

High efficiency chemical mechanical polishing for silicon wafers using a developed slurry

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ABSTRACT

Improving the material removal rate (MRR) of silicon wafers is a challenge in chemical mechanical polishing (CMP), to meet the demands of the development of integrated circuits. In this study, four environmentally friendly additives, including sorbitol, gluconic acid, citric acid, and ammonium citrate, were incorporated into polishing slurries to promote the MRR of silicon wafers. The polishing results reveal that the highest MRR was obtained by ammonium citrate as an additive. When the concentration of ammonium citrate was 0.05 mol/L, the MRR increased by 71.6% to 1979.88 Å/min, and the surface roughness Sa was decreased from 1.131 nm to 0.563 nm. Meanwhile, the polishing slurry containing colloidal silica as abrasives maintained good dispersibility. Polishing mechanism was interpreted using electrochemical analysis, X-ray photoelectron spectroscopy, and coefficient of friction tests. It is indicated that NH_4^+ ions, generated by hydrolysis of ammonium citrate, could modify the electrical characteristics of the silicate layer and catalyze the chemical reactions between Si atoms and H_2O on the surface of silicon wafers. This work emphasizes the interfacial action between the polishing slurry and silicon wafers and provides a new idea for high efficiency CMP of silicon wafers in the manufacture of integrated circuits and photovoltaic industry.

1. Introduction

Silicon is the most widely used semiconductor material in the field of integrated circuits (ICs) and photovoltaic industry due to its abundance, low cost, and remarkable synergy with silicon dioxide [1–4]. In the manufacture of ICs, chemical mechanical polishing (CMP) is employed as the only global planarization technology for processing silicon wafers [5,6]. As the feature size of ICs decreases and the size of silicon wafers increases, higher requirements of the material removal rate (MRR) are placed on the CMP process of silicon wafers [7]. More efforts have focused a lot of attention on the development of polishing slurry. Generally, polishing slurry, consisting of abrasive particles, pH regulators, chemical additives, and deionized (DI) water, which is a key factor affecting the MRR of silicon wafers during the polishing process [8].

At present, numerous studies have been conducted on the effects of polishing slurries on the CMP of silicon wafers. However, corrosive and/or toxic chemical additives are still broadly applied in polishing slurries

for the CMP of silicon wafers. For instance, Bae [9] utilized ethylenediamine and diethylenetriamine to accelerate the hydrolysis reaction of Si atoms on the silicon surface, resulting in increased MRR of silicon wafers. Unfortunately, these chemicals are harmful to human health and the environment [10,11]. In an effort to study the impact of amines on the MRR of silicon wafers, Dandu [12,13] prepared an abrasive-free polishing slurry containing the extremely flammable and toxic chemical, ethylamine. Hwang [14] adopted ammonium hydroxide as an additive in the polishing slurry to evaluate the influence on the surface quality of silicon wafers after polishing, while ammonium hydroxide is a reagent that is harmful to the natural environment. The presence of non-environmentally friendly chemical additives in polishing slurries not only poses a hazard to humans and the natural environment but also increases the cost of subsequent waste liquid treatment [15]. This contradicts the idea of green processing and manufacturing [16].

During the CMP process, Si atoms on the surface of the silicon wafers react with OH^- and H_2O in the polishing slurry to form a layer of

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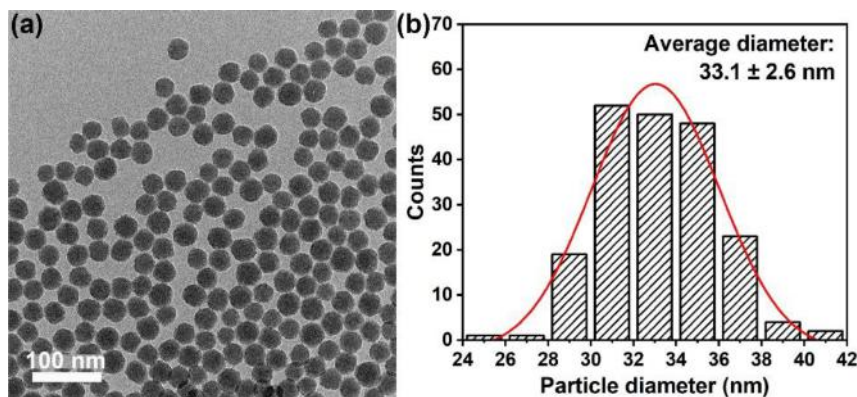
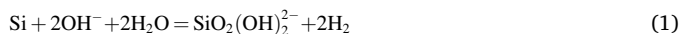


Fig. 1. The TEM image (a) and particle diameter distribution (b) of the SiO_2 particles.

silicates (Eq. (1)) in an alkaline environment [17]. This generated layer is subsequently removed by the abrasive particles under the action of pressure and rotational speed [18]. This is the typical mechanism of material removal during the polishing process. However, the complexity of polishing mechanism implies that other ions in polishing slurry may be involved in the intricate coupling reaction. This means that the MRR of silicon wafers could be improved by adding cations or anions to the preparing slurry [19]. Therefore, in order to improve the MRR and further understand the polishing mechanism, the synergistic effect between the ions in polishing slurry, polishing pad and silicon could be profoundly explored in detail.



In this study, four environmentally friendly additives, sorbitol, gluconic acid, citric acid, and ammonium citrate, were mixed into the polishing slurries to investigate the effects of the additives on the MRR of silicon wafers. Emphatically, the impact of ammonium citrate concentration on the MRR was then examined. Electrochemical tests, coefficient of friction (COF), and X-ray photoelectron spectroscopy (XPS) analysis were performed to comprehend and validate the mechanisms of the additives in CMP for efficiently enhancing the MRR.

2. Materials and methods

2.1. Materials

Potassium hydroxide (KOH), sorbitol ($\text{C}_6\text{H}_{14}\text{O}_6$), gluconic acid ($\text{C}_6\text{H}_{12}\text{O}_7$), and citric acid ($\text{C}_6\text{H}_8\text{O}_7$) were all purchased from Sinopharm Chemical Reagent Co., Ltd. Ammonium citrate ($\text{C}_6\text{H}_5\text{O}_7(\text{NH}_4)_3$) was acquired from Shanghai Macklin Biochemical Co., Ltd. All of the above-mentioned reagents are analytical. The SiO_2 particles were synthesized at the Dalian Institute of Chemical Physics and have an average diameter of 33.1 nm. 18.25 M Ω ·cm deionized (DI) water was utilized throughout all the experiments in this work.

2.2. CMP tests

SiO_2 particles, KOH, environmentally friendly additives (such as sorbitol, gluconic acid, citric acid, and ammonium citrate), and DI water made up several 400 mL polishing slurries. KOH was used to regulate the pH of the polishing slurry to 10.5.

4-in. silicon wafers (p-type, <100>), Jingxin Electronic Technology Co., Ltd) were polished on the UMT-TriboLab CMP machine (Bruker Corporation, USA). During the polishing process, the polishing pressure was set as 2.8 psi, the carrier/platen rotational speed as 87/80 rpm, the polishing slurry flow rate as 80 mL/min, and the polishing time as 2 min. A polyurethane polishing pad (Sub 400&IC1000, Dow Electronic Materials, USA) was employed for the tests. The polishing pad was

conditioned with a diamond grit conditioner (3 M Company, USA) for 30 s under 0.175 psi pressure before each CMP test. After CMP, the silicon wafers were cleaned with absolute ethanol and nonwovens and then dried with compressed air.

2.3. MRR and surface roughness after CMP tests

The mass loss of silicon wafers before and after CMP was weighted to calculate the MRR of polishing. The equation of calculation is as below [20]:

$$\text{MRR} = \frac{\Delta m}{\rho \cdot s \cdot t} \quad (2)$$

Where Δm is the mass loss before and after polishing, ρ is the density of silicon (2.33 g/cm^3), s is the area of the silicon wafer, and t is the polishing time. A precision electronic balance (ESJ200-4A, Longteng Electronics Co., Ltd, China) was employed to measure the mass loss of the wafers, and its weight resolution is 0.1 mg.

The surface roughness and morphologies of wafers before and after CMP were characterized by a 3D non-contact optical surface profiler (New View TM 9000, ZYGO, USA) and atomic force microscope (AFM, NanoWizard, Bruker, USA).

2.4. Characterizations of abrasive particles

A Malvern Zeta-sizer Nano instrument (Nano-ZS90, Thermo Fisher Scientific, USA) was used to measure the hydrodynamic diameter, polydispersity index (PDI), and zeta potential of the SiO_2 particles, as well as the conductivity of the polishing slurry. The morphology of particles was characterized by an environmental transmission electron microscope (ETEM, Titan Themis G3, Thermo Fisher Scientific, USA).

2.5. Electrochemical tests

Before the electrochemical experiments, the silicon slices were lapped with SiC sandpaper. Then, they were ultrasonic cleaned and dried using absolute ethanol and compressed air, respectively. The polishing slurries containing sorbitol, gluconic acid, citric acid, and ammonium citrate as additives were used as the electrolytes during the tests, whereas the control group of the slurry was without additives. The potentiodynamic polarization curves were measured utilizing the three-electrode setup of the electrochemical workstation (CHI760E, Shanghai Chenhua, China). The silicon slices were employed as the working electrode, the platinum electrode as the counter electrode, and the Ag/AgCl electrode as the reference electrode. The scan rate was set as 0.005 V/s during the electrochemical tests.

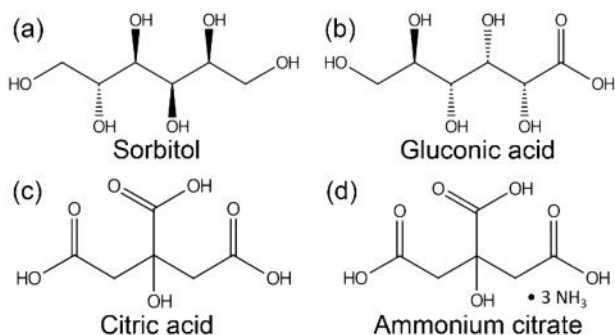


Fig. 2. The chemical structure of sorbitol (a), gluconic acid (b), citric acid (c) and ammonium citrate (d).

2.6. XPS tests

Before the XPS tests, the native oxide layer on the silicon surface was removed using an HF aqueous solution ($\text{H}_2\text{O}:\text{HF} = 1:50$) for 1 min, followed by a DI water rinse and hot air drying. Then, one of the prepared slices was used as the control group without any process, and the other two were immersed into the polishing slurries with 0 and 20 mmol ammonium citrate, respectively, for 15 min at 60°C . DI water and hot air were used again to clean and dry the slices after immersion. An XPS analyzer (Escalab 250 Xi, Thermo Fisher Scientific, USA) with an Al K α x-ray source was adopted for the tests. CAE mode (Pass Energy 20.0 eV, 0.1 eV step size) was employed for high-resolution spectra. All binding energies were calibrated with carbon at $\text{C } 1 \text{ s} = 284.8 \text{ eV}$.

3. Results and discussion

3.1. Abrasive particles characterization

Fig. 1 shows the morphology and particle diameter distribution of the SiO_2 particles used in the polishing slurries. It can be seen from Fig. 1 (a), the spherical particles are monodisperse and no agglomeration occurs before being mixed into the polishing slurries. Also, the average diameter of the SiO_2 particles is $33.1 \pm 2.6 \text{ nm}$, and they mainly have a concentrated distribution between 30 and 36 nm (Fig. 1(b)).

3.2. Effects of additives on the MRR

Sorbitol, gluconic acid, citric acid, and ammonium citrate are the four kinds of green additives and were introduced into the polishing slurries. These four additives have similar structures and their chemical structures are shown in Fig. 2. Sorbitol and citric acid are widely distributed in fruits, and gluconic acid and ammonium citrate are produced by glucose and citric acid, respectively. All of them are non-toxic and friendly to both human and the environment [21–24].

It is well known that while ammonium citrate will entirely dissociate in alkaline environments, sorbitol does not dissociate. When dissociation takes place in solutions with various pH values, gluconic acid and

citric acid will generate diverse compounds. Fig. 3 displays the distribution of compounds generated by the dissociation of gluconic acid and citric acid in solution at various pH values. When the pH of the polishing slurries was adjusted to 10.5, complete dissociation of gluconic acid and citric acid occurs in the slurries, producing $\text{C}_6\text{H}_{11}\text{O}_7^-$ and $\text{C}_6\text{H}_5\text{O}_7^{3-}$, respectively. This is to say, gluconic acid, citric acid, and ammonium citrate, as additives, will be completely dissociated in the polishing slurries for silicon wafers polishing, except for sorbitol.

The effects of various additives introduced to the polishing slurries on the MRR of silicon wafers and the ionic strength of the slurries after the pH was adjusted to 10.5 using KOH were shown in Fig. 4. The polishing slurry without additives was set as the control group and the MRR of that were $1037.58 \text{ \AA}/\text{min}$. Compared with the control group, the MRR of silicon wafers with sorbitol as an additive in the polishing slurry decreased to $963.47 \text{ \AA}/\text{min}$, but the MRR with gluconic acid, citric acid, and ammonium citrate as additives increased significantly to 1201.69, 1418.74 and $1725.78 \text{ \AA}/\text{min}$, respectively. As sorbitol would be adsorbed on the surface of the silicon wafers and prevented the chemical reaction of Si atoms on the surface with OH^- ions and H_2O , the MRR decreased when sorbitol was used as an additive [25].

The explanation for the increase in MRR is that the ionic strength of the polishing slurries dramatically increased compared to the control group after the introduction of the additives, and the higher the ionic strength, the higher the MRR [26]. Since gluconic acid, citric acid and ammonium citrate additives are all acidic chemicals, more KOH is needed to raise the pH of the polishing slurries to 10.5, which results in a large amount of K^+ ions being introduced into the slurries. This is the cause of the enhanced ionic strength of the polishing slurries. When citric acid was used as an additive, the ionic strength of the polishing slurry was higher than that of gluconic acid as an additive, due to the stronger acidity of citric acid. The NH_4^+ ions dissociated from ammonium citrate in the polishing slurry raised the ionic strength when ammonium

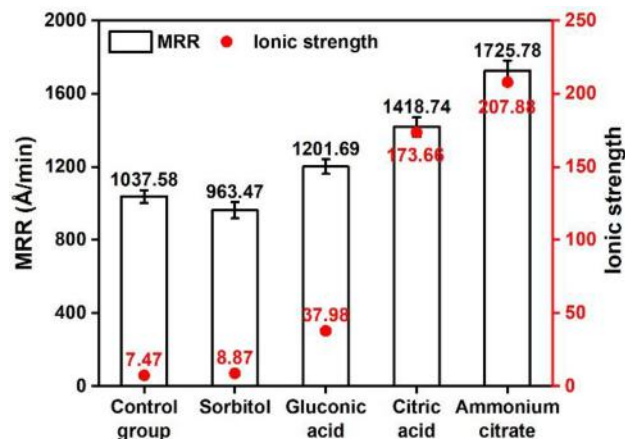


Fig. 4. Effects of the different additives in the polishing slurries on the MRR and the ionic strength of the polishing slurries at 10.5 pH.

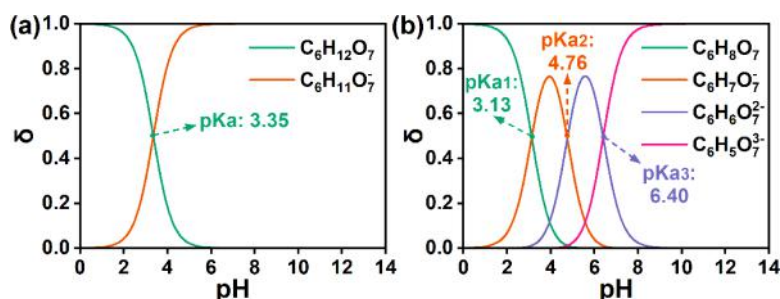


Fig. 3. Distribution coefficients of several species after the dissociation of citric acid (a) and ammonium citrate (b) at various pH conditions.

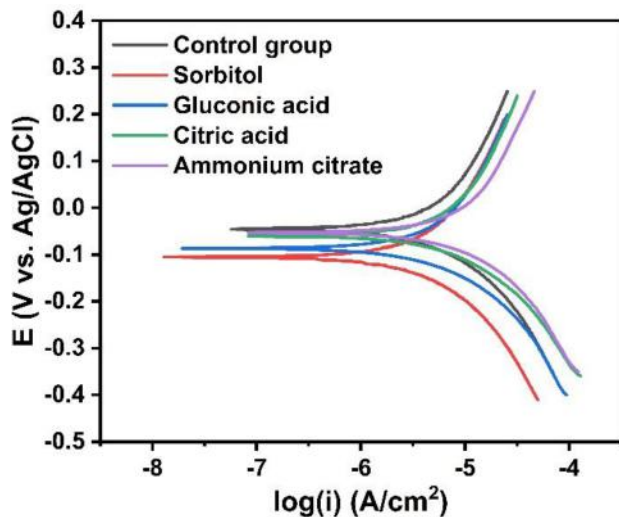


Fig. 5. The potentiodynamic polarization curves of silicon wafers in polishing slurries with various additives.

Table 1

E_{corr} and I_{corr} values of working electrode obtained from the potentiodynamic polarization curves.

Additives	Control group	Sorbitol	Gluconic acid	Citric acid	Ammonium citrate
E_{corr} (V)	-0.046	-0.105	-0.087	-0.061	-0.053
I_{corr} (A/cm ²)	4.83×10^{-6}	3.68×10^{-6}	5.19×10^{-6}	7.40×10^{-6}	9.46×10^{-6}

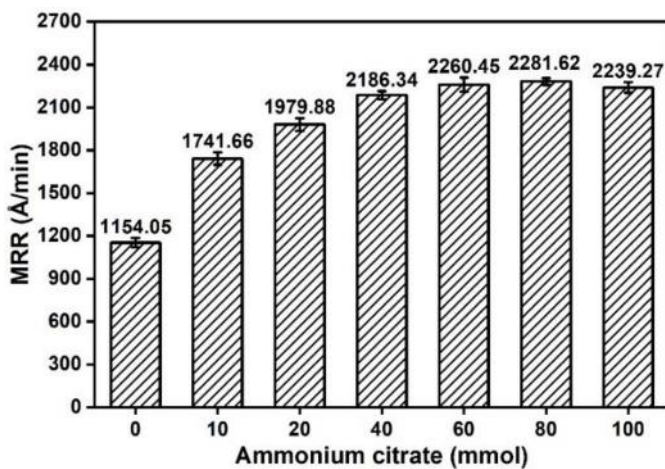


Fig. 6. The MRR of silicon wafers polished by slurries with various amount of ammonium citrate.

citrate was used as an additive, even though citric acid is more acidic than ammonium citrate. This experiment demonstrates that the main cause of the increase in MRR is a rise in the ionic strength of the polishing slurries; in other words, the introduction of K^+ ions and NH_4^+ ions in polishing slurries can increase the MRR of silicon wafers.

3.3. Electrochemical analysis

To investigate the mechanism of the 4 types of additives on the MRR of silicon wafers, the potentiodynamic polarization curves of silicon wafers in polishing slurries with different additives were analyzed using an electrochemical workstation, as depicted in Fig. 5. Table 1 lists the

self-corrosion voltage (E_{corr}) and self-corrosion current density (I_{corr}) values of silicon wafers. The I_{corr} of gluconic acid, citric acid, and ammonium citrate as additives all increased when compared to the control group, except for sorbitol as an additive, which decreased, and the I_{corr} of ammonium citrate was the highest, reaching 9.46×10^{-6} A/cm². I_{corr} can be used to characterize the corrosion rate of the slurries on the silicon wafers, and the higher the I_{corr} , the faster the corrosion rate [27]. As a result, the use of ammonium citrate as an additive in the polishing slurry results in the highest corrosion rate to silicon wafers and the lowest corrosion rate was gained when sorbitol was added to the slurry. These results are consistent with the MRR results obtained with various additives (Fig. 4).

3.4. Effects of ammonium citrate on the MRR and surface roughness

Since the MRR of silicon wafers was highest when ammonium citrate was used as an additive, the impact of the concentration of ammonium citrate on the MRR was investigated. Fig. 6 shows the variation of MRR with increasing the amount of ammonium citrate. The polishing slurry without ammonium citrate as an additive got an MRR of 1154.05 Å/min. The MRR reached a maximum of 2281.62 Å/min as the concentration of ammonium citrate rose to 80 mmol, and then began to decrease slightly as the concentration rose to 100 mmol. This demonstrates that the addition of appropriate concentration of ammonium citrate to the polishing slurry has a significant effect on the MRR of silicon wafers.

The roughness and surface morphologies of silicon wafers before and after CMP with a polishing slurry containing 20 mmol ammonium citrate as an additive were measured using an optical surface profiler and AFM, as illustrated in Fig. 7. The initial roughness S_a and S_z of the silicon wafer before CMP were found to be 1.115 and 12.077 nm in a measurement area of $868.148 \times 868.148 \mu m^2$ (Fig. 7(a)) and 1.131 and 22.070 nm in a measurement area of $10 \times 10 \mu m^2$, respectively. Following CMP, the roughness S_a and S_z of the wafer were decreased to 0.681 and 9.192 nm in a measurement area of $868.148 \times 868.148 \mu m^2$ and 0.563 and 10.690 nm in a measurement area of $10 \times 10 \mu m^2$, respectively. The use of ammonium citrate as an additive in the polishing slurry resulted in an enhancement of the surface quality of the silicon wafers.

3.5. Effects of ammonium citrate on the parameters of polishing slurry

Polishing slurry is a crucial part of the CMP technology and the stability of the slurry is an important parameter to measure its performance [8,28]. Large particles formed by agglomeration of the SiO_2 particles are the main cause of scratches and damage to silicon wafers during the polishing process [29,30]. Fig. 8 shows the influences of ammonium citrate concentrations on the diameter distribution and the zeta potential of the SiO_2 particles and the conductivity of the polishing slurries. As can be seen in Fig. 8(a), the diameter distribution curves of SiO_2 particles in polishing slurries containing various concentrations of ammonium citrate are all single peaks. However, when the concentration raised to 60, 80, and 100 mmol, the peaks of the curves shifted to the right. The increases in the mean particle diameter indicated that slight agglomeration of the SiO_2 particles in the polishing slurry when the concentration of ammonium citrate exceeded 40 mmol. Fig. 8(b) depicts that as the concentration of ammonium citrate reached 60 mmol, the absolute value of the particles' zeta potential declined to a minimum and then began to rise. The double electric layer on the surface of the SiO_2 particles was compressed as a result of NH_4^+ ions being adsorbed onto the particles' surface. This is the reason for the decrease in zeta potential. The zeta potential increased may be due to the agglomeration of particles. The concentration of $C_6H_5O_7^{3-}$ and NH_4^+ ions in the polishing slurries was the cause of the constant increase in the conductivity of the polishing slurry.

It was found from Fig. 8(a) that the SiO_2 particles in the polishing slurries had a slight agglomeration when the concentration of

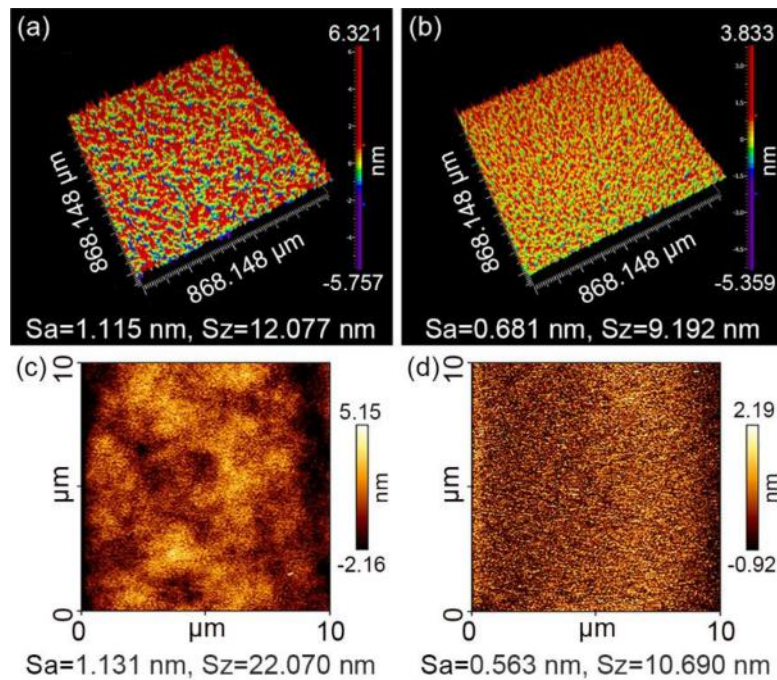


Fig. 7. Surface morphology of the silicon wafers before (a), (c) and after CMP (b), (d) using a polishing slurry with 20 mmol ammonium citrate as an additive.

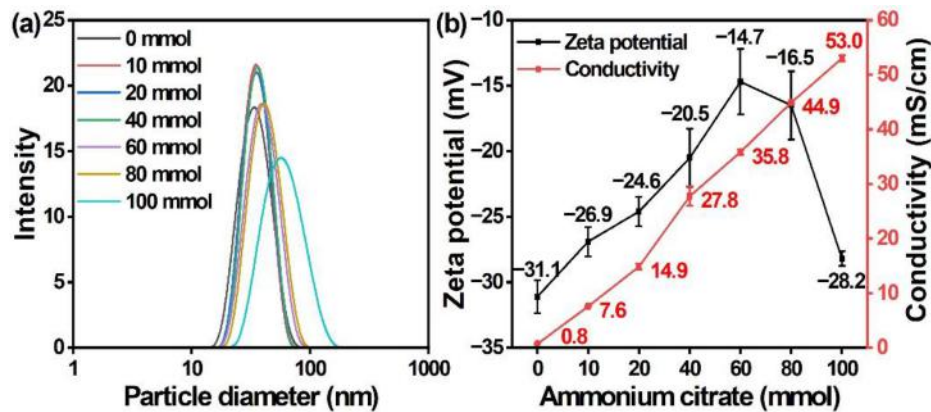


Fig. 8. Influences of ammonium citrate concentrations on (a) the diameter distribution of SiO_2 particles, (b) the zeta potential of SiO_2 particles and conductivity of the slurry.

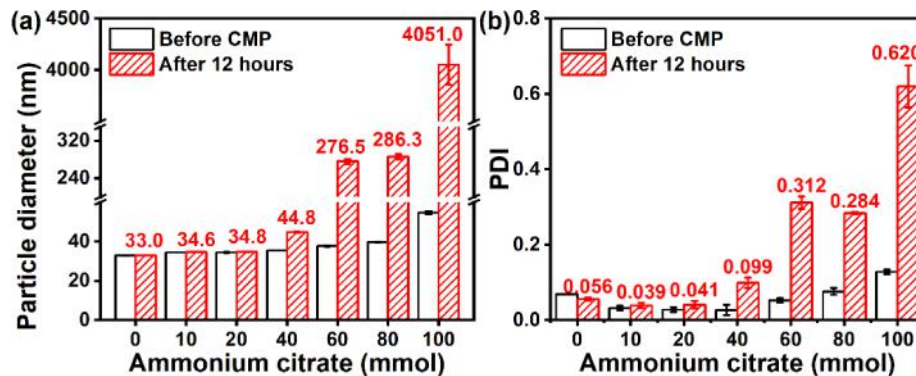


Fig. 9. Influences of ammonium citrate concentration on (a) the particle diameter and (b) the PDI of the polishing slurries before CMP and after a storage of 12 h.

ammonium citrate exceeded 40 mmol. Therefore, the parameters of the SiO_2 particles were tested again after a storage of 12 h Fig. 9 shows the diameter and PDI values of SiO_2 particles before CMP and after 12 h of

storage. After 12 h, the diameter of the SiO_2 particles remained nearly unchanged when the concentration of ammonium citrate was 20 mmol. The PDI value of 0.041 also indicated that the particles maintained good

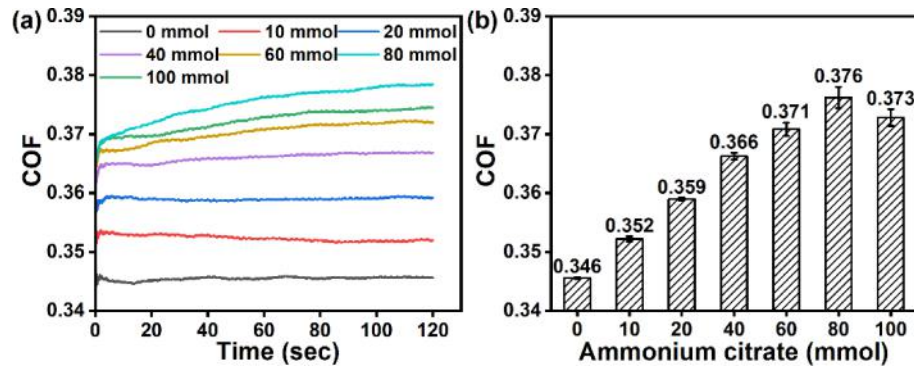


Fig. 10. The variation of the COF curve and value over (a) the polishing time and (b) the concentration of ammonium citrate.

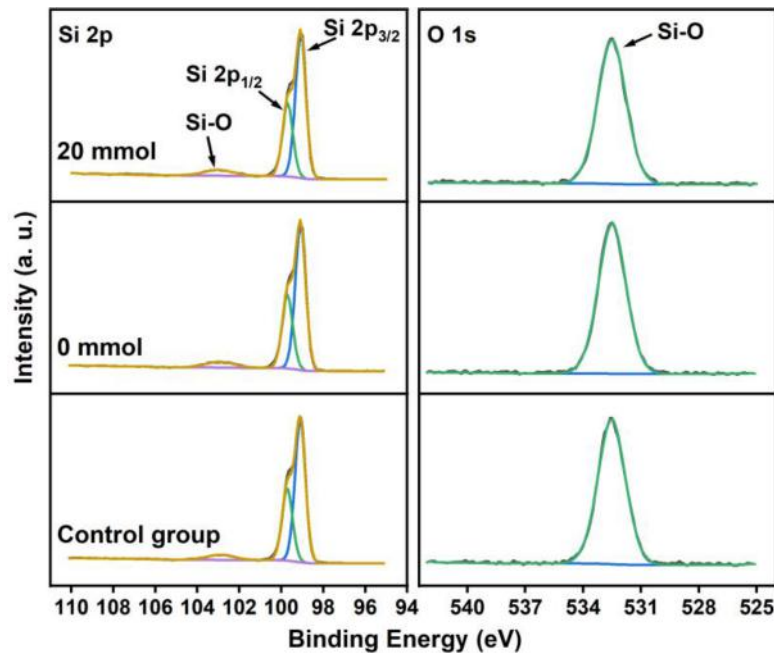


Fig. 11. The XPS spectra of Si and O elements on the silicon surface after be immersed in the slurries with different concentrations of ammonium citrate.

dispersibility and were monodisperse [31]. However, as the concentration continued to raise, both the particle diameter and the PDI increased slightly or significantly. As a result, the polishing slurry could maintain good dispersibility for 12 h or more time at the concentration of ammonium citrate is 20 mmol (0.05 mol/L), which is adequate for commercial use. At this concentration, the MRR of silicon wafers was 1979.88 Å/min, which was 71.6% higher than the control group.

3.6. COF analysis

COF can be used to reflect the mechanical motion between the silicon wafer, abrasive particles, and polishing pad, and the magnitude of the COF value indicates the mechanical effect during the polishing process [32]. Fig. 10 shows the variation of the COF values over the

Table 2

the effect of ammonium concentrations on the atomic% of Si and O elements on the silicon surface.

Ammonium citrate	Si (2p _{1/2} + 2p _{3/2})	Si 2p	O 1s
Control group	88.22	2.82	8.96
0 mmol	86.88	3.28	9.84
20 mmol	86.19	3.40	10.41

concentration of ammonium citrate. The COF value rose with an increasing concentration of ammonium citrate until it decreased at a concentration of 100 mmol. This finding is consistent with the MRR value obtained by various concentrations of ammonium citrate (Fig. 6) and demonstrated that ammonium citrate could promote the MRR of silicon wafers by enhancing the mechanical effect during the polishing process.

In alkaline environment, SiO₂ particles and silicates, generated by the reaction of Si atoms with OH⁻ ions and H₂O on the wafer surface all have a negative surface charge [33]. Due to the electrostatic repulsive force between negative charges, it is challenging for SiO₂ particles to remove the silicates on the wafer surface, which weakens the mechanical effect during the polishing process. When the positive charged NH₄⁺ ions were introduced into the polishing slurries, they would be adsorbed on the wafer surface. This reduces the negative charge on the wafer surface and further reduces the electrostatic repulsive force between the surface and the SiO₂ particles, which makes it easier for the SiO₂ particles to remove the silicates from the wafer surface during the polishing process. As a result, the use of ammonium citrate as an additive to the polishing slurries could improve the MRR of silicon wafers.

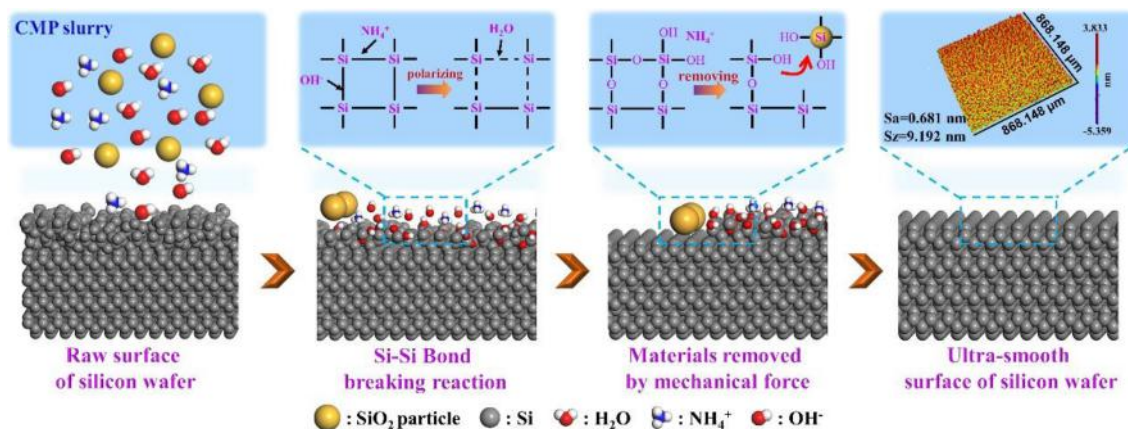


Fig. 12. Schematic diagrams of the CMP mechanism of the silicon wafers.

3.7. XPS analysis

To investigate the contribution of NH_4^+ ions to the MRR of silicon wafers, the XPS spectra of Si and O elements on the wafer surface after being immersed in the polishing slurries were depicted in Fig. 11. The peaks 99.7 and 99.1 eV corresponded to the Si $2p_{1/2}$ and Si $2p_{3/2}$ of Si-Si bonds, respectively [34], and the binding energy located at 102.9 and 532.5 eV were attributed to the Si-O bonds [35,36]. The atomic% data of Si and O elements was listed in Table. 2. The presentation of O elements on the wafer surface in the control group might be due to the DI water cleaning and hot air drying [37]. When the silicon wafer was soaked in the polishing slurry without ammonium citrate (0 mmol), compared with the control group, the atomic% of Si ($2p_{1/2} + 2p_{3/2}$) in the Si-Si bonds decreased while this of Si 2p and O elements in the Si-O bonds increased. The reason for the atomic% changes was that OH^- in the slurry catalyzed the reaction between Si and H_2O to generate the $\text{SiO}_2(\text{OH})_2^{2-}$ silicates by polarizing and weakening the Si-Si bonds on the wafer surface (Eq. (1)) [17]. When the concentration of ammonium citrate increased to 20 mmol, the atomic% of Si ($2p_{1/2} + 2p_{3/2}$), Si 2p, and O elements had the same changes compared with the slurry without ammonium citrate. This result demonstrated that NH_4^+ could facilitate the chemical reaction between Si and H_2O in the polishing process. NH_4^+ in the polishing slurries was more powerful than OH^- in pulling the electrons from the Si atoms due to the inductive effect and partially polarizing the Si-Si bonds, which is the reason why ammonium citrate could promote the MRR of silicon wafers [12].

3.8. Material removal mechanism of silicon wafers

According to the electrochemical tests, COF, and XPS spectra analyses, the CMP mechanism was proposed, as depicted in Fig. 12. During the polishing process, OH^- and NH_4^+ ions in the alkaline polishing slurry will catalyze the chemical reactions between the Si atoms of the raw surface and H_2O by partially polarizing and weakening the Si-Si bonds, resulting in the generation of $\text{SiO}_2(\text{OH})_2^{2-}$ silicates on the silicon surface, and ultimately leading to the formation of a silicate layer. Furthermore, NH_4^+ ions will be adsorbed onto the negatively charged silicate layer due to electrostatic attraction, thereby reducing the electrostatic repulsion between the silicate layer and the negatively charged SiO_2 particles. This facilitates the mechanical removal of the silicate layer on the wafer surface by the SiO_2 particles. This process will be repeated multiple times until a smooth surface is achieved.

4. Conclusion

In this study, four environmentally friendly additives were introduced to the polishing slurries for polishing silicon wafers. Except for

sorbitol, gluconic acid, citric acid, and ammonium citrate, all of which made a significant contribution to the rise in the MRR of silicon wafers. The addition of ammonium citrate is most efficient in promoting MRR. Then, the influence of ammonium citrate concentration on MRR was investigated, and it was discovered that the polishing slurry had the best dispersibility at a concentration of 20 mmol (0.05 mol/L). Meanwhile, the MRR increased by 71.6% to 1979.88 Å/min compared with the control group, and the surface roughness S_a was improved to 0.563 nm. The mechanism of ammonium citrate promoting the MRR of the silicon wafers was studied by using COF and XPS tests. During the polishing process, NH_4^+ ions generated by the hydrolysis of ammonium citrate could weaken the electrostatic repulsive force between the silicates on the silicon surface and the SiO_2 particles. As a result, the silicates were removed more effectively by the SiO_2 particles. This was the first reason for the increased MRR. NH_4^+ ions had a stronger catalytic ability for the chemical reaction of Si and H_2O than OH^- ions, which was another reason why NH_4^+ ions could promote the MRR of silicon wafers.

Author contributions

Wenxiang Xie performed the experiments, wrote the paper and analyzed the mechanism of CMP. Shiqiang Yu and Li analyzed the mechanism and revised the paper. Xiangxiang Cui, Qinming Gu, and Zeyun Wang supplied some experimental assistance. Zhenyu Zhang conceived the projects.

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

The authors are unable or have chosen not to specify which data has been used.

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