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An Enhanced and Efficient Technique for the Precision Lapping of High-Quality Sapphire Workpieces

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Abstract— *In double-sided lapping of sapphire, slurries containing large grain size boron carbide abrasives (B4C slurry) are commonly used to quickly flatten the sapphire substrate. However, this method often causes significant surface damage, requiring additional time for removal in subsequent processing steps. This paper presents experiments using different slurries for lapping sapphire, including a slurry with small-size diamonds (diamond slurry), a slurry with a mixture of small-size diamonds and silicon dioxide abrasives (mixed abrasives slurry), and the mixed abrasives slurry combined with ultrasonic vibration of the 304 stainless steel lapping tool. Based on the lapping characteristics observed, a three-stage lapping strategy is proposed. Initially, the diamond slurry is used for one hour. This is followed by the mixed abrasives slurry. Finally, the mixed abrasives slurry is used with ultrasonic vibration assistance for the last half hour of lapping. This proposed approach was verified through a two-hour lapping process of sapphire. Results showed that this method produced a uniformly lapped surface with minimal damage, achieving a material removal rate of 85% compared to using B4C slurry. Additionally, the material removal rate increased by 94%, and the surface roughness Sa improved by 44% compared to using only the diamond slurry.*

Keywords— *Ultrasonic vibration, Lapping, Mixed abrasives, Sapphire.*

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I. INTRODUCTION

Sapphire has been widely applied in the production of gallium nitride (GaN)-based light emitting diodes (LED) due to its excellent mechanical and chemical properties. From the ingot, sapphire undergoes three processing stages, namely, slicing, planarization, and polishing to become the substrate ready for growing gallium nitride epitaxial layer. Processing of sapphire is difficult because of its hardness and brittleness. Besides, each process may cause defects, and the removal of these defects may be time-consuming during post-processing. After slicing the sapphire ingots into wafers, double-sided lapping process is applied first to achieve double-sided flatness of the substrate, reduce its surface roughness, and remove the surface damage left by slicing. The slurry containing large grain size boron carbide (B4C) free abrasives is generally used during this processing stage. The mechanical force resulted from the movement of large grain size hard abrasives can lead to fast material removal, thus achieving the purpose of improving double-sided parallelism of the substrate. However, this may induce new pits and damages on the substrate surface though processing time may decrease. In case the damages are extensive, more likely than not, they will not be completely removed by the next stage's single-sided lapping process where its main objective is to fast reduce surface roughness of the wafer. The comparatively softer copper lapping plate incorporated with smaller size diamonds is used at this stage's process. The material removal rate is low and decreases with time as well. As a result, the large and deep pits may remain un-removed as those illustrated in Fig. 1(a). On the contrary, controlling surface defects to an acceptable degree in the first stage not only can lead to complete removal of defects in the subsequent single-sided lapping process as depicted in Fig. 1(b), it may greatly reduce the processing time.

There had been several reports on the planarization of sapphire wafer in the past. Yusunaga et al. [1] used a stainless steel ring but absence of abrasives to polish sapphire wafers. The results showed that a loose solid-phase chemical reaction layer or the so-called passivation layer formed on the sapphire wafer surface at the existence of ferric oxide (Fe2O3) during the polishing process. This layer was then removed by the following mechanical actions to obtain a flattened surface while preventing sub-surface damages. Accordingly, the mechano-chemical polishing, or MCP for short was named for this kind of material removal process. Gutsche *et al*. [2] proposed the relationship between the activation energy and the material removal rate in polishing of sapphire. By using the mixture of pure water and silicon dioxide (SiO2) abrasives as the slurry, they confirmed that the solid-phase chemical reaction between silicon dioxide and the sapphire had taken place.

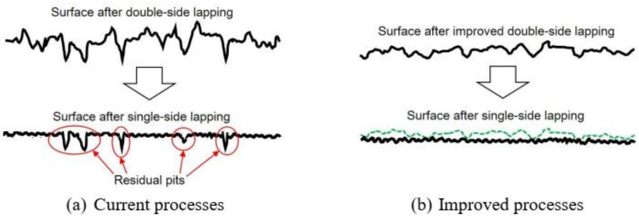


Fig. 1 Problems encountered in double-sided lapping and the concept of improved process.

To promote chemical reaction, Liao et al. investigated the ultrasonic vibration assisted MCP of SiC by ferric oxide abrasives from microscopic viewpoint [3-5]. They pointed out that the material removal rate in MCP under the assistance of ultrasonic vibration still follows the Preston's equation [6-8]. The transverse ultrasonic vibration provides additional energy to facilitate generation and removal of passivation layer leading to the increase of material removal rate [8-10]. However, the material removal rate becomes too low to remove the already existing scratches and pits once the asperities on the surface are flattened and reaction can no longer continue effectively.

The objective of this paper is to propose a lapping strategy that can achieve a high material removal rate while leaving no pits or surface damages for the following process. The slurry containing smaller grain size diamonds is chosen to prevent large and deep pits from generating on the surface but a satisfactory material removal rate can still be maintained. In order to enhance the material removal rate, silicon dioxide soft abrasives are added into diamond slurry (mixed abrasives) and 304 stainless steel lapping tool is used to take the advantage of solid-phase chemical reaction. The ultrasonic vibration assisted lapping using the mixed abrasives slurry on the ferric dioxide based lapping tool is also investigated.

Experiments

The lapping machine used in this study is schematically shown in Fig. 2(a). The substrate was the 2-inch (50.8 mm in diameter) standard C-axis sapphire substrate of 0.50 mm in thickness supplied by Unionlight Technology Co., Ltd., China. The polishing tool was made of AISI 304 stainless steel material, and the lapping area was 8 mm in diameter as shown in Fig. 2 (b). The B4C slurries was composed of 100 ml propylene glycol, 20 ml deionized water, 6 ml suspension, and 0.65g (0.5 wt%) of 40 μm in size B4C abrasives. The diamond slurry has the same composition except B4C abrasives was changed to small grain size of 10 μm diamonds. For the mixed abrasives slurry, 5 wt% concentration 10 μm in size SiO2 abrasives was added to the diamond slurry. These three slurries were used separately in the lapping experiments. The lapping parameters are summarized in Table 1.

Prior and during the experiment, the material removal depth and surface roughness were measured at four lapping regions by a 3D laser confocal microscope (VK-9700, Keyence Company, Japan). During the experiment, measurements were conducted once every 30 minutes. For measuring surface roughness, the cutoff and sampling length values were 0.08 mm, and 0.25 mm, respectively. Before and after the experiment, a scanning electron microscope (SEM) (JSM-6390, JEOL Ltd., Japan) and confocal microscope were employed to obtain the morphology of the lapped surface for detailed observation.

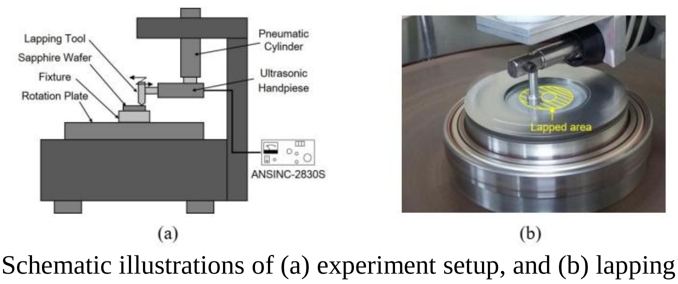


Fig. 2 Schematic illustrations of (a) experiment setup, and (b) lapping area.

Table 1 Lapping Parameters

Down pressure (MPa)	0.37
Rotational speed (RPM)	90
Processing time (hr)	2
Abrasives in the slurry	40 μm B4C
	10 μm diamond
	10 μm diamond + 10 μm SiO2 powder

II. RESULTS AND DISCUSSION

The surface morphologies, 3D images, and surface contours of the original sapphire substrate and after lapping for 2 hours with the use of B4C slurry measured by the laser confocal microscope are shown in Fig. 3 and Fig.4, respectively. The surface after lapping by using slurry of small grain size diamonds is shown in Fig. 5. It can be seen from Fig. 3 that there are many pits on the original substrate surface with the surface roughness of Sa 0.40μm and Smax 9.02 μm. Many large and deep pits are created on the surface after lapping using the large grain size B4C abrasives slurry (referring to Fig. 4). The surface roughness increases significantly to Sa 0.95μm and Smax 22.53 μm. This confirms that lapping by using slurry of large grain size abrasives can induce large pits. However, the material removal depth after two hours lapping is 66.02 μm which leads to a high average material removal rate (MRR) of 33.01 μm/hr. Comparatively, there are still pits on the surface after two hours lapping with the use of small size diamond slurry as depicted in Fig. 5. Nevertheless, the surface is quite even and uniform. Besides, the scratches and large pits left by slicing have been removed as it can be seen from the SEM images of surface left by slicing and after lapping shown in Figs 6(a) and 6(b), respectively. A significantly smaller surface roughness of Sa 0.41μm and Smax 6.39 μm is obtained as well. However, it should be noted that the resulting material removal depth is reduced to 29.04 μm, or equivalently the average material removal rate is only 14.52 μm/hr.

To understand the characteristics of lapping with the slurry of small size diamond abrasives more comprehensively, variations of the material removal depth and material removal rate with time are drawn and shown in Fig. 7. Both curves become gentle gradually with increasing time, and there is rarely any material removal at long lapping period. The decrease of material removal rate with lapping time is related to the smoothness of the substrate surface and the sharpness of the abrasive grain. The actual contact area between the substrate and the lapping tool increases gradually with the smoothing of the surface. This in turn causes a decrease of average pressure acting on the asperities of the surface. Hence, it becomes more difficult for the abrasive to penetrate into the substrate to remove the material. Apparently, the material removal rate would decrease. Moreover, the diamond abrasive wears over lapping time and its grain size decreases from 12.21μm to 8.83 μm. At the same time the sharp cutting edge becomes blunt and loses its material removal capability. The surface roughness with respect to lapping time is shown in Fig. 8. There is a slight increase of surface roughness at 0-0.5 hour that could be due to the unevenness of surface generated by the mechanical action of diamond abrasives. Thereafter, it reveals similar trend as that of material removal rate, and further improvement is not achievable once lapping has lasted for a specific long period. The surface roughness obtained after two hours lapping is $S_a = 0.41$μm and $S_{max} = 6.39$ μm. It should be noted that the final surface roughness is larger than that of the original substrate.

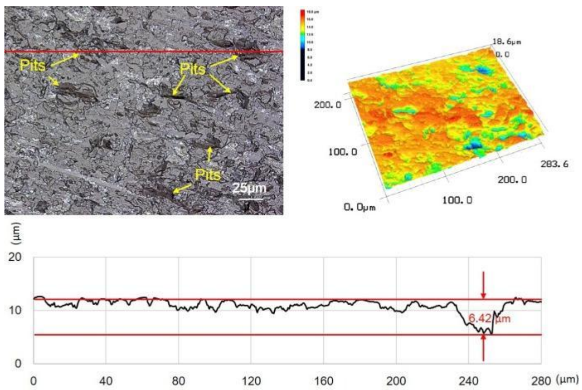


Fig. 3 Morphology, 3D image, and surface contour of the surface before lapping.

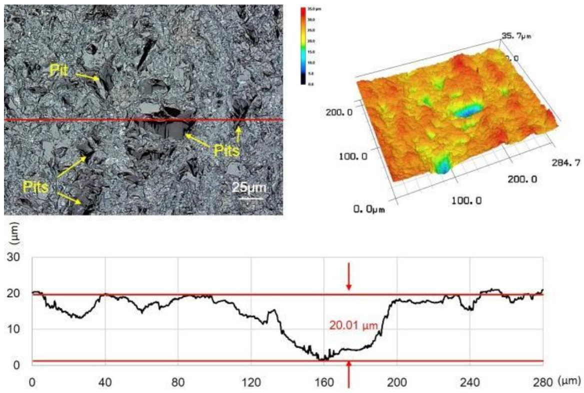


Fig. 4 Morphology, 3D image, and surface contour of the surface lapped by using the slurry of large grain size B4C abrasives.

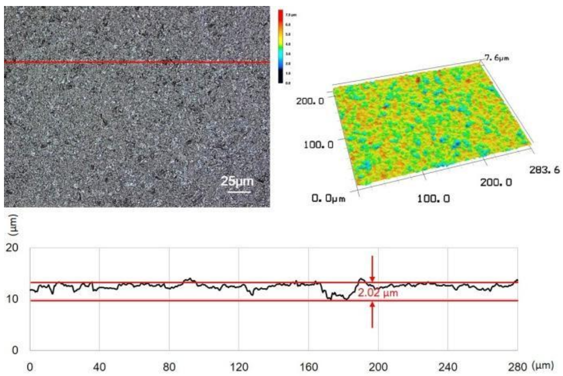
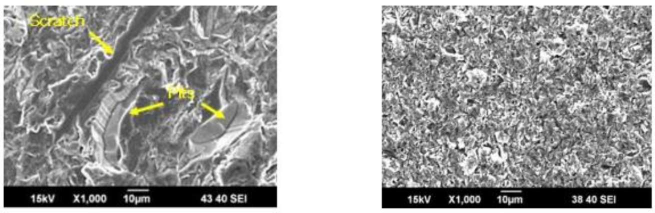


Fig. 5 Morphology, 3D image, and surface contour of the surface lapped by using the slurry of small size diamond abrasives.



(a) Before lapping (b) After lapping

Fig. 6 SEM images of the surface (a) left by slicing, and (b) after lapping by using diamond slurry.

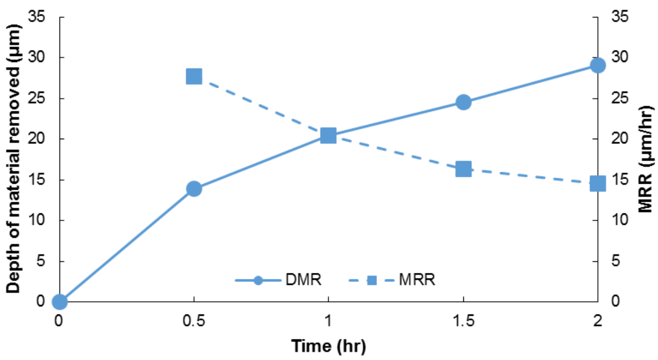


Fig. 7 Depth of material removed and material removal rate (MRR) of lapping using diamond slurry.

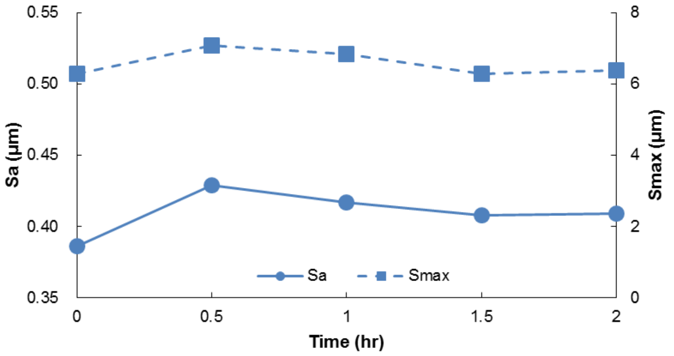
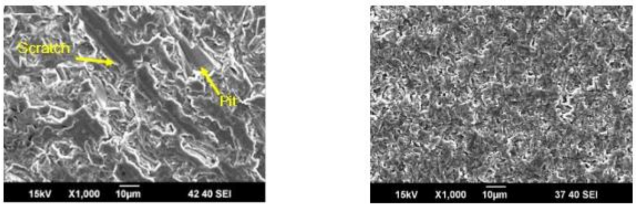


Fig. 8 Surface roughness of lapping using diamond slurry.

The SEM images of surface left by slicing and after lapping with the mixed abrasives slurry are shown in Figs. 9(a) and 9(b), respectively. Similar to the use of the diamond slurry, there is no scratch and large pit left on the surface after lapping. Fig. 10 shows the material removal depth and material removal rate with lapping time. Unlike the use of the diamond slurry, the material removal depth increases monotonically with time rather than becoming gentle after a long lapping period. The material removal rate is between 20.50 µm/hr and 21.61 µm/hr. This is less than the initial value of that by using the diamond slurry alone (27.43 µm/hr). However, it maintains at a steady value and does not decrease with time. The material removal rate at two hours lapping time is larger than that using the diamond slurry. Fig. 11 shows the surface roughness with lapping time. It increases within the first 30 minutes and then remains more or less constant, and after two hours lapping, Sa is about 0.46µm, while Smax is around 7.50 µm. Figs. 12(a) and 12(b) show the diamond distribution in the lapping region when the diamond slurry and mixed abrasives slurry are used, respectively. It is clear that there are far more diamonds in the mixed abrasives slurry. Quantitatively, it is over 600 versus around 300. During the lapping process, the abrasives are forced to flow outward because of the rotation of the sapphire substrate. The outward motions of the diamond abrasive are retarded by the addition of the SiO_2 soft abrasives, and hence more number of diamonds participate material removal leading to a higher and more steadily material removal rate. Furthermore, since the surface has undergone mechanical action by more diamond abrasives, its roughness is also higher as compared to that by the use of diamond slurry.



(a) Before lapping (b) After lapping

Fig. 9 SEM images of the surface (a) left by slicing, and (b) after lapping by using the mixed abrasives slurry.

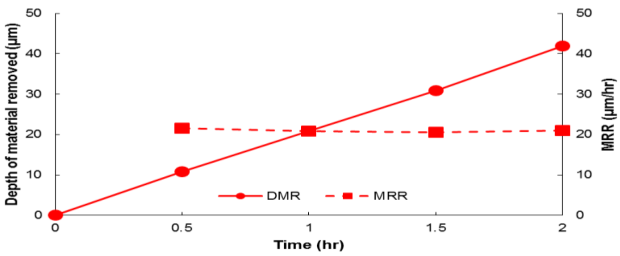


Fig. 10 Depth of material removed and MRR of lapping using mixed abrasives slurry.

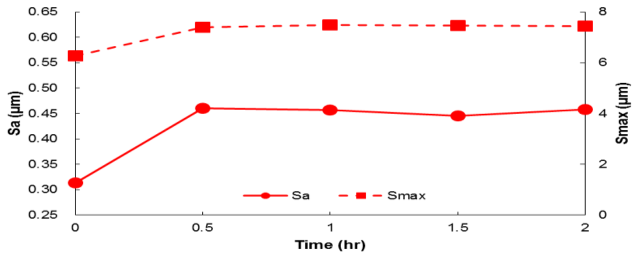
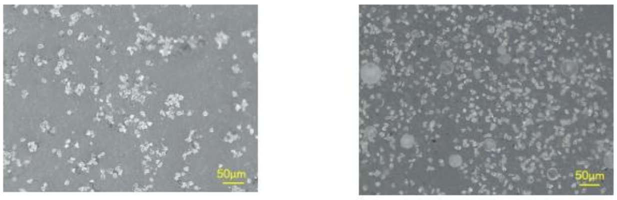


Fig. 11 Surface roughness vs. lapping time using mixed abrasives slurry.



(a) 10µm diamond slurry (b) Mixed abrasive

Fig. 12 Diamond distribution in the lapping region by using (a) diamond slurry, and (b) mix abrasives slurry.

Fig. 13 shows the material removal depth and material removal rate with respect to lapping period in the ultrasonic vibration assisted lapping with the use of mixed abrasives slurry. The material removal rate is 8.94 µm/hr at the beginning half hour and reduces to 5.60 µm/hr after two hours lapping. The final value only accounts for 1/3 of the case without ultrasonic vibration assistance which is around 20.50 µm/hr. Observation of the number of diamond abrasives in the lapping region reveals that there is around one hundred diamonds only as compared to 600 without ultrasonic vibration assistance and 300 with the use of diamond slurry. The extremely few diamonds could be due to cavitation induced by the ultrasonic vibration which excludes the diamonds out of the lapping region. It is clear that the material removal rate drops drastically. However, the surface roughness of Sa = 0.25 µm, and Smax = 3.23µm after lapping as shown in Fig. 14 is very small as compared to that without ultrasonic vibration assistance case (cf. Sa = 0.46 µm and Smax = 7.50 µm). The thermal energy resulting from friction of the lapping tool on the sapphire surface caused by the ultrasonic vibration is responsible for the improved surface roughness. This additional energy facilitates sold-phase chemical reaction among the sapphire substrate and SiO2 as well as Fe2O3. Since there are few diamonds participating material removal in this case, removal of the passivation layer of the reaction product by SiO2 abrasives and lapping tool of ferric oxide (Fe2O3) by means of MCP mechanism prevails. The hardness of either SiO2 abrasive or ferric oxide is far less than the hardness of sapphire. Hence a small surface roughness is resulted.

Proposed Approach

Observations of the above experimental results show that as far as material removal depth is concerned, the use of the diamond slurry for lapping has the highest material removal depth in the first 30 minutes. But as compared with the use of mixed abrasives slurry, the difference diminishes with time, and there is about half number of diamond abrasives participating material removal. After lapping with the use of the mixed abrasives slurry for one hour, the material removal rate maintains constant over time and exceeds that of using diamond slurry. The ultrasonic vibration assisted lapping with the use of mixed abrasives slurry leads to the least material removal rate but the best lapped surface quality. Hence, three-stages lapping is proposed to reduce the lapping time while achieving satisfactory surface quality. Diamond slurry is used for lapping first for the beginning 30 minutes. It is followed by lapping with the mixed abrasives slurry for the next one hour. Finally, the ultrasonic vibration assisted lapping by using mixed abrasives slurry takes over for the last 30 minutes.

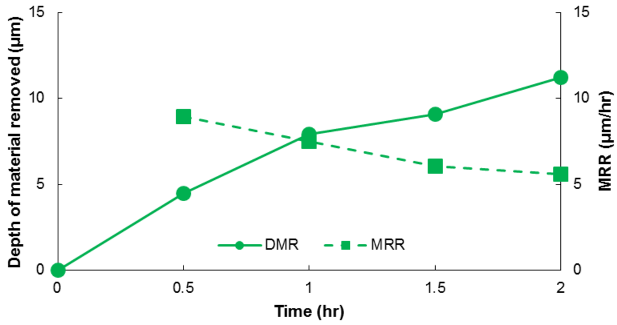


Fig. 13 Depth of material removed and MRR in the ultrasonic vibration assisted lapping with the use of mixed abrasive lapping.

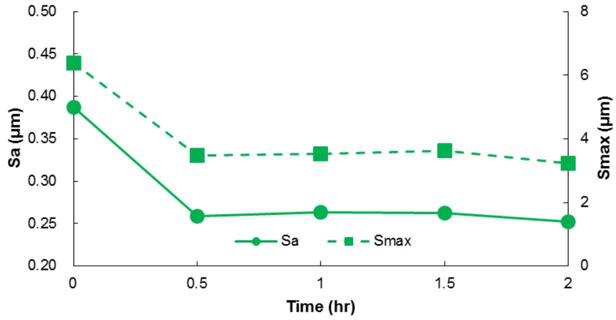
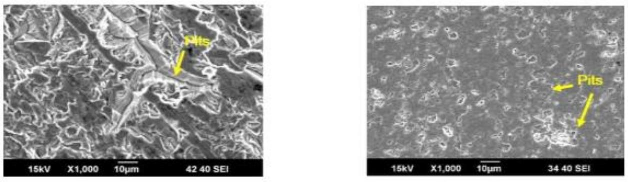


Fig. 14 Surface roughness in ultrasonic vibration assisted lapping with the use of mixed abrasives slurry.

Figs. 15(a) and 15(b) show the SEM images of surface left by slicing and after the proposed 3-stages lapping. A quite even and smooth surface with no scratch and large pit is observed. Fig. 16 and Fig. 17 show the material removal depth as well as material removal rate, and the surface roughness against lapping time, respectively. The same quantities obtained by using the diamond slurry, mixed abrasives slurry and the assistance of ultrasonic vibration with mixed abrasives slurry are also drawn in the same figures for comparison. It can be seen from Fig. 16 that 3-stages lapping has the highest material removal rate among the lapping approaches studied in this paper. The MRR increases from the beginning of lapping to 0.5 hour. Then it starts to drop slowly. The average MRR is 28.15 µm/hr, and it is 85% of the MRR by using the slurry of large grain size B4C abrasives. On the other hand, the surface roughness increases from Sa 0.39 µm and Smax 6.95 µm of the original substrate to Sa 0.47 µm and Smax 7.55 µm at around 1.5th hour lapping, and then begins to drop rapidly to the final values of Sa 0.23 µm and Smax 3.45 µm at the end of two hours lapping period. The surface quality is far better than that of the original substrate, and it is also the best among all approaches.

The material removal depth or rate from 0.5 hour to 1.5 hour lapping period for 3-stages lapping strategy is larger than that of the case when the same slurry is applied all the way throughout the lapping period. The reason why this happens is because the surface being lapped by the mixed abrasives slurry at 0.5 hour in 3-stages lapping is coarser (ref. Fig. 17) than that of the original substrate. Hence, there is a relatively higher average pressure on the actual contact surface, and apparently leading to a higher material removal rate. The same reasoning applies to the third stage's lapping as well where ultrasonic vibration is applied. The coarse and uniform surface at the end of second stage's lapping also leads to a rapid drop of surface roughness of the third stage's lapping.



(a) Before lapping (b) After lapping

Fig. 15 SEM images of the surface (a) left by slicing, and (b) after the proposed 3-stages lapping.

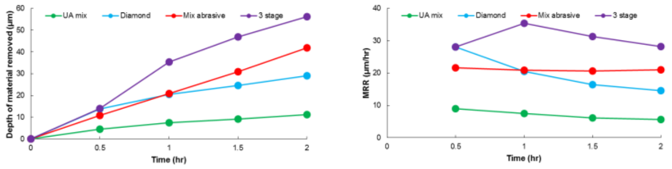


Fig. 16 Material removal depth and material removal rate of the proposed 3-stages lapping.

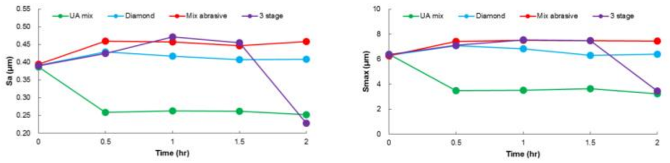


Fig. 17 Surface roughness of the proposed 3-stages lapping.

III. CONCLUSION

This study explored the feasibility of improving lapping sapphire substrate efficiency and surface quality through the use of mixed abrasives and the ultrasonic vibration assistance. The use of small grain size diamond slurry for lapping leads to the highest material removal depth during the early stage of lapping period, but the extent quickly decreases with time. The surface roughness also shows the same trend. The material removal depth by using the mixed abrasives slurry in lapping is not as large as that of using diamond slurry during the early stage of lapping. But it maintains a steady increase that the material removal rate maintains almost constant, and not decreases with time.The ultrasonic vibration assisted lapping with the use of mixed abrasives slurry substantially decreases the surface roughness but with a considerably low material removal rate. A 3-stages lapping of sapphire substrate is proposed, and verified. It results in the best material removal depth and surface roughness among all approaches under study. The material removal rate reaches 28.15 μm/hr, and it is 85% of the use of slurry containing large grain size B4C abrasives. It increases by 94% as compared to the use of diamond slurry. The surface roughness of Sa drops from 0.41 μm to 0.23 μm (44% improvement) and from Smax 6.39 μm to 3.45 μm.

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