The Large Size Wafer Study of Chemical Mechanical Polishing

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ABSTRACT

Chemical mechanical polishing CMP is currently the only method that can offer a complete planarization VLSI production technique. This paper uses a CMP process simulation machine and applies gray scale image method to acquire a CCD image which is processed by software Optimas treatment. This method can estimate the amount and distribution of polishing slurry injected between the wafer and the polishing pad. With this technique, this paper proposes an optimal slurry injection study for CMP large-sized wafers. The experiment shows that the optimal slurry injection position for 12-inch wafers is IP<30%. For injection amount at low speeds, Q=100-150 ml/min is suggested while at high speeds, Q>200 ml/min can be used. Moreover, how the changes in distance between the wafer and the polishing pad center to affect gray scale and non-uniformity are studied. Experimental data indicate that when the wafer edge extends beyond the center of the polishing pad, this can increase polishing pad rotation speed and achieve the removal rate of those, which do not extend beyond the central periphery. However, extending beyond the center will affect the transmission efficiency of the slurry. Thus, it is suggested that the optimal distance extending from the center should be R_{we}<3cm.

Keywords: chemical mechanical polishing, slurry, removal rate, non-uniformit

大尺寸晶圓之化學機械研磨研究

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摘要

化學機械研磨簡稱CMP，是現在唯一能夠提供VLSI製程全面平坦化的技術。本文以一CMP流場模擬機，採用灰階度方法將CCD影像圖由影像擷取軟體處理，使用這種技術可估算出進入晶圓與研磨墊間之研磨液的量與其分布。利用這個技術，本文提出大尺寸晶圓之化學機械研磨研究。實驗顯示 12 吋晶圓之研磨液最佳注入位置為IP<30%。最佳注入量在低轉速下建議使用注入量Q=100-150 ml/min，而在高轉速下建議使用Q>200 ml/min的流量。此外亦研究改變晶圓與研磨墊中心距離對灰階度與非均勻性的影響。實驗數據顯示，晶圓邊緣跨越研磨墊中心距離時，可藉著提高研磨墊轉速而達到與未跨中心相近的移除率，但是跨越中心會影響研磨液的傳遞效率。因此建議跨越中心距離R_{we}<3cm有最佳的效果。

關鍵字: 化學機械研磨、研磨液、移除率、非均勻性

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Ⅰ. INTRODUCTION

In recent years, CMP has already become a standard procedure in semiconductor fabrication, is especially important in the planarization of narrowing width and greatening wafers. Several researchers have proposed factors that affect CMP polishing efficiency, which will affect removal rate and non-uniformity. These processing variables are part of slurry contents, polishing rotation speed, polishing pad quality, amount of slurry injected and position. Currently, no systematic research has been done on large-sized wafer injection conditions and no study has been made on the effect of the distance between the wafer and the polishing pad center on CMP.

CMP uses a something similar to a traditional "grinder" for mechanical polishing. Along with complementary chemicals solution, which we call slurry, employing planarization techniques smooth the uneven contours of the wafer surface. Figure 1 shows a simplified sketch of the CMP planarization processing equipment which consists of a polishing table and a holder. While the holder holds at the back of the wafer, a positive force is applied to push the wafer surface on the polishing pad to the polishing table. During CMP, both the polishing table and the holder rotate the same direction. At the same time, the slurry will be helpful the CMP process, which flows along a pipe and a constant supply rate to the polishing pad. The so-called CMP is to use the chemical reaction provided by the slurry and the mechanical polishing on the wafer on the polishing table to remove the deposited bumps on the wafer surface via planarization technique.

Regarding related research, the software CFX-F3D by Fu and Chou [1] builds a three dimensional procedure that uses a numerical method to simulate CMP processes and to estimate the fluid shearing stress. Runnel [2,3] points to the relationship between slurry shearing stress and polishing rate, and thus the shearing stress changes are used to show polishing rate changes. Moreover, the peripheral average shearing stress distribution is used to compute for the non-uniformity. The values of the shearing stress and the non-uniformity obtained from the simulation that changes with the polishing pad rotation speed accorded with the experimental values obtained by Modal et al. [4]. Coppeta et al. [5] uses laser induced fluorescence to measure the thickness of the slurry and observed the situation of the flow and the non uniformity. Research discovered that when the slurry injection position is near 33% of the polishing pad radius, the largest fluorescence intensity is obtained while a decrease is observed when the radius is greater than 40%. Moreover, Rogers et al. [6] likewise studied the effect of the polishing pad which shows that the polishing pad rotation speed, polishing pad surface situation, and slurry flow rate all affect the status of the flow. Stavreva et al. [7] used and compared two types of polishing pads IC1000 and IC1000/Suba IV. Their study showed that polishing pads with better shrinkage have good uniformity and higher removal rate. Concerning the modeling of removal rate from the view point of solid wear, Srinivasa-Murthy et al. [8] and Wang et al. [9] described a fundamental three-dimensional physical model that related the observed nonuniformity during CMP to the variation of Von Mises stress on the wafer surface. The model essentially assumed solid-solid contact between the pad and the wafer. Liu et al. [10] developed a wear model for CMP processing based on kinematics and elastic theory. Ahmadi and Xia [11] applied the mechanical contact theory to analyze the interaction between the abrasive and wafer surface, and studied the removal process of wafer surface due to abrasive. Lin and Lo [12] developed a 2D axisymmetric quasi-static finite element model with carrier backpressure compensation for CMP. Regarding flow field observations, aside from Coppeta et al. [13] used laser induced fluorescence to measure the property of the slurry. Chou et al. [14] designed a CMP experimental simulation setup and used gray scale differences to show different polishing rates. Their results show a similar trend to the study done by Modak et al. [4] using IPEC Avanti 427 machine. The mean gray scale image does not always increase with increasing slurry inject rate. The mean gray scale image significantly increases as slurry injects rate increases from 50 to 100 ml/min. However, it reaches a maximum at around slurry inject rate

= 150 ml/min. Thus, it is easy to use gray scale image values to represent measurements of actual removal rates. Using this technique, the optimal values for slurry injection position and flow rate can be used for all types of wafer sizes.

Furthermore, CMP procedures are complex and current studies on simplified internal flow field of the two bias center rotation disks are scarce. In addition, the fluid characteristics of the slurry and its chemical properties, the situation of the polishing pad surface and the deformities, and various other reactions have to be combined and thus are very difficult to control. Most CMP experiments have to buy expensive CMP machines and to prepare costly wafers. The precision equipment used for CMP analytical experiments on polishing rate and non-uniformity such as SEM are not only expensive but also tedious to operate. Rodel Co. statistics show that the consumables used in CMP processing such as slurry and polishing pad make up 25% of the entire process. For the production in the semiconductor industry, they mostly set CMP production variables conformed to the values provided by the equipment supplier. Other manufacturing variables such as wafer size, wafer pressure, polishing pad quality, slurry quality, polishing pad rotation speed, slurry injection rate and position all can possibly be changed depending on the requirements. If the reference values provided by the equipment manufacturer are still followed, then the polishing rate may decrease, non-uniformity increase, and wastage of the polishing pad and slurry may result. This will affect the passing rate of the wafer and will result in technical and cost lowering bottlenecks. Thus, this study designs a CMP process simulation machine and uses a gray scale image method on the CCD image by image processing software. This technique can estimate the amount of slurry introduced between the wafer and the polishing pad, finding the optimal slurry injection position and amount, and controlling CMP processing.

Ⅱ. RESEARCH METHOD

This paper uses a type of visible process technique to observe the flow field distribution of the slurry on the polishing pad surface and of the polishing pad and the wafer during CMP process. The relationship between the mean gray scale image and the average removal rate can also be compared. For 12-inch wafers, the effect of the distance between the wafer and the polishing pad center on the gray scale image and non-uniformity would be studied in this paper. In addition, when the wafer edge exceeds the polishing pad center, the polishing situation is likewise observed. The best slurry injection position and amount is found when the wafer edge exceeds the polishing pad center.

2.1 Experimental equipment

The experimental equipment used in this study is a self-designed CMP process simulation experiment setup as shown in Fig. 1. Its exterior components can be divided into a rotating disk structure, a position control platform, and image acquisition equipment. In order to enable visibility of the flow field, a transparent glass disk replaces the silicon wafer. The wafer has a 12-inch diameter; the polishing pad is Rodel Suba 400 with 27-inch diameter. The slurry Nalco 2360 can be bought in the market. It contains a lot of microscopic particles, which reflects light. The light source is a sodium lamp, which is not only stable and gives off a strong light, but also is much cheaper than the dual emission laser used by Coppeta et al. [13]. The image acquisition equipment is a charged coupled device (CCD) camera, which takes images between of the polishing pad and wafer slurry flow process. The manual pressurization system and auxiliary device on the positioning platform can be adjusted and the pressure can be controlled, too. Fig. 2 shows a top view of the rotating disk platform. The wafer radius is R while the distance between the wafer edge and the polishing pad center is R_{we}; the distance between the wafer center and the polishing pad center is $R_w = R + R_{we}$. The two disks both rotate in counterclockwise directions. The polishing pad rotating speed is Ω = 20～60 ±0.5 rpm; the wafer rotating speed is ω = 20～60 ±0.5 rpm. The distance between the slurry injection position and the polishing pad center is R_i.

2.2 Image analysis method

In order to get semi-quantitative results from the CCD image, we used a gray scale image method for analysis. With image

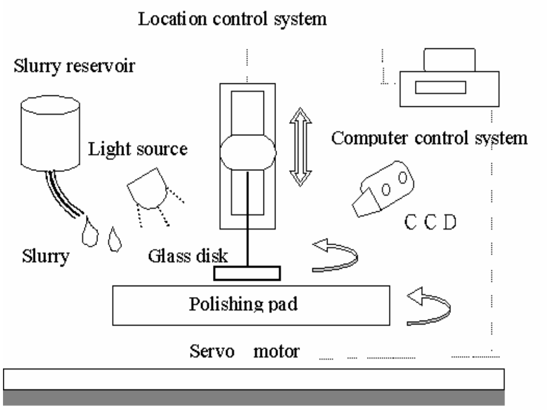

Fig.1. CMP experimental apparatus.

acquisition software Optimas, the gray scale image distribution of the slurry in the gap between the polishing pad and the wafer is computed. Because the slurry contains a lot of particles, after Optimas processing, they are seen as fluid particles and the number of particles indicates the gray scale image values. Thus, using the gray scale image variations from the wafer image, we can estimate the amount of slurry between the polishing pad and the wafer. Since the amount of slurry entering the gap and the polishing rate are related, thus, the gray scale image value is related to polishing rate.

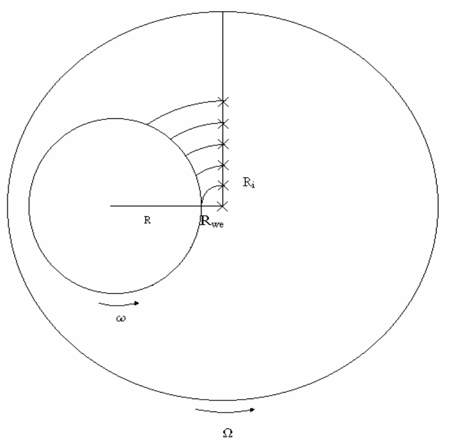

Fig.2. Top view of the rotating disk platform.

Gray scale image analytical method is a type of digital image processing. The digital image is obtained from an image acquisition device, which captures continuous images to a video card. The video card will digitize the image based on the brightness degrees. The digitized image is the pixel composed of different degrees of lightness. Each pixel has a fixed position and gray scale image value. The more pixels an image has, the higher is its resolution. The image that this experiment has acquired is an 8-bit gray image with brightness values from 0 to 255 where 0 is the darkest and 255 the lightest. This image is processed in Optimas and then the obtained data is sent to Excel for further analysis. The mean value of gray scale image is obtained by averaging over 48 points across each wafer, and the non-uniformity is calculated in terms of a percentage of the standard deviation of the 48 points over the mean value of the gray scale image. The formulas are defined and list below:

$$NU = (\sigma / MGS)\%$$

Where σ represents denotes the standard deviation of the 48 points across each wafer.

Ⅲ. RESULTS AND DISCUSSION

Under the same operating conditions, that is wafer rotating speed of ω=32rpm, flow rate Q=150 ml/min, injection position R_i/R_o=0%, and polishing pad rotating speed Ω=10-40rpm, Fig. 3 compares the mean gray scale image changes under various polishing pad rotating speeds with the experimental values obtained by Modak et al. [4] The experiment of Modak et al. shows that removal rate increases as polishing pad rotating speed increases. Increased polishing pad rotating speed means relative speed increase in any point on the wafer. It can thus be deduced that the relative speed and polishing rate are directly related. This paper uses a gray scale image measurement method, which shows the same trend. Thus, it is relatively easy to make use of gray scale image method measurements to take the place of removal rate measurements. Figure 4 shows how non-uniformity changes with polishing pad-rotating speed. When the wafer speed is the same as the polishing pad speed, the non-uniformity is the lowest and so its uniformity is the best.

When the slurry injection amount is Q=150ml/min, fixed the wafer rotating speed is ω and the polishing pad rotating speed is Ω, this makes $\omega=\Omega$=40rpm. Changing the injection position R_i and divided by the radius of the polishing pad R_o, the non-dimensional injection position is obtained IP=(%R_i/R_o). Fig.5 shows how the mean gray image scale and non-uniformity changed with varying injection position IP. When the position is IP=0-30%, the mean gray scale and non-uniformity have small changes. At this time, the injection position falls inside the wafer edge and polishing pad center. When IP>30%, the mean gray image scale significantly drops while the non-uniformity increases. This means that the polishing is at its

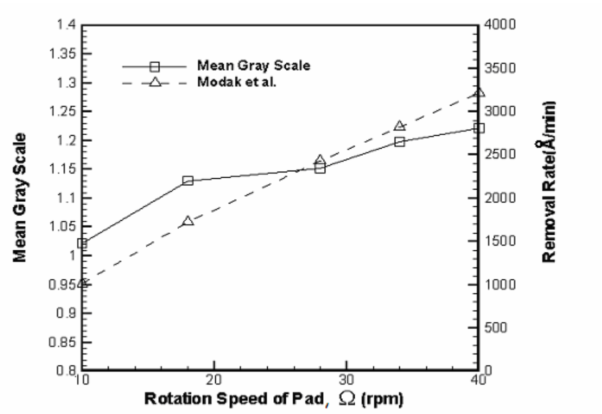

Fig.3. Variations of mean gray scale image with pad rotation speed Ω for wafer rotating speed ω=32rpm, flow rate Q=150 ml/min, injection position R_i/R_o=0%, Removal rate data of Modak are also shown for comparison.

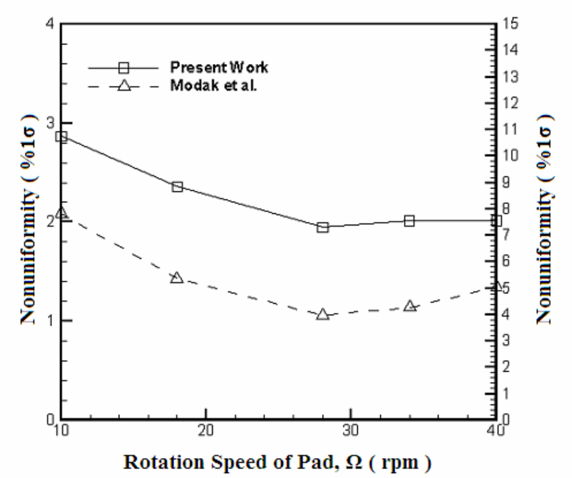

Fig.4. Variations of non-uniformity with pad rotation speed Ω for wafer rotating speed of ω=32rpm, slurry inject rate Q=150 ml/min, injection position R_i/R_o=0%, Non-uniformity data of Modak are also shown for comparison.

worst and at this time, the injection position falls outside the wafer edge and polishing pad center. It can be concluded that when the injection position is within the wafer and the polishing pad center, through the wafer rotation, the slurry is carried to all the surfaces of the wafer, offering enough amount of slurry. When the injection position is outside the wafer and polishing pad center, there is not enough slurry from the center to the half of the wafer and thus the mean gray scale drops while non-uniformity increases.

Regarding the optimal injection amount experiment, based on the conclusions from the injection position, when it is IP=0%, injection amount is Q=50-250 ml /min, the experiments conducted at $\Omega=\omega$=20,30, and 40rpm, results are shown in Fig. 6. This experimental results can be discussed in two ways. First, increased rotating speed results in higher mean gray scale image; thus, if increased polishing rate is desired, increasing wafer and polishing pad rotating speed is a method that can be considered. Moreover, the curve of $\Omega=\omega$ =40rpm is higher than the slope of 20 and 30 rpm. At high rotating speeds, the changes in mean gray scale image due to varying slurries are more significant. Therefore, at low rotating speeds, injection amount of Q=100-150 ml/min is recommended while at high rotating speeds, Q>200 ml/min injection amount can be used.

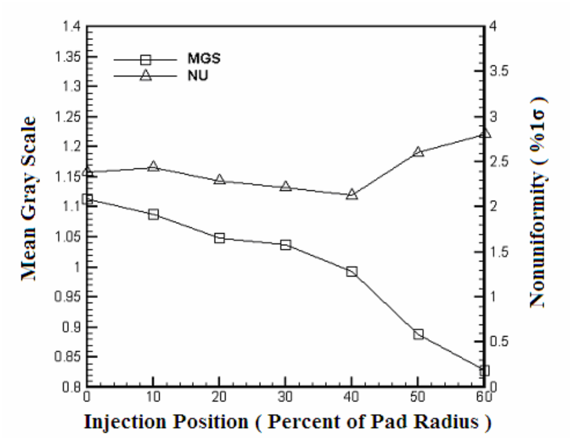

Fig.5. Mean gray scale (MGS) image and non-uniformity(NU)changes with varying injection position for Q=150ml/min, fixed the wafer rotating speed is ω and the polishing pad rotating speed is Ω, this

makes $\omega=\Omega=40$rpm.

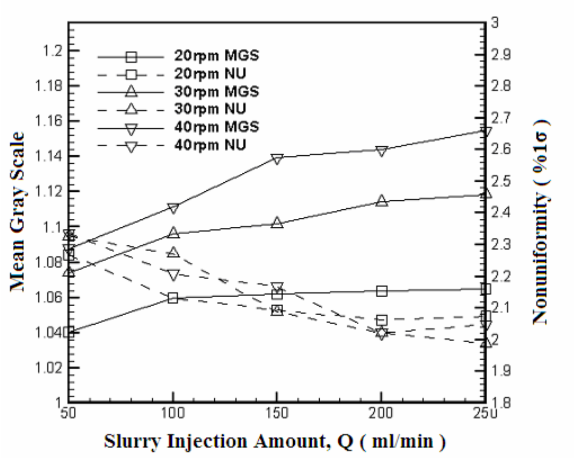

Fig.6. The optimal slurry injection amount experiment for the experiments conducted at $\Omega=\omega=20,30$, and 40rpm, IP=0%

Fig. 7 shows the effect of changing the distance from the wafer and polishing pad center while keeping rotational speed and its relative speed fixed. At a fixed rotating speed, the moving wafer will change the wafer and polishing pad center distance; for shorter distances to the center, the relative speed likewise diminishes. When the distance of the wafer and polishing pad center is equal to the wafer radius, that is R_w=15cm, the wafer boundary is exactly at the polishing pad center's position. The experiment shows that the mean gray scale image lowers as the distance to the center diminishes. Before and after the wafer edge exceeds the polishing pad center, there is no significant change in mean gray scale image, and it still keeps a decreasing slope. When changing the distance from the center, the non-uniformity does not exhibit any significant change.

Fig. 7 shows another group of curves, the fixed relative speed mean gray scale image and the non-uniformity curves. When the distance to the center is decreased while keeping the same relative speed, both rotating speeds of the wafer and the polishing pad have to be increased. The experiment indicates that when the speed is constant, the mean gray scale image still lowers according to the diminishing central distance; however, the decreasing trend tapers off. Theoretically, the relative speed remains the same while the polishing rate should remain the same. However, the experimental results show that when the curve gradually descends, the reason for this effect can be due to that the wafer edge exceeds the polishing pad center position, which lowers the efficiency of the spreading of the slurry. This phenomenon becomes more significant when the wafer edge exceeds the polishing pad center is further exceeded. Since the experimental equipment setting is from 10-60rpm, and the wafer and polishing pad rotation speed setting is from 40 and 30 rpm, the wafer edge exceeds the polishing pad center distance from the center are 3 and 6 cm respectively. Beyond this distance, while keeping the same relative speed, a higher rotation speed will be more than the operating specifications of the equipment. Fig. 8 shows that when the wafer edge exceeds the polishing pad center distance from the center is 6 cm, it is difficult to prevent lowering mean gray scale image values while the rotating speed is increased; moreover, the non-uniformity likewise increases.

In order to understand the best slurry amount for the wafer edge exceeds the polishing pad center position, the slurry amount is set as $R_i=R_{we}$. Because a larger wafer edge exceeds the polishing pad center position would lower the slurry spreading efficiency. Thus the wafer edge exceeds the polishing pad center distance is set to be

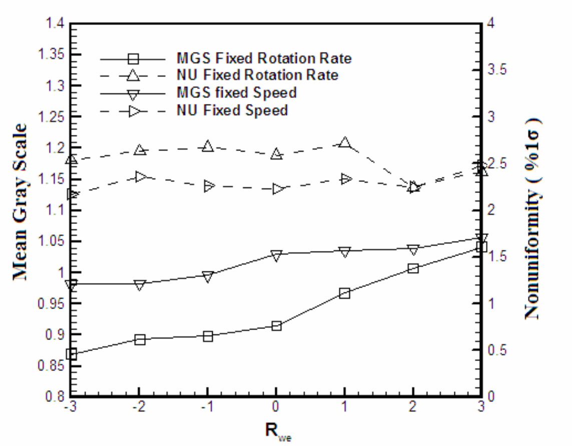

Fig.7. The effect of changing the distance from the wafer and polishing pad center while keeping rotational speed and its relative speed fixed,

Q=150ml/min and $\Omega=\omega$=40rpm. R_{we}=3cm while the center is R_w=12cm. We did separate experiments for the various values of $\Omega=\omega$=20,30,40,50, and 60rpm to find the best slurry amount for each rotating speed as indicated in Fig. 9. Results show that with higher rotating speeds, faster injection rate is required.

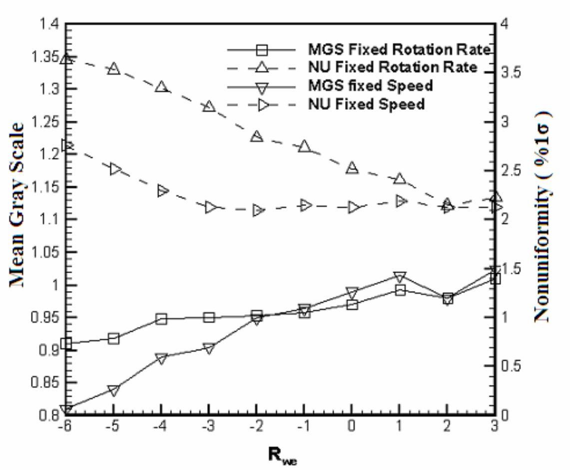

Fig.8. The effect of changing the distance from the wafer and polishing pad center while keeping rotational speed and its relative speed fixed, Q=150ml/min and $\Omega=\omega$ =30rpm.

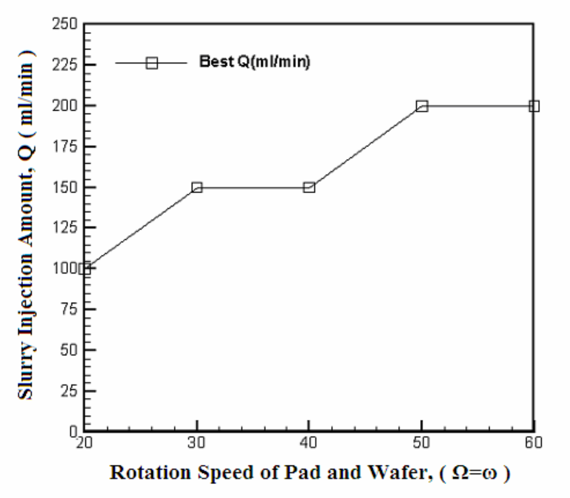

Fig.9. The best slurry amount for the wafer edge exceeds the polishing pad center for the slurry amount is set as $R_i=R_{we,}$ the wafer edge exceeds the polishing pad center distance is set to be R_{we}=3cm while the center is R_w=12cm.

IV. CONCLUSION

By observing the variation of the flow field in the gap between the polishing pad and the wafer through experiment and theoretical analysis, this paper generalizes optimal slurry injection conditions for large-sized wafer CMP. Furthermore, the study explores the effect of changing distances between the wafer and the polishing pad as well as the results when the wafer edge exceeds the polishing pad center. The following conclusions were derived:

(1) The experimental results of the variation of the gray scale image and non-uniformity changes resulting from polishing pad-rotating speed is close to the experimental data obtained by Modak et al. In addition, the experiment can be easily repeated and is stable. It can thus be deduced that the relative speed and polishing rate are directly related. When the wafer speed is the same as the polishing pad speed, the non-uniformity is the lowest and so its uniformity is the best. Thus, a simpler gray scale image measurement can replace actual measurements of polishing rate.

(2) The experiment on the optimal slurry injection position and amount was done on 12-inch wafer. Regarding injection position, slurry located far from the polishing pad center cannot be directly induced by the polishing pad entering the gap between the polishing pad and the wafer, relying only on the wafer rotating motion. Thus the gray scale image lowers while the non-uniformity increases and the polishing results become worse. The experiment shows that the optimal slurry injection rate for 12-inch wafers is IP<30%. For the slurry amount, when a certain amount is reached, further increase will not affect the gray scale image and this amount is thus the optimal injection amount. Increasing polishing rotating speed will require more slurry. This indicates that at a higher rotating speed, more slurry flows out of the gap between the wafer and the polishing pad, which will naturally require more slurry to make up for the loss. Therefore, at

low rotating speeds, injection amount of Q=100-150 ml/min is recommended while at high rotating speeds, injection amount Q>200 ml/min can be used.

(3) At a fixed rotating speed, changing the wafer and polishing pad center distance will lower the gray scale image but the non-uniformity will not display any significant changes. Before and after the wafer edge exceeds the polishing pad center, while maintaining the same changes, there is no significant effect from the wafer edge exceeding the polishing pad center. When the distance to the center is lowered while the rotating speed is increased and the relative speed is maintained, the gray scale image will increase; but the increasing exceeding distance from the center will cause the slurry spreading rate to lower. Thus, the exceeding distance to the center should not be too much.

(4) The study on the optimal slurry injection for wafer edge exceeding the polishing pad center by 3 cm has been conducted. The optimal injection position is the distance of the wafer edge exceeds the polishing pad center. The optimal injection amount is changed with the different rotating speed. The research method and results can be used as referable variables in designing future 16 and 18-inch wafer CMP platforms.

NOMENCLATURE

IP: non-dimensional injection position IP=(%R_i/R_o, Percent of Pad Radius)
MGS: Mean gray scale
NU: non-uniformity
Q: slurry inject rate
R: radius of wafer
R_i: distance between pad center and slurry injection position
R_o: radius of the polishing pad
R_w: the distance between the wafer center and the polishing pad center
R_{we}: distance between polishing pad center and wafer edge
Ω: pad rotation speed
ω: wafer rotation speed

REFERENCES

[1] Fu, M. N., and Chou, F. C., "Flow simulation for chemical mechanical planarization," Japanese Journal of Applied Physics, Part 1: Regular Papers and Short Notes and Review Papers, Vol. 38, pp. 4709-4714, 1999.

[2] Runnels, S. R., "Feature-Scale fluid-based erosion modeling for chemical mechanical polishing," Journal of the Electrochemical Society, Vol. 141, pp. 1900-1904, 1994.

[3] Runnels, S. R., "Advances in physically based erosion simulators for CMP," J. Electronic Materials, Vol. 25, pp. 1574-1580, 1996.

[4] Modak, A., Monteith, P., and Parekh, N., "Components of within-wafer nonuniformity in a dielectric CMP process," Proc. of 1997 CMP-MIC Conference, Santa Clara, CA, pp. 169-172, 1997.

[5] Coppeta, J., Rogers, C., Philipossian, A. and Kaufman, F. B., "A Technique for Measuring Slurry Flow Dynamics During Chemical Mechanical Polishing," Proc. of Material Research Society, Vol. 447, pp. 95-100, 1997.

[6] Rogers, C., Coppeta, J., Racz, L., Philipossian, A., Kaufman, F.B., Bramono, D.," Analysis of flow between a wafer and pad during CMP processes," Journal of Electronic Materials, Vol. 27, No. 10, pp. 1082-1087, 1998.

[7] Stavreva, Z., Zeidler, D., Plotner, M., and Drescher, K., "Characteristics in Chemical Mechanical Polishing of Copper: Comparison of Polishing Pads," Appl. Surf. Sci., Vol. 108, pp. 39-44, 1997.

[8] Srinivasa, M. C., Wang, D., Beaudoin, S.P., Bibby, T., Holland, K., Cale, T.S., "Stress distribution in chemical mechanical polishing," Thin Solid Films, 308-309, pp. 533-537, 1997.

[9] Wang, D., Lee, J., Holland, K., Bibby, T., Beaudoin, S., Cale, T., "Von Mises stress in chemical-mechanical polishing processes," Journal of the Electrochemical Society, Vol. 144, pp. 1121-1127, 1997.

[10] Liu, C. W., Dai, B. T., Tseng, W. T., Yeh,

C. F., “Modeling of the wear mechanism during chemical-mechanical polishing,” Journal of the Electrochemical Society, Vol. 143, pp. 716-721, 1996.

[11] Ahmadi, G., Xia, X., “A model for mechanical wear and abrasive particle adhesion during the chemical mechanical polishing process,” Journal of the Electrochemical Society, Vol. 148, No. 3, G99-G109, 2001.

[12] Lin, Y. Y., Lo, S. P., “Finite element modeling for chemical mechanical polishing process under different back pressures,” Journal of Materials Processing Technology, Vol. 140, pp. 646-652, 2003.

[13] Coppeta, J., Rogers, C., Racz, L., Philipossian, A. and Kaufman, F. B., “Investigating slurry transport beneath a wafer during chemical mechanical polishing processes”, Journal of the Electrochemical Society, Vol. 147, pp. 1903-1909, 2000.

[14] Chou, F. C., Fu, M. N., and Wang, M. W., “A general Optimization for slurry injection during chemical mechanical polishing”, Journal of the Electrochemical Society, Vol. 147, pp. 3873-3878, 2000.