MATEC Web of Conferences **82**, 02001 (2016) DOI: 10.1051/matecconf/20168202001
D2ME 2016

Combined Ultrasonic Elliptical Vibration and Chemical Mechanical Polishing of Monocrystalline Silicon

Defu LIU[a], Tao CHEN and Riming YAN

College of Mechanical and Electrical Engineering, Central South University, Changsha, Hunan province, 410083, China

Abstract. An ultrasonic elliptical vibration assisted chemical mechanical polishing(UEV-CMP) is employed to achieve high material removal rate and high surface quality in the finishing of hard and brittle materials such as monocrystalline silicon, which combines the functions of conventional CMP and ultrasonic machining. In theultrasonic elliptical vibration aided chemical mechanical polishingexperimental setup developed by ourselves, the workpiece attached at the end of horn can vibrate simultaneously in both horizontal and vertical directions. Polishing experiments are carried out involving monocrystalline silicon to confirm the performance of the proposed UEV-CMP. The experimental results reveal that the ultrasonic elliptical vibration can increase significantly the material removal rate and reduce dramatically the surface roughness of monocrystalline silicon. It is found that the removal rate of monocrystalline silicon polished by UEV-CMP is increased by approximately 110% relative to that of conventional CMP because a passive layer on the monocrystalline silicon surface, formed by the chemical action of the polishing slurry, will be removed not only by the mechanical action of CMP but also by ultrasonic vibration action. It indicates that the high efficiency and high quality CMP of monocrystalline silicon can be performed with the proposed UEV-CMP technique.

1 Introduction

Chemical mechanical polishing (CMP) is a popular finishing process by using a combination of chemical reactions and mechanical forces [1-2]. CMP is widely used to finish materials with great hardness, high wear resistance and chemical inertness including monocrystalline silicon, sapphire, copper, gallium nitride (GaN) or silicon carbides (SiC), which are employed frequently in integrated optoelectronic and semiconductor devices. With the rapid development of integrated optoelectronic

[a] Corresponding author: liudefu@csu.edu.cn

and semiconductor industries, higher polishing quality and efficiency of CMP are requested.

However, the present research results show that the conventional CMP technology is hard to obtain high material removal rate (MRR) and perfect polished surface simultaneously due to the material's properties [3-4]. To acquire both high MRR and great polished surface quality simultaneously, ultrasonic vibration is introduced into conventional chemical mechanical polishing process, which has been proved to bevery useful to improve the polishing quality and efficiency for the hard and brittle materials [5-7], such as wafer and sapphire.

Wenhu Xu,*etl*. [2] developed an ultrasonic flexural vibration assisted chemical mechanical polishing (UFV-CMP) system to improve both MRR and surface quality of sapphire substrates. The MRR of UFV-CMP was 2.5 times larger than that of conventional CMP. The roughness and flatness of the sapphire surfaces polished by UFV-CMP were 0.83Å and 0.12μm respectively, which were much better than that of conventional CMP. Ming-Yi Tsai, *etl*. [6] introduced an ultrasonic vibration assisted chemical mechanical polishing (UV-CMP) method to finish copper substrates. It was found that material removal rate of the copper substrates increased by approximately 50-90% relative to that of conventional CMP, and the roughness of the substrate surfaces was also improved dramatically. Li Liang, *etl*. [7] applied ultrasonic vibration with the frequency of 27.99kHzto the CMP of wafer. According to the large amounts of experiments on the chemical mechanical polishing assisted by ultrasonic vibration, it was found that morphologies of silicon wafers polished by UV-CMP were superior to that of conventional CMP. A novel model of UV-CMP for silicon wafer was proposed, which could be used to explain the experimental results.

In this paper, an innovative chemical mechanical polishing method named "ultrasonic elliptical vibration assisted chemical mechanical polishing (UEV-CMP)" aimed at achieving high material removal rate and high surface quality simultaneously is presented and applied in the finishing of monocrystalline silicon. The UEV-CMP experimental setup, which can make work piece vibrate simultaneously in both horizontal direction and vertical direction with the same ultrasonic frequency, is developed. To investigate the material removal characteristics of UEV-CMP, the experiments about the effects of ultrasonic vibration on chemical corrosion of reagent and mechanical impact of abrasive particles are conducted respectively. The combined ultrasonic elliptical vibration and CMP process is expected to improve the polishing efficiency and quality for monocrystalline silicon.

2 Experimental setup

The ultrasonic elliptical vibration can be synthesized by two ultrasonic vibrations in orthogonal directions with the same frequency [8]. A schematic of the ultrasonic elliptical vibration transducer combined by a longitudinal vibrator and a bending vibrator is illustrated in Fig. 1. The transducer consists of one end cap, 2 ring-shape piezo-electric actuators, one middle cap, 4 half ring-shape actuators and one front cap, which are bonded together by a bolt. The exciting alternating current with high frequency generated by an ultrasonic generator is transported to the ring-shape PZT actuators and the half ring-shape PZT actuators, which generate longitudinal vibration and bending vibration respectively under the converse piezoelectric effect. The direction of longitudinal vibration and the direction of bending vibration are orthogonal. The longitudinal ultrasonic vibration wave signals generated by the ring shape actuators and the bending ultrasonic vibration wave signals generated by the half-ring shape actuators can be transferred to the workpiece by the ultrasonic horn. At the same time, the vibration amplitude of the workpiece fixed at the end of the horn is amplified by the horn.

Ultrasonic elliptical vibration assisted chemical mechanical polishing experiments are performed on a UEV-CMP machine designed by ourselves. The schematic of the UEV-CMP experimental setup designed for the polishing experiments is illustrated in Fig. 2. The experimental setup mainly consists of an ultrasonic elliptical vibration apparatus illustrated in Fig. 1, and a polishing machine. The polishing pressure can be adjusted by changing the weight on the node point of horn. The polishing slurry can be provided to the interface between polishing pad and workpiece. This experimental setup is convenient to work as ultrasonic vibration assisted CMP or conventional CMP governed by the operation of the two switches to control the ultrasonic generator. As shown in Fig. 2, when both the switch 1 and the switch 2 are turned off, the workpiece does not vibrates, this polishing process is called conventional CMP; when the switch 1 is turned on and the switch 2 is turned off, the workpiece just vibrates ultrasonically along horizontal direction, this polishing process is called ultrasonic horizontal vibration assisted CMP (UHV-CMP); when the switch 1 is turned off and the switch 2 is turned on, the workpiece just vibrates ultrasonically along vertical direction, this polishing process is called ultrasonic vertical vibration assisted CMP (UVV-CMP); when both the switch 1 and the switch 2 are turned on, the workpiece vibrates ultrasonically along an elliptical trajectory, this polishing process is called ultrasonic elliptical vibration assisted CMP (UEV-CMP). The ultrasonic generator converts 50Hz electrical supply to high frequency (20 kHz ~ 50 kHz) AC output. Under the circumstances, the workpiece fixed at the end of horn also vibrates at the same frequency. When the output power of the ultrasonic generator is 180W, the amplitudes of the workpiece are 3μm and 2.5μm in horizontal direction and vertical direction respectively measured by laser Doppler vibration meter LK-G5001V.

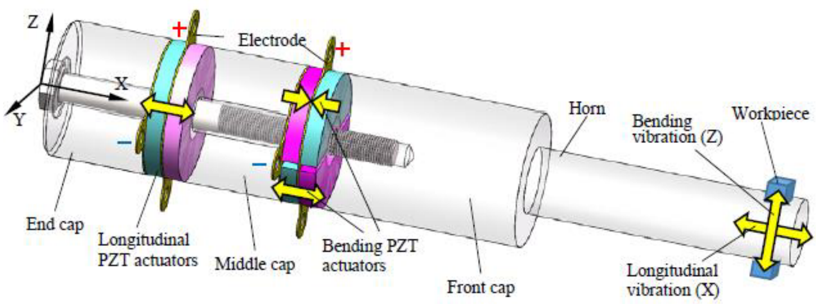


Figure 1. A schematic of ultrasonic elliptical vibration device

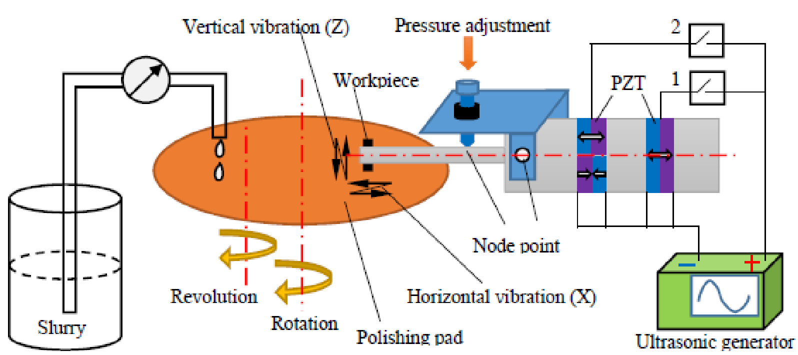


Figure 2. Schematic of ultrasonic elliptical vibration assisted CMP experimental setup

 DOI: 10.1051/matecconf/20168202001

3 Experimental details

Ultrasonic elliptical vibration assisted chemical mechanical polishing (UEV-CMP) experiments are conducted to evaluate the polishing quality. The polishing process parametersare listed in Table 1. The workpiece size is 10mm×10mm. The workpiece material is monocrystalline silicon. The polishing padis made of polyurethane. The material of the abrasive particles is silica (SiO_2), and the abrasive size of particles is 50nm. The polishing experiments are divided 4 different groups. 20 workpieces are polished in each experiment of conventional CMP, UHV-CMP, UVV-CMP, and UEV-CMP. The MRR is determined on the basis of weight loss of workpieces before and after polishing. The surface roughness values and morphologies of the polished silicon workpieces are measured and observed by Veecoprofilometer equipment.

Table 1. Polishing parameters of CMP

Polishing parameters	Value	Polishing parameters	Value
Polishing time /min	30	Rotation speed of pad /(r·min^{-1})	3
Abrasive size of particles /nm	50	Revolution speed of pad /(r·min^{-1})	30
Slurry density /(g·cm^{-3})	0.96	Polishing pressure /kPa	51.43
Concentration of polishing particles	2%	Ultrasonic vibration frequency /kHz	35.3
pH value of slurry	9	Horizontal ultrasonic amplitude /μm	3
Slurry feed rate /(ml·min^{-1})	15	Vertical ultrasonic amplitude /μm	2.5

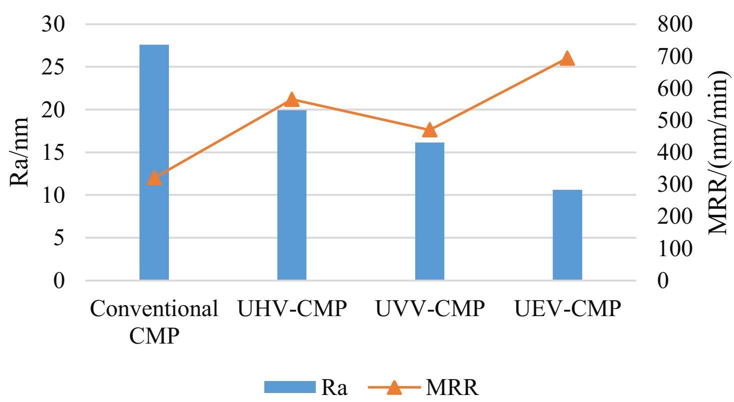


Figure 3. The relations between MRR, roughness and polishing process

The MRRs of the workpieces polished by conventional CMP, UHV-CMP, UVV-CMP and UEV-CMP are 320.1, 565.2, 469.7 and 693.6 nm/min respectively, as shown in Fig. 3. It can be known that the MRR of UEV-CMP increases significantly compared to that of conventional CMP. The relation between surface roughness and polishing process is also plotted in Figure 3. The average surface roughness Ra values of 20 workpieces polished by conventional CMP, UHV-CMP, UVV-CMP, UEV-CMP respectively are 27.61, 19.94, 16.14 and 10.61nm respectively. It can be seen from Fig. 4

that the surface roughness of the workpieces polished by conventional CMP, UHV-CMP, UVV-CMP, UEV-CMP respectively decrease significantly. Hence, ultrasonic vibration has significant effect on the MRR and surface roughness of workpiece polished by CMP. Especially, both the MRR and surface quality are improved greatly when the workpiece is polished by UEV-CMP.

4 Material removal mechanism

To clearly evaluate the material removal mechanism of ultrasonic elliptical vibration assisted chemical mechanical polishing, the effects of ultrasonic vibration on chemical corrosion of polishing solutionand mechanical impact of abrasive particles are studied respectively by design of experiments.

4.1 The effects of ultrasonic vibration onchemical corrosion

Experiments of ultrasonic vibration assisted chemical corrosion on silicon are conducted to evaluate the effects of ultrasonic vibration on chemical corrosion of polishing solution. The size and material of the specimens used in the chemical corrosion experiments are same with that of the workpiece used in the above polishing experiments. The original specimens are cleaned by ultrasonic vibration in absolute ethyl alcohol and deionized water respectively. The chemical reagent used in experimentsis NaOH with concentration of 2mol/L. The specimen is fixed at the end of the horn of the ultrasonic elliptical vibration device shown in Fig. 1and they are immersed in the NaOH solution. The experiments are performed for 30minutes with or without assistant of ultrasonic elliptical vibration respectively for comparing the effects. The frequency of the ultrasonic elliptical vibration is 35.3 KHz. Fig. 4 shows the process of chemical corrosion experiments.

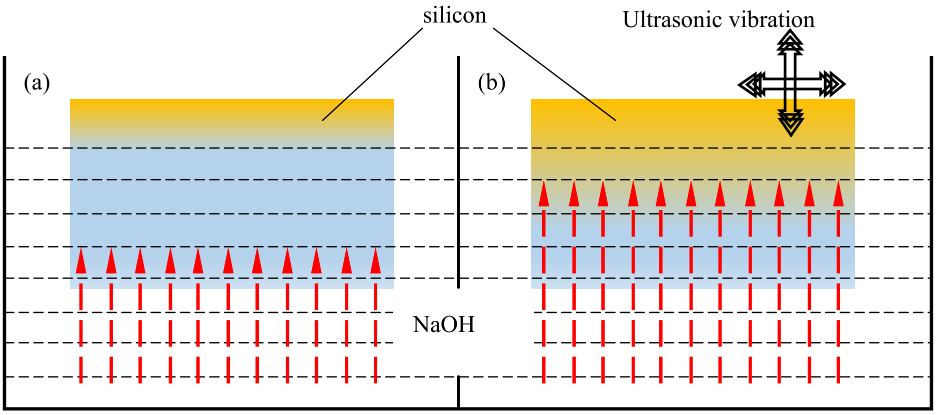
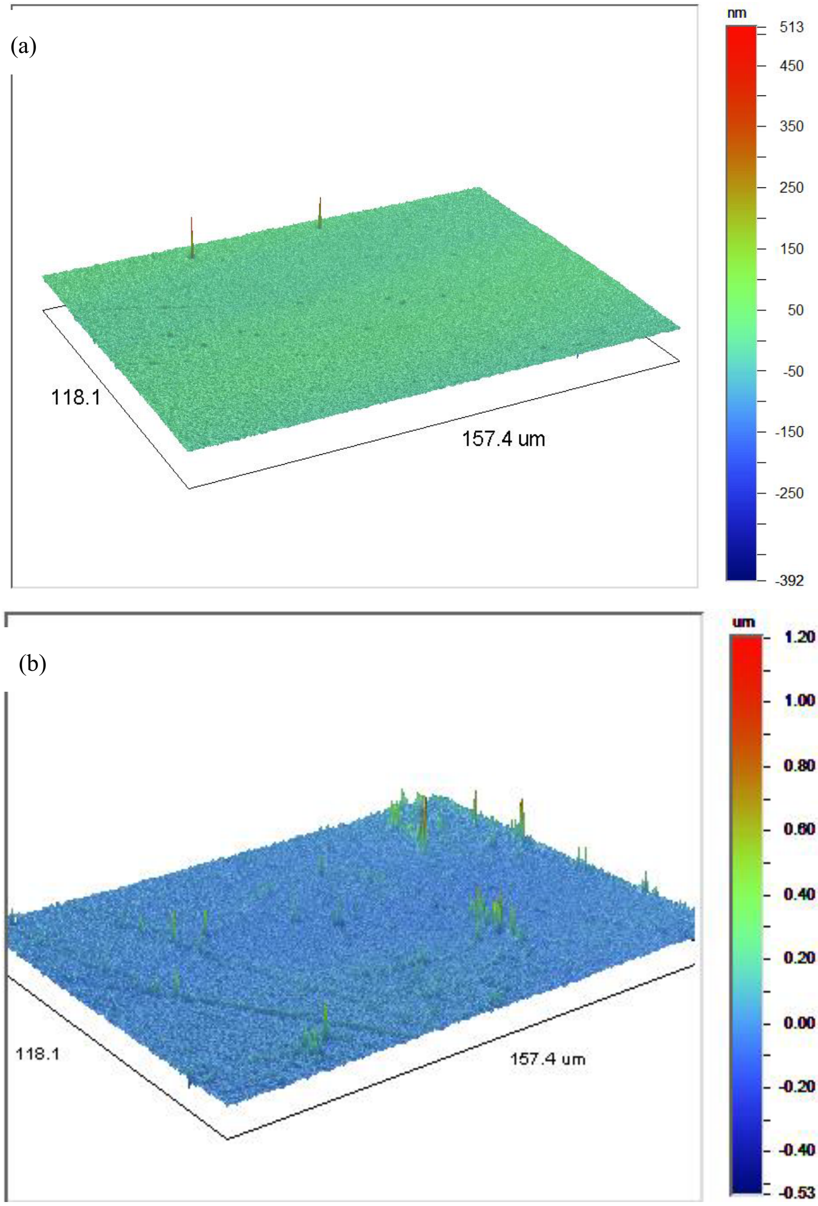


Figure 4. Chemical corrosion experiments (a)without assistant of ultrasonic vibration and (b) with assistant of ultrasonic vibration

The surface morphologies of the original specimen, the specimen corroded by NaOH solution without assistant of ultrasonic vibration, and the specimen corroded by NaOH solution with assistant of ultrasonic vibration are shown in Fig. 5. The roughness value of the original surface is only 8.62nm. However, the roughness value of the specimen surface corroded by NaOH solution without assistant of ultrasonic vibration is20.28nm, while the roughness value of the specimen surface corroded by NaOH solution with assistant of ultrasonic elliptical vibration increases to 191.66nm. The results indicate that the ultrasonic elliptical vibration assisted chemical corrosion can increase the speed of chemical reaction significantly.



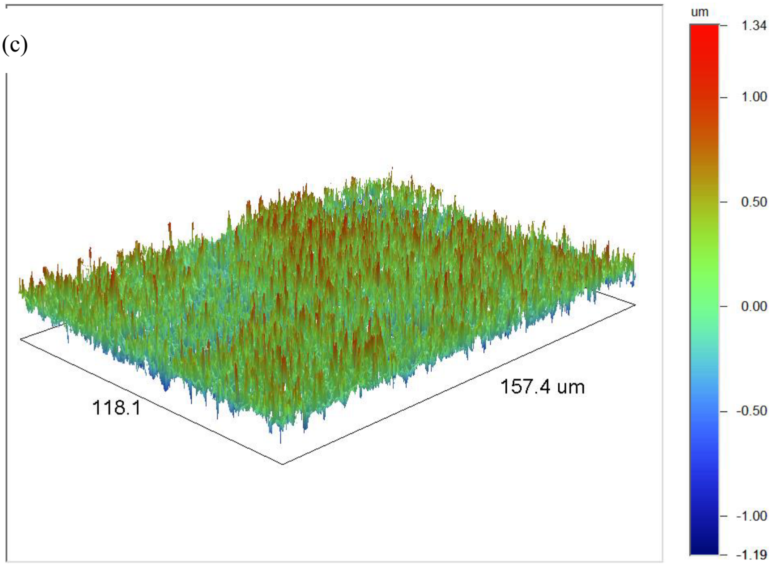


Figure 5. (a) The original surface of specimen, (b) The surface corroded by NaOH solution without assistant of ultrasonic vibration, and (c) the surface corroded by NaOH solution with assistant of ultrasonic elliptical vibration

4.2 The effects of ultrasonic vibration on mechanical impact of abrasive particles

The experiments of impact of abrasive particles on specimen are designed to evaluate the effects of ultrasonic vibration on the mechanical impact of particles on specimen. The material of specimens is silicon, and the size of the specimen is also 10mm×10mm. The specimens are put into the polishing slurry withα-Al_2O_3, SiO_2 and CeO_2nanoparticlesrespectively, as shown in Fig. 6. Ultrasonic vibration is imposed on the specimen through the ultrasonic vibration device shown in Fig. 1. The frequency of the ultrasonic vibration is also 35.3 KHz. The physical parameters of the specimen and the abrasive particlesα-Al_2O_3, SiO_2 and $CeO_2$are listed in Table 2. It can be observed from Table 2that α-Al_2O_3, $SiO_2$are harder than the specimen, while CeO_2 is softer than the specimen.

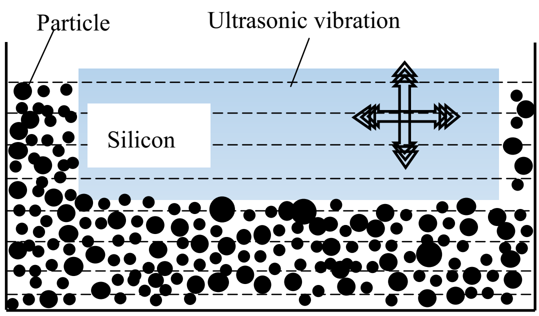


Figure 6. The effects of ultrasonic vibration on mechanical impact of particles

 DOI: 10.1051/matecconf/20168202001

Table 2. The parameters of materials involved in experiments of mechanical impact of particles

	Specimen	**α-Al_2O_3**	**SiO_2**	**CeO_2**
Hardness /GPa	9.8	21	11	8.9
Density /g·cm^{-3}	2.329	3.9	2.2	7.65
Modulus of Elasticity /GPa	112.4	370	73	165
Poisson's Ratio	0.28	0.22	0.17	0.5

The surface morphologies of specimens impacted byα-Al_2O_3, SiO_2 and CeO_2 particles with assistant of ultrasonic vibration are shown in Fig. 7, Fig. 8andFig. 9respectively. The experimental results indicate that the hard particles (α-Al_2O_3, SiO_2) cause obviouspitson the specimen surface, while the soft particles (CeO_2) do not cause this phenomenon. Moreover, the pits caused byα-Al_2O_3particles are more, larger and deeper than those caused bySiO_2 particle, which means the particle is harder, the removed effects is more obvious. The results meet well with the impact wear theory. Therefore, it can be supposed that the hard particles can cause plastic scratch effects on soft materials under assistant of ultrasonic vibration, while the soft particles cannot.

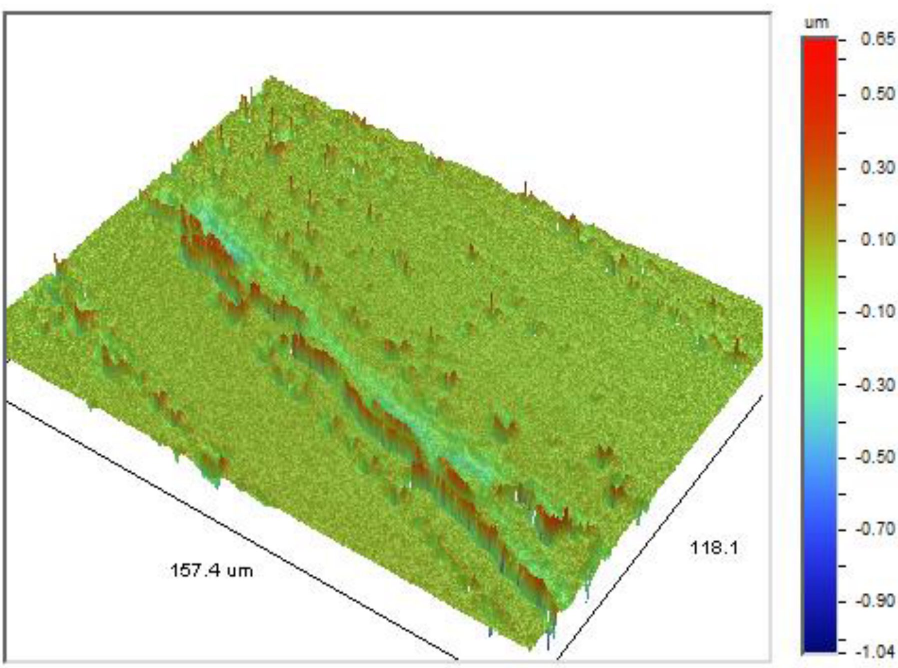


Figure 7. Surface morphology of specimen impacted by α-Al_2O_3 particles with assistant of ultrasonic vibration, Ra=47.83nm, ×40

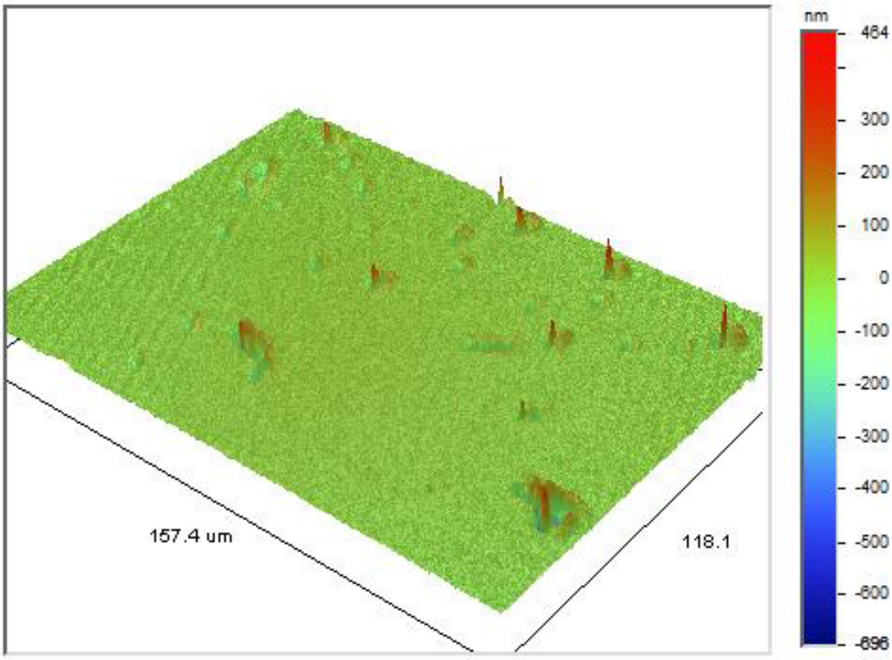
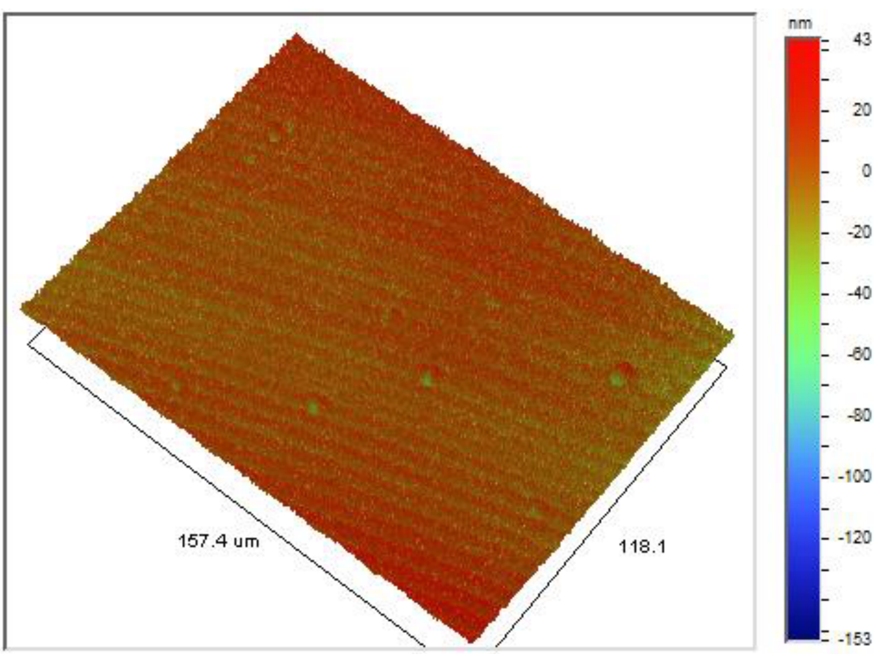


Figure 8. Surface morphology of specimen impacted by SiO_2 particles with assistant of ultrasonic vibration, Ra=15.14nm, ×40



(a)

Figure 9. Surface morphology of specimen impacted by CeO_2 particles with assistant of ultrasonic vibration, Ra=12.68nm, ×40

5 Conclusions

This paper presents an experimental investigation of the characteristics of a monocrystalline silicon polished by ultrasonic elliptical vibration assisted chemical mechanical polishing process. UEV-CMP is able to improve the MRR and polished surface quality of monocrystalline silicon greatly compared with conventional CMP. The MRR of silicon samples polished by UEV-CMP is 693.6 nm/min, which is twice larger than that obtained by conventional CMP. The polished surface roughness value of UEV-CMP is 10.61nm, which is much better than 27.61nm obtained by conventional CMP. For UEV-CMP, a soft layer on workpiece surface formed by the chemical action of the polishing slurry will be removed not only by the mechanical action of conventional CMP but also by the ultrasonic vibration action of UEV-CMP. The combined actions of ultrasonic elliptical vibration and conventional CMP can facilitate better polished surface and higher MRR.

Acknowledgements

The authors would like to thank the National Natural Science Foundation of China (Grant 51275534) and Natural Science Foundation of Hunan province of China (Grant 2015JJ2153) for their support to this work.

References

1. H. S. Lee, H. D. Jeong. CIRP Annals-Manu. Tech. **58**, 485-490 (2009)
2. H. Gong, G. Pan, Y. Zhou, X. Shi, C. Zou, S. Zhang. Appl. Surf. Sci. **338**, 85-91 (2015)
3. H. Zhu, L.A. Tessaroto, R. Sabia, V.A. Greenhut, M. Smith, D.E. Niesz. Appl. Surf. Sci. **236**, 120-130 (2004)
4. X. Hu, Z. Song, Z. Pan, W. Liu, L. Wu.Appl. Surf. Sci. **255**, 8230-8234 (2009)
5. W. Xu, X. Lu, G. Pan, Y. Lei, J. Luo. Appl. Surf. Sci. **256**, 3936-3940 (2010)
6. M. Tsai, W. Yang. Int. J. of Mach. Tools and Manu. **53**, 69-76 (2012)
7. L. Li, Q. He, M. Zheng, Z. Liu.Ultrasonics **56**, 530-538 (2012)
8. H. Suzuki, T. Moriwaki, T. Okino, Y. Ando. CIRP Annals-Manu. Tech. **55**, 385-388 (2006)