Materials Science in Semiconductor Processing 151 (2022) 107043

Contents lists available at ScienceDirect

Materials Science in Semiconductor Processing

journal homepage: www.elsevier.com/locate/mssp

Effect of slurry particles on PVA brush contamination during post-CMP cleaning

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ARTICLE INFO

Keywords:
Brush scrubbing
Post-CMP cleaning
Silica abrasive
Ceria abrasive
Contamination
Cross-contamination
Brush loading

ABSTRACT

PVA (polyvinyl acetal) brush scrubbing is a widely used post-CMP cleaning process due to its low cost and high cleaning efficiency. However, during these processes, the PVA brush gets contaminated with abrasive particles that result in wafer cross-contamination and reduced cleaning efficiency. This study investigated the effects of abrasive types such as silica and ceria, the slurry pH, and the scrubbing process parameters on brush contamination. Ceria slurries showed significantly more contamination of brushes compared to silica slurries. The brush contamination increased with a decrease in pH from 7 to 4 due to increased electrostatic attractive forces between the ceria particles and the brush surfaces, although very low brush contamination was observed by the ceria slurries at pH 10 due to a strong electrostatic repulsion. Conversely, very low brush contamination was observed for the silica slurries at all pH values due to the reduced interaction between the particles and the brush surface (electrostatic repulsion). Furthermore, there was no significant effect of gap distance and brush rotation speed on brush contamination. The abrasive concentration and the contamination process time showed a linear relationship as the contamination was significantly increased by increasing the abrasive concentration in slurry and process time. These results indicate that brush contamination is more sensitive to the abrasive nature and concentration, the slurry pH, and the process time than to other parameters.

1. Introduction

Chemical mechanical planarization (CMP) is a key process for polishing wafer surfaces and has become critical for manufacturing semiconductor devices below 10-nm [1–4]. This scaling-down of devices demands nano-size abrasives with controlled formulations to achieve the required planarization by CMP. Further, this imposes stringent requirements on the post-CMP cleaning process to reduce the defectivity for yield enhancement and device reliability. Therefore, post-CMP cleaning needs to be performed meticulously to control defectivity. In post-CMP cleaning processes, the polyvinyl acetal (PVA) brushes effectively remove contaminants, and the physical forces responsible for cleaning wafer surfaces with PVA brushes result in a low cost of ownership [5].

In the PVA brush cleaning process, the contact elastic forces, hydrodynamic drag forces, and frictional forces between the brush and the particles are the dominant forces responsible for removing the particles [6–9]. Better cleaning performance can be achieved by optimizing the brush rotation speed, the gap distance between the brush and the wafer, the solution flow rate, and/or the cleaning chemistry [10]. The tribological properties of the brush, such as the dynamic coefficient of friction (COF) as a function of brush gap distance, the contact pressure, and the shear forces between the PVA brush and the wafer are effective in reducing the defectivity [11–15].

However, the brush itself can be a source of defects. This may be due to either the presence of impurities in the incoming brushes, improper brush break-in methods, or the brush being overused (cleaning too many wafers), which might result in excessive particle loading. Sahir et al. [16] reported on excessive brush loading and its subsequent effect on cross-contamination. Lee et al. [17] reported on the presence of residual organic impurities in the incoming PVA brushes generated from the brush manufacturing process, and Kim et al. [18] investigated the brush

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https://doi.org/10.1016/j.mssp.2022.107043
Received 18 April 2022; Received in revised form 8 August 2022; Accepted 8 August 2022
Available online 18 August 2022

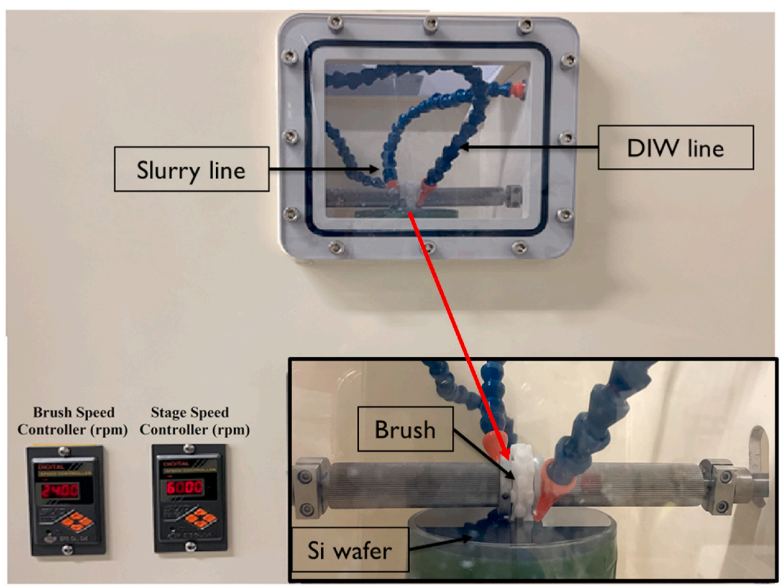
cross-contamination effect in the CMP in-situ cleaning module. A successful break-in method was established by Lee et al. [19] whereby scrubbing the new brush on numerous dummy wafers reduced the incoming brush impurities. Further, Lee et al. [20] observed that strong micro turbulence and shock waves generated during an ultrasound-assisted cleaning process effectively and rapidly removed the particulate residue present in the incoming PVA brushes without damaging the brushes. Recently, Kim et al. [21] reported the effects of various process parameters such as the rotation speed of the wafer and the brush, the gap distance, and the de-ionized water (DIW) flow rate on cross-contamination of the PVA brush during post-CMP cleaning. Cho et al. [22] reported the effect of rotation speed on cleaning efficiency, and An et al. [23] reported that cross-contamination was highly dependent on the zeta potential of the brush, the wafer, and the abrasives. Interestingly, all of these studies indicated the importance of cross-contamination and highlighted some root causes for this effect. However, none of them considered the interaction of abrasives and the brush surface during the post-CMP cleaning process.

Among the abrasives, silica is commonly used for dielectric and metal CMP, whereas ceria is widely adopted for oxide CMP processes [24,25]. The porous structure of PVA brushes allows abrasive entrapment during brush scrubbing, which might lead to micro-scratches during enhanced downforce or low brush rotation speed during scrubbing, resulting in reduced brush life [26]. Recently, the interaction of ceria particles with silicon oxide surfaces during CMP and post-CMP cleaning was investigated [27,28], but not many studies have addressed the contamination of PVA brushes with abrasive particles. Therefore, it is important to understand the interaction between abrasives and PVA brush surfaces during the brush scrubbing process. This will help to overcome the brush cleaning issues for yield enhancement and defect reduction.

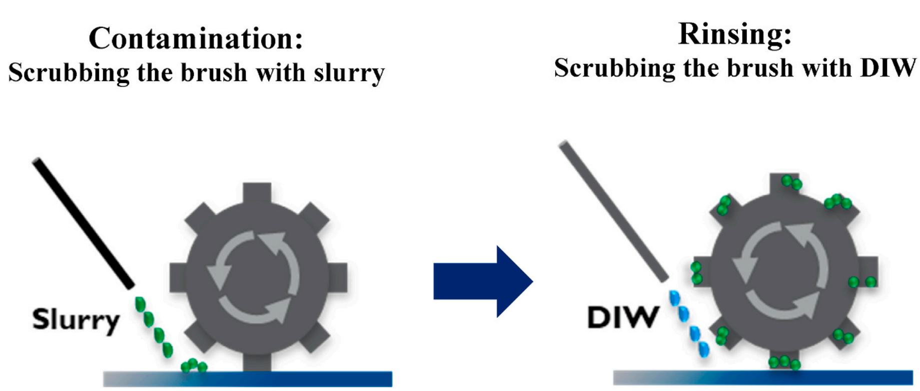
This study investigated the contamination of PVA brushes by abrasives during brush scrubbing. Initially, the contamination by silica or ceria particles at different pH levels was analyzed to understand the effect of slurry pH on the abrasives and brush interactions. Furthermore, the effect of different process parameters such as brush gap distance, brush rotation speed, process time, and abrasive concentration on contamination of PVA brushes during scrubbing was evaluated by qualitative and quantitative analysis techniques — FE-SEM and ICP-OES, respectively.

2. Experimental materials and procedure

PVA brushes (200 mm, BS101-0, AION Co. Ltd., Japan) were used



(a)



(b)

Fig. 1. (a) Lab-scale roller brush scrubbing module, and (b) procedural schematics adopted for evaluating the brush contamination at different process parameters.

with 4-in. prime bare silicon (Si) wafers as a substrate for investigating the brush loading. Silica (150-nm mean size, Sigma-Aldrich, USA) and ceria (100-nm mean size, US Research Nanomaterials Inc., USA) particles were used as abrasives in this study. The chemicals HNO_3 (60%, Samchun Chemicals Korea) and KOH (85–87%, Daejung Chemicals & Metals, Korea) were used to adjust the slurry pH. The silica and ceria slurries used for contamination were prepared by adding different concentrations of abrasive in DIW and adjusting the pH of slurries by pH adjustors. No other additives were added to both ceria and silica slurries. These slurries were further used for all contamination experiments as well as for zeta potential measurement.

2.1. Brush contamination process

A 22-mm brush was cut out of a 200-mm brush and soaked in DIW for at least 24 h before use to maintain its wet condition. The contamination experiments were carried out by placing the 22-mm brush on a mandrel with a staged Si wafer, as shown in Fig. 1(a). The brush contamination was performed by scrubbing the brush on the Si wafer in the presence of slurry, followed by DIW rinsing, as presented in Fig. 1(b). A lab-scale, roller-type brush scrubber (CSY Co., Korea) was used for the scrubbing experiments [20].

The effects of the abrasive type and slurry pH on brush contamination were investigated by preparing 0.01 wt% silica and ceria slurries at pH 4, 7, and 10. The brush contamination was performed by supplying slurries at 150 mL/min while rotating the brush for 1 min on the Si wafer. This contamination process was followed by a 2-min DIW rinsing step to remove loosely attached abrasive particles. The brush and wafer rotation speeds were maintained at 240 and 50 rpm, respectively, with a gap distance of −2 mm.

Based on the contamination results, the effects of the scrubbing process parameters on brush contamination were evaluated using ceria slurries prepared at pH 4. The effects of different process parameters, such as abrasive concentration (0.005, 0.01, 0.05, and 0.1 wt%), gap distance (0, −1, and −2 mm), brush rotation speed (50, 100, 200, and 300 rpm) and process run time (30 s, 1, 3, and 5 min) were considered on brush contamination while maintaining the DIW rinsing condition as described previously. The other experimental parameters adopted for brush contamination analysis are summarized in Table 1.

2.2. Brush contamination analysis

The evaluation of brush contamination was carried out by analyzing the dried brush nodules qualitatively and quantitatively. The qualitative analysis was performed using a field emission scanning electron microscope (FE-SEM) (MIRA3, TESCAN., Czech Republic). The abrasive concentration and brush contamination were estimated quantitatively by digesting the dried contaminated brush nodules in a nitric acid (HNO_3) and hydrofluoric acid (HF) mixture, and using inductively coupled plasma optical emission spectrometry ICP-OES (iCAP™ 7000 SERIES, Thermo Fisher Scientific, USA). The surface charge of the slurries was analyzed with a zeta potential analyzer (ELS-Z2000, Otsuka Electronics, Japan). The brush nodules were ground to a fine powder using sandpaper (4000-μm film sandpaper, 3 M Co., USA). This ground powder was mixed with DIW at different pH values to estimate the brush surface charge using the zeta potential analyzer.

Table 1
Reference conditions for brush scrubber during the scrubbing process.

No.	Process Parameter	Value
1	Slurry pH	4/7/10
2	Wafer rotation speed (rpm)	50
3	Slurry/DIW flow rate (mL/min)	150
4	Slurry concentration (wt.%)	0.005/0.01/0.05/0.1
5	Gap distance (mm)	0, −1, −2
6	Brush rotation speed (rpm)	50/100/200/300
7	Contamination process time	30 s,1 min, 3 min, 5 min

3. Results and discussion

3.1. Effect of abrasive nature on brush contamination

Brush scrubbing is one of the most common methods in post-CMP cleaning. However, the scope of brush deterioration by abrasive contamination during the scrubbing process is still unclear. In this study, the effects of two commonly used abrasives, silica, and ceria, were considered to evaluate brush contamination. The effects of abrasive type and pH on brush contamination are reported in Fig. 2. FE-SEM images shown in Fig. 2(a) indicate that silica slurry produced relatively higher contamination in the PVA brush at pH 4, reduced contamination at pH 7, and no contamination was observed at pH 10. The ceria slurries showed a significant effect of pH on contamination of the PVA brush compared to silica slurries, as shown in Fig. 2(b). The PVA brushes were heavily contaminated by ceria at pH 4 during scrubbing, but this was reduced at pH 7 and was very low at pH 10. Considering the effect of abrasive type, ceria produced very high brush contamination compared to silica.

The effects of abrasive type and pH were further confirmed quantitatively by using ICP-OES analysis, and the results are reported in Fig. 2 (c). The results confirm the presence of higher ceria concentration on the PVA brushes compared to silica under all of the pH conditions. The abrasive contamination showed a trend of increased contamination at acidic pH that gradually decreased with an increase in the pH of the slurry.

Fig. 3 provides a better understanding of the pH-dependent contamination and an evaluation of the interaction mechanism based on the surface charges of the silica, the ceria, and the PVA brush. Silica exhibits an isoelectric point (IEP) ~2 [19,29], whereas the IEP for ceria depends on the synthesis process and may vary from 5–11 [11,19,29,30]. It can be seen from Fig. 3 that the PVA brush and the silica particles exhibit a negative surface charge under all pH conditions. These similar surface charges for the silica particles and the PVA brush results in electrostatic repulsion between them, which is the reason for the low contamination observed at pH 4. The magnitude of the electrostatic repulsion increased with an increase in the pH due to increased negative surface charges, which resulted in no contamination of the PVA brush with silica particles at pH 7 and 10.

The interaction between ceria and the PVA brush could be expected to be significantly different from silica, as ceria exhibits a high positive surface charge at acidic pH that changes to ~0 at pH 7 and is highly negative at pH 10. Ceria particles and the PVA brush showed opposite surface charges at pH 4, as shown in Fig. 3, which resulted in a strong electrostatic attraction. These attractive forces between the ceria and the brush are the reason for the very high contamination observed. The contamination was reduced at pH 7 due to weak electrostatic attraction as compared to pH 4. This pH-dependent phenomenon is schematically presented in Fig. 4(a) and Fig. 4(b). Initially, there were no particles present on the brush which is represented by the left side schematic of Fig. 4(a) and (b). However, the right side of the schematic after arrows indicates that in the presence of a continuous supply of ceria/silica slurry during scrubbing, the abrasive particles were loaded to the brush (due to electrostatic attraction) as shown in Fig. 4(a) and a very few particles were contaminated to the brush (due to electrostatic repulsion between brush and abrasives) as presented in Fig. 4(b). Therefore, for ceria at pH 4 and 7, the abrasives were positively charged and the brush had a negative surface charge which resulted in high brush contamination after scrubbing as indicated by Fig. 4(a). Whereas, ceria at pH 7 and silica at pH 4, 7, and 11, and the brush surfaces at all pH investigated, were negatively charged, generating an electrostatic repulsion force resulting in low contamination, as represented by Fig. 4(b). These results indicate that the contamination primarily depended on the abrasives, which subsequently affected the interaction mechanism by controlling the surface charges.

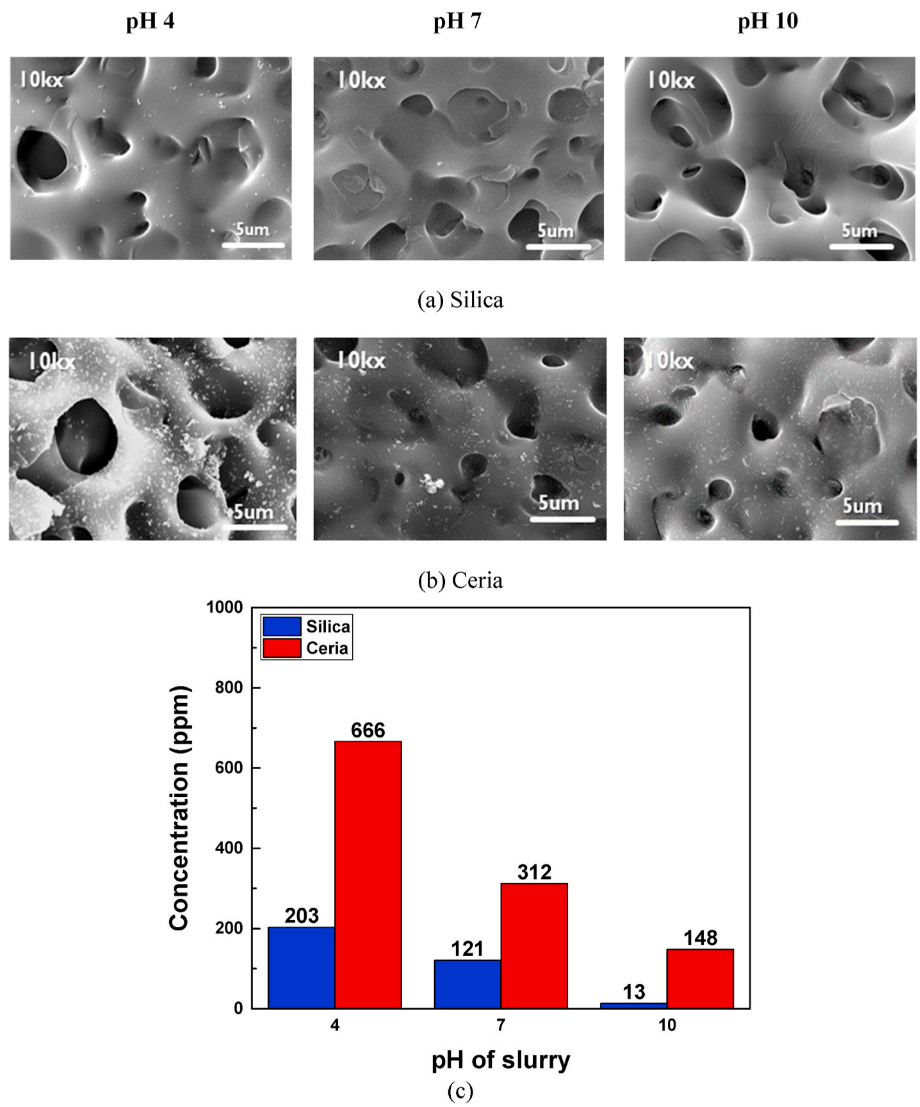


Fig. 2. The effect of pH on brush contamination by 0.01 wt% (a) silica and (b) ceria slurries (FE-SEM images at 10 kX), and corresponding (c) ICP-OES data.

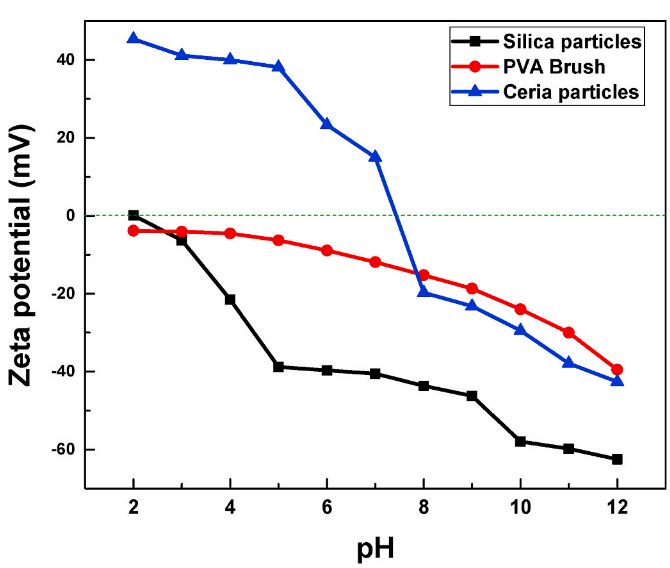


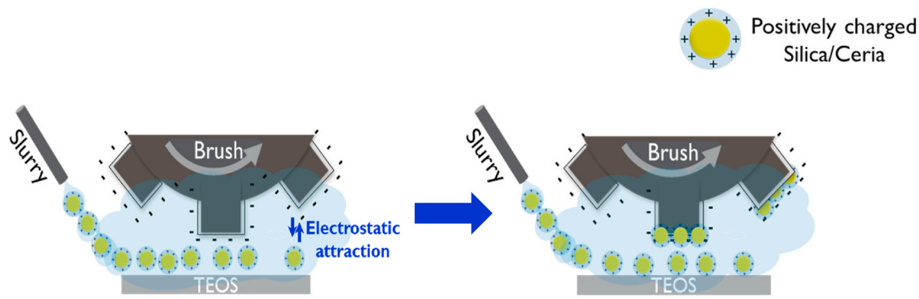
Fig. 3. Zeta potentials of the PVA brush and the ceria and silica particles measured at different pH.

3.2. *Evaluation of process parameters for PVA brush contamination*

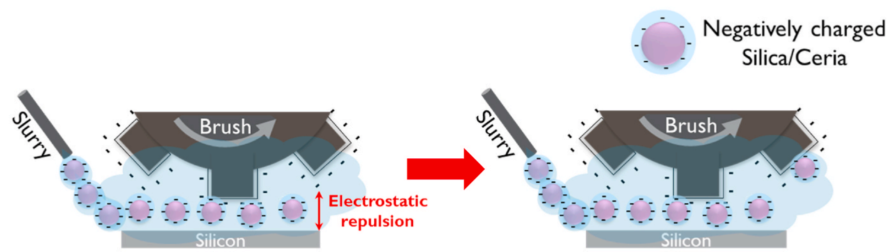
Significant contamination of the PVA brush was observed at pH 4 for both silica and ceria abrasives. Therefore, the effects of abrasives concentration were investigated using slurries at only pH 4 due to the higher level of contamination observed.

3.2.1. *Effect of abrasive concentration*

First, the brush contamination was evaluated with different concentrations of abrasives, as presented in Table 1, Fig. 5, and Fig. 6, indicating the effect of ceria and silica concentration on contamination of the PVA brush. It can be seen in Fig. 5(a–d) that the PVA brush contamination was increased by increasing the ceria concentration from 0.005 to 0.1 wt%. Similarly, increased ceria contamination of the brush was observed in the ICP-OES analysis results, with an increase in the abrasive concentration, as shown in Fig. 5(e). 0.05 wt% concentration of ceria slurry, providing significantly high contamination to the brush, was opted as an optimized concentration for further processing. Similar to the trend observed for ceria concentration, an increase in brush contamination was observed by increasing the silica concentration in slurry from 0.005 to 0.1 wt% as presented in Fig. 6(a–e). This increase in brush contamination by increasing abrasive concentration in the slurry was due to the higher availability of abrasive (ceria/silica) particles to



(a)



(b)

Fig. 4. Schematic representation of interaction mechanism between the PVA brush and abrasive particles (ceria and silica); (a) electrostatic attraction and (b) electrostatic repulsion between oppositely charged abrasive particles and the brush.

interact with the brush surface while maintaining the same electrostatic forces at pH 4. However, the brush contamination with ceria was more severe as compared to the silica for the same concentration of abrasives at pH 4. Therefore, this study concludes that at pH 4, the high concentration of ceria particles and the attractive electrostatic forces present between the brush and the ceria particles resulted in higher contamination. Hence the effect of other process parameters such as gap distance, rotation speed, and scrubbing time, was investigated further using only 0.05 wt% ceria slurries at pH 4.

3.2.2. Effect of gap distance

The gap distance can directly affect the pressures applied between the brush and the wafer during scrubbing, and shorter gap distances and higher compression improve particle removal due to increased drag force [31]. However, the gap distance might also influence the entrapment of particles in the brush during contamination or cleaning. This possible effect of gap distance was evaluated by employing different gap distances, as shown in Table 1. In Fig. 7(a-d), both the FE-SEM and ICP-OES results indicate that the contamination levels remained the same, and no significant effect of gap distance on brush contamination was observed. These results confirm that the physical forces applied during scrubbing did not affect the contamination level and that the electrostatic interaction was mainly responsible for the PVA brush contamination with ceria particles.

3.2.3. Effect of brush rotation speed

The effect of brush rotation speed is also an important factor that may play a vital role in PVA brush contamination during scrubbing. The rotation speeds significantly influence the drag/friction forces that are generated during scrubbing, which subsequently influence the particle removal efficiency of the process [31–33]. Therefore, different rotation speeds were used to study the effect of brush rotation on brush contamination (Table 1). The rotation speeds can affect the contact of the brush with the wafer as an increase in rotation speed increases the shear forces and torques generated during scrubbing that subsequently affects the particle removal from the wafer surface [32–36]. Initially, there were no particles present on the wafer surface, which reduces the significance of drag force or rotation speeds on brush contamination by scrubbing. As shown in Fig. 8, the increase in rotation speed resulted in only insignificant changes in the contamination level of the brush at all rotation speeds resulting in a similar level of ceria contamination to the brush. Furthermore, the DIW rinsing followed by contamination can remove the weekly attached particles. However, the presence of a higher concentration of abrasives on the brush after contamination at all rotation speeds indicates a strong interaction between the brush and abrasives such as a strong electrostatic interaction. Hence, the dominating effect of electrostatic interaction during the squeeze-release (stick-slip [34]) phenomenon controls the brush contamination by abrasives, which indicates that the rotation speed is not a major factor to consider regarding brush contamination by abrasives.

3.2.4. Effect of process time

The brush scrubbing time directly influences the cleaning performance, as the longer the processing time, the better the cleaning efficiency will be [22]. Therefore, to evaluate the effect of process time, the contamination process was performed as a function of time, as presented in Table 1 and shown in Fig. 9. It can be observed in Fig. 8 that the brush contamination with ceria particles increased with the increase in the scrubbing time. Unlike brush rotation speed and gap distance, the processing time was directly related to the contamination. These results demonstrate that a longer interaction time between the brush and the abrasive particles resulted in higher contamination with reduced process yield and brush life. Therefore, understanding the brush and abrasive interaction mechanism is important to control the cleaning process. This study signifies the importance of an effective conditioning process to address the high PVA brush contamination by ceria particles for future studies.

4. Conclusion

The interaction between PVA brushes and abrasives during post-CMP cleaning was investigated in this study. Silica and ceria, the most commonly used abrasives in CMP processes, were evaluated for their role in PVA brush contamination. An electrostatic repulsion present between silica and the PVA brushes resulted in very low contamination of silica particles under all pH conditions i.e., pH 4, 7, and 10. However,

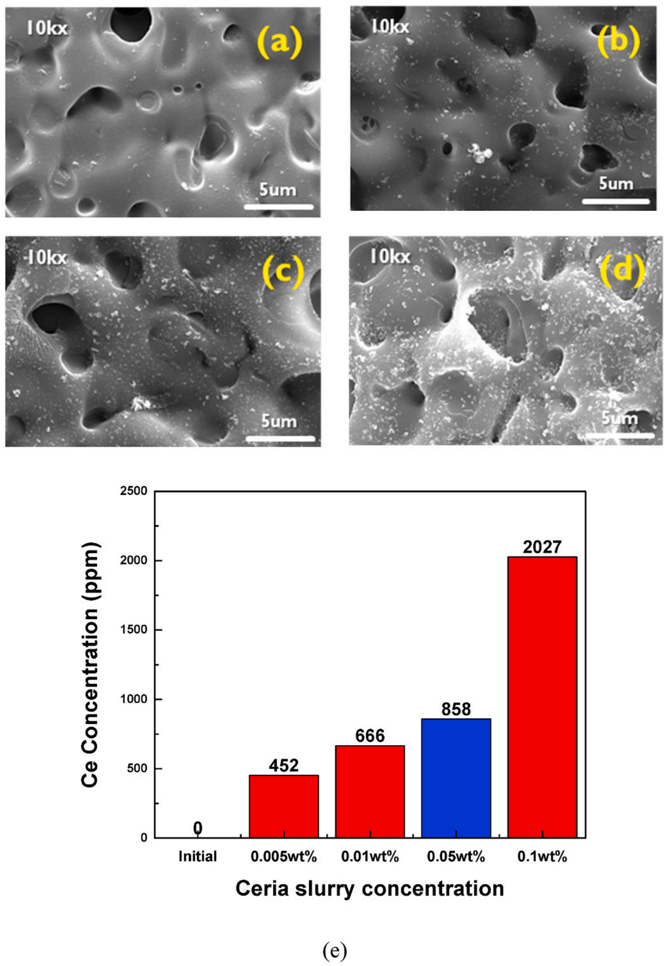


Fig. 5. The effect of ceria concentration on brush contamination after scrubbing with pH 4 ceria slurry; FE-SEM results for (a) 0.005 wt%, (b) 0.01 wt%, (c) 0.05 wt%, (d) 0.1 wt% ceria, and (e) ceria concentrations in the brush by ICP-OES.

the interaction between ceria and the PVA brushes varied based on the slurry pH. At pH 4, the ceria and the brush exhibited an electrostatic attraction that resulted in very high contamination of the brush surface. With the increase in the pH, the reduction in electrostatic attraction produced reduced contamination at pH 7 and 10. At pH 4, several other scrubbing process parameters were evaluated to better understand the high brush contamination by ceria particles. The gap distance and brush rotation speed showed an insignificant effect on brush contamination, whereas the brush contamination increased significantly with increases in the abrasive concentration and processing time. Very high PVA brush contamination was observed for 0.05 wt% ceria particles at pH 4 at a processing time of 5 min. Therefore, it can be stated that brush contamination strongly depends on the type of interaction between the abrasives and the brushes that need to be controlled for improved process efficiencies. The interactions investigated in this study can be applied to optimize brush cleaning processes for improved process yields and longer brush life.

CRediT authorship contribution statement

Samrina Sahir: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hwi-Won Cho:** Investigation, Formal analysis. **Palwasha Jalalzai:** Investigation. **Suprakash Samanta:** Supervision. **Satomi Hamada:** Supervision. **Tae-Gon Kim:** Supervision. **Jin-Goo Park:** Writing –

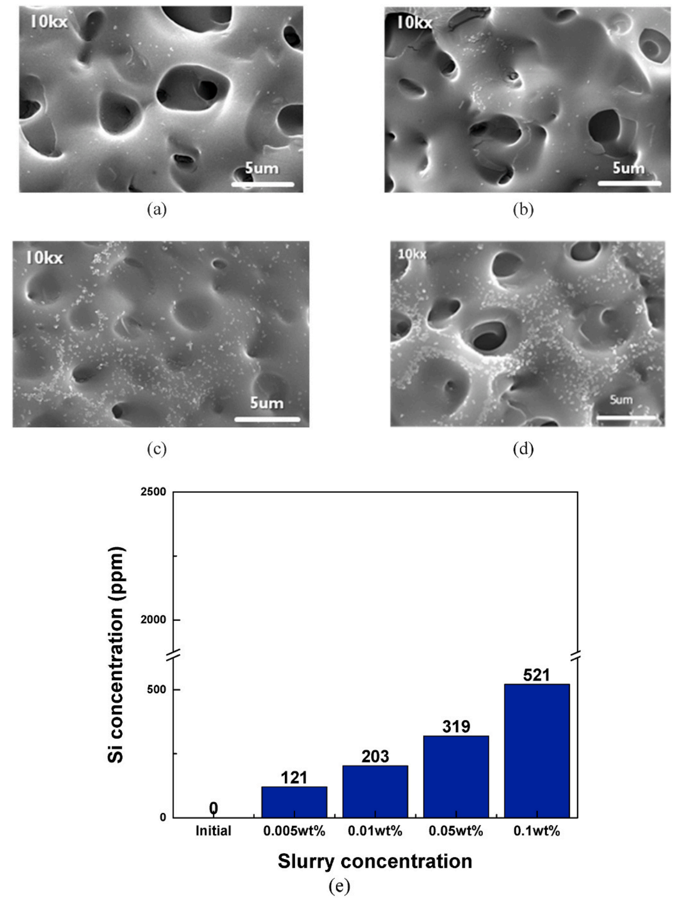


Fig. 6. The effect of silica concentration on brush contamination after scrubbing with pH 4 silica slurry; FE-SEM results for (a) 0.005 wt%, (b) 0.01 wt%, (c) 0.05 wt%, (d) 0.1 wt% silica, and (e) silica concentrations in the brush by ICP-OES.

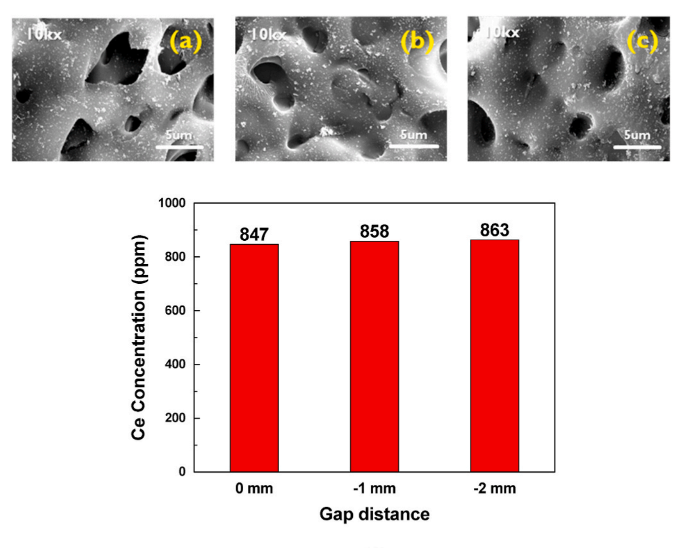
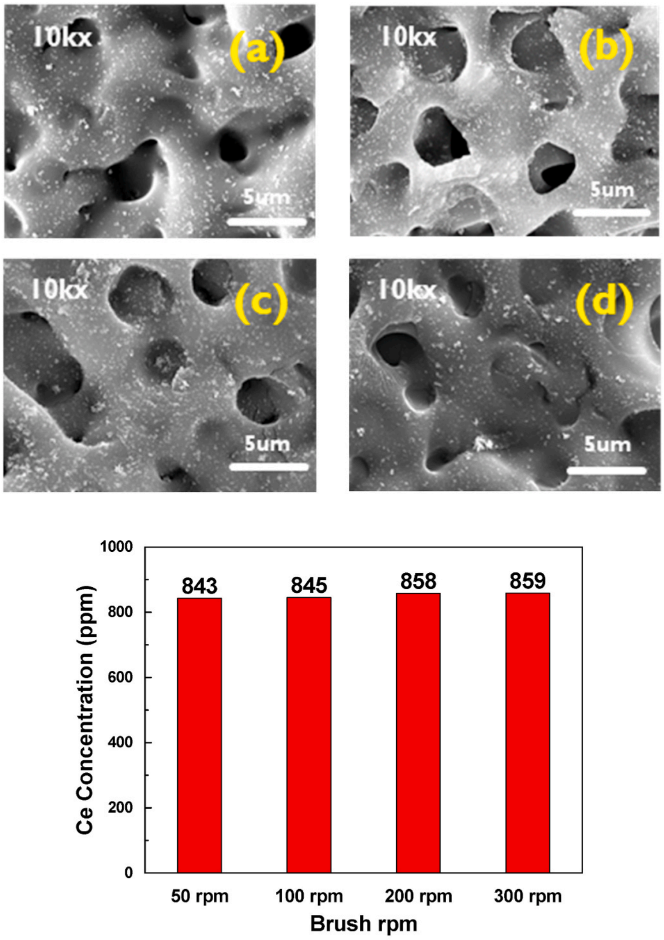


Fig. 7. The effect of gap distance on brush contamination with pH 4 ceria slurry (0.05 wt%); FE-SEM images for (a) 0 mm, (b) −1 mm, (c) −2 mm gap distance, and (d) ceria concentration in the brush by ICP-OES.



(e)

Fig. 8. The effect of brush rotation speed on brush contamination (0.05 wt% ceria slurry at pH 4); FE-SEM images for (a) 50 rpm, (b) 100 rpm, (c) 200 rpm, (d) 300 rpm rotation speed, and (b) ceria concentration in the brush by ICP-OES.

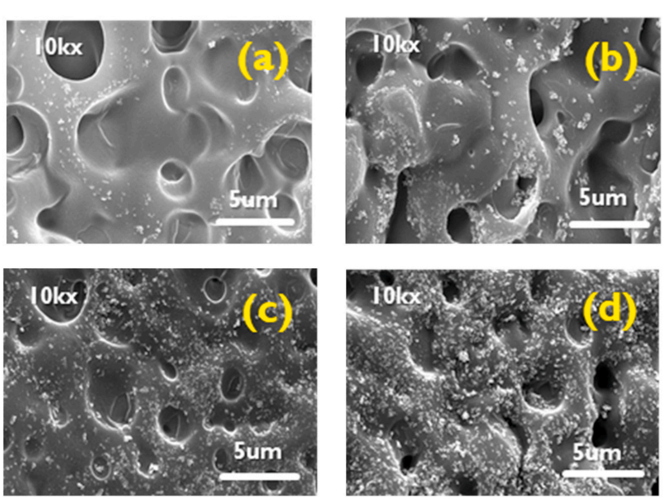


Fig. 9. The effect of scrubbing time on brush contamination with ceria slurry (0.05 wt% and pH 4); FE-SEM images for (a) 30 s, (b) 1 min, (c) 3 min, and (d) 5 min scrubbing.

review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] K.S. Gokhale, B.M. Moudgil, Particle technology in chemical mechanical planarization, Kona-Powder and Particle 25 (2007) 88–96, https://doi.org/10.14356/kona.2007010.

[2] R.R. Schaller, Moore's law: past, present, and future, IEEE Spectrum 34 (1997) 52–59, https://doi.org/10.1109/6.591665.

[3] D. Roy, Perspective-electrochemical assessment of slurry formulations for chemical mechanical planarization of metals: trends, benefits and challenges, ECS J. Solid State Sci. Technol. 7 (2018) P209–P212, https://doi.org/10.1149/2.0231804jss.

[4] M. Tsujimura, Enhanced open innovation: CMP innovation to open new paradigm, ECS J. Solid State Sci. Technol. 8 (2019) P3098–P3105, https://doi.org/10.1149/2.0161905jss.

[5] M. Krishnan, J.W. Nalaskowski, L.M. Cook, Chemical mechanical planarization: slurry chemistry, materials, and mechanisms, Chem. Rev. 110 (2010) 178–204, https://doi.org/10.1021/cr900170z.

[6] Y. Huang, D. Guo, X. Lu, J. Luo, Mechanisms for nanoparticle removal in brush scrubber cleaning, Appl. Surf. Sci. 257 (7) (2011) 3055–3062, https://doi.org/10.1016/j.apsusc.2010.10.115.

[7] W.-T. Tseng, C. Wu, T. McCormack, J.C. Yang, Post cleaning for FEOL CMP with silica and ceria slurries, ECS J. Solid State Sci. Technol. 6 (2017) P718–P722, https://doi.org/10.1149/2.0101710jss.

[8] K. Mikhaylichenko, High Shear Force Chemical Mechanic Cleaning for CMP Defect Reduction, Surface Preparation and Cleaning Conference (SPCC 2017), 2017. Austin, Texas, USA.

[9] G. Zhang, G. Burdick, F. Dai, T. Bibby, S. Beaudoin, Assessment of post-CMP cleaning mechanisms using statistically-designed experiments, Thin Solid Films 332 (1998) 379–384, https://doi.org/10.1016/S0040-6090(98)01038-4.

[10] P.B. Zantye, A. Kumar, A.K. Sikder, Chemical mechanical planarization for microelectronics applications, Mater. Sci. Eng. R Rep. 45 (2004) 89–220, https://doi.org/10.1016/j.mser.2004.06.002.

[11] K. Xu, R. Vos, G. Vereecke, G. Doumen, W. Fyen, P.W. Mertens, M.M. Heyns, C. Vinckier, J. Fransaer, Particle adhesion and removal mechanisms during brush scrubber cleaning, J. Vac. Sci. Technol. B 22 (2004) 2844–2852, https://doi.org/10.1116/1.1815319.

[12] J.C. Yang, Nano-Scale Scratch Impact on 7nm Device and its Improvement by Predictable CMP Process Conditions, SEMICON KOREA, 2017.

[13] J.C. Yang, H.J. Kim, V. Govindarajulu, D. Koli, J. Mazzotti, Research Activities on Defect Improvement of CMP Process in 1x Nm Foundry Device, CMPUGM, Korea, 2016.

[14] T.H. Lee, Post-CMP In-Situ Cleaning Process Challenges for 14/7nm Nodes, 25th Korea Surface Cleaning User Group Meeting, Korea, 2017.

[15] G. Chen, Z. Ni, Y. Bai, Q. Lia, Y. Zhao, The role of interactions between abrasive particles and the substrate surface in chemical-mechanical planarization of Si-face 6H-SiC, Royal Soc. Chem. 7 (2017) 16938–16952, https://doi.org/10.1039/C6RA27508G.

[16] S. Sahir, H.-W. Cho, T.-G. Kim, S. Hamada, N.P. Yerriboina, J.-G. Park, Study on PVA brush loading and conditioning during shallow trench isolation post-CMP cleaning process, ECS J. Solid State Sci. Technol. 11 (2022), 024004, https://doi.org/10.1149/2162-8777/ac5166.

[17] J.H. Lee, M.K. Poddar, K.-M. Han, H.-Y. Ryu, N.P. Yerriboina, T.-G. Kim, Y. Wada, S. Hamada, H. Hiyama, J.-G. Park, Comparative evaluation of organic contamination sources from roller and pencil type PVA brushes during the post-CMP cleaning process, Polym. Test. 90 (2020), 106669, https://doi.org/10.1016/j.polymertesting.2020.106669.

[18] H.J. Kim, Effect of brush treatment and brush contact sequence on cross-contaminated defects during CMP in-situ cleaning, J. Korean Soc. Tribologists Lubrication Engineers 31 (2015) 239–244, https://doi.org/10.9725/kstle.2015.31.6.239.

[19] J.H. Lee, H.-Y. Ryu, J.-K. Hwang, N.P. Yerriboina, T.-G. Kim, S. Hamada, Y. Wada, H. Hiyama, J.-G. Park, A breakthrough method for the effective conditioning of PVA brush used for post-CMP process, ECS J. Solid State Sci. Technol. 8 (6) (2019) P307–P312, https://doi.org/10.1149/2.0111906jss.

[20] J.H. Lee, M.K. Poddar, N.P. Yerriboina, H.-Y. Ryu, K.-M. Han, T.-G. Kim, S. Hamada, Y. Wada, H. Hiyama, J.-G. Park, Ultrasound-induced break-in method for an incoming polyvinyl acetal (PVA) brush used during the post-CMP cleaning process, Polym. Test. 78 (2019), 105692, https://doi.org/10.1016/j.polymertesting.2019.105962.

[21] H.J. Kim, G. Bohra, H. Yang, S.G. Ahn, L. Qin, D. Koli, Study of the cross-contamination effect on post-CMP in situ cleaning process, Microelectron. Eng. 136 (2015) 36–41, https://doi.org/10.1016/j.mee.2015.03.033.

[22] H.C. Cho, Y.M. Kim, H.S. Lee, S.B. Joo, H.D. Jeong, The effect of PVA brush scrubbing on post-CMP cleaning process for damascene Cu interconnection, Solid State Phenom. 145–146 (2009) 367–370. https://doi.org/10.4028/www.scientific.net/SSP.145-146.367.

[23] J. An, Y. Park, H. Jeong, Structural effect of PVA brush nodule on particle removal efficiency during brush scrubber cleaning, Int. J. Precis. Eng. Manuf. 13 (2012) 451–454, https://doi.org/10.1007/s12541-012-0058-7.

[24] J. Gulicovski, I. Bračko, S.K. Milonjić, Morphology and the isoelectric point of nanosized aqueous ceria sols, Mater. Chem. Phys. 148 (2014) 868–873, https://doi.org/10.1016/j.matchemphys.2014.08.063.

[25] H.J. Kim, Abrasive for Chemical Mechanical Polishing, Abrasive Technology: Characteristics and Applications, 2018, https://doi.org/10.5772/intechopen.72364.

[26] X. Gua, T. Nemoto, A. Teramoto, T. Ito, S. Sugawa, T. Ohmi, Reduction of scratch on brush scrubbing in post-CMP cleaning by analyzing contact kinetics on ultra low-k dielectric, ECS Trans. 19 (7) (2009) 103–109, https://doi.org/10.1149/1.3123779.

[27] K.-M. Han, S.-Y. Han, S. Sahir, N.P. Yerriboina, T.-G. Kim, N. Mahadev, J.-G. Park, Contamination mechanism of ceria particles on the oxide surface after the CMP process, ECS J. Solid State Sci. Technol. 9 (2020), 124004, https://doi.org/10.1149/2162-8777/abcf13.

[28] S. Sahir, N.P. Yerriboina, S.-Y. Han, K.-M. Han, T.-G. Kim, N. Mahadev, J.-G. Park, Investigation of the effect of different cleaning forces on Ce-O-Si bonding during oxide post-CMP cleaning, Appl. Surf. Sci. 545 (2021), 149035, https://doi.org/10.1016/j.apsusc.2021.149035.

[29] J.A.A. Júnior, J.B. Baldo, The behavior of zeta potential of silica suspensions, New J. Glass Ceram. 4 (2) (2014) 29–37, https://doi.org/10.4236/njgc.2014.42004.

[30] J. Seo, J.W. Lee, J. Moon, W. Sigmund, U. Paik, Role of the surface chemistry of ceria surfaces on silicate adsorption, ACS Appl. Mater. Interfaces 6 (2014) 7388–7394, https://doi.org/10.1021/am500816y.

[31] K. Xu, R. Vos, G. Vereecke, G. Doumen, W. Fyen, P.W. Martens, M.M. Heyns, C. Vinckier, J. Fransaer, F. Kovacs, Fundamental study of the removal mechanisms of nano-sized particles using brush scrubber cleaning, J. Vac. Sci. Technol. B 23 (5) (2005) 2160–2175, https://doi.org/10.1116/1.2052713.

[32] A.A. Busnaina, H. Lin, N. Moumen, J.-W. Feng, J. Taylor, Particle adhesion and removal mechanisms in post-CMP cleaning processes, IEEE Trans. Semicond. Manuf. 15 (4) (2002) 374–382, https://doi.org/10.1109/TSM.2002.804872.

[33] M. Ito, T. Sanada, A. Fukunaga, H. Hiyama, Brush deformation effects on poly vinyl acetal brush scrubbing, ECS J. Solid State Sci. Technol. 7 (4) (2018) P201–P208, https://doi.org/10.1149/2.0191804jss.

[34] T. Miyakia, T. Sanada, Y. Mizushima, A. Fukunaga, H. Hiyama, Contact area distribution during PVA brush scrubbing, ECS Trans. 92 (2) (2019) 183–189, https://doi.org/10.1149/09202.0183ecst.

[35] Y. Sampurno, Y. Zhuang, X. Gu, S. Theng, T. Nemoto, T. Sun, F. Sudargho, A. Teramoto, A. Philipossian, T. Ohmi, Effect of various cleaning solutions and brush scrubber kinematics on the frictional attributes of post copper CMP cleaning process, Solid State Phenom. 145–146 (2009) 363–366. https://doi.org/10.4028/www.scientific.net/SSP.145-146.363.

[36] W. Peng, C. Guan, S. Li, Efficient fabrication of ultrasmooth and defect-free quartz glass surface by hydrodynamic effect polishing combined with ion beam figuring, Opt Express 22 (11) (2014) 1395–13961, https://doi.org/10.1364/OE.22.013951.