



Dependence of pad performance on its texture in polishing mono-crystalline silicon wafers

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ABSTRACT

Mono-crystalline silicon wafers are important materials in the semiconductor industry for fabricating integrated circuits and micro-electro-mechanical systems. To ensure high surface integrity of polished wafers, the effect of pad texture and its variation on the pad performance needs to be understood. This paper studies experimentally the dependence of pad performance on its texture deterioration by investigating its correlation with polishing time, polishing pressure, and material removal rate. The study concludes that material removal rate decreases as the cylindrical cell structure of a pad is gradually deteriorated, that there is a pad life limit beyond which polishing quality can no longer be maintained, and that the workable pad life can be extended to a certain degree by applying higher polishing pressure.

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1. Introduction

There has been considerable research interest in the polishing of mono-crystalline silicon wafers, because silicon is one of the major materials in fabricating electronic devices and polishing is a key process in producing silicon wafers with satisfactory surface integrity. In a typical polishing process, a silicon wafer is pressed against a relatively soft polymeric pad with a continuous supply of abrasive slurry. Material removal from the wafer during polishing is through the contact interaction between the wafer and abrasives held on the pad while the wafer and pad are in relative sliding motion. Details of mechanical interaction among the wafer, pad and abrasive slurry have been discussed elsewhere, for example in the papers by Jianfeng and Dornfeld [1], Zhao and Chang [2] and Zarudi and Zhang [3].

To the authors' knowledge, most studies so far concentrate on process variables of polishing such as pressure, velocity, slurry flow rate, lubrication, material removal rate, planarization and surface roughness. Zarudi and Zhang [3] investigated the polishing-induced subsurface damage in silicon wafers in relation to polishing conditions. Zarudi and Han [4] followed the dimensional analysis method proposed by Sun et al. [5] to estimate the polishing rate variations. Biddut et al. [6] reported an alternative polishing process, a solely mechanical damage-free polishing, to reduce the disposal-related production cost of chemical additives

used in the commonly use chemo-mechanical polishing (CMP). Mullany and Byrne [7] discussed the effect of slurry viscosity on the chemo-mechanical polishing process. Shih-Chieh and Meng-Long [8] and Forsberg [9] studied the process parameter effects on material removal rate and polishing uniformity. However, some researchers [10–13] have observed that the properties of a polishing pad have a significant influence on the material removal rate. Nevertheless, a clear understanding of the mechanisms in relation to these observations is unavailable.

This paper will experimentally investigate the effect of pad texture on its performance in polishing mono-crystalline silicon wafers. A focus of the study is to understand pad texture variation in relation to polishing time, pressure and material removal rate.

2. Experiment

Experiments were conducted on commercially available (100) silicon wafers using a PM5 auto-lap precision lapping/polishing machine from Logitech, as shown in Fig. 1a. The thickness of the wafers before polishing experiment was 700 μm. The polishing process is schematically illustrated in Fig. 1b, where the abrasives used in distilled water slurry were alumina particles of about 50 nm in average diameter. The polishing pad, of the diameter 300 mm, was Chemicloth Polishing Cloths, SKU:0CON-352 of Logitech made of urethane. The polishing conditions used are summarized in Table 1. The polishing tests under each condition listed in the table were repeated 3 times. In the tests, the volumetric concentration of the abrasive slurry was 2.5% and the flow rate of the slurry was

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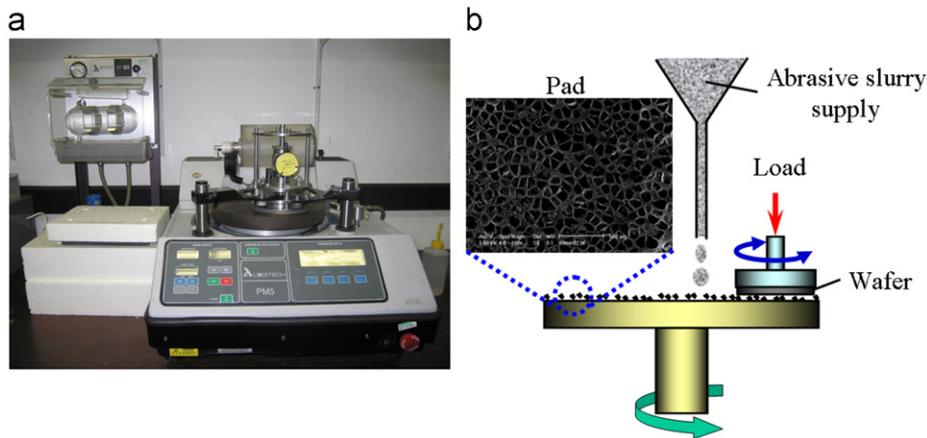


Fig. 1. The polishing set-up. (a) The PM5 Auto-Lap Precision Lapping/Polishing Machine used for the polishing experiments in this study; (b) a schematic illustration of a polishing process, showing the porous surface structure of a polishing pad, the slurry application, the polishing loading, and the relative motion mechanism of the polishing operation.

Table 1
Polishing conditions.

Polishing Time (min)	Nominal Pressure (kPa)	Velocity (m/s)
30	10 and 25	0.143
60		
90		
150		

25 ml/min. It is worth clarifying that different from a CMP, in the entire test here the polishing was performed without any chemical additives in the slurry to avoid possible chemical effect on the pad wear. In other words, the polishing slurry consists of only alumina abrasives and distilled water.

The surface texture of the pad and the composition characterization for assessing the percentage of abrasive particles retained after a polishing operation were carried out by energy dispersive X-ray (EDX) spectroscopy on a scanning electron microscope (SEM), XL30. Abrasive particles retained on the polishing pad were quantified by a comparative measurement of Aluminum over Carbon, the main elements in the abrasive particles and pad material (Urethane), respectively. The surfaces of the polished silicon wafers were investigated under a scanning probe microscope (SPM), PicoSPM, operating in the atomic force microscopy (AFM) mode.

The imprints of the wafer-pad/abrasive contact areas in polishing, as the shown in Fig. 2, were obtained by the following process. First, a piece of the pad after a polishing operation with planned polishing time and pressure was cut off while the abrasives retained. This piece of pad was coated uniformly by black carbon and was then pressed on to a clean glass slide at a pressure identical to that in the polishing operation. The black carbon imprint on the glass slide mimicked approximately the contact situation of the wafer-pad/abrasive system in the polishing operation. The imprint images were analyzed by image editing software on an optical microscope, Leica Qwin Plus, to give a quantitative the measure of the contact areas.

3. Results and discussion

3.1. Variation of pad texture with polishing time

To understand the effect of polishing time on the variation of the pad surface texture without the influence of other factors, the polishing pressure in this set of tests was kept unchanged at

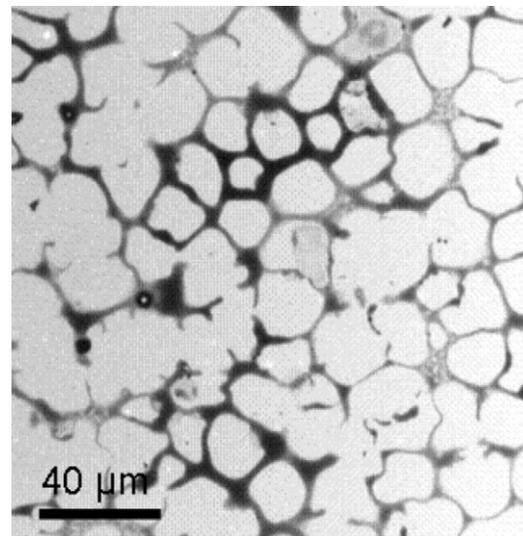


Fig. 2. A typical imprint of the contact area between a glass slide and a polishing pad with abrasive particles. The imprint was taken at the pressure of 10 kPa. Note that the dark areas were the contact areas.

10 kPa. Fig. 3 shows the cross-sectional SEM micrographs, with the corresponding top-view as inserts, of the textures of the pad surfaces after different polishing durations. It is clear that the texture deterioration builds up with time and the texture cells were worn out gradually. The polishing between 60 min (Fig. 3c) and 100 min (Fig. 3d) seems to be a critical stage during which the pad wear induced dramatic topographic changes in the networked cells of the pad texture from their original cylindrical shapes, which can retain abrasive particles effectively, to bowl shapes which can hardly keep hold of the particles. Wear of the pad became excessive after 100 min (Fig. 3d) and the pad's original texture was mostly destroyed, e.g. after a polishing of 150 min (Fig. 3e).

Because of the cell structure deterioration, which alters the abrasive retaining ability of the polishing pad, it is expected that pad performance in terms of polishing efficiency will change. This is confirmed by examining the material removal rate from the silicon wafer against polishing time; in other words, against the extent of the pad texture deterioration. Table 2 and Fig. 4 show that the initial wear of the pad in the period before 60 min does not lead to noticeable performance degradation, because the

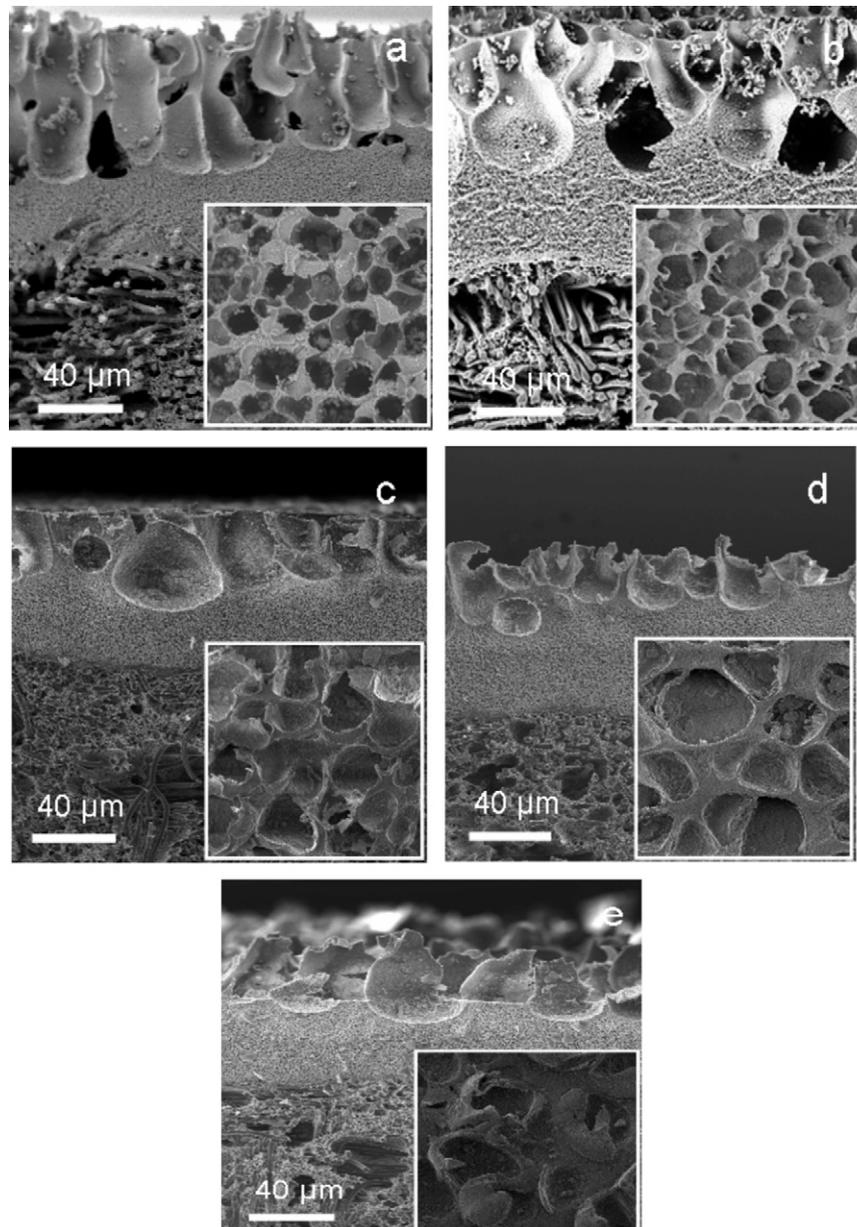


Fig. 3. SEM microphotos showing the texture variation of pads with polishing time. All tests were carried out under a constant polishing pressure (10 kPa). (a) new pad, (b) after 30 min of polishing, (c) after 60 min of polishing, (d) after 100 min of polishing, and (e) after 150 min of polishing.

Table 2

Average material removal rate in wafer thickness under the polishing pressure of 10 kPa.

Polishing time interval (min)	Thickness removed within the time interval (μm)	Average material removal rate with the time interval ($\mu\text{m}/\text{min}$)
0–30	2.236 ± 0.14	0.075 ± 0.005
30–60	2.162 ± 0.10	0.072 ± 0.003
60–90	1.835 ± 0.03	0.061 ± 0.001
90–120	1.833 ± 0.08	0.061 ± 0.003
120–150	1.006 ± 0.10	0.034 ± 0.003

The rates were calculated with a time interval of 30 min, i.e., a rate value here is an average in 30 min.

decrease in the material removal rate is minimal up to 60 min of the polishing. This is in agreement with the above observation that up to 60 min the pad cells still had their cylindrical shapes for

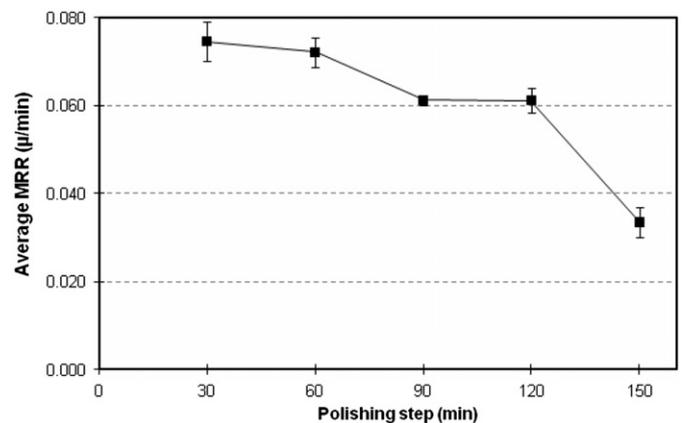


Fig. 4. Average material removal rate in thickness of the wafer.

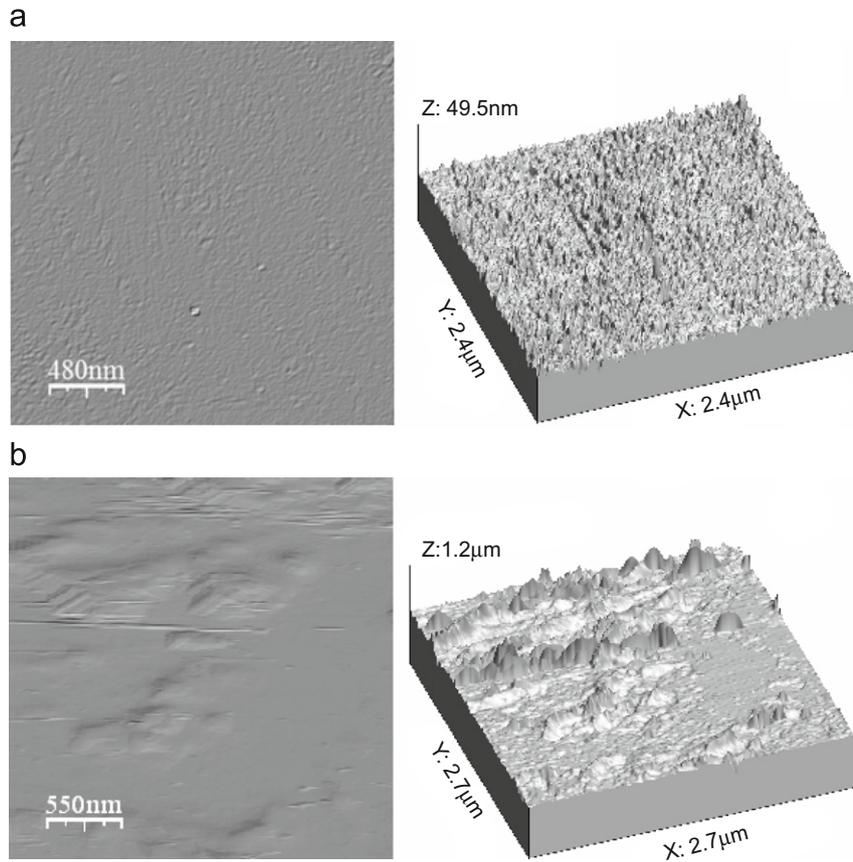


Fig. 5. Polished silicon wafer surfaces. (a) after 30 min of polishing, and (b) after 150 min of polishing.

retaining abrasives. When the bowl shapes of the cells emerge, the material removal rate decreases quickly as shown in Fig. 4. When such a worn pad is still used, apart from the problem of poor polishing efficiency (*i.e.* lower material removal rate), surface integrity of a polished wafer cannot be satisfactory, as shown in Fig. 5.

3.2. Contact area and pad's ability in retaining abrasives

The variation in contact area between a pad (including abrasives) and a wafer, as well as the pad's ability in retaining abrasives during polishing, can reflect the performance change of the pad.

Fig. 6 shows that, regardless of the polishing pressure, the contact area reaches its maximum at around 30 min of polishing and then decreased gradually. Based on the discussion on the pad texture deterioration in Section 3.1, it is expected that the contact area will decrease when the height of the pad's surface cells reduces due to pad wear. This is because less and less cell walls in the process can be in direct contact with the wafer when the cell walls wear away, but the abrasives, of which the diameter change is minimal, will function as the separator between the pad and the wafer. However, it is not straightforwardly expected that the contact area increases so significantly in the first 30 min of polishing. This phenomenon becomes understandable if we note the following. At the beginning of a polishing, the networked cells have much narrower openings with many being even capped, as shown in Fig. 3a. Such microstructures do not allow abrasives to penetrate into the cavities of majority of the cells, and hence direct contacts are mostly between the wafer and the abrasives.

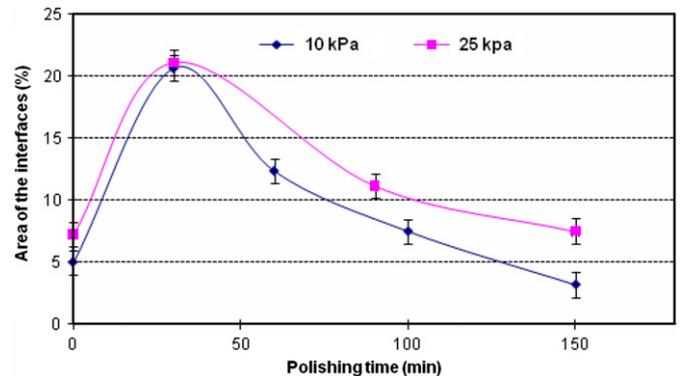


Fig. 6. Contact area variation with polishing time and pressure.

Therefore, the contact area is small at the beginning of polishing. When the narrow openings and caps of the cells are worn out, abrasives can penetrate into the cell cavities, and more cell walls get into direct contact with the wafer, leading to a total contact area increase before the considerable deterioration of the cell walls. The above interpretation is supported by the contact area values after the pad cells have been destroyed, say after 150 min of polishing as shown in Fig. 4, at which direct contacts are again between the abrasives and the wafer mostly.

From Fig. 4, we can see that the contact area variation in polishing has a direct correlation with the pad's ability in retaining abrasives during polishing. This is confirmed by the variation of the alumina concentration on the pad surface (measured by EDX) as shown in Fig. 7, where a higher

concentration means that more alumina particles had been retained on the pad. Corresponding to the contact area variation, the alumina concentration, and thus the abrasive retaining ability of the pad, increases with the polishing time initially, reaches a maximum at around 60 min of polishing, and then drops and becomes almost steady after 100 min of polishing.

3.3. Effect of polishing pressure

The magnitude of polishing pressure affects the pad–abrasive–wafer interaction process and in turn influences the performance of a pad. To understand this, in addition to the above polishing tests at 10 kPa, a series of experiments were carried out under a polishing pressure of 25 kPa. It is interesting to note that under the higher polishing pressure, the process of contact area reduction gets slower (Fig. 6) and the abrasive retaining ability of the pad becomes higher (Fig. 7). This indicates that increasing the polishing pressure has altered the wear rate of the pad's texture. The SEM images in Fig. 8 show that after polishing for 150 min, the pad surface under 25 kPa (Fig. 8a) has worn out less in comparison with that under 10 kPa (Fig. 8b). In other words, after the polishing of 150 min, the pad under the polishing pressure of 10 kPa can no longer retain abrasives but that under the polishing pressure of 25 kPa still can. A question is therefore: How can a higher polishing pressure extend the life of a pad? This may be qualitatively answered by the dependence of pad–abrasive interaction upon the polishing pressure as described below.

A pad has a porous surface structure (Fig. 3). Depending on the location of an abrasive particle on the pad surface, e.g. sitting in a valley or settling on a pad asperity, the pad–abrasive–wafer process can be described by the following three interaction modes as illustrated in Fig. 9:

- Mode A: Two-body contact sliding between an abrasive particle and the wafer. The particle in this case is embedded

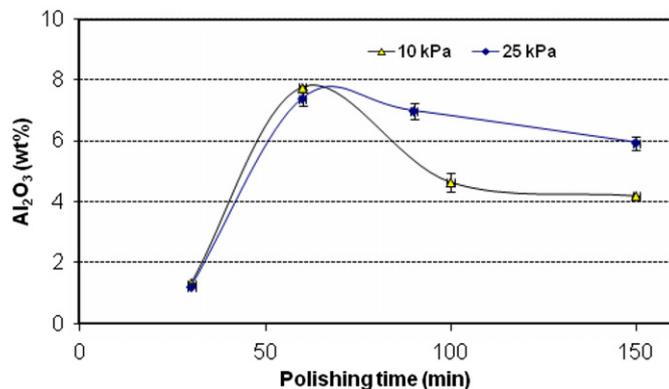


Fig. 7. Variation of aluminum concentration with polishing time.

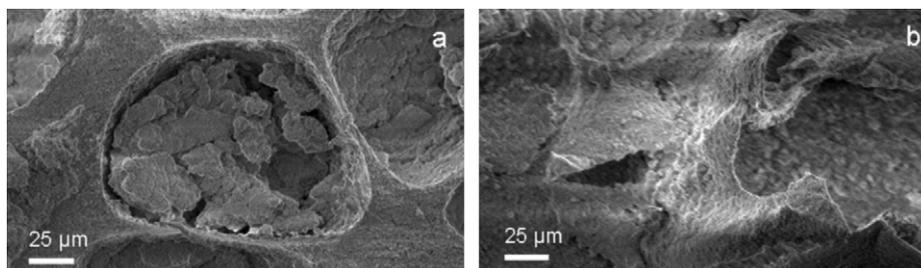


Fig. 8. SEM microphotos of pad after 150 min polishing at pressure (a) 25 kPa, and (b) 10 kPa.

to the pad, and sliding between the particle and pad does not occur, or is negligible compared with that between the particle and the wafer. With this mode, the particle does not wear the pad, or the pad wear by the particle is negligible.

- Mode B: Three-body contact sliding. In this case, a particle slides and rotates between the pad and wafer, and wears both their surfaces.
- Mode C: Abrasive impingement. In this scenario, an abrasive particle moves in the slurry fluid within a cavity formed by the networked pad cells/asperities, driven by the relative motion of the wafer and pad through the slurry. The particle can impact on the wafer surface, thus polish the wafer; or it can hit the pad, causing the pad wear.

When Mode A dominates, the polishing rate on the wafer is high. To have this Mode, abrasives must be retained by the pad relatively firmly, which happens mostly in the first 60 min as discussed previously. In polishing there are always some Mode B abrasives, but as time elapses the pad wears out and more and more abrasives change from Mode A to Mode B. As a result, the material removal rate in polishing the wafer decreases, and the pad wear accelerates.

A higher polishing pressure, however, will flatten the pad asperities and cells more significantly. This will make more abrasives in the Mode A interactions with the pad and wafer, and consequently reduce the number of abrasives in Modes B and C. As such, the wear rate of the polishing pad can be reduced as observed in experiment (Fig. 8). However, this does not mean that a greater polishing pressure is always better. For any polishing process with given a given slurry composition, there should be an optimal polishing pressure. For example, if the pressure is too high, a pad can be simply broken or a wafer in polishing can be easily damaged.

4. Conclusions

This study has established a relatively clearer figure about the effect of pad texture and its variation on the pad performance when polishing mono-crystalline silicon wafers. The following conclusions can be made from the investigation:

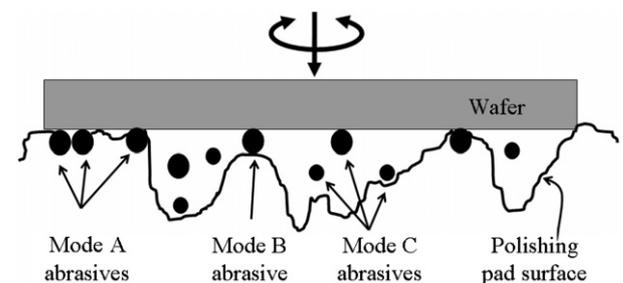


Fig. 9. A schematic illustration of the pad-abrasive-wafer interaction modes.

- (1) When the cylindrical cell network of a pad texture is destroyed, performance of the pad will become very poor. A continuous application of the pad will lead to a low material removal rate and will produce silicon wafers of poor surface integrity.
- (2) The ability of a pad in retaining abrasive particles during polishing is central to an effective polishing. A pad can maintain its good retaining ability until a bowl topographic structure appears.
- (3) A greater polishing pressure, within an allowable range, can increase the life of a pad. The mechanism is that the flattening of the pad surface can increase the number of abrasive particles in the Mode of two-body contact sliding so as to reduce the wear rate of the pad texture.

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