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Dynamic tuning of chemical–mechanical planarization operation via sliding-mode theory

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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 of control for 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. 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.

Keywords: Dynamic tuning; Chemical mechanical planarization; Dishing

1. Introduction

Chemical–mechanical planarization (CMP) was developed during the early 1980s. At that time, multilevel interconnect technology was being pushed to the limits of circuit density and performance. Therefore, a better planarization technique was needed that would allow smaller geometries for metal linewidth and spacing (wiring pitch), vias and contacts [1]. Among many planarization techniques, CMP is a widely accepted technique to provide a globally planarized surface for microelectronic wafer fabrication. In recent years, the device levels and density have increased continuously; however, these densities have now brought resistance–capacitance (RC) time delays to a level that can appreciably slow circuit speeds and thus impede further advances in circuit performance. The emerging trend in LSI technology is therefore toward the replacement of aluminum or aluminum alloys by copper as the metal wiring material

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because of its low resistivity and high electromigration resistance [2–4].

Several research efforts have been reported on modeling the CMP of interlevel dielectrics (ILD), shallow trench isolation (STI), and tungsten. However, the CMP processes for copper damascene interconnects indicate unique characteristics and more complicated polishing mechanisms than conventional ILD, STI and tungsten CMP. The translation of tungsten or ILD CMP to copper CMP is not simply a change in materials [5]. Thus optimized CMP becomes an important objective. Despite recent advances in CMP, some manufacturing concerns associated with successful implementation of CMP remain to be overcome [6,7]. The physical interactions among the wafer, slurry and pad make the copper CMP very sensitive to operating conditions [6]. Most of the research work on CMP is focused on detailed removal mechanism and slurry chemistry [2,3, 8–11]. Much less work has been done on the operational aspects of CMP, especially the process control side of CMP operation. One of the most important variables: the setting of removal rate for the planarization process was studied by Chiu et al. [12]. In their research, an analogy between the "Soft Landing" of a spacecraft and the CMP process was established and the optimal time control law was used. However, from the viewpoint of control engineering, optimal control is not so practical in real world. Therefore, a robust operation region of parameters and an incorporated operation strategy (three strategies) were proposed by Kao et al. [6]. To further improve the performance of CMP process, a more feasible method namely sliding-mode control will be employed to set the operation profile of CMP process through "Dynamic Tuning" method to enable the CMP process more close to soft landing.

Variable structure control (VSC) with sliding-mode control (SMC) was first proposed and elaborated in the early 1950s in the Soviet Union by Emelyanov and several coresearchers. In their pioneer works, the plant considered was a linear second-order system modeled in phase variable form. Since then, VSC has developed into a general design method for a wide spectrum of system types [13]. 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". It should be mentioned that the system performance will not be influenced by any matched disturbances, and the control strategy provides an effective and robust control for certain classes of nonlinear systems subject to modeling uncertainties in the sliding mode. One of the 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 peculiar system characteristic is claimed to result in superb system performance which includes insensitivity to parameter variations, and complete rejection of matched disturbances. To this date, some theoretical problems of VSC are investigated deeply and comprehensively; some new synthesis methods of VSC are presented and are extended to many kinds of systems, thus the distance between theory and practice is reduced significantly. This control method is used in more and more systems because of its inherent advantages [14].

In this paper, the problem statement will be presented in Section 2. In Section 3, the design of SMC controller (setting operation profile via SMC) and simulation results will be shown. The discussions will be presented in Section 4 followed by the conclusion.

2. Problem statements

2.1. Dynamic tuning (in situ/within-wafer control)

Recently, the CMP systems have been widely studied and applied to the wafer manufacturing in semiconductor industry. Most of people who are devoted to do research on the CMP process focus their efforts on the process improvement, i.e. finding the perfect composition of process parameters, namely, "Golden Recipe." Nevertheless, it can not be realized in real world scenarios because the existence of disturbances, noise, and uncertainty. The inherent characteristics/flaws 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?

In the CMP process, process control covers consumables and equipment tool parameters to improve performance. 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 [15]. Besides, the method of run-to-run control is based on statistic data of process performance. As the requirement of degree of planarization increases, within-wafer CMP control is necessary. Less effort has been done on this subject except the works of Chiu et al. [12]. In the same way, from operational aspect of CMP process, within wafer control will be attempted in this paper. For control system design, a dynamic model which is not too complex and can describe the system behavior reasonably is necessary. Unfortunately, unless the conceptual description used in the works of Chiu et al. [12], there is not any dynamic model with physical meanings of CMP process among the research efforts which have been reported on modeling the CMP of copper, ILD or STI. In the following section, some proposed mechanism/model by Chiu et al. [12] will be shown to support and clarify the operation aspect of CMP process control.

2.2. Conceptual description of CMP process (dynamics)

In general, the dynamic equation of the copper removal can be described as [12]

$$\frac{\mathrm{d}\tilde{h}}{\mathrm{d}t} = -R, \tag{1}$$

$$\frac{\mathrm{d}R}{\mathrm{d}t} = u, \tag{2}$$

where $\tilde{h}$ represents the thickness of copper to be removed, R is the removal rate and u is the system input. For convenience, (1) and (2) are further changed into the following state equation:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{b}u + \boldsymbol{d}(\boldsymbol{x}, t), \tag{3}$$

where

$$\boldsymbol{x} = \begin{bmatrix} \tilde{h} & R \end{bmatrix}^{\mathrm{T}} \in R^2, \quad \boldsymbol{A} = \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix},$$

$$\boldsymbol{b} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad \text{and} \quad \boldsymbol{d} = \begin{bmatrix} -0.1t \\ -0.1 \end{bmatrix}.$$

Note that the initial value of the system $\boldsymbol{x}(0) = \begin{bmatrix} 8000 & 0 \end{bmatrix}^{\mathrm{T}}$. The selection of disturbances is based on the investigations of run-to-run controller of CMP, just like the works of 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. In Section 3, the controller design and some simulation results will be made based on this model.

2.3. Mechanism/model with physical meanings

Among the research of CMP process, a detailed mechanism of chemical effects can not be derived yet, but some combined model are tried to include the chemical effect and mechanical effect [4,21]. In this work, the equation proposed by Luo et al. [4] will be employed, that is

$$R = (KP + B)V + R_{\mathrm{C}}, \tag{4}$$

where R denotes the polish rate, K is proportional constant, P and V are applied downward pressure and linear velocity of the wafer relative to the polishing pad, respectively. Based on Preston equation, two additional terms were included to represent polish rate data better. R_{C} was inserted to represent the purely chemical reaction of the slurry during the copper CMP process and B represents the greater dependence of the polish rate on the relative velocity. Note that these constants were determined by the least squares procedure of experimental data and the unit of R_C is the same to removal rate (polish rate) R.

Although many technical problems of the metal CMP process have been solved, a major remaining issue is the dishing of the metal line. Dishing may cause many drawbacks, like an increased resistance, a higher current density and lower planarity. Consequently, dishing reduces the speed of signal propagation through the circuit, and threatens the reliability of the metal line at high current densities. Recently, dishing has been categorized as a must-be-controlled parameter in CMP [20,22]. In the work of Nguyen et al. [20,22], a mathematical model of dishing phenomenon was established. That model accounts for the dependence of dishing on the feature size and polish time using the morphology and the properties of the polishing pad and process parameters. In this work, the other copper dishing model which was proposed by Lin [5] will be employed to verify dynamic tuning method, that is

$$h_D = (S-1)PH\xi \ln\left(\frac{w}{w_0}\right)\left(1-e^{-K_{Cu}EVt}\right), \tag{5.1}$$

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; h_{S0} is the initial step height; 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

$$S = \frac{R_{Cu}}{R_{Ta}} = \frac{K_{Cu}}{K_{Ta}}. \tag{5.2}$$

Note that (4) and (5) are both derived based on Preston equation; (5) was established mainly via the conformity (compression) of pad, i.e. this model attributes planarization to properties of wafer-pad contact. Some proofs will be mentioned in the following sections via the above equations which have been established and verified by other researchers.

2.4. Control objective

From Eq. (5), it is clear that the process parameters, like P and V, play important roles in the forming of dishing in addition to the feature size, polish time and properties of pad. One of the methods of reducing critical problems occurred in CMP process is to optimize these process parameters. In this work, one new 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.

The experimental data of Wijekoon et al. [18] indicate that at a constant speed (or pressure) the dishing varies linearly with pressure (or speed). To integrate these conclusions, it is clear that the defect of dishing can be further reduced if the formulation of profile of operation parameters can be set appropriately in bulk-polish and over-polish stages. However, the higher loads of process parameters (larger values of P and V) will increase the removal rate in (4). To maintain acceptable throughput and performance, the operation scheme has to be worked out. Note that it is not sufficient to improve the performance by adjusting mechanical loads (P and V). The chemical load (represents oxidizer concentration in this paper) is an important factor, too.

3. CMP operation via SMC

3.1. Design

From Chen and Chang [16], to design a controller via SMC, the procedure can be concluded into two steps, that is: first, to specify a sliding function $s(\boldsymbol{x})$ which will switch the system to move toward control goal while the system is in the sliding mode; Second, to determine the control input u

which will force the system to hit the sliding surface and generate the sliding mode in a finite time. 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 SMC and Integral SMC and so on. In this work, a convenient and powerful method which is also proposed by Chen and Chang [17], namely, Virtual eigenvalue method is used in controller design.

3.2. Simulation

In SMC design, the first thing that has to be addressed is the convergence of the sliding function. In Fig. 1, it is clear that the system reaches the sliding-mode ($s=0$) in a finite time, about 0.6 min. This result represents that the design is successful, i.e. the control law works. Additionally, to visualize whole performance of the system, phase–plane analysis is a powerful tool. Fig. 2 shows the phase–plane sketch 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 shows the plot of control input which also varies smoothly. The last one is Fig. 4, and it shows time history of removed copper thickness and (copper-) material removal rate during CMP process separately. In Fig. 4, the more detailed profile of these two important parameters are presented. The CMP process will finish in about 1.7 min (102 s), and the removal rate will decrease to about zero at the same time.

3.3. Control input concretization

To clarify the control input *u,* the mechanism which is presented in Section 2.3 is repeated here. From the system dynamic Eq. (3) and the material removal model (4), the control input is shown by differentiating (4), and (3) can be formulated as

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{U} + \boldsymbol{d}(\boldsymbol{x}, t), \tag{6}$$

where

$$\boldsymbol{x} = \begin{bmatrix} \tilde{h} & R \end{bmatrix}^{\mathrm{T}} \in R^2, \quad \boldsymbol{A} = \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix},$$

$$\boldsymbol{B} = \begin{bmatrix} 0 & 0 \\ KV & KP + B \end{bmatrix}, \quad \boldsymbol{U} = \begin{bmatrix} \frac{\mathrm{d}P}{\mathrm{d}t} & \frac{\mathrm{d}V}{\mathrm{d}t} \end{bmatrix}^{\mathrm{T}}, \quad \boldsymbol{d} = \begin{bmatrix} -0.1t \\ -0.1 \end{bmatrix}$$

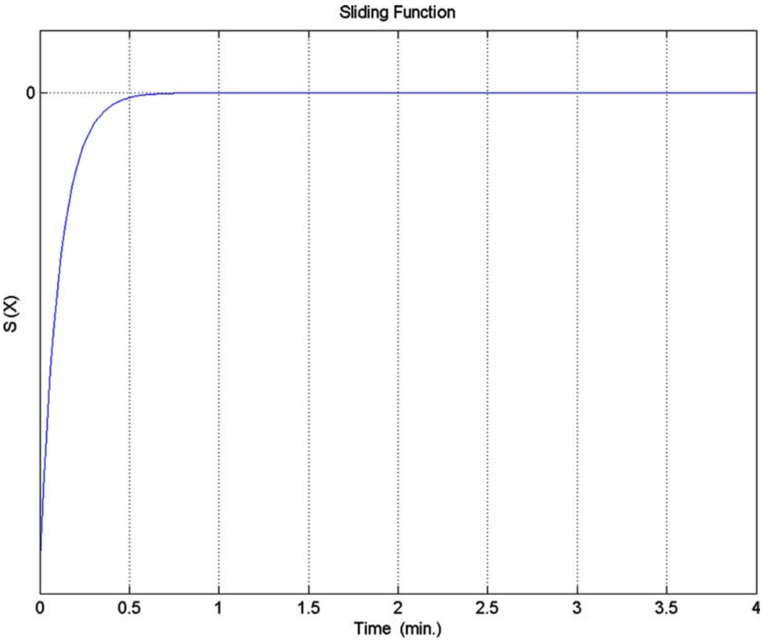

Fig. 1. Sliding function.

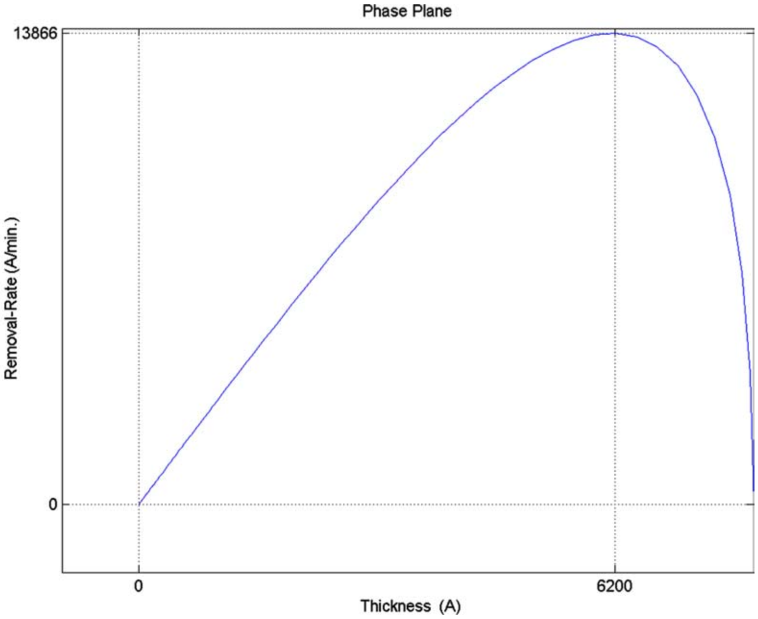

Fig. 2. Phase–plane plot.

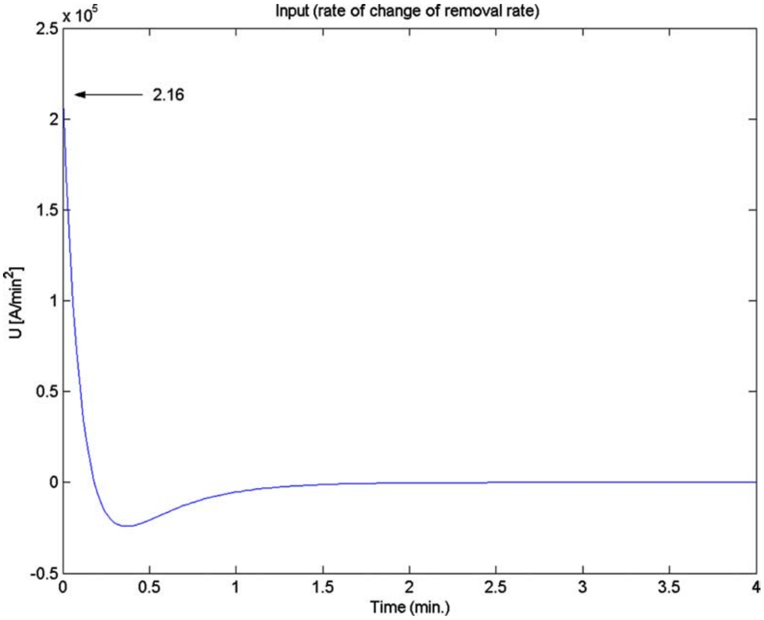

Fig. 3. Control input (the maximum value is equal to 216,000 Å/min^2).

and the initial value of the system is $\boldsymbol{x}(0)=[8000\ 0]^T$. The elements of $\boldsymbol{U}$**,** $\frac{\mathrm{d}P}{\mathrm{d}t}$ and $\frac{\mathrm{d}V}{\mathrm{d}t}$, can be transferred to the design/actuators of equipment. Note that constraints of applied downward pressure and linear relative velocity are not considered in (6). 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 Kao

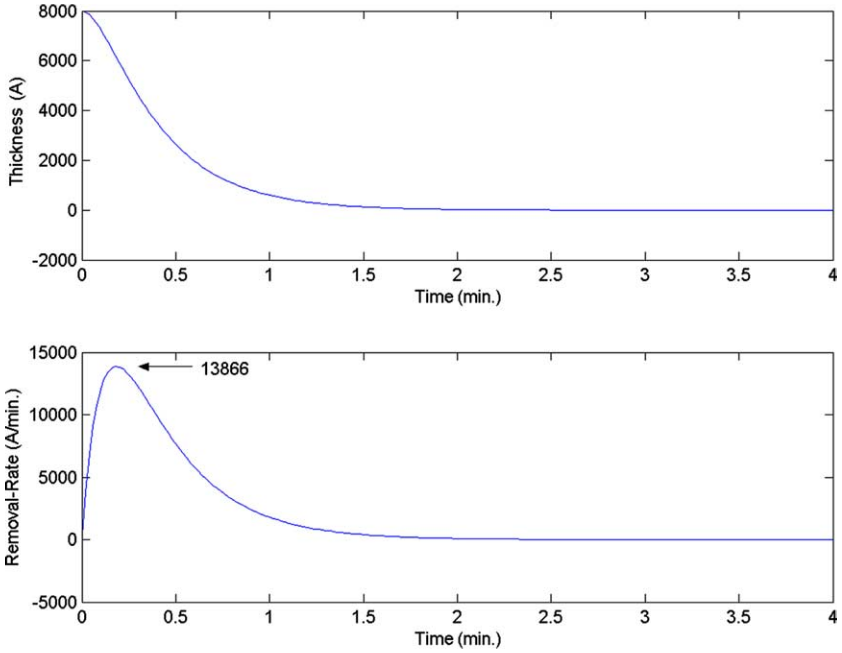

Fig. 4. Realistic trajectory (the maximum removal rate is equal to 13,866 Å/min).

et al. [6], some experiments were carried out over a wide range of oxidizer concentration. They indicate that the copper removal rate of copper CMP will follow a specific trend as the concentration increases. Fortunately, the trend, shown in Fig. 5, is similar to the operation profile which is shown above (Fig. 4). 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

$$\boldsymbol{U} = \begin{bmatrix} \frac{\mathrm{d}P}{\mathrm{d}t} & \frac{\mathrm{d}V}{\mathrm{d}t} & \frac{\mathrm{d}Rc}{\mathrm{d}t} \end{bmatrix}^{\mathrm{T}} \quad \text{and}$$

$$\boldsymbol{B} = \begin{bmatrix} 0 & 0 & 0 \\ KV & KP + B & 1 \end{bmatrix}.$$

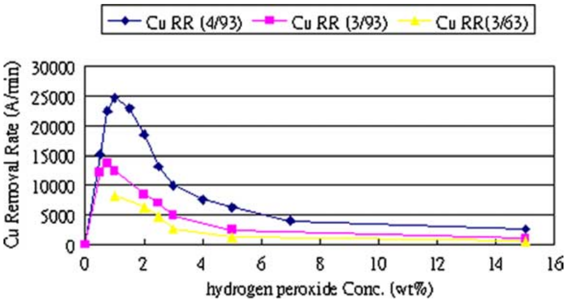

Fig. 5. Removal rate (Å/min) as a function of oxidizer concentration for different pressure and speed settings: $P=4$ p.s.i. and $V=93$ rpm; $P=3$ p.s.i. and $V=93$ rpm; $P=3$ p.s.i. and $V=63$ rpm [6].

Note that the relation between oxidizer concentration and R_C (with specific slurry) was proposed by Luo et al. [4], as shown in Fig. 6. Note that reduction of removal rate at higher H_2O_2 concentration in both figures, Figs. 5 and 6, is 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 Steigerwald et al. [11] and Kao et al. [6], 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 Nguyen et al. [9]. They revealed that less dishing would

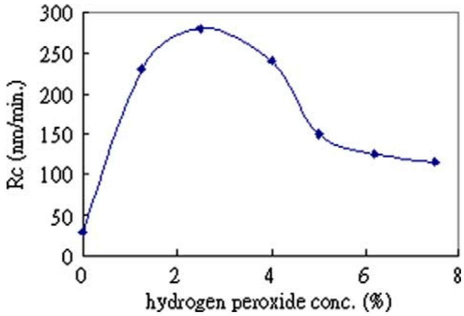

Fig. 6. Effect of H_2O_2 concentration on the value of R_C with specific slurries from Rodel [4].

be obtained from higher oxidizer concentration in the slurry.

To integrate the research achievements [6,8,9,11,19,20,22], the control inputs integration of control inputs described must be coordinated in harmony with each other. In other words, Section 2.4 can be implemented with these considerations of chemical effects. The dynamic tuning operation of CMP process is then coordinated, as shown in Fig. 7. Fig. 5 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. 7 means the increasing of removal rate (before about 0.2 min of second plot of Fig. 4). 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. 7, the values of operation parameters, P, V and R_C, can be assigned with 3.5 p.s.i., 93 rpm, 300 nm/min, respectively (this set of parameter represents the constraint which is assigned in this work). 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 will cause less dishing from the results shown by Nguyen et al. [9] because a more effective passivation layer is formed with higher oxidizer concentration and protects the recess areas.

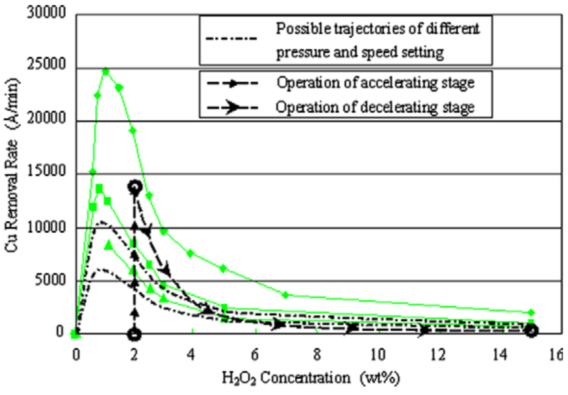

Fig. 7. Dynamic tuning operation of CMP process.

3.4. Verification

From the descriptions above, it is obvious that operation profile can be set in many ways if upper limit is the only one constraint for each input. Therefore, a new problem will be raised, what is the best tuning/operation profile? It will not be discussed in this paper. Here, one possible operation profile will be chosen to verify the effect of dynamic tuning operation of CMP process. 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 1.7–3.5 p.s.i., 40–95 rpm and 2–5%, respectively. Note that relative velocity is transferred to platen/carrier rotational speed.

The dishing model (5) is used to verify the ability of dynamic tuning method and the result is shown in Fig. 8. It is clear that dishing is suppressed from

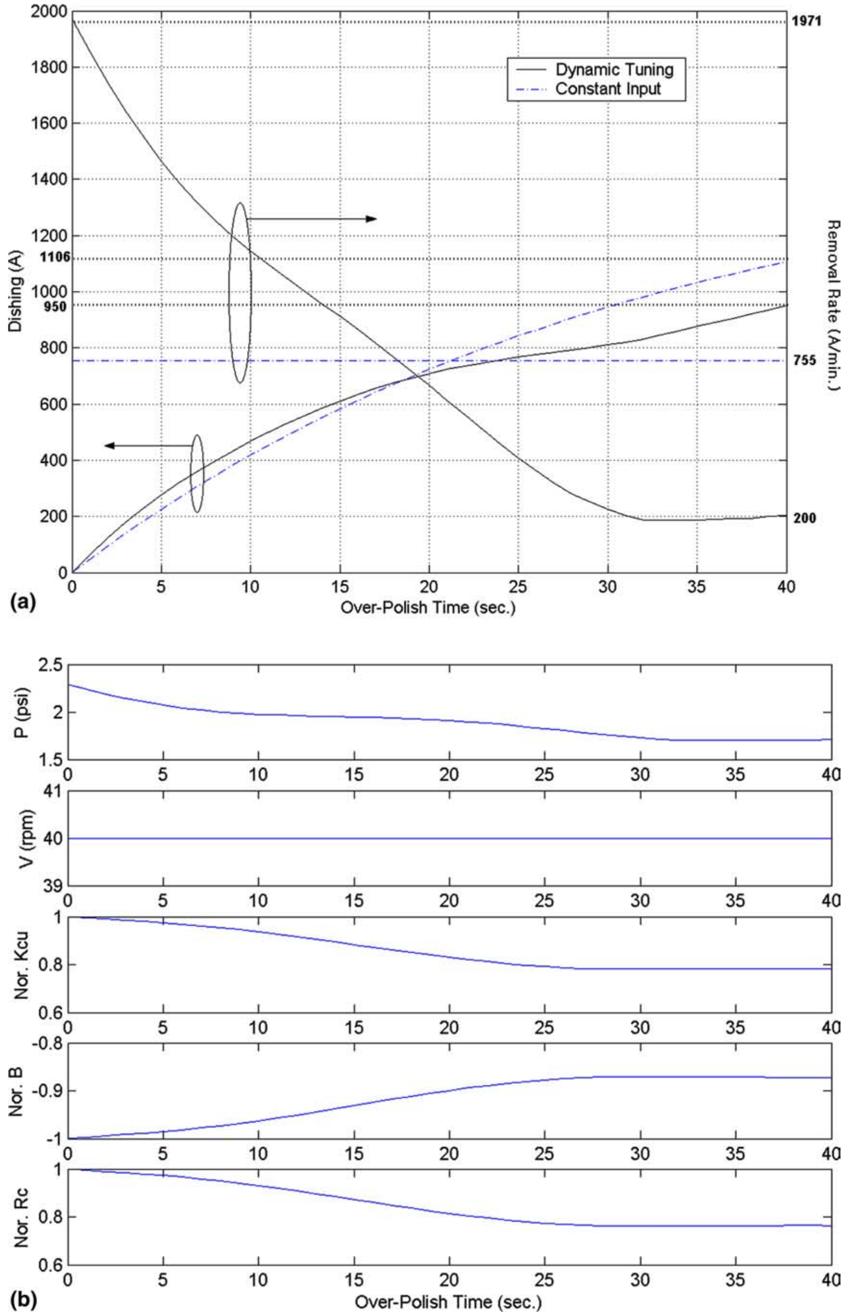

Fig. 8. (a) Comparison of dishing between dynamic tuning and corresponding constant input (copper removal). (b) Variations of parameters (K_{cu}, B and R_C are normalized forms).

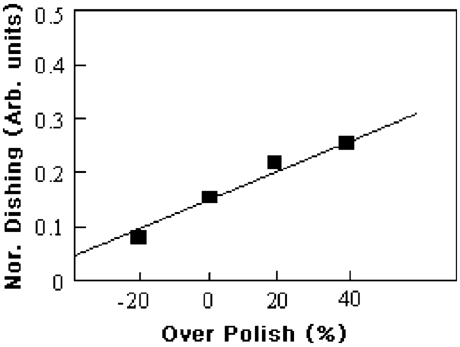

Fig. 9. Effect of over polish on the extent of dishing [18].

1106 to 950 Å in Fig. 8(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. 8(b) displays the sketch of variations of parameters during the over-polish stage. Note that the variations of K_{cu}, B and R_{C} are caused by changing the oxidizer concentration.

To complete simulate the strategy of dynamic tuning, the step height reduction (bulk copper polishing) must be included in. But the validity of the available model of step height reduction proposed by Lin [5] and Fu and Chandra [8] are not consistent with the experiment data proposed by Wijekoon et al. [18], as shown in Fig. 9. The figure reveals that the dishing will exist before the end of process and linearly increases with overpolish/time. This experiment data points out that initial value of dishing will not be zero (i.e. non-zero step height will exist before transition to dishing). However, the step height in the models by Lin and Fu will decrease with time exponentially during bulk copper polishing stage. Both models [5,8] conflict with the experiment data [18]. Therefore, the verifications will be done by some experiments in future research. The illustration of the difference of surface height in the bulk-polish stage and over-polish stage is shown in Fig. 10 (regardless of oxide erosion).

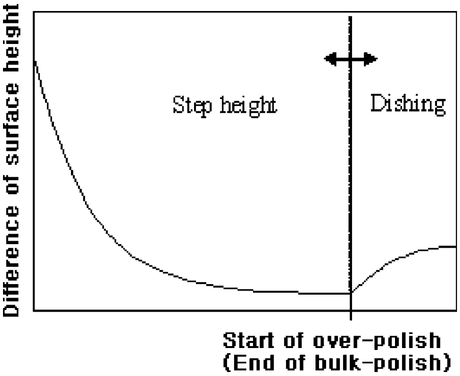

Fig. 10. Illustration of the difference of surface height in the whole process.

4. Discussion

In CMP process, the chemical and mechanical effects have to be operated in harmony for maintaining acceptable performances and throughput. The procedure is a 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.

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 Section 5, 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.

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. 4). 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 [12,18,19]. 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 [8,9,20]. 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, that is, 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. 7). (This point is shown in the difference between Fig. 8(a) and 4.) In other words, Dynamic Tuning operation approach operating 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.

5. 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 done 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 operation provides a new aspect of CMP operation and it might be a candidate for within wafer control in CMP process. 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.

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