PCD pad conditioners for low pressure chemical mechanical planarisation of semiconductors

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Abstract: Instead of attaching individual diamond grits to a metal substrate, Advanced Diamond Disk (ADD) are manufactured by Electro Discharge Machining (EDM) of sintered Polycrystalline Diamond (PCD) to form cutting pyramids of a designed shape. This is not possible with single crystal diamond grits that possess obtuse solid angles for dressing plastic pads. The test data

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IPR2024-00534
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confirmed that ADD can dress pad more effectively than conventional pad conditioners with discrete diamond grits. Moreover, the service lives of ADD and pad can both be lengthened due to the much milder dressing action. These unique features of ADD can reduce significantly the Cost of Consumable (CoC) of Chemical Mechanical Planarisation (CMP) for the manufacture of advanced semiconductors.

Keywords: Chemical Mechanical Planarisation; CMP; diamond dresser; Polycrystalline Diamond; PCD; pad conditioner.

Reference to this paper should be made as follows: Sung, J.C., Tsai, M-Y., Aoki, M., Chou, C-S. and Sung, M. (2008) 'PCD pad conditioners for low pressure chemical mechanical planarisation of semiconductors', *Int. J. Abrasive Technology*, Vol. 1, Nos. 3/4, pp.327–355.

Biographical notes: James C. Sung helped develop diamond synthesis technologies at GE Superabrasives in 1970s, and initiated the diamond film technologies used latter by Norton Diamond Film in 1990s. He invented diamond grid pad conditioners now used worldwide for CMP manufacture of semiconductors. He is now the president of Diamond Technology Center of Kinik Company in Taiwan. He holds over 100 patents related to various diamond products, including nanodiamond cosmetics and amorphous diamond solar cells. He is also the Professor at both National Taiwan University and National Taiwan University of Technology.

Ming-Yi Tsai is a PhD candidate at National Taiwan University, and also a Professor at National Chin-Yi University of Technology. His research activities are directed toward the dressing behaviour of pad conditioners for chemical mechanical planarisation.

Marehito Aoki is the Leading Engineer who fabricated the ADD pad conditioner at Ishizuka Materials. He also worked as Engineer at Tomei Diamond, the largest diamond company in Japan.

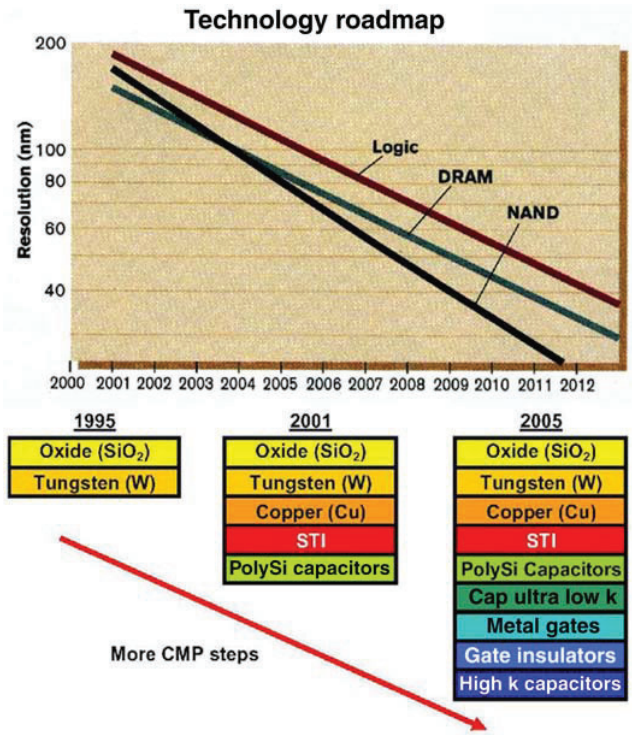
Cheng-Shiang Chou is the Project Manager at Kinik Company in Taiwan. He is responsible for the development of new CMP pad conditioners.

Michael Sung is the Vice President of Advanced Diamond Solutions that offer diamond products in CMP and in other segments of electronic industry.

1 Introduction: chemical mechanical planarisation

The semiconductor chips (e.g. ULSI) has been progressing by following the so-called Moore's Law. As a result, the number of transistor numbers on a CPU has been doubling about every 18 months since the Law was predicted in 1965. Due to the relent miniaturisation of transistors, the circuitry for the chip must be down sized continually. The line, wide of the circuitry (node) is now encroaching upon the virus domain (10–100 nm). In addition, more layers of circuitry must be laid down to meet the increasing demand of logic designs. In order to deposit layers for making nanometer-sized features, each layer must be extremely flat and smooth during the semiconductor fabrication. Consequently, Chemical Mechanical Planarisation (CMP) has been employed by the industry to manufacture semiconductor devices (Figure 1).

Figure 1 The progression of Moore's Law for logic and memory devices of semiconductors with the increasing complexity of IC architecture along with the decreasing of the node size (see online version for colours)



The CMP is accomplished by polishing the wafer with a polymer pad (e.g. polyurethane). The pad is mounted on a rotating platen with controlled speed. A slurry is introduced to the pad that will spread across the pad surface by spinning of the pad and by pushing around with both wafer and pad conditioner. The slurry contains nanometer (e.g. 100 nm) sized abrasive particles (e.g. ceria) that are dispersed in a chemical solution (e.g. hydrogen peroxide). During the polishing action, chemical reactants (e.g. copper oxide) from the surface of the circuitry will be abraded away by free moving abrasive particles suspended in the slurry (Figure 2).

During the CMP process, the polished debris must be removed periodically, otherwise, the pad top will be loaded with dirt known as glazing. In order to get rid of the accumulation of the removed materials, a diamond pad conditioner is used to push the waste around and eventually discharge the debris along the pad periphery. In addition to the elimination of contaminants deposited on the pad top, pressure must be increased locally on the pad asperities to cause the abrasion at the contact points between wafer and pad. In order to create the pressurised points, the contact area must be reduced. Hence, the same diamond pad conditioner must groove the pad top to create asperities. The size and distribution of these asperities actually determines the efficiency of the polishing and the quality of the polished wafer (Song et al., 2004; Tsai et al., 2004) (Figure 3).

Figure 2 The CMP layout that includes a rotating pad, a feeding slurry and a rotating pad conditioner (see online version for colours)

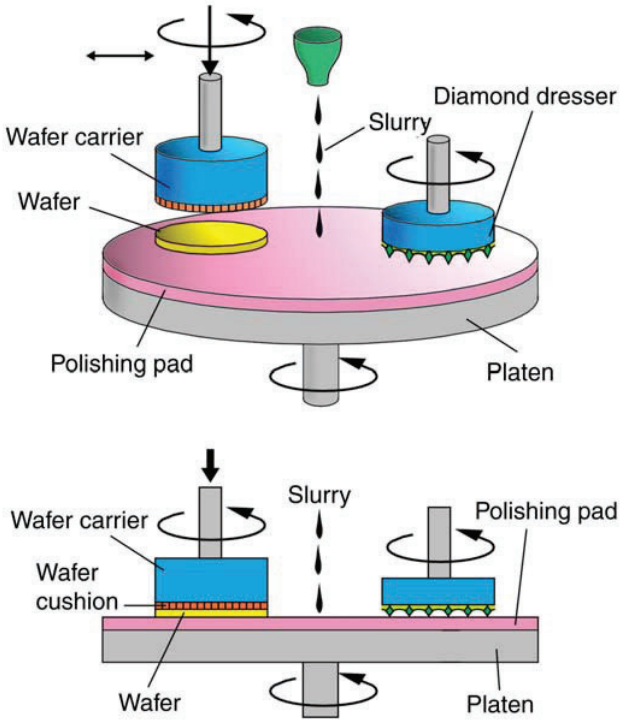


Figure 3 Each diamond grit on the pad conditioner can cut out a groove on the pad surface (see online version for colours)

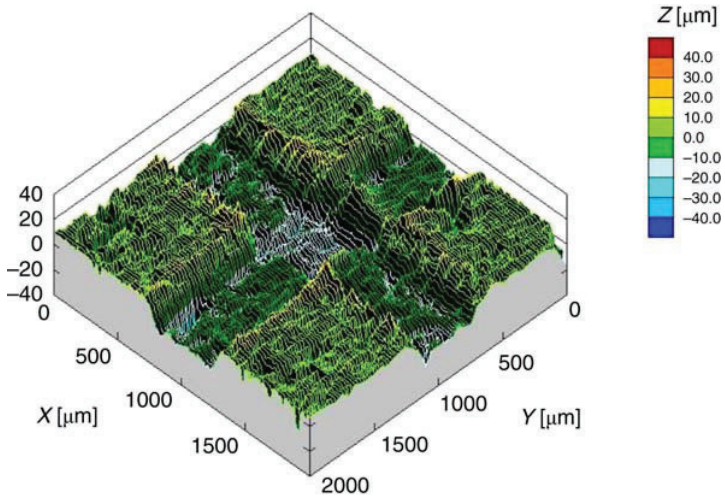
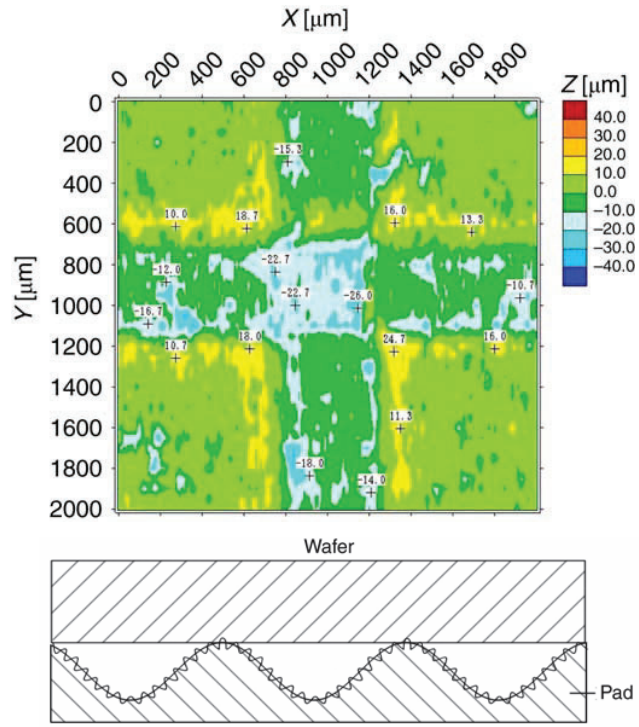


Figure 3 Each diamond grit on the pad conditioner can cut out a groove on the pad surface (see online version for colours) (continued)



Note: The groove is flanked by the rids that is piled up by the plastic deformation of the pressed pad underneath the diamond tip. These ridges from wavy asperities on the pad. The polishing occurs at the contact of points of these asperities on the wafer, particularly those protruded locations that need removal of excess material. by Traversing of a pad by a single crystal of diamond (data of Ming-Yi Tsai).

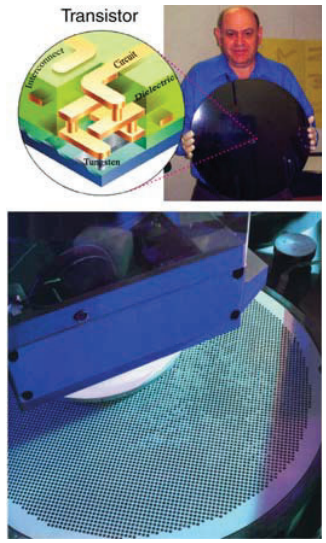
2 Low pressure CMP

Although diamond grit pad conditioners are effective in dressing CMP pads for polishing current designs of integrated circuitry, they are not suitable for making future devices with nodes smaller than 65 nm. This is because that with the decreasing size of the copper wires, non-uniform thickness due to rough or over polishing will change the electrical conductivity dramatically. Moreover, due to the use of coral like dielectric layers, the fragile structure must be polished very gently to avoid disintegration. Hence, the pressure for CMP must be reduced significantly.

New CMP processes, such as by assisting with electrolysis (e.g. Applied Materials ECMP) of copper or by using air film cushion support of wafer (e.g. TSK), are being pursued to reduce the polishing pressure on the contact points between wafer and pad. As a consequence of gentler polishing action, the polishing rate of the wafer will decrease. To compensate for the loss of productivity, polishing must occur

simultaneously over the entire surface of the wafer. In order to do so, the contact spots between wafer and pad must be small in area, but numerous in quantity. This is in contrast to current CMP practice that the contacted areas are relatively large, but there are insufficient number of them, so the contact pressure can be enhanced to achieve higher material removal rates (Figure 4).

Figure 4 The size of future 450 mm (16 inches) silicon wafer is 10 million times (10^7x) larger than the node size (45 nm) of the transistors (top diagram) and ECMP process (bottom diagram) (see online version for colours)



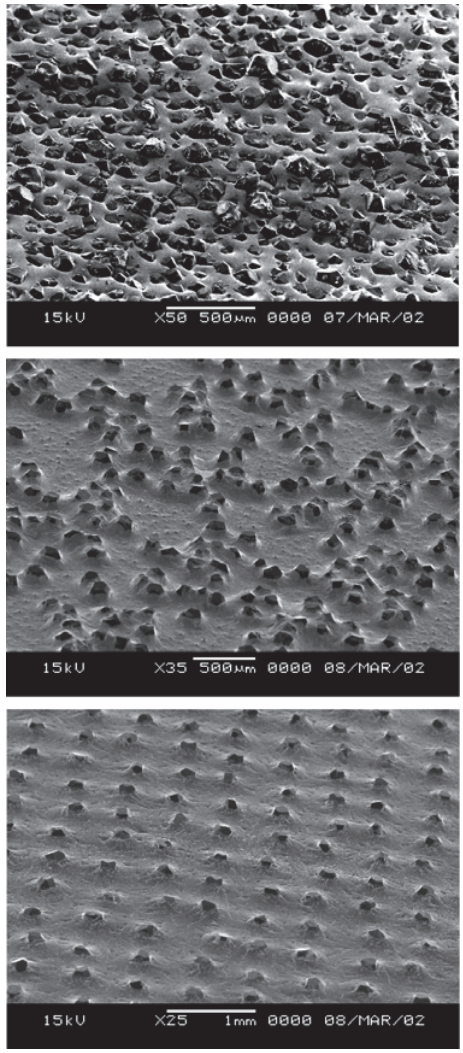
Note: In order to polish the soft copper layer burried in the delicate low-*k* dielectric matrix, the contact pressure between the IC and the tips of pad asperities for ECMP must be one order of magnitude lower than that for conventional CMP. In the ECMP process (bottom diagram), the contacted points on the copper layer are oxidised to form ooze by anodising it with the electrically conducting pad. So the polishing is accomplished not by the brutal force but by cleaning with the uniform asperities.

In order to polish fragile wafers more and more gently, the pad asperities must be reduced. On the other hand, to prevent the polishing rate from declining, more contact points must be created. Consequently, the pad asperities need to be finer in size but more in number. However, the more delicate the polishing becomes, the higher risk for causing scratching on the wafer. In order to avoid this risk, the highest tips of all asperities must be fully levelled. Otherwise, the protrusion of a few 'killer asperities' can ruin the polished wafer. The diamond tips on the current pad conditioners vary more than 50 microns in heights so they cannot avoid forming killer asperities on the pad.

3 Conventional diamond pad conditioners

Conventional diamond pad conditioners contain single crystal diamond grits that are attached to a metal substrate by either electroplating of nickel or brazing with alloy. The distribution can be random or regular (Figure 5).

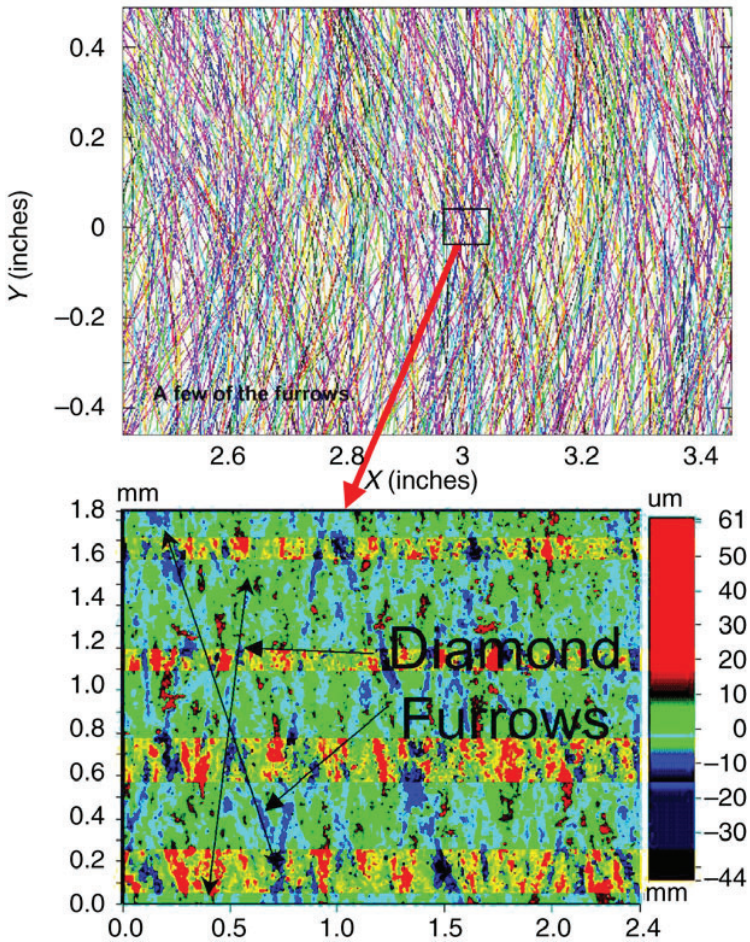
Figure 5 The first generation of diamond pad conditioners containing chaotically distributed diamond grits, typically retained in an electroplated nickel layer (top diagram). The second-generation pad conditioners having clusters of diamond grits that are held by weak braze (middle diagram)



Note: The author invented the third generation pad conditioners that have been manufactured by Kinik Company under the trade name of DiaGrid® pad conditioners (e.g. US Patent 6,039,641) (Sung, 2000). DiaGrid® pad conditioners not only have a regular distribution of diamond grits, but also each diamond is massively bonded by burying in a strong braze (bottom diagram).

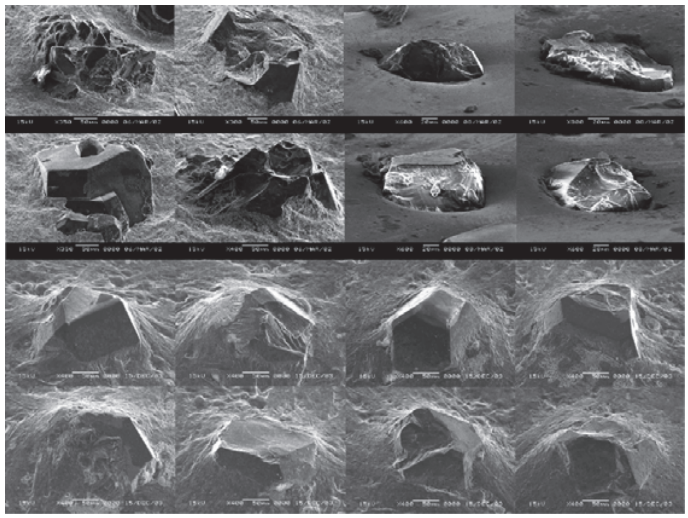
Due to the poor distribution of diamond grits and their large variations in tip heights, the asperities curved by the conventional pad conditioners are not uniform. Consequently, the polishing performance of wafers for the current CMP processes cannot be fully optimised (Figure 6).

Figure 6 The chaotic cutting grooves on a pad produced by dressing with conventional diamond pad conditioners (Rohm-Haas brochure) (see online version for colours)



When diamond grit is dragged across the pad surface, the groove it forms depends on its tip protrusion and the crystal orientation. Conventional diamond pad conditioner is incapable to control these variables. All diamond pad conditioners used today have diamond grits attached to a flat surface. As a result, their tips vary in heights greatly. This is because diamond has different sizes and shapes. Even with the stringent control of the sieves, the diamond sizes may still vary by 40%. Furthermore, the diagonal length of the same diamond is often 40% larger than that measured between parallel faces. Consequently, the diamond tip heights may vary more than half of the average size even when all grits are sitting on a flat surface. Due to the large variations of the diamond size and the tip height, the pad dressed will have asperities that also vary in sizes and heights. As the diamond grits vary in size, shape and orientation, their cutting behaviours are uncontrollable, nor are the uniformity of the polished wafers (Sung, 2006) (Figure 7).

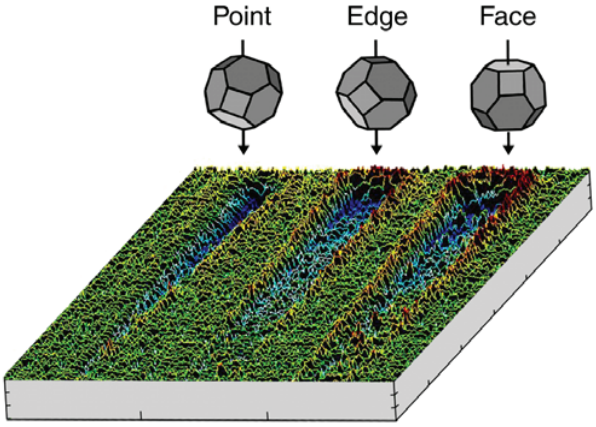
Figure 7 Conventional diamond pad conditioners contain diamond grits with different shapes and every crystal has a unique orientation



Note: The top rows show electroplated diamond grits; the bottom rows, brazed grits.

The orientation of diamond grit has a dramatic effect in plowing the pad, a sharp point of diamond can do more cutting than pushing on the plastic pad. On the other hand, a dull diamond tip may press more on the pad than removing material. Hence, the grooves generated by a conventional diamond pad conditioner are all different, not only in size, but also in geometry. All such variations can cause polishing anomalies of the wafer (Tsai et al., 2004) (Figure 8).

Figure 8 The cutting grooves traversed by a descending diamond tip down to about 100 microns below the contact level. The diamond was oriented with the point (left), edge (middle) and face toward the pad (see online version for colours)



Note: With the increase of contact surface area during the cutting action, more and more plastic deformation of the pad was formed (data of Ming-Yi Tsai).

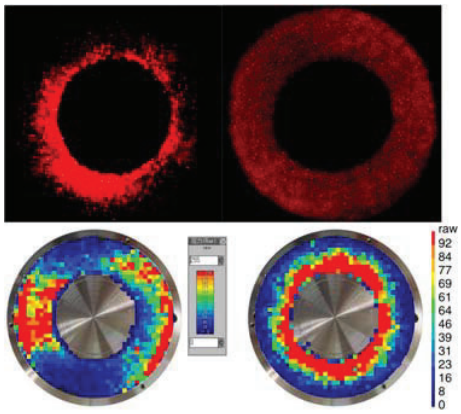
4 Advanced diamond pad conditioner

A revolutionary new design of diamond pad conditioner is now available, this Advanced Diamond Disk (ADD) has identical cutting pyramids with tips extended to the same height. Consequently, ADD can dress pads to achieve unprecedented uniformity in asperities. The furrows are more evenly spaced, the grooves have similar shapes and there are no killer asperities. All these unique features are needed to achieve uniform polishing of delicate wafers of the future (Figure 9).

Figure 9 The commercial ADD samples for ECMP in the front and the state-of-the-art CMP pad conditioner DiaGrid® disks lying in the backside (see online version for colours)

The flatness of ADD and the tip height variation of the cutting pyramids can be mapped based on optical focal depths (e.g. instrument provided by FRT) and pressure sensitive detectors (e.g. instrument provided by Tekscan). It is desirable to have tips located along a slight convex plane so that the number of cutting tips engaged in dressing the pad is maximised (Figure 10).

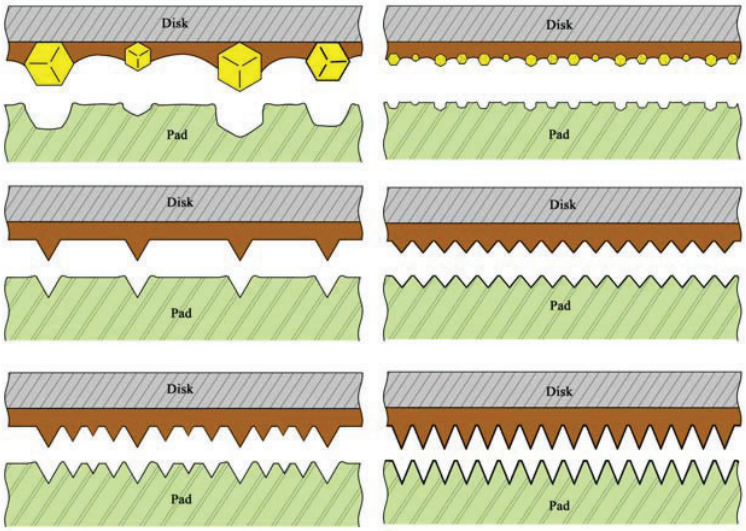
Figure 10 Distorted ADD (left diagrams) versus isotropic ADD (right diagrams) (see online version for colours)



Note: The red colour marks the high points of the pyramid tips that may cutting deeper into the pad.

In order to improving the diamond tip levelling of a conventional diamond pad conditioner, smaller diamond grits must be used to reduce their spread in size distribution. However, smaller size diamond has a much lower protrusion that can impair the flow of slurry. The narrow gaps between diamonds may also trap dirt, a potential cause of wafer defectively. The conventional pad conditioner can only select either fine diamond size or low crystal protrusion, but not both. In contrast, ADD can possess both attributes. In other words, the diamond tips can be levelled without sacrificing their protrusions (Figure 11).

Figure 11 With the current designs of pad conditioners, diamond tip heights vary significantly due to the differences of diamond size, shape and orientation (top diagrams) (see online version for colours)

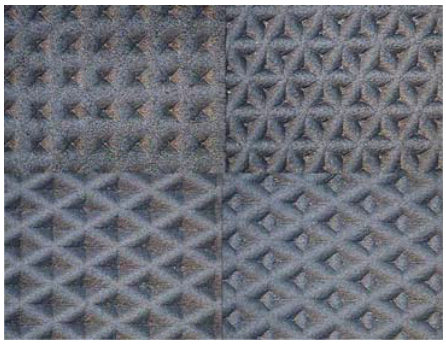


Note: As a result, the dressed pad asperities will vary greatly in depth and in shape. ADD having levelled diamond tips and identical shapes and the dressed pads having much more uniform asperities (middle diagrams). In addition, the size and shape of ADD's cutting pyramids can be designed. Hence, the dressed pad asperities may have structured asperities to achieve special results of polishing.

Another great advantage of using ADD is that the cutting elements are formed, so that they can be designed with structures, such as by forming terraces. In this way, the high level pyramids can cut into the pad while the cutting depth is gauged by the stopper of the lower terrace. In this way, not only the killer asperities are avoided, but also each asperity has the same length. Consequently, the polishing behaviour can be controlled for each and every asperity.

One immediate application of ADD is to dress pads for polishing hard drives of computer memories. In this case, the pad conditioners are not fastened to a fixed handle, but they are encircled in a gear wheel that turns relative the pad on both sides (top and down). As the diamond becomes very small (e.g. 40 microns) for the pad conditioners, they tend to stick to the pad above and below. This problem can be solved by using ADD with tight tip spacing but with much higher tip protrusion. In this case, the 'lotus effect' for perching water droplets is used to separate rotating polishing pads (Figure 12).

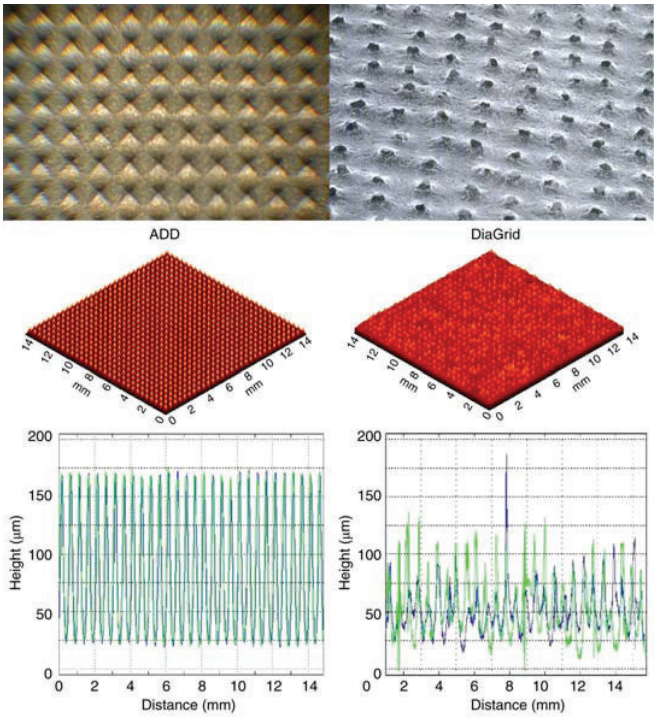
Figure 12 The cutting tips of ADD tailor made in shape and in distribution



Note: This flexibility makes ADD the unique pad conditioners for ECMP manufacture of future Moore's Law semiconductors with node sizes of 45 nm, 32 nm and 22 nm.

The contrast between ADD and DiaGrid® pad conditioner is dramatic in the global view of optical microscopy, and in the detailed layout of the array as well as the profiling of the cutting tips as revealed below (Figure 13).

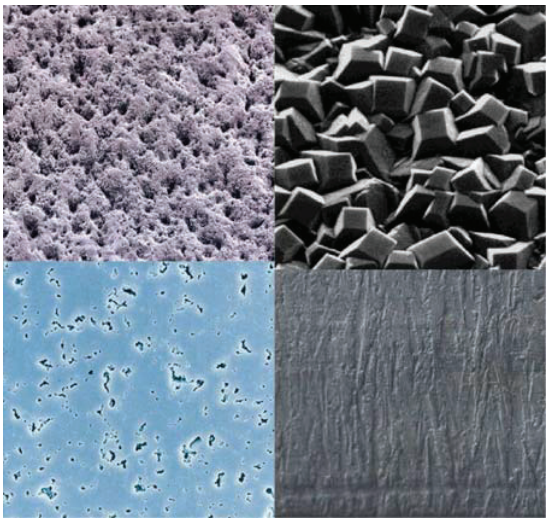
Figure 13 The vivid comparison of the cutting tips between ADD and DiaGrid® pad conditioner confirms that the former is far superior than the latter in dressing the pad for making semiconductors with virus sized transistors (see online version for colours)



5 Polycrystalline diamond

ADD is made of Polycrystalline Diamond (PCD) that contains micron powder of diamond fully sintered together. Each diamond grain is strongly supported by merging with surrounding grains so the global structure is virtually a continuous diamond mass. This is in contrast of diamond film formed by Chemical Vapour Deposition (CVD) that contains columnar diamond grains loosely attached together. The latter has been used for making pad conditioners, but invariably they failed due to the weak structure of the CVD diamond film (Sung et al., 2006a,b) (Figure 14).

Figure 14 PCD matrix made of the intergrowth of microscopic diamond grains (left diagram). PCD having high impact strength due to such a network of randomly oriented crystals. CVD diamond films containing fibrous grains loosely held together (right diagram) (see online version for colours)



Note: Such a structure is vulnerable to stress, so it is not suitable for making pad conditioners.

PCD is normally used to make cutting tools for shaping metals, woods, polymers or even glass. In such applications, the blank is cut through by wire-Electro Discharge Machining (EDM) into small triangles. Each triangle is then brazed to a steel tool shank. ADD represents the first attempt to use a PCD blank without cutting into pieces, but rather to preserve the diamond table to form a pattern of cutting pyramids with different size, shape and spacing (Figure 15).

In order to assure that the PCD blank is sound with micron diamond fully sintered, and also the PCD layer thickness is uniform, ultrasonic echoing is used to scan the PCD layer to reveal the thickness distribution and the defects that may be present (Figure 16).

Figure 15 PCD blanks of different sizes cut into pieces before brazing individual ones onto different tool shanks for using as cutting tools (see online version for colours)

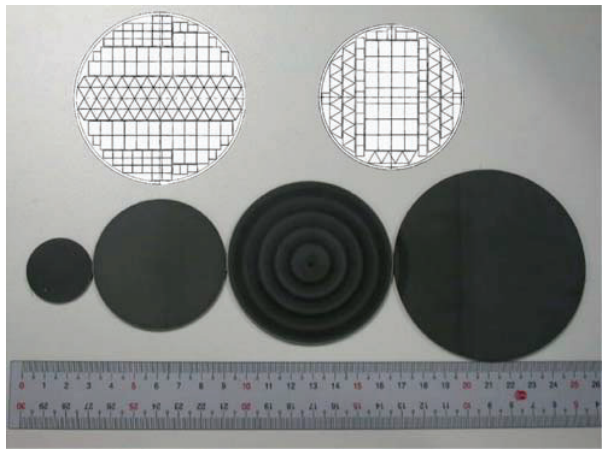
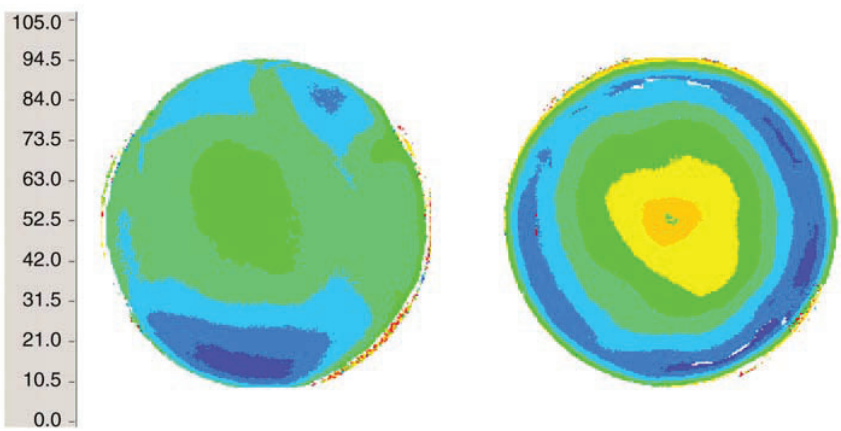


Figure 16 The scan map of jumbo PCD (100 mm in diameter) that revealed uniform thickness of PCD layer with micron diamond fully sintered (left diagram) and thicker interior of the PCD layer with voids distributed on periphery (right diagram) (see online version for colours)



All diamond pad conditioners used today rely on attaching diamond crystals with a matrix, typically made of metal. In contrast, ADD does not need a matrix because it is curved out from a monolithic PCD. The bonding strength of PCD is an order higher than any means of attaching diamond. Consequently, the risk associated of catastrophic loss of a cutting tip is the least for ADD (Figure 17).

The vulnerability of a cutting element is measured by the ratio of its dressing stress against the adherence strength. For ADD, not only its adherence strength is the highest, its dressing stress is also the lowest. This is because all ADD cutting pyramids are levelled to the same height, hence there is no single pyramid that may poke to high as to receive an excessive stress. Consequently, ADD is the lest likely pad conditioner that may have diamond pullouts (Figure 18).

Figure 17 The relative adherence strength of cutting elements on pad conditioners of various designs (see online version for colours)

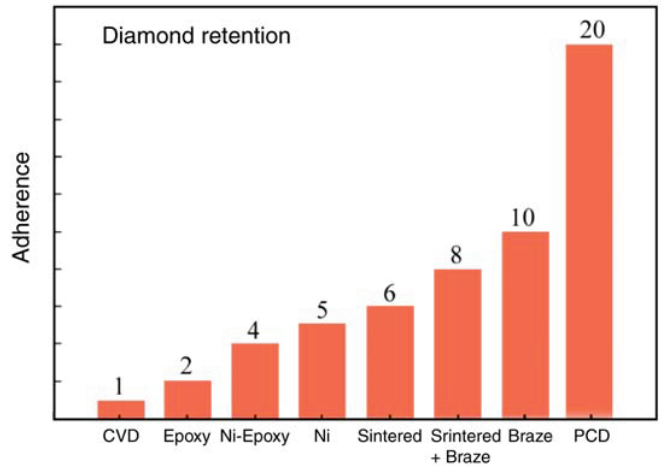
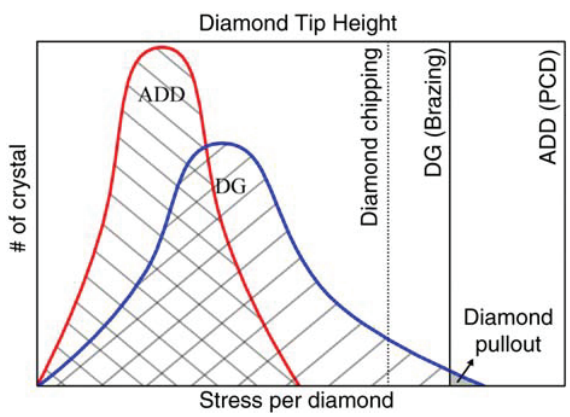


Figure 18 ADD has the least spread of cutting tip heights and the largest bonding strength for pyramids (see online version for colours)



Note: Hence, the risk of losing a cutting element form ADD is the least. In contrast, a conventional pad conditioner may have diamond pullout due to the increased impact on highly protruded diamond.

6 The design of ADD

ADD's surface can be tailor designed to form cutting elements of different sizes and shapes. They may be tailor made to exhibit a predetermined structure.

A combination of sizes and shapes of cutting pyramids may be designed to occupy the same surface of ADD. For example, two sets of cutting pyramids may be used to achieve opposite functions, one for cutting and the other for stopping. In this case, the cut grooves on the pad are not only uniform in shape, but also they have a fixed depth (Figures 19 and 20).

Figure 19 ADD's cutting pyramids can be designed to suit specific applications (see online version for colours)

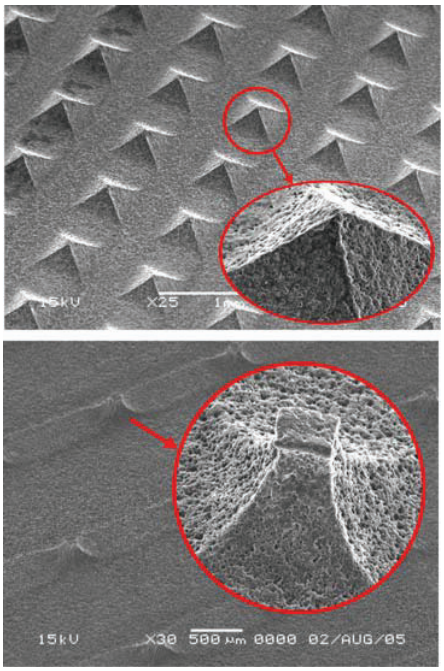
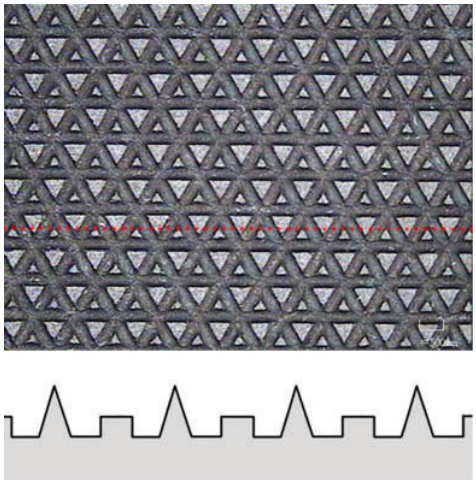
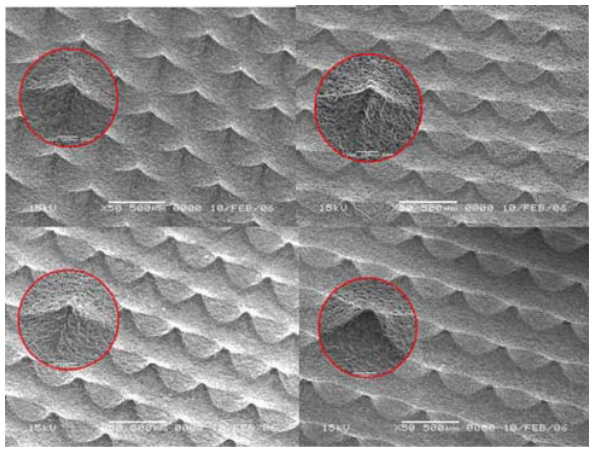


Figure 20 A novel design of ADD that possesses sharp cutting edges and flat penetration stoppers in between, slurry moving tunnels are also created to facilitate the removal of cutting debris (see online version for colours)



For the conventional application of ADD in CMP, cutting elements of simple pyramids are used. Such ADD can outperform conventional pad conditioners in dressing efficiency and service durability (Figure 21).

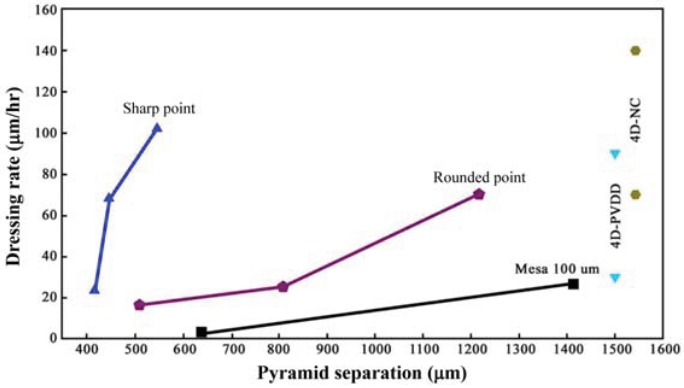
Figure 21 Examples of ADD cutting pyramids (see online version for colours)



7 Pad consumption rate

If ADD is covered with identical PCD pyramids, it can generate similar grooves of substantially equal depth. Hence, the pad asperities are more uniform in size and shape. Moreover, the pad is not overly consumed so its life would be extended considerably. Furthermore, because the workload is fully shared by all cutting pyramids, the wear on each pyramid is very slow, so ADD's dressing life would be much longer than conventional diamond pad conditioners. ADD was tested to dress pads and their cut rates are more consistent than conventional pad conditioners (Figure 22).

Figure 22 The pad-dressing rate of ADD as a function of pyramids spacing, and mesa table size (see online version for colours)

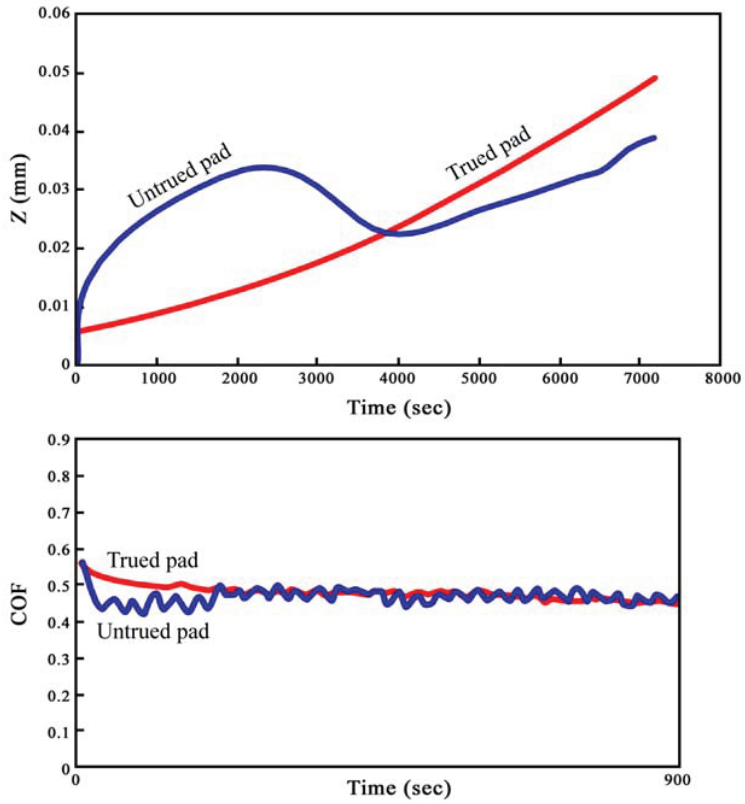


Note: The above tests were performed under a load of 11.5 kg. The right side markings are ranges for commercial DiaGrid® pad conditioners manufactured by Kinik Company, where PVDD refers to a diamond-like carbon coating on the braze alloy, and NC means no coating exist on the pad conditioner. In the above diagram 4D refers the diamond has euhedral crystal morphology (the most perfect diamond).

8 Diamond cutting resistance

ADD can save pads by dressing only necessarily to resurface the asperities. Hence, an ADD dresses a pad very slowly. In order to accommodate the much smaller pad consumption rate of ADD, the pad surface must be trued first before dressing, for example, by using a PCD planer (refer to the other paper) or even a conventional pad conditioner. Without truing the pad first, the dressing behaviour of ADD can be masked by the waviness of the pad surface (Figure 23).

Figure 23 The pad consumption as a function of dressing time for ADD (see online version for colours)



Note: The trued pad reveled the real dressing rate of ADD (top diagram). The Coefficient of Friction (COF) of ADD sliding against the pad confirmed that the trued pad was cut smoothly with continual contact, but the wavy pad was cut with 'stick slip' due to the bumpy sliding of ADD on the pad top (bottom diagram). In the above test, the pad dressing rate for ADD was 25 microns/hr.

Although an ADD can dress pad gently, but its frictional force of dressing is on par with aggressive conventional diamond dressers. Hence, the shallow dressing of ADD cutting tips at numerous paths of the pad received similar resistance force from deep dressing of few grooves by conventional pad conditioners. This comparison demonstrated that ADD

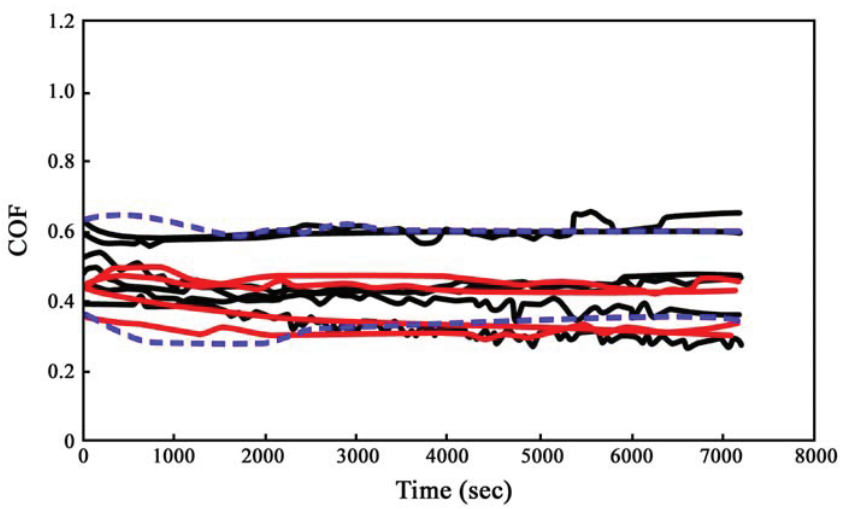
produced asperities are finer, but much more in number. Hence, the polishing of the wafer with the pad dressed by ADD will be more uniform, but not necessarily slower than that dressed by conventional pad conditioners.

Compared to conventional pad conditioners, an ADD has a much larger number of cutting tips that are sharing the dressing load, consequently, ADD will wear out much slower, that is, with a much longer service life.

9 ADD's dressing effectiveness

When the pad conditioner is used to dress a glazed pad, the COF will increase due to the creation of asperities on the pad surface. However, the effectiveness in dressing is dependent on the number of working crystals in grooving the pad. This effectiveness can be measured by the time required to saturate the pad surface with asperities (Figure 24–26). Because ADD has vastly more working crystals, it can dress the pad much faster than a typical diamond dresser such as a DiaGrid® pad conditioner (Sung et al., 2006a,b).

Figure 24 The COF of ADD (red curves) comparable to that of DiaGrid® pad conditioners manufactured by Kinik Company (see online version for colours)



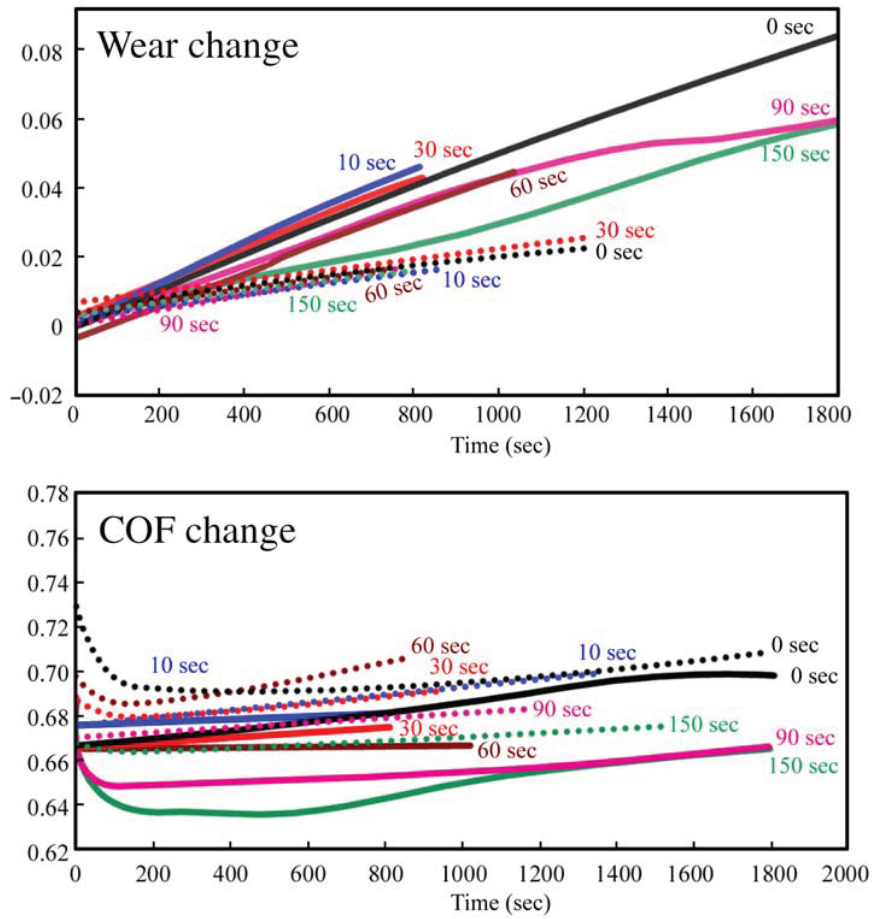
Note: The dot lines showed two experimental pad conditioners (Organic Diamond Disks (ODD)) with exceptionally high and low COF.

The pad consumption rate (P) may be expressed as the product of the effectiveness (E) of pad dressing and the pad-dressing rate (D) as follows:

$$P(\text{micron}) = E(\text{time}) \times D(\text{micron/time}) \tag{1}$$

In this expression, the pad consumption rate for ADD = 25 microns/hr × 15 sec or about 0.1 micron. For comparison, DiaGrid® pad conditioner P is about four times as big. Other brands pad conditioners may consume even more pad materials during dressing.

Figure 25 The pad wear rate (top diagram) and the COF (bottom diagram) as a function of dressing time (see online version for colours)



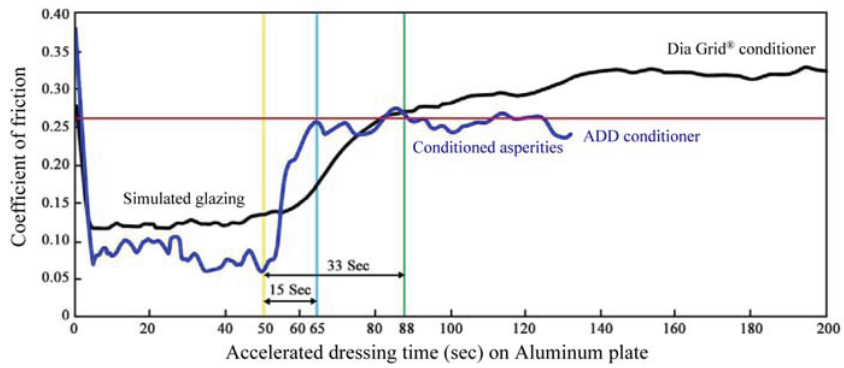
Note: The numbers denote the time spent in accelerated dulling the cutting tips in order to demonstrate the durability of the pad conditioners. The dotted lines are for DiaGrid® pad conditioners; and solid lines, ADD. Note that although COF data did not show the sign of decay, the pad dressing rates were slowed down considerably due to the fast wearing of the protruded diamond grits on DiaGrid® pad conditioners.

The efficiency (F) of pad dressing for a pad conditioner may be defined as follows:

$$F(\text{micron-time}) = P(\text{micron}) \times E(\text{time}) \tag{2}$$

For ADD, this efficiency is about 1.5 micron-sec. In contrast, the conventional pad conditioners have the efficiency of about 15 micron-sec that reveals the waste in pad material and dressing time, a loss that the CMP manufacture can recover by using ADD for pad dressing.

Figure 26 The effectiveness of dressing pad is measured as the time required to restore the pad COF after glazing (see online version for colours)

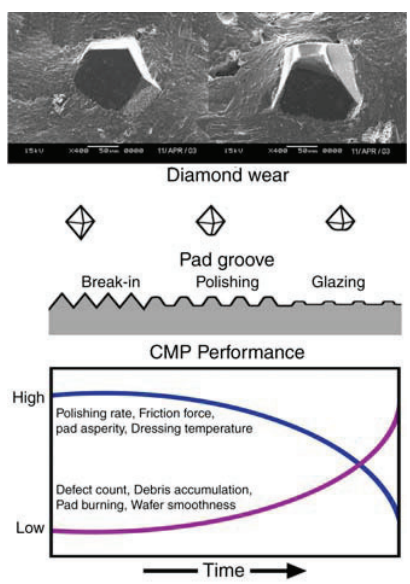


Note: In the above experiment, the glazing is artificially created by pressing the pad with a flat glass. This glazing process will flatten asperities so the COF will plummet to a stable low level.

10 Pad dressing behaviours

A pad conditioner's life is limited by its most worn cutting tips. As soon as the diamond becomes dull, the pad asperities cannot be renewed. As a result, the polishing rate plummeted. At the same time, the pad is loaded with polishing debris, so the defect count of the wafer increases (Figure 27).

Figure 27 The dulling of diamond cutter (upper diagram) and its effects on the sharpness of the pad asperities (middle diagram) and the resultant wafer polishing performance (lower diagram) (see online version for colours)

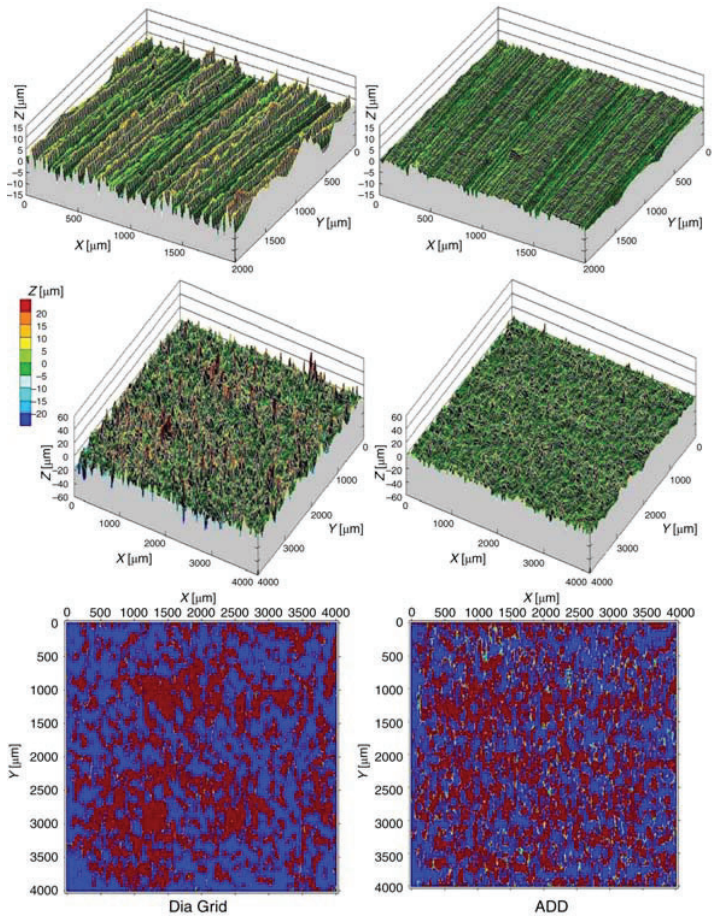


If diamond tips are levelled, the dressing work can be shared by all diamond cutter. As a result, no diamond is excessively worn, so the diamond pad conditioner can last longer. Moreover, because the pad is not overly consumed, so the pad life will also be longer.

11 ADD's dressing uniformity

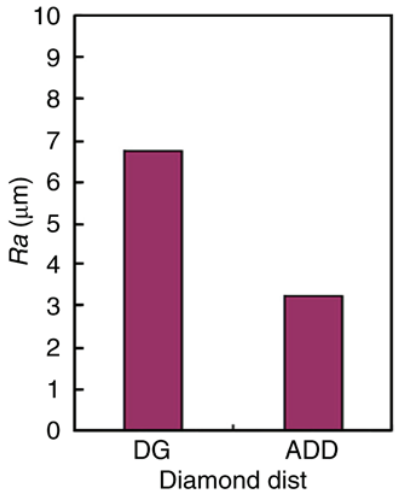
ADD can cut asperities much more uniform than conventional pad conditioners. This pad uniformity will translate into wafer uniformity. Moreover, as both the pad conditioner and the pad are worn much less, their lives would be significantly longer than conventional practice of CMP (Ishizuka et al., 2006) (Figures 28 and 29).

Figure 28 ADD can dress pad to create asperities with high uniformity and the cross section of asperities at similar loading ratio (see online version for colours)



Note: The 'killer asperities' that may cause dishing on copper circuitry are completely removed. The above diagrams were generated after half hour's dressing. Both pad conditioners contain cutting elements spaced at 500 microns. The red color covers the high points on the pad surface.

Figure 29 The surface roughness of pad dressed by ADD significantly less rugged when compared with DiaGrid® pad conditioner (data of Ming-Yi Tsai) (see online version for colours)



The distributions of asperities are quantified as reproduced below (Figure 30).

ADD cannot only dress pad more uniformly, it may also reduce the already low 'killer asperities' that are troublesome due to their ability to over polish the delicate circuitry (Figure 31).

Figure 30 The distribution of asperities dressed by ADD much tighter than that of DiaGrid® pad conditioner (data of Ming-Yi Tsai) (see online version for colours)

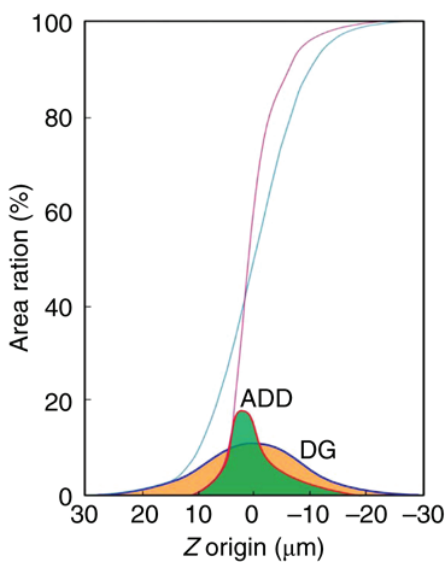
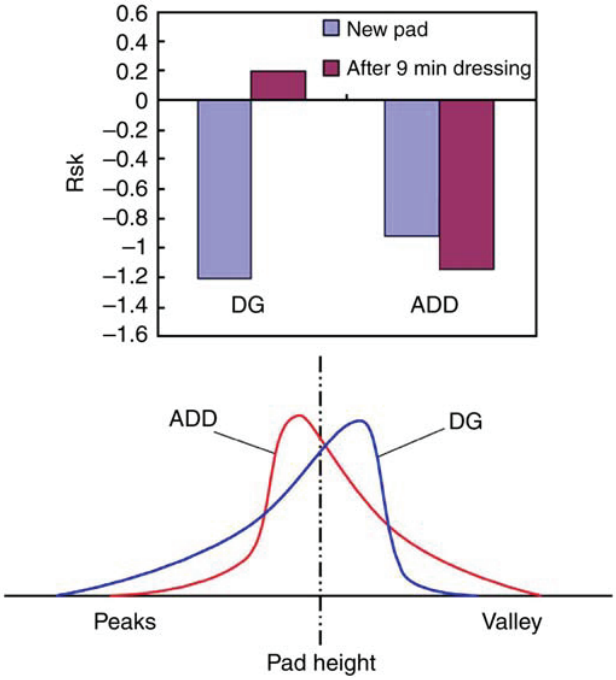


Figure 31 ADD dressed pad show more valleys than peaks, a feature that avoids the presence of 'killer asperities' that protrude too high above the average asperities (data of Ming-Yi Tsai) (see online version for colours)



The dressing behaviour of ADD is highly reproducible and it is independent to the original roughness of the pad. This reproducibility can assure the consistency of the wafer polishing by CMP (Figure 32).

Figure 32 ADD dressing is effective and reproducible (see online version for colours)

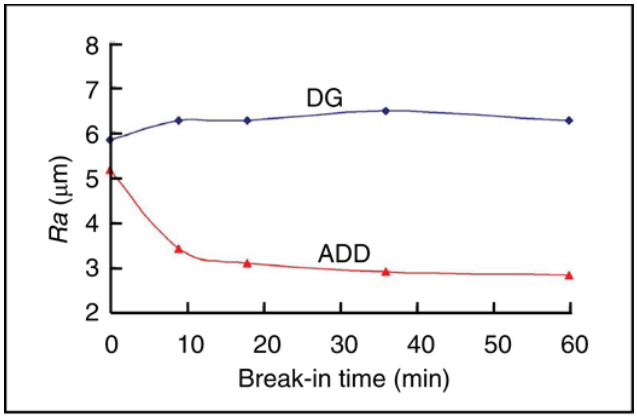
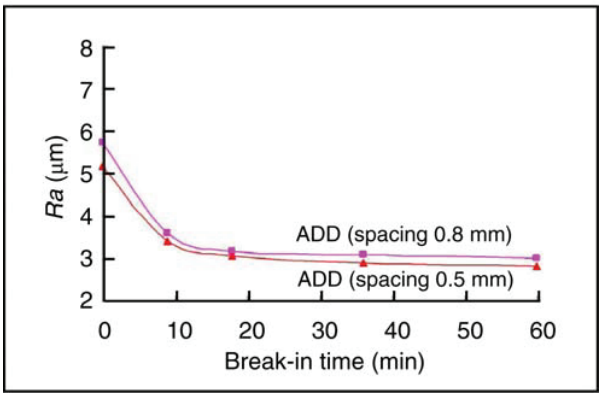


Figure 32 ADD dressing is effective and reproducible (see online version for colours) (continued)

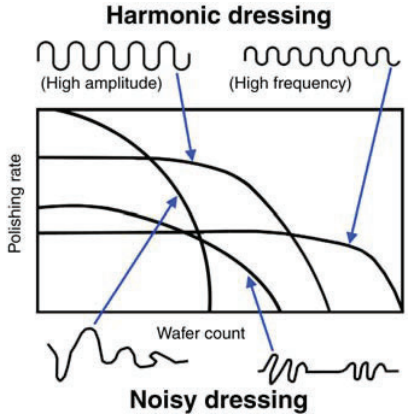


Note: Moreover, it is insensitive to the spacing of cutting elements although the life of the dresser is proportional to the number of cutting elements (data of Ming-Yi Tsai).

12 ADD's dressing durability

The asperities may resemble waves with amplitudes as the height and frequency as the density. Hence, the pad may be dressed to exhibit various wave patterns with harmonic and noisy characteristics. The amplitude of asperities often determines the polishing rate of the wafer; and the frequency, the uniformity of the wafer (Sung, 2001) (Figure 33).

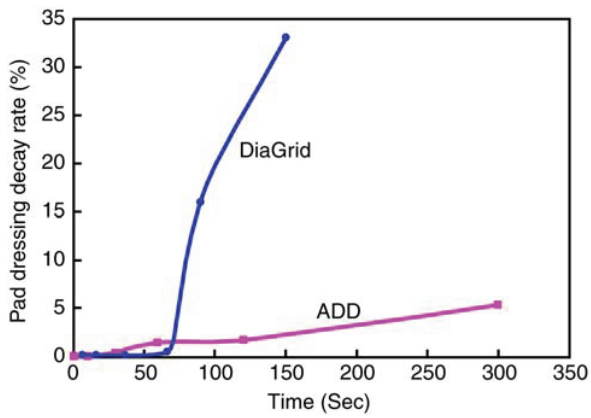
Figure 33 The dressing pattern of the pad affecting the polishing performance of the wafer (see online version for colours)



Note: The harmonic pattern may sustain the polishing rate longer. The polishing rate, however, is controlled by the optimised 'amplitude' of the dressing pattern. But the service lives of the diamond dresser, and also the pad, are more dependent on the 'frequency' of the dressed pattern.

Because ADD has all cutting pyramids levelled, it can create asperities with low amplitude and high frequency. As a result, the wafer can be polished uniformly at high removal rate. Moreover, because every cutting tip is used during dressing, ADD's life will be much longer than conventional pad conditioners. The experiments confirmed that ADD can be extremely durable as demonstrated in the following Figure 34 (Ishizuka et al., 2006).

Figure 34 The relative decay rates of pad dressing rates during an accelerated testing protocol (see online version for colours)



Note: DiaGrid showed a catastrophic failure after a certain time. Hence, ADD cutting pyramids can last much longer than conventional diamond pad conditioners. The ordinate shows the percentage decline of pad dressing rate. The abscissa shows the time for the pad conditioner to cut an aluminum plate as the means to accelerate the dulling process of cutting tips.

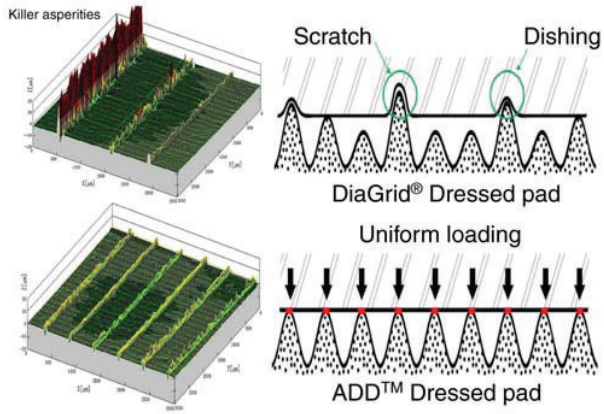
13 Polishing behaviour of ADD

The performance of pad conditioners can be measured by two most critical parameters, the longevity of the pad conditioner and the pad; and the effectiveness of the pad dressing. The longevity can be improved by levelling of cutting tips that increases the number of working crystals on the pad conditioner. The effectiveness of the pad dressing may be improved by the sharpness of the cutting tips, the sharper, the faster to create the density of pad asperity as required for polishing.

Due to the even loading of the pad and the uniformity of asperities, wafer polishing can be much more uniform. Moreover, because the polishing can only be achieved by the contact between wafer and pad, ADD with more polishing points generated on the pad may polish at a higher removal rate even if the individual polishing rate is low at each contact point. The low-pressure contact at each polishing point will also assure the uniformity of the polish performance (Ishizuka et al., 2006) (Figure 35).

Due to the seriated feature of PCD surfaces and edges, ADD can cut pads cleaner with less tearing. Moreover, the pad dressed has a higher specific surface area than that dressed by a conventional pad conditioner. The more textured pad surface can trap more abrasive particles on asperities. Consequently, a higher polishing rate of wafer or a reduced usage of slurry may be achieved.

Figure 35 The contrast of polishing behaviours between ADD and conventional pad conditioners (see online version for colours)



Note: ADD can achieve the same polishing efficiency with improved wafer quality. Note that ADD dressed pads do not contain 'killer asperities' that may ruin the soft copper circuit, if not the layer of vulnerable dielectric layer.

14 The advantages of ADD

The unique features of ADD and their advantages in CMP versus conventional diamond pad conditioners are tabulated below (Table 1).

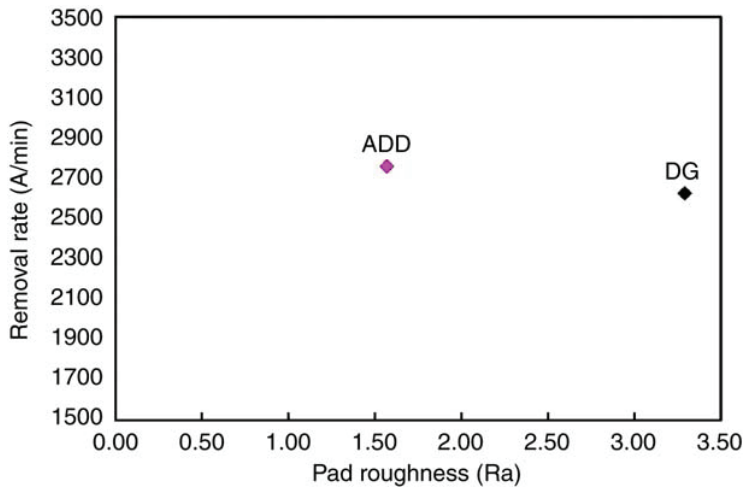
Table 1 The contrasted features of ADD versus DiaGrid

	DiaGrid	*ADD*
Diamond levelling	> 50 μm	< 20 μm
Dressing rate	> 50 μm/hr	> 20 μm/hr
Working crystals	< 10%	> 90%
Brocken crystals	> 20%	< 1%
Diamond shape	Irregular	Symmetrical
Diamond angle	> 100	< 90
Dressing stress	Large (Tearing)	Low (Cutting)
Dressing temperature	High	Low
Acid proof	No	Yes
Pad life	Short	Long
Disk life	Short	Long
Asperity	Random	Uniform
Uniformity	Low	High

In summary, ADD has the potential to consume less pad to achieve higher polishing rates of wafers. In addition, with the further progression of Moore's Law, ADD can be the enabler of future CMP for making devices with node sizes smaller than 65 nm.

As a result of the durability of ADD and its ability to minimise the pad wear, the number of wafers polished per installation of pad and pad conditioner combination will be much more. The machine down time saved due to the long ADD life can reduce the overall Cost of Ownership (CoO) significantly for the manufacture of complex semiconductors (Figure 36).

Figure 36 ADD is uniquely capable to achieve the high polishing rate of wafers with the low dressing rate of pads (see online version for colours)

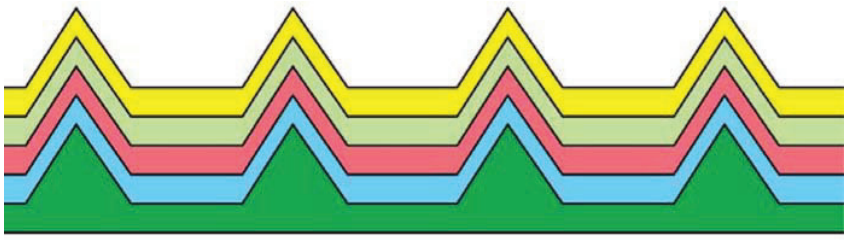


Note: It is actually a pad savor for CMP manufacture of semiconductors.

15 The resharpening of ADD

There is another marvel feature of ADD that may further reduce Cost of Consumable (CoC), that is, ADD is reusable. Conventional diamond pad conditioners cannot be repaired when the diamond becomes dull. However, ADD can be resurfaced with sharp pyramids recreated many times. Consequently, the unit cost per wafer pass for CMP with ADD can be significantly lowered. The CoO may be further reduced due to the longer dressing life of ADD as well as the extended pad life due to the gentle dressing of ADD (Figure 37).

Figure 37 The resharpening of ADD cutting pyramids after each use to duplicate the same profile (see online version for colours)



Acknowledgements

ADD were manufactured by Tomei Diamond Company of Japan under the license of the author. The pad dressing data (cut rate) were supplied by Kinik Company of Taiwan. The Coefficient of Friction (COF) and wear rate measurements were measured at Center of Tribology of USA. The micrographs of pad asperities were provided by Ming-Yi Tsai.

References

Ishizuka, H., Ishizuka, H., Tsai, M.Y., Nishizawa, E., Sung, C.M., Sung, M. and Monteith, B.G. (2006) 'Advanced diamond disk for electrolytic chemical mechanical planarization', *2006 VMIC Conference, 23rd International VLSI/ULSI Multilevel Interconnection Conference, State-of-the-art Seminar and Exhibition*, Fremont, CA, USA.

Song, S.M., Sung, C.M., Hu, C.C., Pai, Y.L., Tsai, M.Y. and Liao, Y.S. (2004) 'Fractal modeling of CMP pad texture', *2004 VLSI Multilevel Interconnection Conference (VMIC)*, Hawaii, USA, pp.255–260.

Sung, C.M. (2000) U.S. Patents 6,039,641.

Sung, C.M. (2001) 'CMP pad dresser: a diamond grid solution', *2001 VLSI Multilevel Interconnection, Specialty Short Course, Advance Chemical-Mechanical-Planarization Processes*, Santa Clara, CA, pp.181–220.

Sung, C.M. (2006) 'PCD planer for dressing CMP pads', *2006 CMP-MIC*, Fremont, CA, USA, pp.613–616.

Sung, C.M., Gitis, N., Khosla, V., Nishizawa, E. and Toganoh, T. (2006a) 'Studies of advanced pad conditioners', *2006 CMP-MIC*, Fremont, CA, USA, pp.412–416.

Sung, M., Sung, C.M., Chou, C.S., Monteith, B.G. and Ishizuka, H. (2006b) 'Advanced polycrystalline diamond pad conditioners for future CMP applications', *2006 VMIC Conference, 23rd International VLSI/ULSI Multileven Interconnection Conference, State-of-the-art Seminar and Exhibition*, Fremont, CA, USA.

Tsai, M.Y., Liao, Y.S., Sung, C.M. and Pai, Y.L. (2004) 'CMP pad dressing with oriented diamond', *2004 VLSI Multilevel Interconnection Conference (VMIC)*, Hawaii, USA, pp.459–463.