

[25] A. Schiltz, "A Review of Planar Techniques for Multichip Modules," *IEEE Trans. Comp. Hybrid, Manuf. Technol.*, Vol.15, No.2, pp.236-244, 1992.

[26] 王建榮、林必窕、林慶福, *半導體平坦化 CMP 技術*, 全華, 台北, 1999。

[27] G. Wu and T. E. West, "Hard Porous Pads for Chemical Mechanical Polishing," SEMICON China, 2003.

[28] J. M. Steigerwald, S. P. Murarka, and R. J. Gutmann, *Chemical Mechanical Planarization of Microelectronic Materials*, John Wiley & Sons, New York, 1997.

[29] K. Kasprzyk and J. Schlueter, "CMP In-Situ Multi-Zone Endpoint Using Optical Metrology," *Proceedings of 2001 CMP-MIC Conference.*

[30] P. Wrschka, J. Hernandez, Y. Hsu, T. S. Kuan, G. S. Oehrlein, H. J. Sun, D.A. Hansen, J. King, and M. A. Fury, "Polishing Parameter Dependencies and Surface Oxidation of Chemical Mechanical Polishing of Al Thin Films," *J. Electrochem. Soc.*, Vol.146, No.7, pp.2689-2696, 1999.

[31] S. R. Runnels, I. Kim, J. Schleuter, C. Karlsrud, and M. Desai, "A Modeling Tool for Chemical-Mechanical Polishing Design and Evaluation," *IEEE Trans. Semicond. Manuf.*, Vol.11, No.3, pp.501-510, 2001.

[32] V. H. Nguyen, P. van der Velden, R. Daamen, H. van Kranenburg, and P. H. Woerlee, "Modeling of Dishing for Metal Chemical Mechanical Polishing," *IEDM Technical Digest., 10-13 Dec.*, pp.499-502, 2000.

[33] G. Fu and A. Chandra, "An Analytical Dishing and Step Height Reduction Model for Chemical Mechanical Planarization (CMP)," *IEEE Trans. Semicond. Manuf.*, Vol.16, No.3, pp.477-485, 2003.

[34] Q. Luo, S. Ramarajan, and S. V. Babu, "Modification of the Preston Equation for the Chemical-Mechanical Polishing of Copper," *Thin Solid Films*, Vol.335, pp.160-167, 1998.

[35] K. D. Young, V. I. Utkin, and Ü. Özgüner, "A Control Engineer's Guide to Sliding Mode Control," *IEEE Trans. Cont. Sys. Tech.*, Vol.7, No.3, pp.328-342, 1999.

[36] J. Y. Hung, W. Gao, and J. C. Hung, "Variable Structure Control: A Survey," *IEEE Trans. Ind. Elec.*, Vol.40, No.1, pp.2-22, 1993.

[37] 陳永平、張浚林, *可變結構控制設計*, 全華, 台北, 2002。

[38] Y.-C. Kao, C.-C. Yu, and S.-H. Shen, "Robust Operation of Copper Chemical Mechanical Polishing," *Microelectronic Engineering*, Vol.65, pp.61-75, 2003.

[39] S. Wang, "Chemical Mechanical Polish," course lecture in NCTU, Jan.14, 2003.

[40] Y.-P. Chen and J.-L. Chang, "A New Method for Constructing Sliding Surfaces of Linear Time-Invariant Systems," *Intern. J. Sys. Sci.*, Vol.31, No.4,

pp.417-420, 2000.

[41] 方政煜，”ULSI 嵌入式銅導線之無研磨粒子平坦化技術”，國立交通大學材料科學與工程研究所碩士論文，2001。

[42] Y. Lin, “Modeling CMP for Copper Dual Damascene Interconnects,” *Solid State Technology*, Vol. 43, Issue 6, pp.111-121, 2000.

[43] J. M. Steigerwald, S. P. Murarka, R. J. Gutmann, D. J. Duquette, “Mechanism of Copper Removal during Chemical Mechanical Polishing,” J. *Vac. Sci. Technol. B*, Vol.13, No.6, pp.2215-2218, 1995.

[44] R. J. Contolini, A. F. Bernhardt, and S. T. Mayer, “Electrochemical Planarization for Multilevel Metallization,” *J. Electrochem. Soc.*, Vol.141, No.9, pp.2503-2510, 1994.

[45] R. Vidal and A. C. West, “Copper Electropolishing in Concentrated Phosphoric Acid,” *J. Electrochem. Soc.*, Vol.142, No.8, pp.2682-2694, 1995.

[46] S.-C. Chang, J.-M. Shieh, C.-C. Huang, B.-T. Dai, and M.-S. Feng, “Pattern Effect on Planarization Efficiency of Cu Electropolishing,” *Jpn. J. Appl. Phys.*, Vol.41, pp.7332-7337, 2002.

[47] S.-C. Chang, J.-M. Shieh, B.-T. Dai, M.-S. Feng, Y.-H. Li, C. H. Shih , M. H. Tsai, S. L. Shue, and R. S. Liang, “Superpolishing for Planarizing Copper Damascene Interconnects,” *Electrochemical and Solid-State Letters*, Vol.6, No.5, pp.G72-G74, 2003.

[48] D. Padhi, J. Yahalom, S. Gandikota, and G. Dixit, “Planarization of Copper Thin Films by Electropolishing in Phosphoric Acid for ULSI Application,” *J. Electrochem. Soc.*, Vol.150, No.1, pp.G10-G14, 2003.

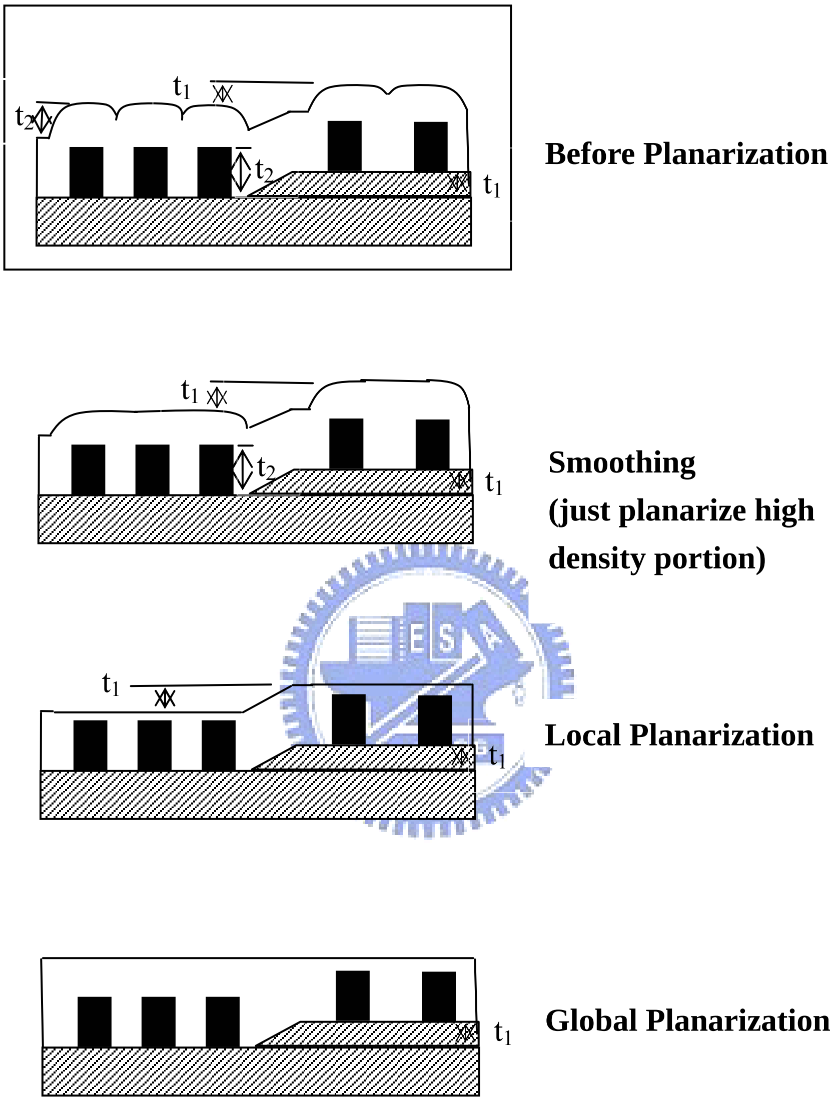


Fig.1.1 Various forms of planarization [26]

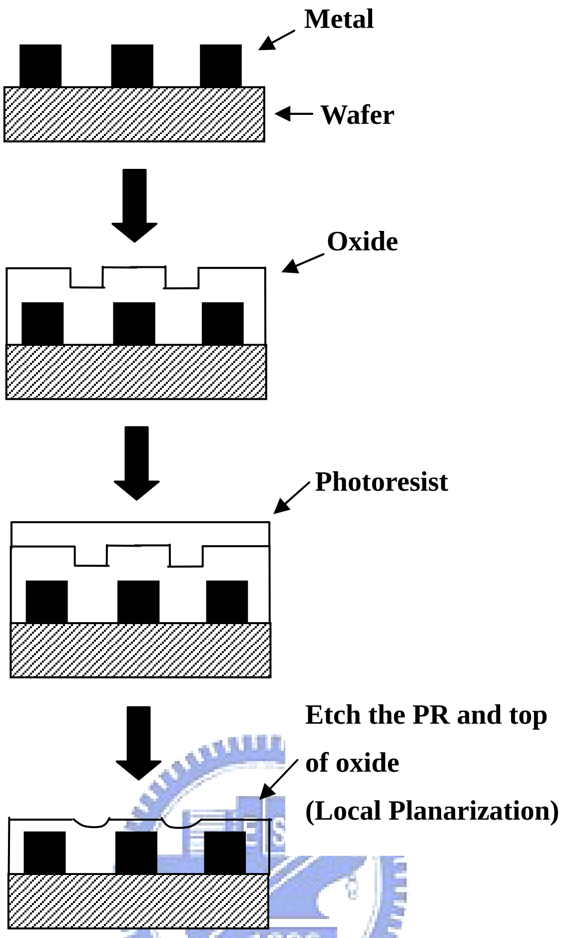


Fig.1.2 etchback process

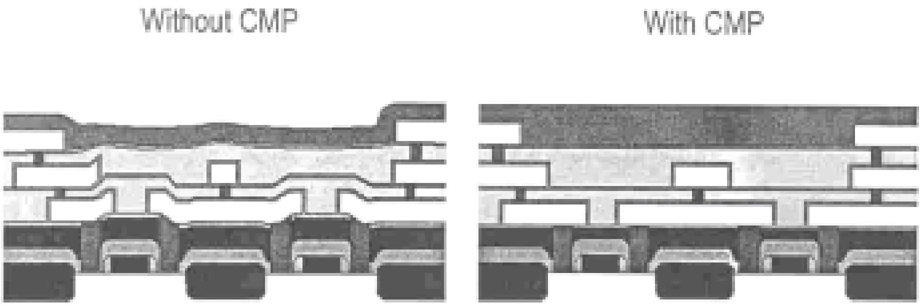


Fig.1.3 Schematic of CMP benefit [40]

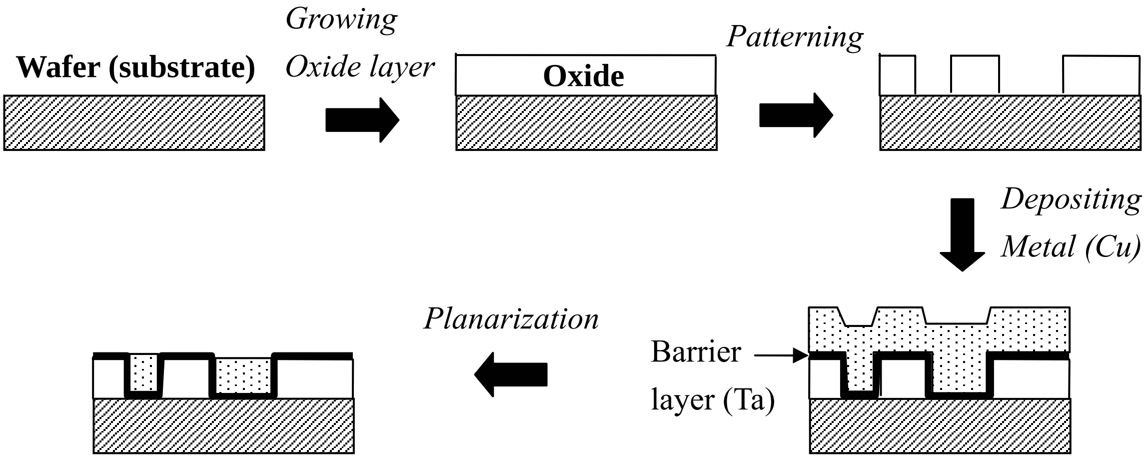


Fig.1.4 Illustration of CMP fabrication process

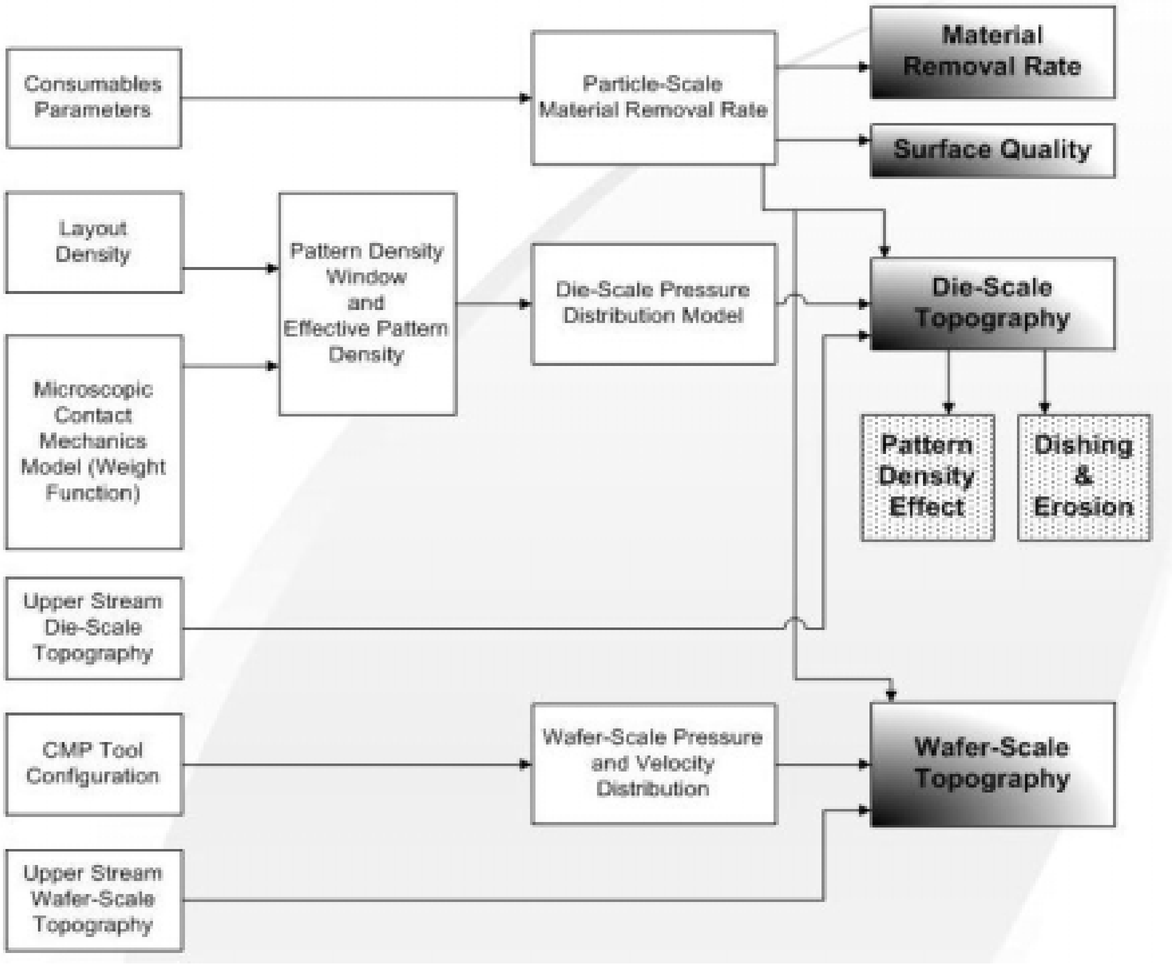


Fig.1.5 Framework of integrated CMP model [12]

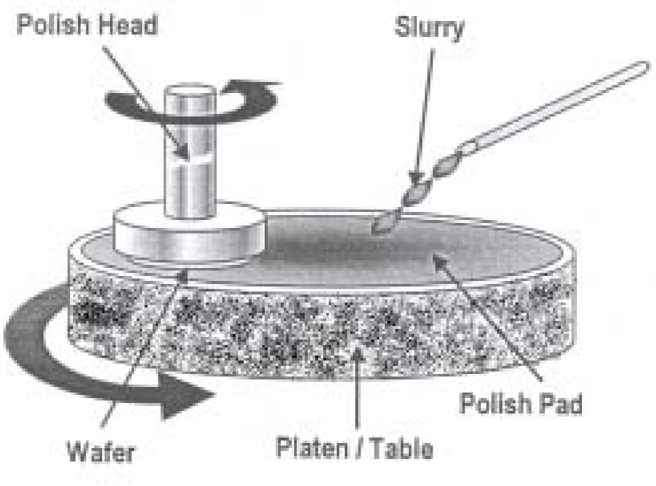


Fig.2.1.1 Schematic of CMP polisher (CMP on Rotary Tool) [40]

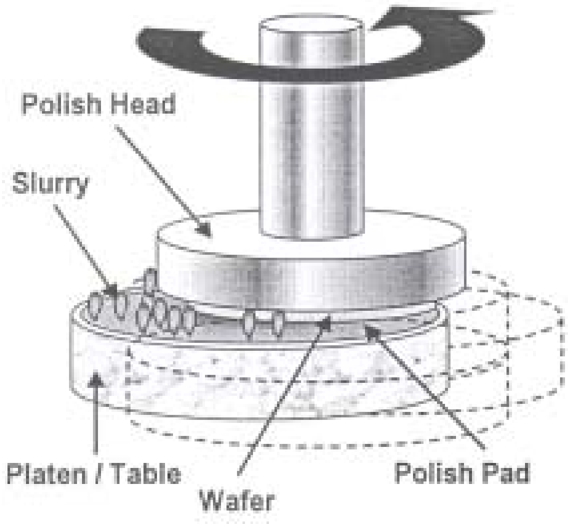


Fig.2.1.2 Schematic of CMP polisher (CMP on Orbital Tool) [40]

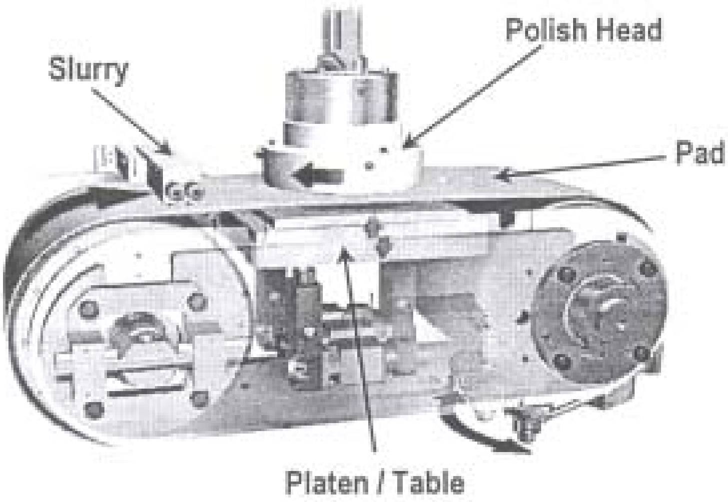


Fig.2.1.3 Schematic of CMP polisher (CMP on Linear Tool) [40]

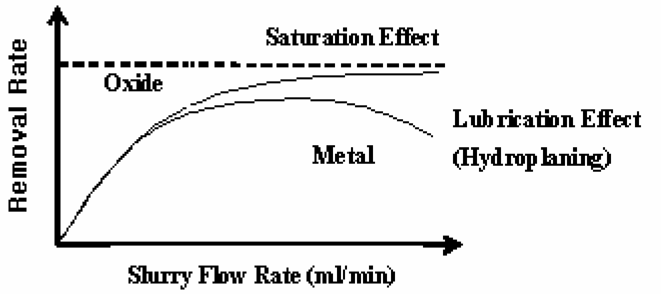


Fig.2.2 Effects of slurry flow rate on the CMP process [40]

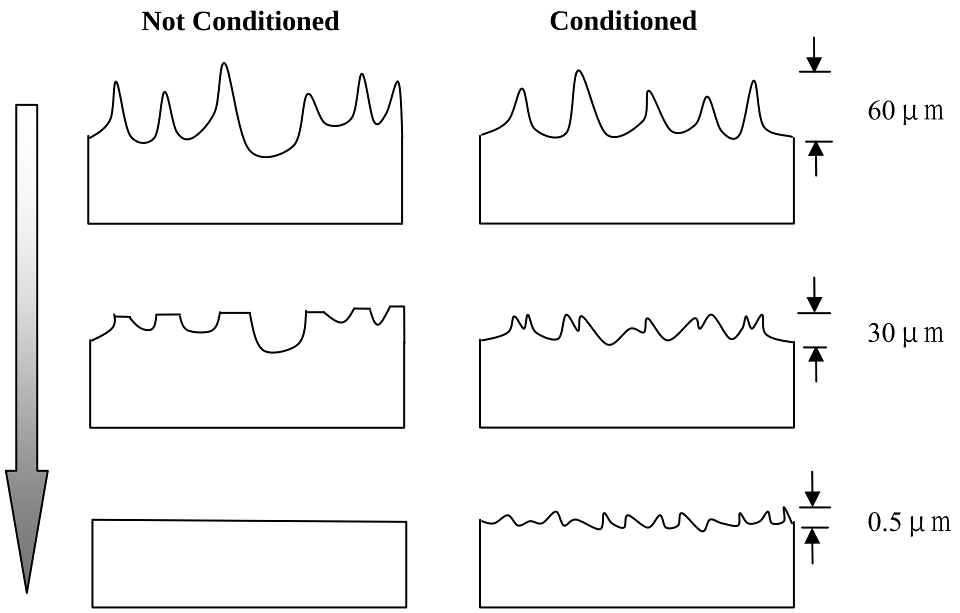


Fig.2.3 Pad conditioning [40]

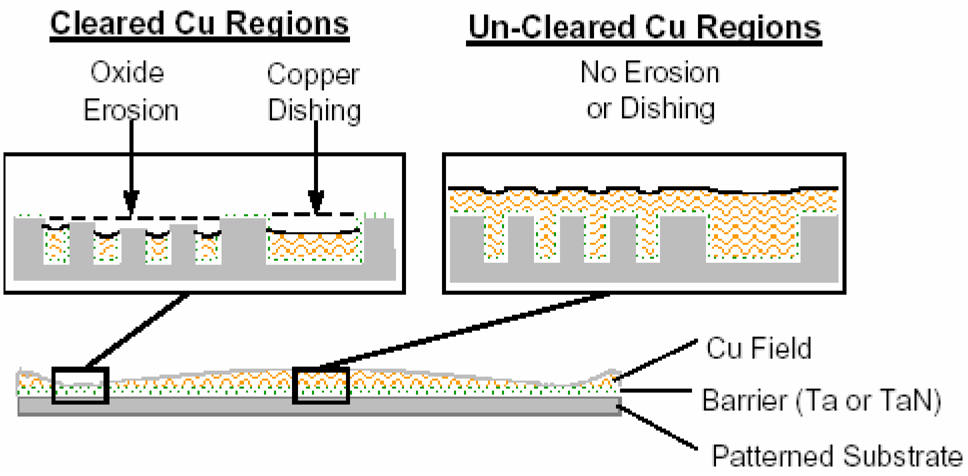


Fig.2.4 Dishing and Erosion

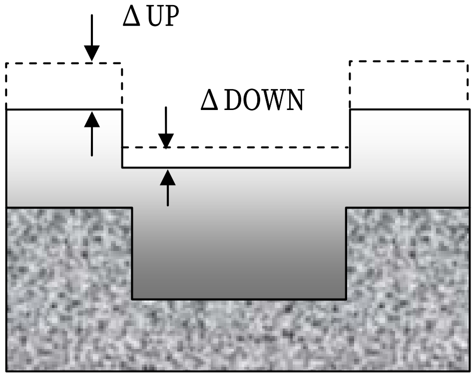


Fig.2.5 Planarization efficiency

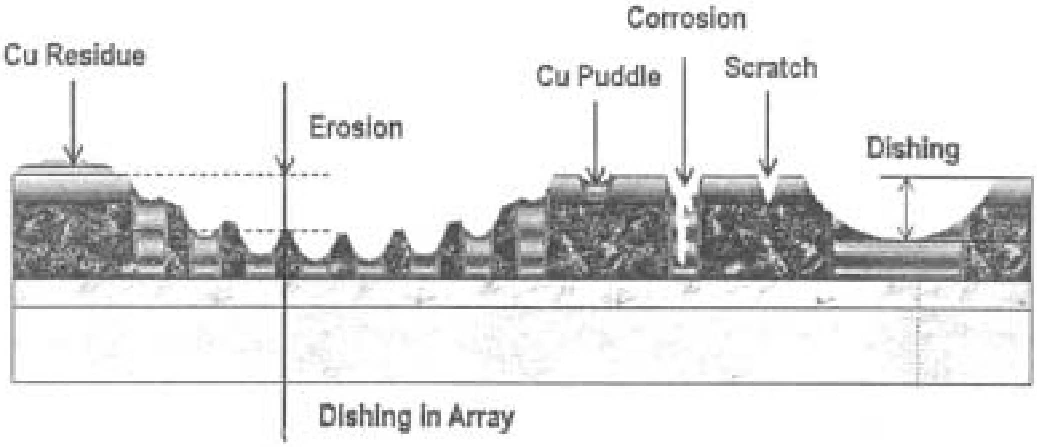
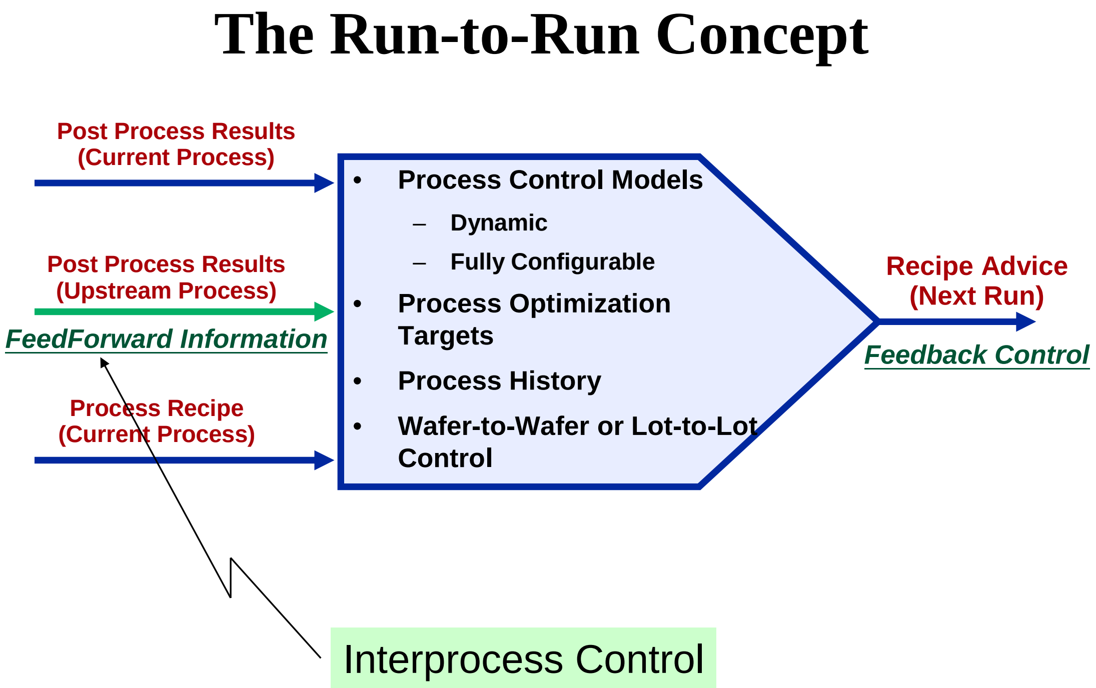


Fig.2.6 Copper CMP Defects [40]



The Run-to-Run Concept

Post Process Results
(Current Process)

Post Process Results
(Upstream Process)

FeedForward Information

Process Recipe
(Current Process)

- Process Control Models
  - Dynamic
  - Fully Configurable
- Process Optimization Targets
- Process History
- Wafer-to-Wafer or Lot-to-Lot Control

Recipe Advice
(Next Run)

Feedback Control

Interprocess Control

Fig.2.7 The Run-to-Run Concept

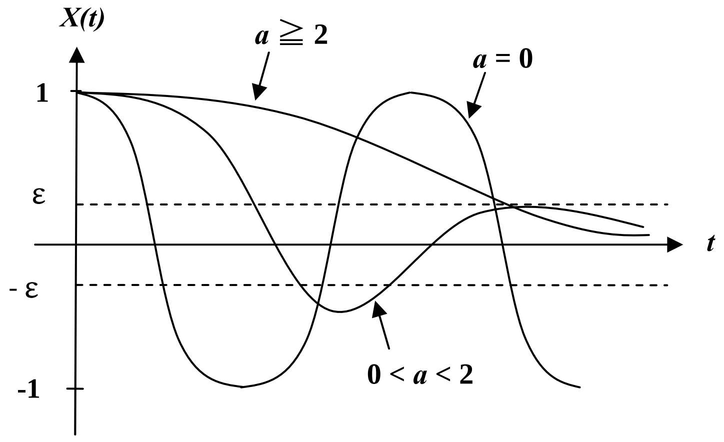


Fig.3.1.1 All possible situations of system by traditional design [38]

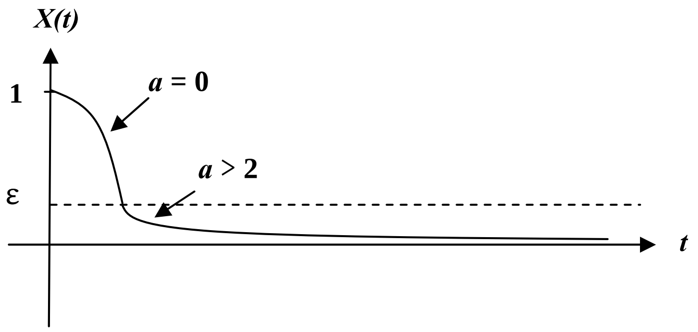


Fig.3.1.2 VSC system response of a simple second order system [38]

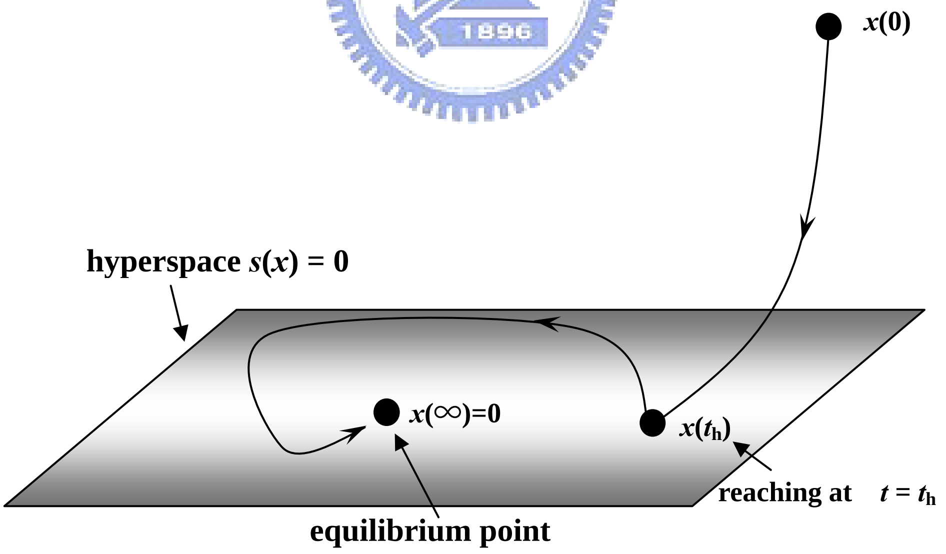


Fig.3.2 The generation of sliding-mode [38]

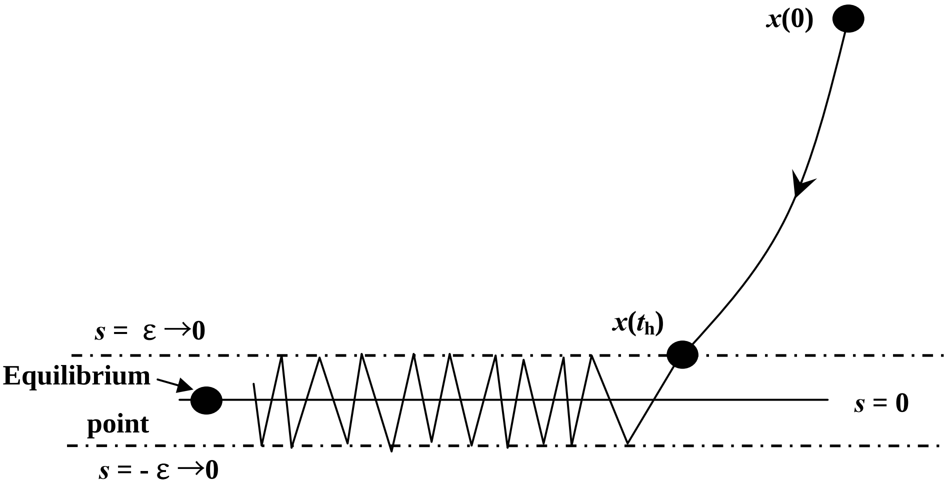


Fig.3.3 The system trajectory in the sliding mode [38]

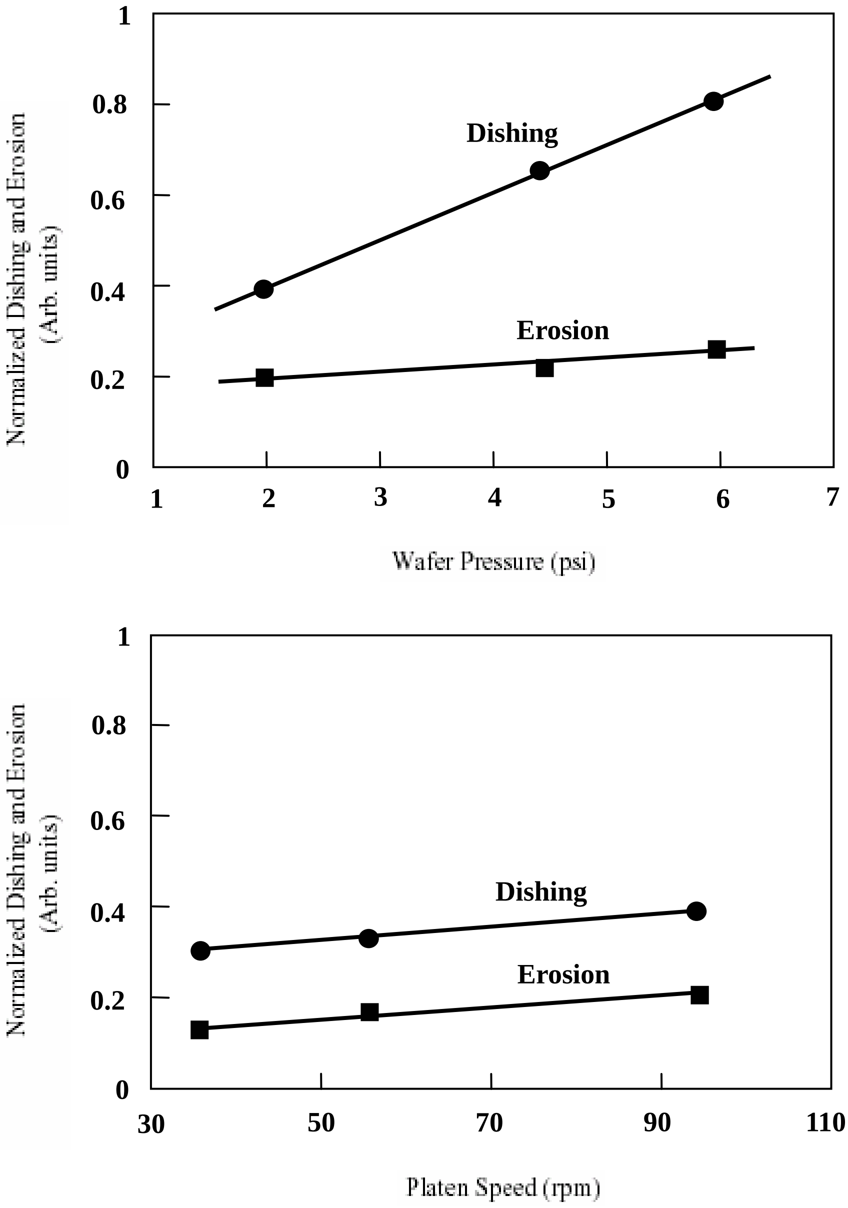


Fig.3.4 Effects of pressure and speed on dishing and erosion [23]

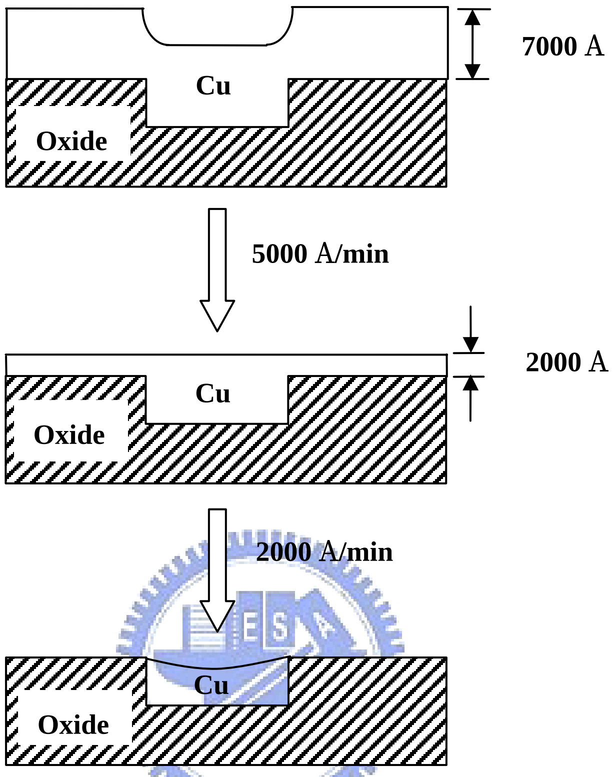


Fig.3.5 Conceptual description of soft landing (R_r =5000 Å/min for the first 5000 Å and R_r =2000 Å/min for the remaining 2000 Å) [39]

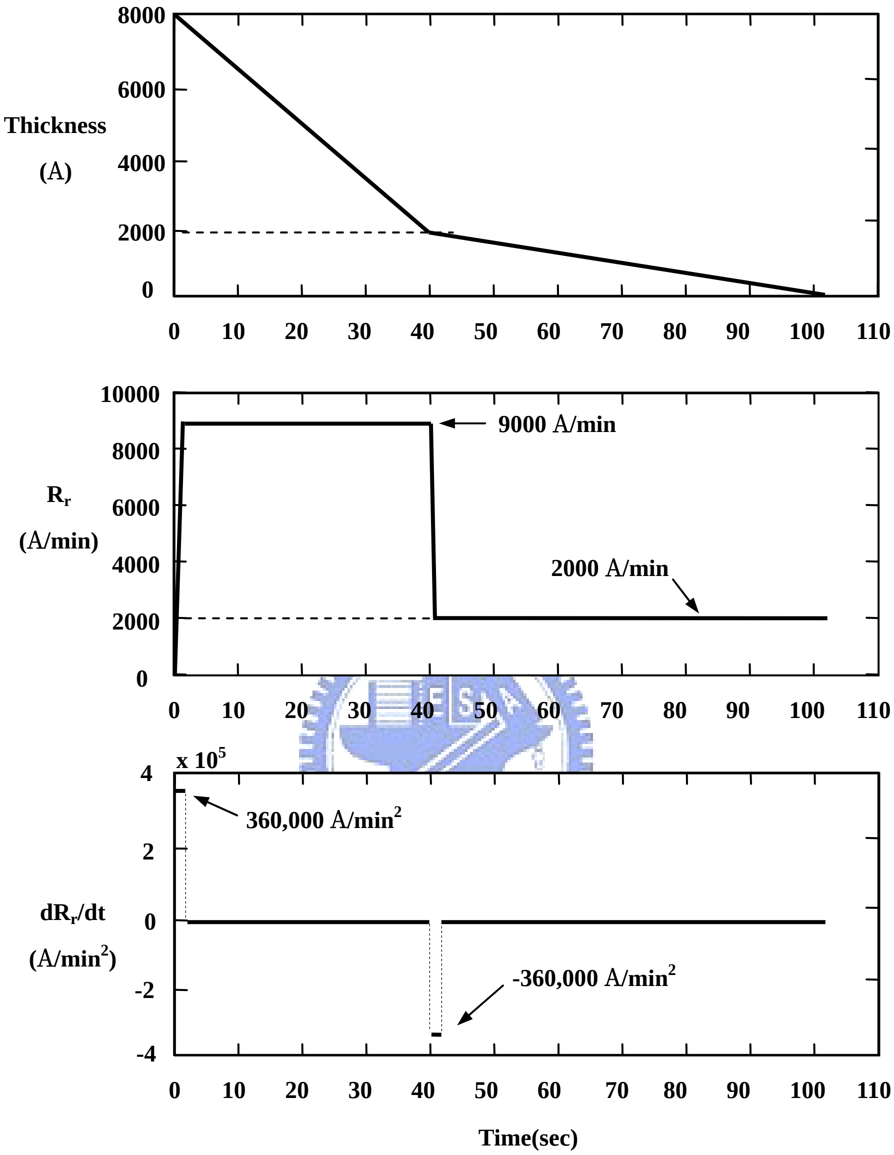


Fig.3.6 Simulation results of CMP operation via optimal control [24]

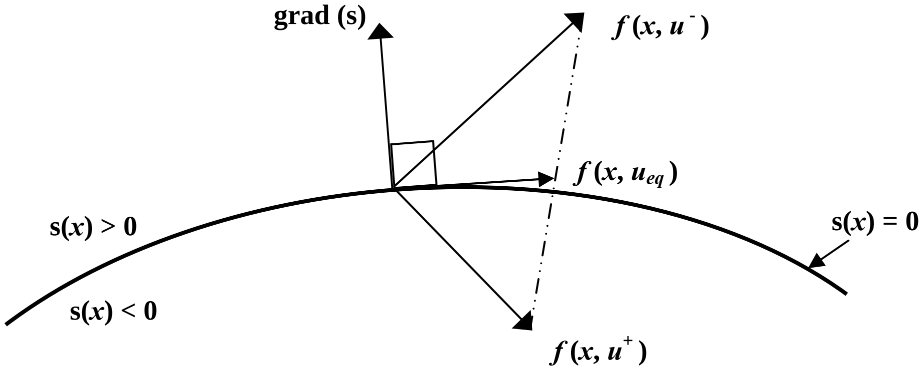


Fig.3.7 Equilibrium control [Filippov, 1988]

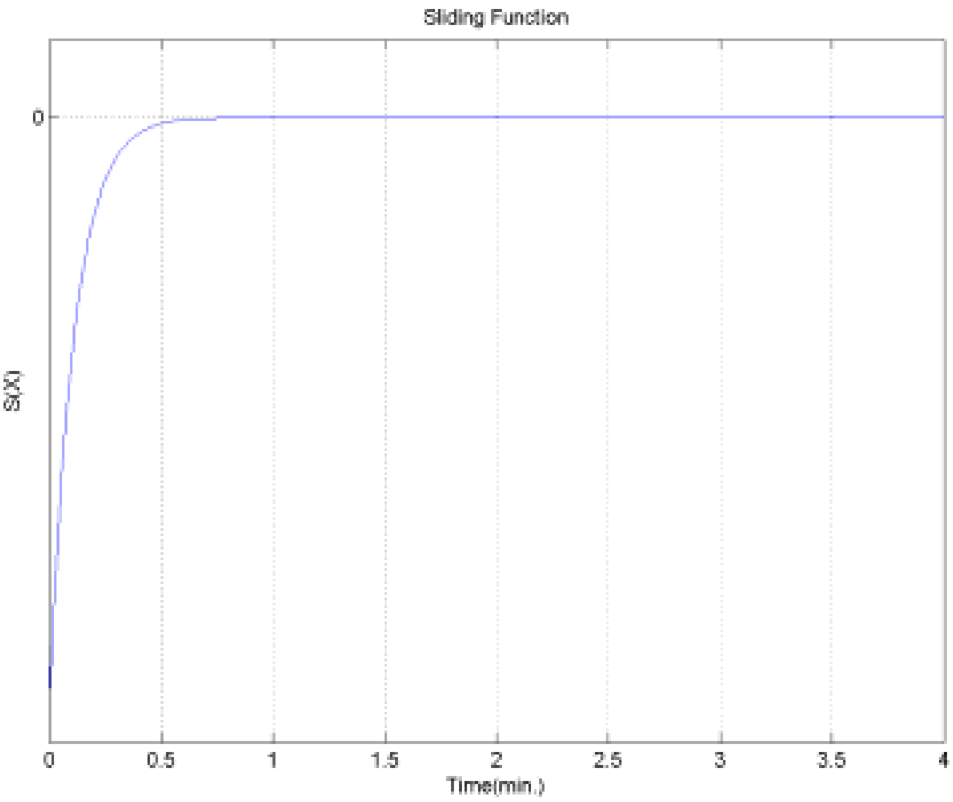


Fig.3.8 Simulation result_Sliding Function

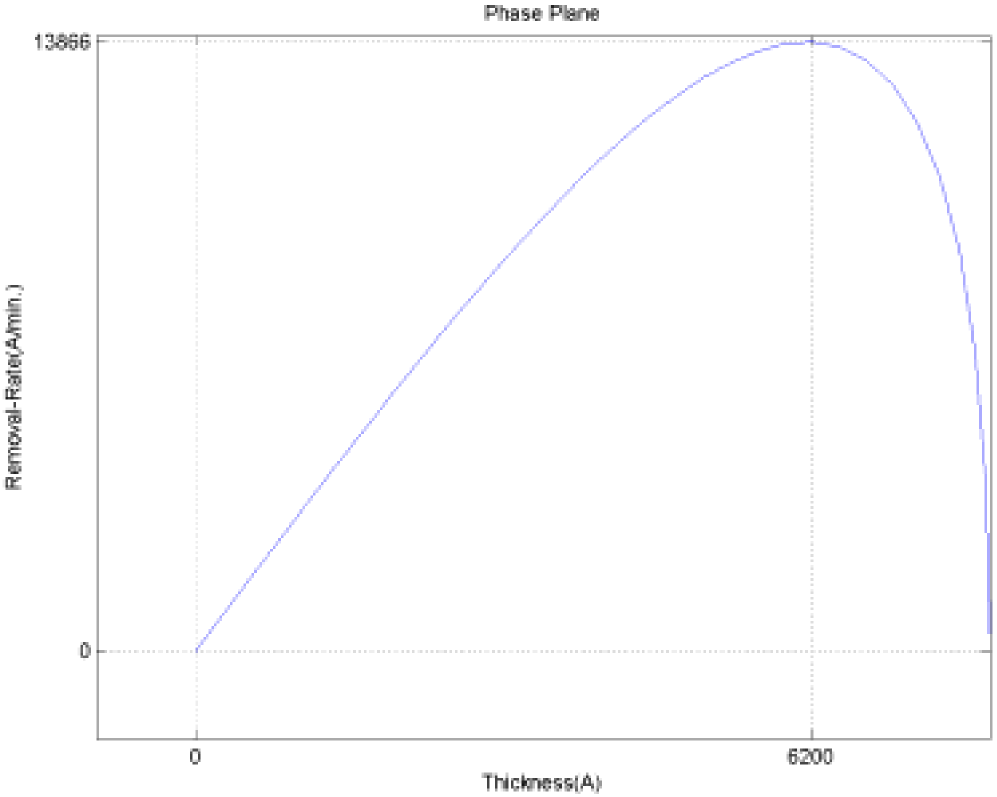


Fig.3.9 Simulation result_Phase-Plane Plot

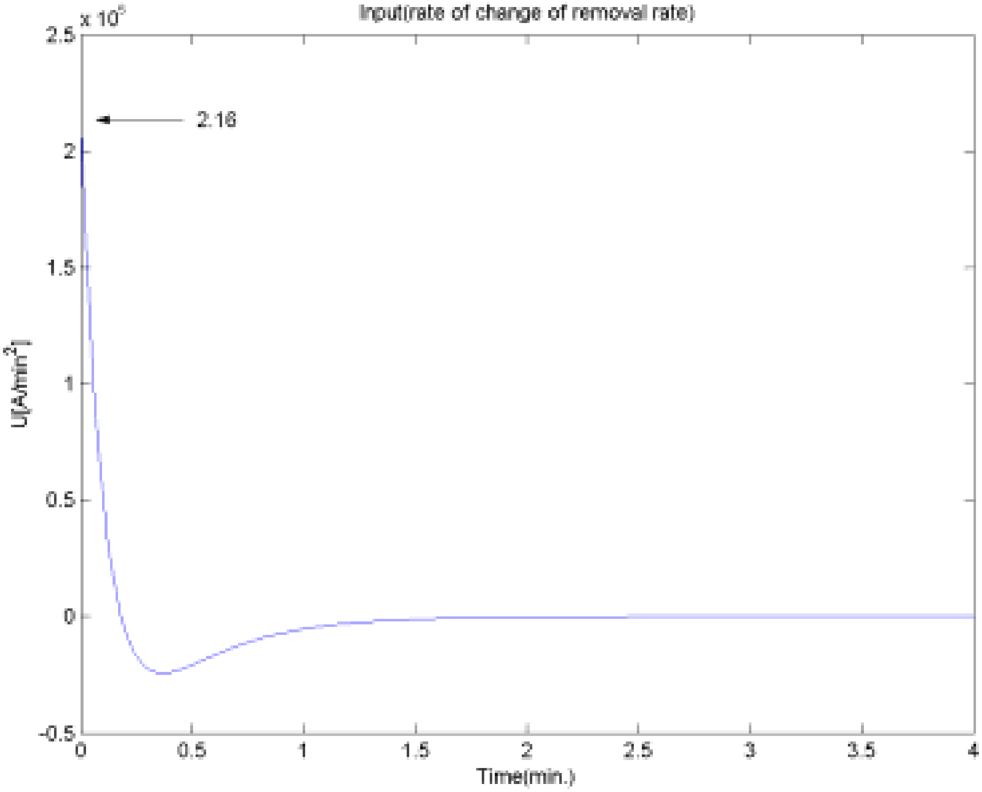


Fig.3.10 Simulation result_Control Input

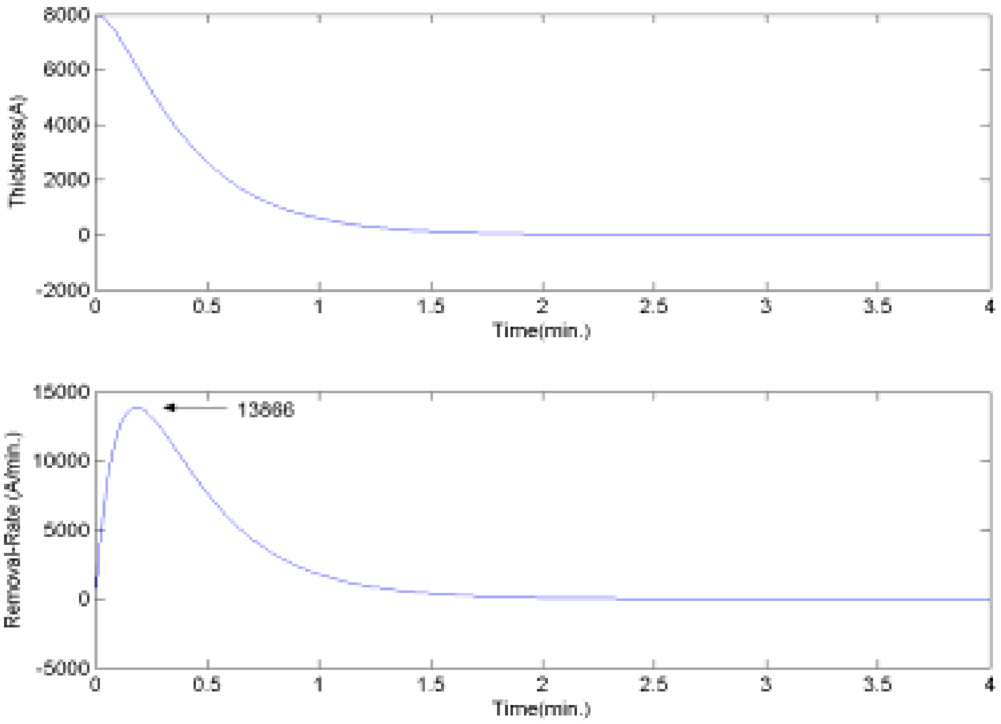


Fig.3.11 Simulation result_State Variables

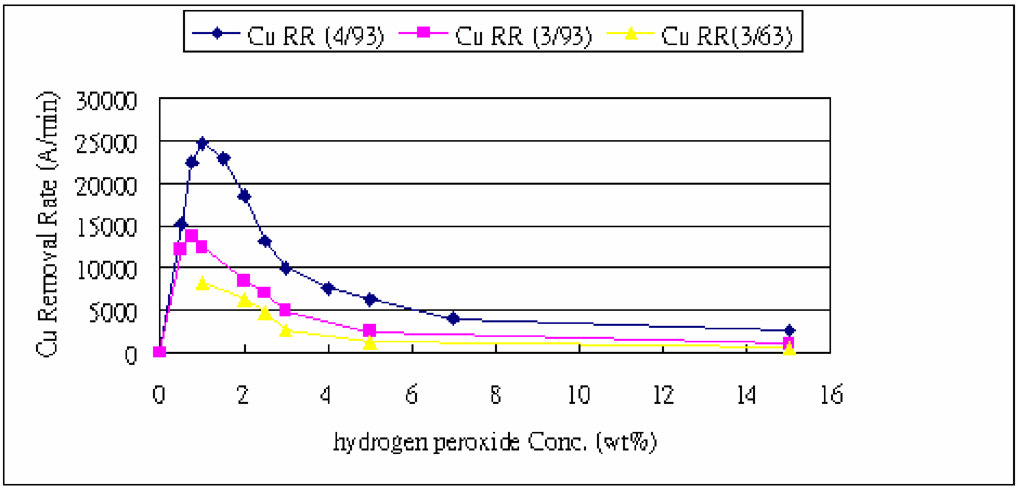


Fig.4.1 Removal rate (A/min) as a function of oxidizer concentration for different pressure and speed settings: P=4 p.s.i. and V=93 rpm, P=3 p.s.i. and V= 93 rpm, P=3 p.s.i. V=63 rpm. [39]

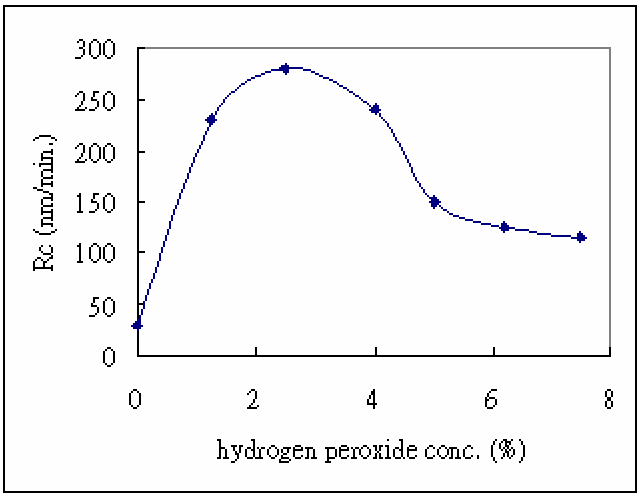


Fig. 4.2 Effect of H_2O_2 concentration on the value of Rc with specific slurries from Rodel [34]

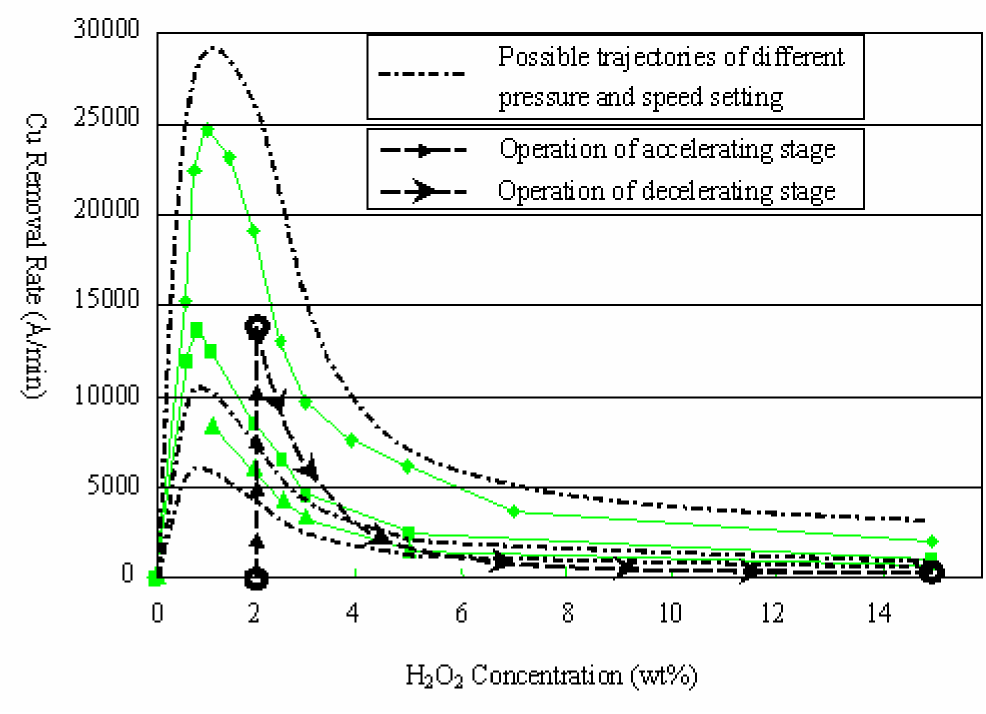
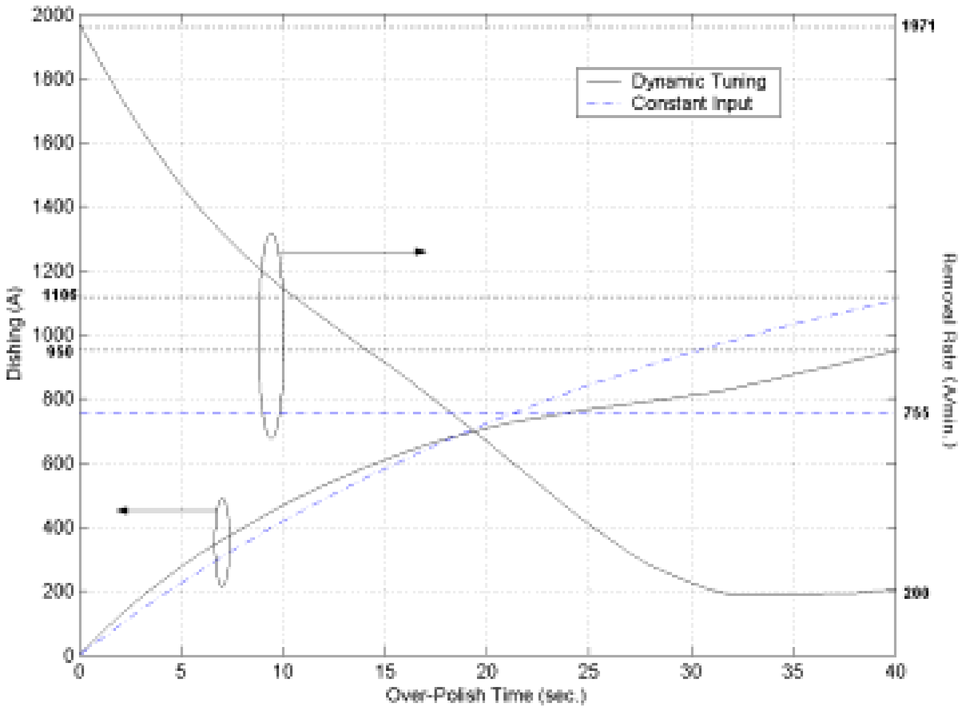
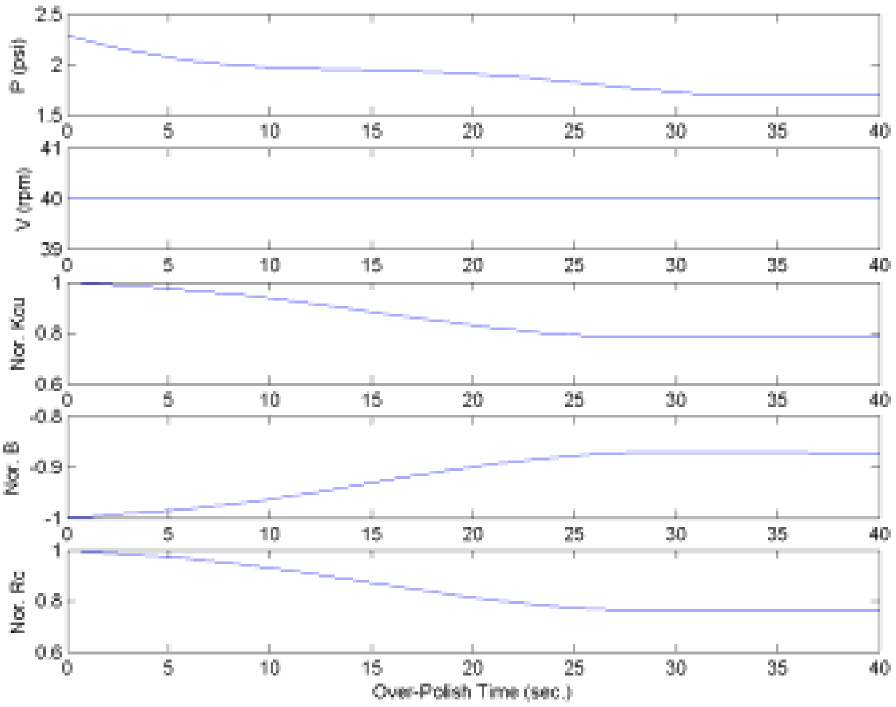


Fig. 4.3 Dynamic tuning operation of CMP process



(a)



(b)

Fig. 4.4 (a) Comparison of dishing between dynamic tuning and corresponding constant input (copper removal)

(b) Variations of parameters (Kcu, B and Rc are normalized forms)

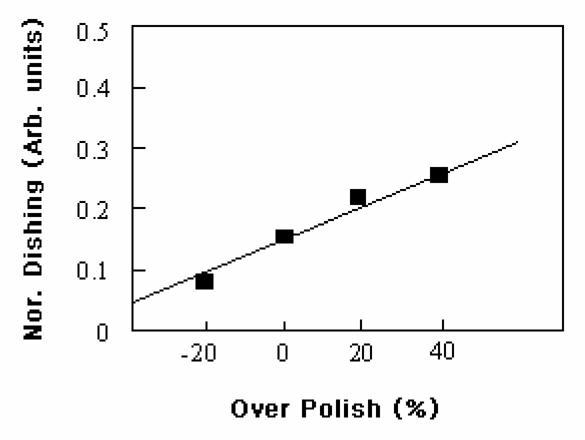
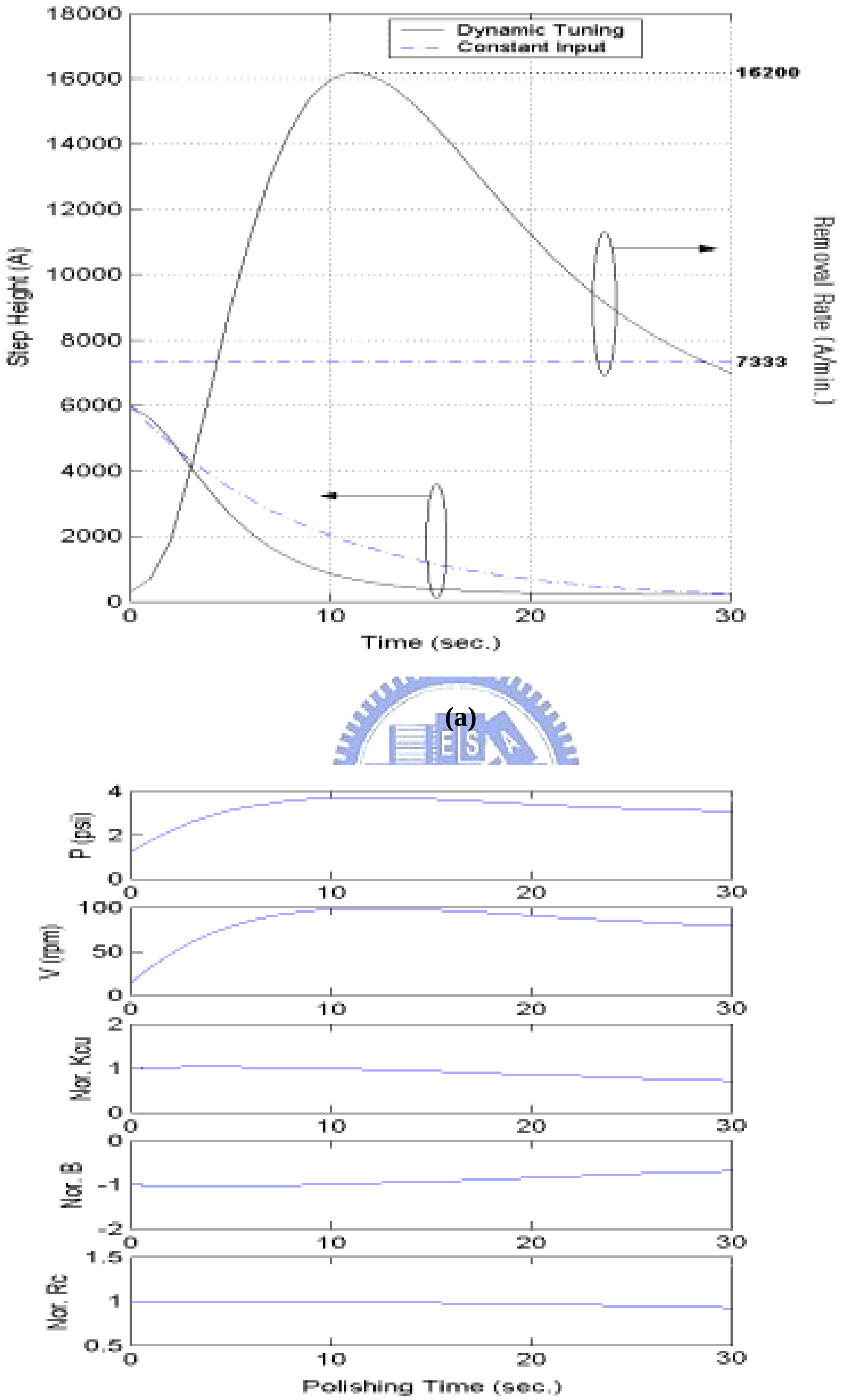


Fig. 4.5 Effect of over polish on the extent of dishing [23]



(a)

(b)

Fig. 4.6 (a)Comparison of step height reduction between dynamic tuning and corresponding constant input (removal rate)

(b)Variations of parameters (Kcu, B and Rc are normalized forms)

	Methods	Procedure	Characteristics
(1)	**Etchback**	Plasma etching or RIE after sputtering	*The procedure is easy to do.* ***The effect of etching is hard to control.***
(2)	**Film Growing**	Bias-sputtering or PECVD	*The film growing and planarization proceed at the same time.* ***Damage and particle contaminant are arisen easily.***
(3)	**Reflowing**	Reflowing after SOG (spin on glass)	*Low cost.* ***Film is unstable.***
(4)	**Selective Deposition**	Selective CVD	*Growing film only on the desired portion.* ***The effect is hard to control.***

Table 1.1 Comparison between common planarization techniques [26]

APPENDIX Ⅰ Stability of the SMC Controller [38]

After substituting (3.13) into (2.15), the system turns into

$$\dot{\boldsymbol{x}} = (\boldsymbol{A} - \boldsymbol{bk})\boldsymbol{x} + \boldsymbol{b}\,u' + \boldsymbol{d}(\boldsymbol{x},t) \tag{3.16}$$

where *u'* can be derived through applying the concept of equilibrium-control. Differentiate (3.12) and replace (3.16) into the equation

$$\dot{s}\Big|_{u'=u'_{eq}} = \boldsymbol{c}(\boldsymbol{A} - \boldsymbol{bk})\boldsymbol{x} + \boldsymbol{cb}\,u'_{eq} + \boldsymbol{cd}(\boldsymbol{x},t) = 0 \tag{3.17}$$

where u'_{eq} is solved as

$$u'_{eq} = -(\boldsymbol{cb})^{-1}\boldsymbol{c}(\boldsymbol{A} - \boldsymbol{bk})\boldsymbol{x} - (\boldsymbol{cb})^{-1}\boldsymbol{cd}(\boldsymbol{x},t) \tag{3.18}$$

Utilizing (3.11) and $\boldsymbol{s} = \boldsymbol{cx} = 0$ (means within the sliding-mode), (3.18) becomes

$$\begin{aligned} u'_{eq} &= -(\boldsymbol{cb})^{-1}\Omega\boldsymbol{cx} - (\boldsymbol{cb})^{-1}\boldsymbol{cd}(\boldsymbol{x},t) \\ &= -(\boldsymbol{cb})^{-1}\boldsymbol{cd}(\boldsymbol{x},t) \end{aligned} \tag{3.19}$$

Substitute (3.19) into (3.16):

$$\begin{aligned} \dot{\boldsymbol{x}} &= (\boldsymbol{A} - \boldsymbol{bk})\boldsymbol{x} + \left(\boldsymbol{I}_n - \boldsymbol{b}(\boldsymbol{cb})^{-1}\boldsymbol{c}\right)\boldsymbol{d}(\boldsymbol{x},t) \\ &= (\boldsymbol{A} - \boldsymbol{bk})\boldsymbol{x} + \left(\boldsymbol{I}_n - \boldsymbol{b}(\boldsymbol{cb})^{-1}\boldsymbol{c}\right)\boldsymbol{b}_r\boldsymbol{d}_r(\boldsymbol{x},t) \end{aligned} \tag{3.20}$$

where $\boldsymbol{b}_r\boldsymbol{d}_r$ represents the mismatched part of the disturbance. Note that the disturbance can be represented as

$$\boldsymbol{d}(\boldsymbol{x},\boldsymbol{t}) = \boldsymbol{bd}_m(\boldsymbol{x},\boldsymbol{t}) + \boldsymbol{b}_r\boldsymbol{d}_r(\boldsymbol{x},\boldsymbol{t}) \tag{3.21}$$

where $\boldsymbol{bd}_m$ represents the matched part of the disturbance and $\boldsymbol{b}_r\boldsymbol{d}_r$ is the mismatched part of the disturbance. Next, (3.20) multiplied by $\boldsymbol{v}$ and $\boldsymbol{c}$ and two equations can be derived as

$$\boldsymbol{v}\dot{\boldsymbol{x}} = \boldsymbol{Jvx} + \boldsymbol{v}\left(\boldsymbol{I}_n - \boldsymbol{b}(\boldsymbol{cb})^{-1}\boldsymbol{c}\right)\boldsymbol{b}_r\boldsymbol{d}_r(\boldsymbol{x},\boldsymbol{t}) \tag{3.22}$$

and

$$\boldsymbol{c}\dot{\boldsymbol{x}} = \Omega\boldsymbol{c}\boldsymbol{x} = 0 \tag{3.23}$$

From Eq. (3.23), it is obvious that the virtual eigenvalue does not have any influence within the sliding-mode. The stability of the sliding-mode can be judged from Eq. (3.22). Neglecting the effects of the mismatched disturbance $\boldsymbol{b}_r\boldsymbol{d}_r$ [9], as long as the selection of elements of J is correct, i.e. to ensure the eigenvalues of J are all negative, the system within the sliding-mode will be stable.

---

[9] Actually, there is not any controller/control-law can eliminate the effects of mismatched disturbances entirely. Neglecting the effects of the term of mismatched disturbance is reasonable only when the magnitude of mismatched disturbance is small compared with that of matched disturbance.

APPENDIX Ⅱ Operation Profiles Setting

The verification can be separated into two parts, over-polish (for copper dishing) and under-polish (for copper step-height). However, the operation profiles' setting is global and preliminary work. The dishing model (2.9) and the step-height model (2.11) will be employed to verify the "dynamic tuning" operation strategy.

To set the operation profiles of parameters, P, V and Rc, two rules must be followed: the variation manner and the bounds. In the accelerating stage (Fig.4.3), P and V must increase continuously and Rc keeps on maximum value(due to the constant oxidizer concentration), 300 nm/min. Note that P and V have to reach the upper limits (3.5 p.s.i., 95rpm) while the accelerating stage is finish. In the decelerating stage (Fig.4.3), P, V and Rc must decrease gradually. Note that the final values (lower limits) are 1.7 p.s.i., 40 rpm and 175 nm/min (corresponding to 5% oxidizer concentration), respectively.

As the fact shown in Fig.4.3, the initial value of oxidizer concentration is set at 2% (corresponding Rc is 300 nm/min) and keeps constant until the maximum removal rate is reached. To obtain the other exact values of the parameters, the data of Fig. 4.1 is used to solve Eq. (2.8). (three equations and three unknowns) From the calculations, the values of K, B and Rc of Eq. (2.8) can be derived at specific oxidizer concentrations. Note that the other values which are not corresponding to these oxidizer concentrations are obtained by Linear Interpolation Method.[10] After collecting the values of factors, P and V are the only adjustable parameters in Eq. (2.8). To fit the removal rate curve shown in Fig. 3.11 by tuning P and V of Eq. (2.8) with these known factors and follow the strategy shown in Fig. 4.3, the variations of P and V can be settled down.

It should be mentioned that these values are assigned at every second. These value sets are worked extra for linear (continuous) form by linear regression. The detailed results are shown below. Note that only the data of over-polish stage is displayed and there will be the same form at

---

[10] It is clear that the factors, K, B and Rc, will be different at different oxidizer concentrations. This calculation is to derive the variations of the factors as the oxidizer concentration varies.

under-polish stage.

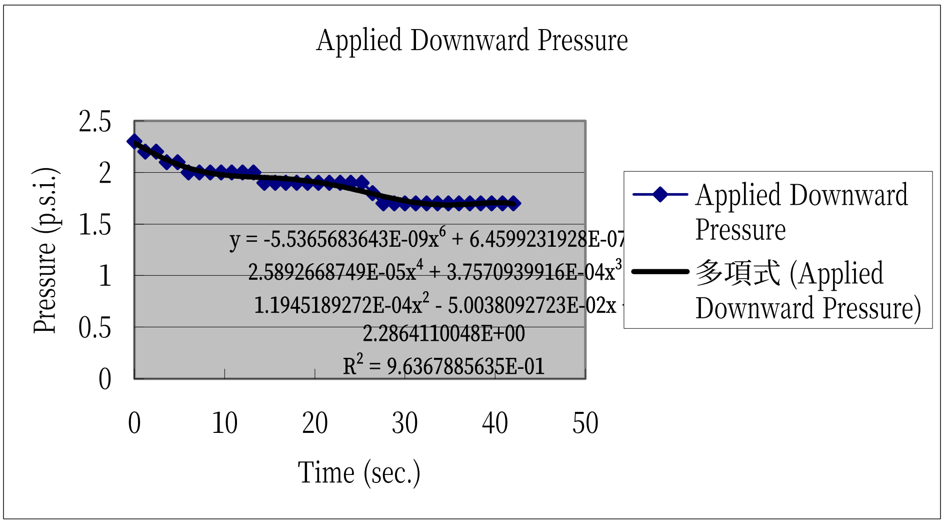


Fig.A.1 Linear regression of applied downward pressure during over-polish

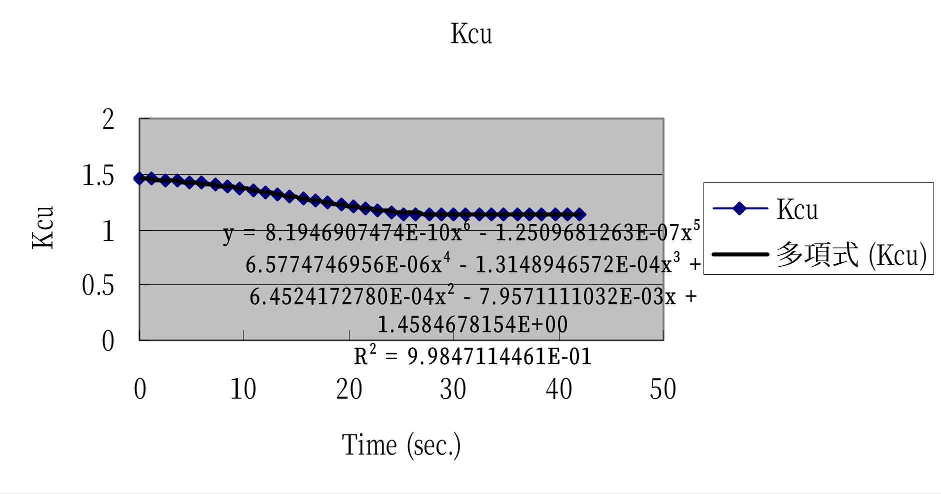


Fig.A.2 Linear regression of factor *K* (Kcu) during over-polish

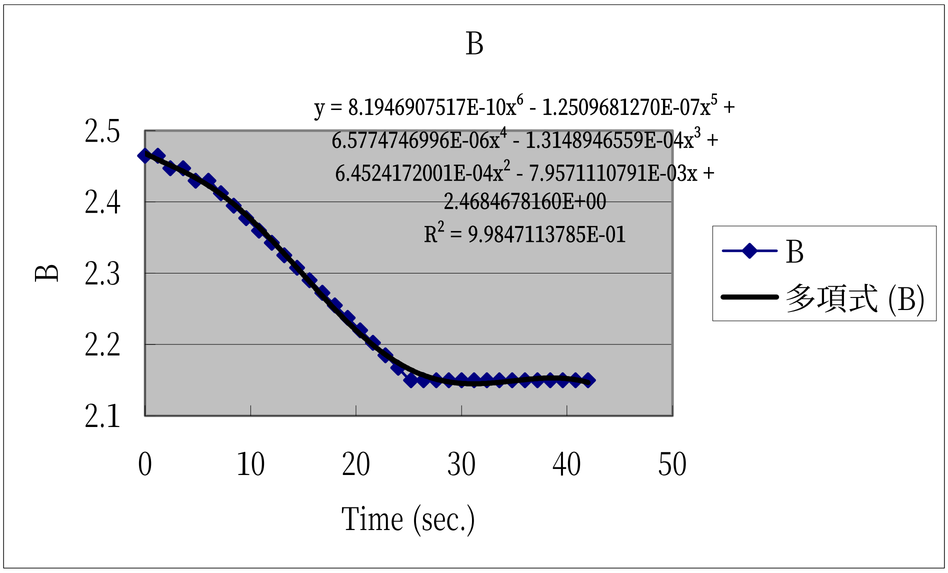


Fig.A.3 Linear regression of factor *B* during over-polish

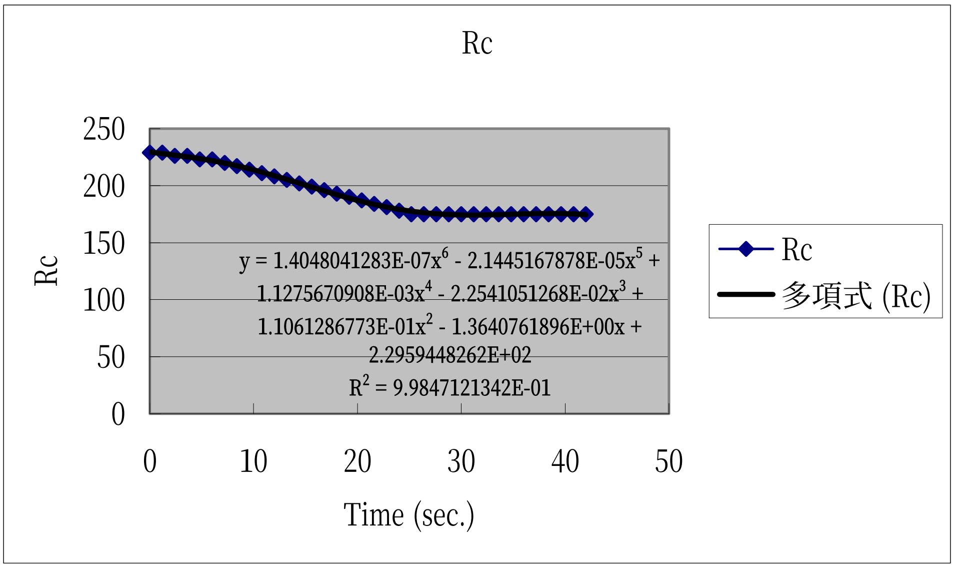


Fig.A.4 Linear regression of factor *R*c during over-polish

These equations of linear regression are then employed to analyze/verify the ability of “dynamic tuning” operation strategy by MatLab software package.