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Chemical-Mechanical Polishing of Copper Wafers Utilizing an Eco-Friendly Slurry

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Abstract**—** *Sapphire crystals, renowned for their exceptional mechanical and optical properties, have increasingly found applications in both defense and civilian sectors. These applications demand high processing efficiency and superior surface quality. Fixed abrasive polishing (FAP) technology, utilizing diamond abrasive pads, is widely adopted due to its high efficiency, controllability, cost-effectiveness, and environmental benefits. However, FAP suffers from a rapid decline in polishing efficiency and ineffective self-correction. This study explores the use of free abrasives (alumina and silica particles) to enhance the self-correcting capabilities of FAP in sapphire polishing, leading to the development of a novel polishing process. To investigate the impact of free abrasives on the polishing process, three methods were designed: FAP polishing without free abrasives, FAP polishing with free abrasives, and polishing using only free abrasives. The study compared material removal rates (MRR), surface roughness (Ra), and topography of both the sapphire and FAP (including the distribution of diamond abrasives and the presence of holes due to abrasive drop-out) after polishing. The results indicate that the material removal rate of sapphire is lowest with FAP polishing without free abrasives, intermediate with free abrasive-only polishing, and highest with combined FAP and free abrasives, achieving an MRR of approximately 80.1078 nm/min and an Ra of about 24 nm. The data and topography analysis suggest that free abrasives significantly enhance the self-correcting capability of FAP, thereby increasing the material removal rate.s*

Keywords**—** *Fixed diamond abrasive pad, Sapphire, Self-correcting, Material removal rate, Surface roughness*.

I. INTRODUCTION

Sapphire single crystals are gaining prominence due to their exceptional properties, including high light traFnsmittance, thermal conductivity, electrical insulation, abrasion resistance, and chemical stability. These properties make sapphire indispensable in various industries, national defense, scientific research, and more. The increasing utilization of sapphire in numerous applications necessitates high precision in processing (such as surface precision and fine processing) and maintaining the integrity of the machined surface [1]. Particularly with the rapid advancements in LED sapphire substrate technology, achieving high integrity and ultra-smooth surface machining has become a significant challenge globally. In the current LED sapphire substrate processing stage, free abrasive polishing is initially employed for wafer backgrinding (BG). Following material thinning, chemical mechanical polishing (CMP) is applied to meet product specifications. The prevalent polishing method, both domestically and internationally, involves loose abrasives. This method is known for its high machining precision, simplicity, and low investment cost, but it suffers from unstable precision and low efficiency [2]. Fixed Abrasive Polishing (FAP) technology was developed to correct the shortcomings of loose abrasive polishing. In FAP, abrasives are embedded within the polishing pad, enhancing polishing controllability and ensuring consistent surface precision. Material removal in FAP primarily relies on the mechanical cutting action of the abrasives in the polishing pad, making the study of fixed abrasive polishing pads crucial, especially concerning the development and enhancement of their self-correcting characteristics. J.Y. Choi developed a fixed hydrophilic abrasive pad utilizing the water-swelling properties of polymers, explained the self-correcting mechanism, and evaluated its characteristics based on swelling rate and wear rate, using a diamond wheel for grinding [3]. Zhu Yongwei enhanced the self-correcting ability of FAP by incorporating magnesium sulfate to create water-soluble pores, thereby increasing chip space [4]. Furthermore, he added copper powder to the resin matrix to improve its hardness and abrasive control capability, thus increasing the material removal rate [5]. Wang Jianbin investigated the effects of sapphire polishing slurry, finding that adding ethylene glycol enhances the surface activity of sapphire [6]. Xu Jun added a pore-forming agent to weaken the network structure and bonding strength of the resin matrix, increasing polishing pressure and thereby improving the self-correcting capability of FAP [7, 8].

The self-correcting mechanism in fixed abrasive polishing (FAP) is primarily driven by the abrasive dust generated during the polishing process. This dust erodes the resin matrix after it has swelled and weakened, thereby exposing fresh abrasives in the subsurface. However, due to the high hardness of sapphire and the minuscule size of the abrasive dust, the erosion effect on the resin matrix is limited. Consequently, the self-correcting process is challenging to achieve, leading to the blockage of gaps between the exposed diamond particles in the polishing pad and affecting the stability of FAP's machining performance. To address this issue, this study introduces a small amount of silica and alumina particles into the polishing slurries. These particles effectively erode the resin matrix of the FAP, facilitating the wear of the resin matrix and the emergence of diamond particles. This approach enhances the self-correcting ability of FAP, resulting in a stable material removal rate and improved surface quality.

II. EXPERIMETAL DESIGN

The cutting blades of single sapphire crystal (A side) were prepared using a 5–10 μm polycrystalline diamond abrasive polishing pad to achieve surface roughness uniformity, resulting in an Ra of 45 nm. The wafers used in the experiments measured 30 mm × 40 mm × 1.5 mm, with each polishing session lasting 30 minutes.

Two types of fixed abrasive polishing pads were prepared:

1# Polishing Pad: Without abrasive particles.

2# Polishing Pad: Containing 3–5 μm single diamond crystal particles, with other components identical to those in the 1# pad.

The polishing slurries used in the experiments were:

A: Deionized water.

B: Ludox with particle sizes ranging from 50–100 nm.

Table 1 Specific factors chosen in the experiment.

Test	Fixed Abrasive Pad	Polishing Slurry	Loose Abrasive Mass Fraction
1	1#	B	-
2	1#	A	5%
3	1#	B	5%
4	2#	A	-
5	2#	B	-
6	2#	A	5%
7	2#	B	5%

Table 2 Polishing parameters

Equipment	Speed of Polishing Disc (rpm)	Speed of Station (rpm)	Polishing Pressure (psi)	Velocity of Slurry (ml/min)	Polishing Time (min)
Polishing Machine	85	80	4	20	60

Additionally, 0.5 μm alumina particles were utilized as loose abrasives for the polishing experiments. The specific factors for each experiment are detailed in Table 1. The polishing process parameters are shown in table 2.

The surface roughness of the sapphire wafer was measured using a white light interferometer. The original thickness of the wafer was determined with a micrometer. The weight of the wafer before and after the experiments was measured using a Sartorius BS224S precision analytical balance, with a precision of 0.1 mg. The material removal rate (MRR, nm/min) was calculated using Equation 1.

$$MRR = \frac{(M_0 - M) \times h_0}{M_0 \times t} \times 10^6 \qquad (1)$$

In the formula, $h0$ represents the initial thickness of the wafer before processing, measured in millimeters (mm). $M0$ and M denote the weight of the wafer before and after polishing, respectively, measured in grams (g). t represents the polishing time, measured in minutes (min).

III. EXPERIMENT RESULTS AND ANALYSIS

3.1. Material Removal Rate Analysis

The material removal rate (MRR) of sapphire under various polishing conditions is depicted in Fig. 1. Samples 1, 2, and 3 exhibit relatively low MRRs. These samples utilize the 1# pad, with polishing slurries containing silica and alumina particles, akin to traditional loose abrasive polishing methods.

In these samples, a minority of abrasives embedded in the polishing pad execute micro-cutting on the wafers, while the majority produce a rolling effect. Due to the relatively low hardness of the resin matrix of the polishing pad used in the experiment, silica and alumina particles exhibit significant yielding during the polishing process. Despite silica having a lower hardness than alumina, its smaller size and higher consistency in the polishing slurry result in a higher MRR for sample 1 compared to sample 2.

However, the cutting effect of silica and alumina particles as abrasives for polishing sapphire remains limited, failing to achieve sufficient material removal. Sample 4, employing the 2# pad, experiences minimal changes in the hardness and elastic modulus of the polishing pad. Consequently, diamond particles exhibit similar yielding behavior during the polishing process, generating a micro-cutting effect. Nonetheless, the low height of diamond particles and their resistance to blunt abrasion contribute to a lower MRR in fixed abrasive polishing compared to free abrasive polishing.

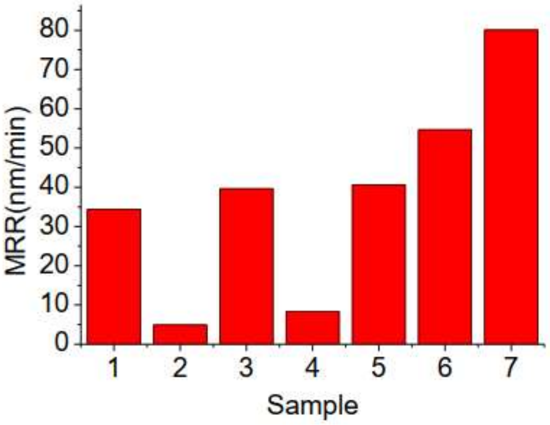

Fig. 1 MRR under different polishing conditions

Samples 5, 6, and 7 utilize the same polishing pad as sample 4, differing only in the composition of the polishing slurry. While sample 4 employs deionized water alone, samples 5, 6, and 7 incorporate silica and alumina particles into the slurry. This addition introduces a rolling effect alongside the cutting effect of fixed abrasives. Theoretically, the material removal rate of these samples should be the combined effect of fixed and loose abrasives. However, in practice, the material removal rate of sample 7 (and sample 6) exceeds that of sample 3 (and sample 2) when combined with sample 4, resulting in an MRR of 80.1078 nm/min.

This discrepancy suggests that silica and alumina particles may not only facilitate a rolling effect on the wafer's surface but also alter the distribution and shape of diamond particles within the polishing pad. This alteration potentially enhances the self-correcting capability of fixed abrasive polishing (FAP) during the polishing process, significantly boosting polishing efficiency.

3.2 Surface Roughness and Morphology Analysis

Fig. 2 illustrates the surface roughness values before and after polishing. Compared to the pre-lapping sample, all samples exhibit a decrease in surface roughness post-polishing. FAP polishing without free abrasive yields the highest surface roughness, followed by FAP polishing with free abrasive, while FAP with free abrasive and no abrasive in the slurry results in the lowest roughness. Additionally, smaller abrasive particle sizes correspond to lower surface roughness levels.

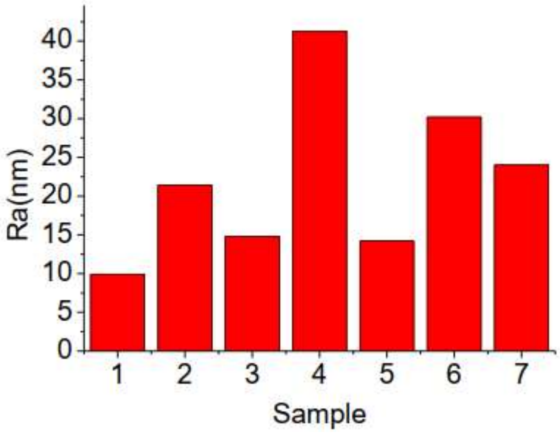

Fig. 2 Surface roughness before and after polishing

Free abrasives introduce a rolling effect during sapphire polishing, influencing surface quality. Consequently, sapphire polished by FAP with free abrasives demonstrates intermediate surface quality between the other two methods.

Fig. 3 Surface topography before and after polishing under different conditions

Fig. 3 displays the surface morphology of wafers under different polishing conditions. Compared to the pre-lapping sample (Fig. 3a), the surface quality of post-polished wafers improves. Sample 1 (Fig. 3b) exhibits some scratches, likely caused by large abrasive particles embedding into the resin matrix and forming pits through abrasive rolling. Sample 2 (Fig. 3c) shows similar scratches to sample 1, with deeper and more pronounced scratches due to the larger size of alumina particles. Uneven distribution of alumina particles results in uneven removal of material.

Sample 3 (Fig. 3d) shows a relatively flat surface with numerous peaks and depressions, similar to samples 1 and 2. Staggered scratches appear on sample 4's surface (Fig. 3e) due to micro-cutting, resulting in a smoother surface.

Samples 5, 6, and 7 (Fig. 3f-h) display minimal scratches, similar to sample 3 but more regular. This improvement is attributed to the erosion and wear of the matrix by silica and alumina particles, leading to a significant increase in the exposed height of diamond particles. As a result, the pressure is primarily borne by the abrasives, leading to increased MRR and surface roughness.

3.3. Polishing Pad Surface Topography Analysis

Fig. 4 illustrates the surface morphology of polishing pads under different polishing conditions. When the polishing slurry consists of deionized water alone, visible diamond particles on the surface of the polishing pad are scarce. The diamond particles appear to be covered with resin matrix and metal, as observed in the local enlargement (Fig. 4a). Only a corner of the diamond particle is visible, limiting its cutting ability.

Conversely, when silica and alumina particles are added to the polishing slurry (Fig. 4b), the number of visible diamond particles on the surface of the polishing pad significantly increases. Additionally, numerous visible pits are present, likely formed by the dropping of diamond particles. This observation suggests that diamond particles are shed and alternately exposed in different regions of the pad. In the local enlargement (Fig. 4b), the diamond particles exhibit a certain height and blade angles, ensuring that sharp diamond particles continuously participate in the polishing process of sapphire.

These findings validate the previous conjecture based on the material removal rate (MRR) and surface quality of the wafer, confirming the importance of sharp diamond particles in achieving effective polishing results.

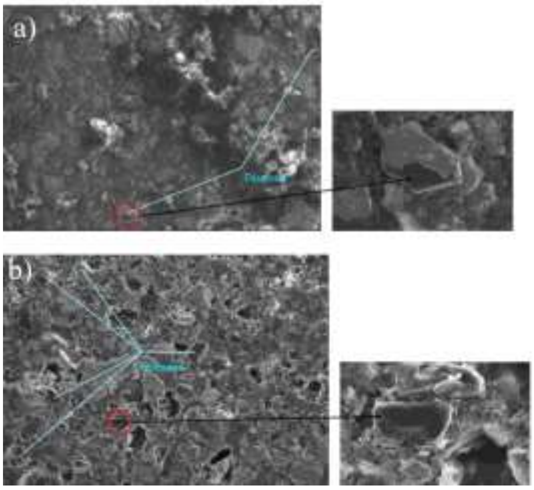

Fig. 4 Surface topography of polishing pad under different polishing conditions (a) FAP (b) FAP with free abrasive

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3.4. Free Auxiliary Fixed Abrasive Polishing Sapphire Model

Fig. 5 illustrates the contact model of fixed abrasives and wafers under different polishing conditions. Diamond particles embedded in the fixed resin matrix of the Fixed Abrasive Pad (FAP) have their exposed tips scratching the wafer surface to achieve material removal. The parameter δcδc represents the critical cutting depth, which is the brittle-ductile transition point of material removal. $\delta 1$ is the depth resulting from an exposed diamond particle cutting into sapphire under the polishing condition of sample 4. $\delta 2$ is the cutting depth resulting from an exposed diamond particle cutting into sapphire under the polishing condition of sample 7, which utilizes a polishing slurry containing alumina and silica particles.

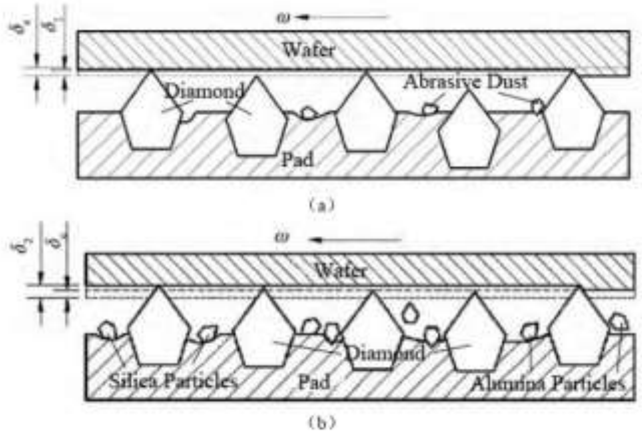

Fig. 5 Fixed abrasive contact with wafer model under different conditions (a) FAP (b) FAP with free abrasive

Due to the limited depth of an exposed diamond particle in the resin matrix of the polishing pad and the small size of the abrasive particles and dust, the self-correcting ability of FAP is constrained. Therefore, under the polishing condition of sample 4, where the exposure height of diamond is low, the proportion of cutting depth ($\delta 1$) being less than the critical depth results in a low material removal rate. Sample 7, on the other hand, utilizes a slurry containing silica and alumina particles, which can consistently repair and maintain the polishing pad. Consequently, the exposed height of diamond particles increases. Under the same pressure conditions, the embedded depth of diamond particles in the wafer's surface increases. As a result, the proportion of cutting depth exceeding the critical depth leads to material removal dominated by brittle removal, resulting in a higher material removal rate.

Fig. 6 illustrates the self-correcting process of traditional FAP under different polishing conditions, where the exposed tips of diamond particles coated by resin matrix scratch the sapphire surface.

In sample 4, where deionized water is utilized, the water swelling effect of the matrix decreases the binding force between its surface and sub-surface. Abrasive dust wears down the matrix, causing dull diamond particles to fall off and exposing ones in the sub-surface. However, due to the significantly higher hardness of the sapphire wafer compared to the polishing pad, abrasives yield significantly during the polishing process. Moreover, the extremely small size of the dust results in finite erosive wear of the matrix. Consequently, dull diamond particles on the surface of the resin matrix cannot be timely removed, and sharp diamond particles in the sub-surface cannot be timely exposed. As a result, the material removal rate (MRR) declines quickly and steadily, and the self-correcting process of traditional FAP is unable to realize effectively (Fig. 6a).

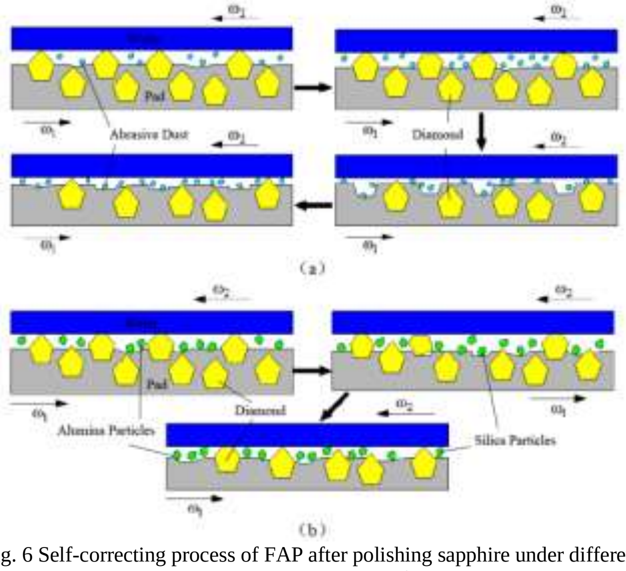

Fig. 6 Self-correcting process of FAP after polishing sapphire under different conditions (a) FAP (b) FAP with free abrasive

In contrast, sample 7 utilizes a slurry containing silica and alumina particles. This slurry flows between the wafer and pad, constantly washing the matrix of the pad. The larger size of silica and alumina particles significantly improves their ability to wear down the swelling pad surface. Blunt diamond particles lacking sufficient holding force drop off, allowing sharp diamond particles to expose the surface of the resin matrix while maintaining a higher height. Additionally, the resin layer or metal coating on the surface of diamond particles wears down quickly, naturally increasing the material removal rate. This process can be recycled, enabling the self-correcting capability of the pad to be realized and maintaining a stable material removal rate for an extended period (Fig. 6b).

In summary, the self-correcting process of fixed abrasive pad with free abrasive polishing sapphire can be described as follows: The exposed tips of diamond particles cut into the wafer to achieve material removal. The swelling effect of the resin matrix reduces the binding force between its surface and sub-surface. Dust, silica, and alumina particles continuously wash the matrix of the pad during the polishing process. Blunt diamond particles lacking sufficient holding force are shed, allowing sharp diamond particles to be exposed on the surface of the resin matrix, maintaining a higher height. This process continues in a cycle, ensuring effective and stable polishing over time.

IV. CONCLUSIONS

Fixed abrasive polishing pads containing silica and alumina particles in the polishing slurries demonstrate excellent self-correcting capabilities during the sapphire polishing process. This is evidenced by a significant increase in the material removal rate, reaching up to 80.1078 nm/min. Compared to free abrasive polishing, this represents a tenfold increase in efficiency. The role of silica and alumina particles in the polishing slurries is clarified: abrasive dust, along with alumina and silica particles, exert strong erosion and abrasion effects on the resin matrix of the polishing pad. This action facilitates the emergence of fresh diamond abrasives from the sub-surface, maintaining a relatively high exposure height. Consequently, the polishing process can proceed consistently, steadily, and efficiently.

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