A Quantitative Analysis of Multi-Scale Response of CMP Pad and Implication to Process Assessments

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The multiscale characteristics of the pad deformation and its surface morphology control the quality and efficacy of the chemical mechanical planarization (CMP) process. The pad microstructure comprised of cell size, wall thickness and surface roughness exhibit temporal variations in the effective pad stiffness at the pad abrasive interface. An experimental and analytical approach is developed to examine a dry IC-1000 pad response at different length scales, utilizing a nano-indentation with a conical tip of 1 μm radius and a flat-punch of 60μm diameter. The quasi-static load-indentation depth plots showed different characteristic trends with varying stiffness at different loading ranges. The measurements showed the role of the porous microstructure to drive a competition between the local cell-membrane indent, bending of cell membrane and the bulk response of the porous pad. These different deformation mechanisms are employed in constructing an equivalent mechanical model for the effective pad elastic stiffness. The model prediction matches well with the force-indentation depth measurements. The developed model is used to investigate the influence of pad property evolution on the propensity of scratch generation during the CMP process. Such physically based models can be utilized to optimize the pad microstructure and morphology to control the spatial and temporal modulation of the material removal rate and the propensity for scratch generation.

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(e.g. Young’s modulus and Poisson’s ratio) as well as lumped up the influence of the pad surface morphology with the local abrasive particle contact.

The salient structural features of the pad (cell size, cell wall thickness & surface roughness) constitute structures that have several small length scales. The effect of the various length scales on the macroscopic mechanical response of the pad under different condition remains largely unexplored due to the deficiency of appropriate experimental techniques and testing protocols to characterize local deformation. To overcome these difficulties, we will utilize nanoindentation, since it has been utilized extensively to probe elastic or visco-elastic local deformation characteristics within a relatively small volume of material. The advances in nanomechanical testing system have been made possible to continuously measure force and displacement as an indentation is made. The indentation load-displacement data thus derived can be used to determine mechanical properties at the sub-micron regime. The developments in indentation testing methods and in modeling of the stress and displacement fields beneath the indenter gives a scope to study the spatial variations in local mechanical properties of the materials. The indentation of materials at nano- and micro-length scales enables in determining the local properties such as stiffness, hardness, elastic modulus, and yield strength and fracture toughness. In the current study, a flat punch of 60 μm diameter and a conical tip of about 1 μm radius will be employed to probe the pad cell membrane property at different length scales. The measured contact stiffness will delineate the interplay between the local particle level deformation and the cell level deformation and flexing.

**Experimental**

**Sample used.**—An IC1000 dry pad without the sub pad is utilized in this study. The examined specimens were taken from a preconditioned pad that has been used in oxide CMP for 66 minutes at a pressure of 6 PSI and 120 RPM. The topography structure of the pad is shown in Fig. 1. It has a cellular structure with a cell diameter of \( D_{cell} \approx 50–70 \mu m \) and cell wall thickness of \( t_{cell} \approx 3–5 \mu m \). The constrained porous structure with pined nodal points and semi-attached cell membrane faces controls the initial stiffness and macroscopic plateau stresses for the cellular material. The details of pad surface roughness are evaluated with a surface profilometer at multiple length scales, relative to the pad cell diameter. There is a long wavelength roughness \( \lambda_{1} D_{cell} \approx 15–20 \) with amplitude \( a_{1} \approx 1–20 t_{cell} \) and within the roughness \( \lambda_{2} t_{cell} \approx 3–5 \mu m \) and \( \lambda_{3} t_{cell} \approx 1–2 \mu m \). Within the local region of these higher summits, the local cell surface roughness has a RMS in the range of 100–200nm and spatial periodicity of about 5–10 μm, as indicated in Fig. 2. A schematic representation of cell diameter \( D_{cell} \), cell wall thickness \( t_{cell} \), long wavelength roughness \( \lambda_{1} \) and local cell surface roughness is shown in Fig. 2.

**Indentation testing.**—Indentation tests were carried out using a Hysitron nanoindenter (TriboIndenter 950). The TriboIndenter is a stand-alone nanomechanical testing system, which has been designed to provide fully automated testing as well as in-situ imaging. Instrumented indentation tests consist of three basic components: an indenter of specific geometry, an actuator for applying the force, and a sensor for measuring the indenter displacements. The load and indenter displacement are continuously controlled and monitored as the indenter is driven into and withdrawn from the test surface. The sample is mounted on the XYZ stage of the TriboIndenter. The X and Y displacements of the stage and the optics of the TriboIndenter are used to locate an indentation region i.e., cell membrane of the porous pad. All test are carried out at the center of the cell. External oblique lighting where used to identify individual cell perimeter and the approximate location of its center. After locating the cell center, the tip is moved for indentation. Mechanical properties are derived from the indentation load-displacement data. The resulting load-displacement data, together with the indenter geometry, can be analyzed to obtain hardness and elastic modulus using well-established, numerically verified mechanical models. All tests were carried out under load control with loading and unloading rate of 100 μN/s and hold time of 5 seconds at the maximum indentation load. The load-displacement plot during one complete cycle of loading and unloading is recorded to evaluate the contact stiffness. In this work, the contact stiffness is considered as the slope of the load vs. indentation depth curve during loading.

**Figure 1.** Polishing pad multi-level structure and mechanical response. SEM for a preconditioned pad surface morphology (IC1000).
Indenters selection.— The pad response is inherently multiscale as depicted on Fig. 1. At the macro-scale, the bulk elastic modulus of the pad material is about 200–500 MPa, with a saturation stress of about 20 MPa. However, for practical range of applied pressure during the CMP process (~50 kPa or less), the initial asperity contact of the pad showed an effective stiffness of 0.5 MPa. The topological details of the pad controls this initial soft response. It is very tempting to utilize such soft response in the modeling of the CMP process. However, the actual local pressure at the abrasive particle level could be several order or magnitudes higher than this level to enable material removal.\[^8,25\] There is an intricate load transfer path from the macroscopic applied pressure to the local particle level, wherein the pad bulk modulus, the cell membrane stiffness and the cell membrane roughness affect the level of load transfer to individual abrasive particle. It has been shown\[^3,8\] that the evolution of the contact area for an average macroscopic pad asperity, \(\lambda\), is given by \(R/\lambda \approx 0.75(P/|E|)^{0.375}\), wherein \(R\) is the radius of the macroscopic pad asperity contact area. Consistent with the properties, microstructure and average macroscopic surface roughness, the average contact area were in the range of \(2R \sim 50–75 \mu m\).

Motivated by these ranges of dimensions, two different indenter tips are utilized in this study, a conical tip and a flat punch (cylindrical indenter). Such selection is thought to provide the characteristics of the pad response at the particle scale, the initial pad cell-level multiasperity contact with the wafer (i.e. local pad-wafer contact region of \(2R\)) as well as the local cell deformation. The geometry of the diamond conical indenter is shown in Fig. 3. The indenter has a 60° half cone angle and a spherical nose radius of about 1 \(\mu m\). The cone indenter has a sharp, self-similar geometry with a simple cylindrical symmetry that makes it attractive from a modeling standpoint. In addition, the stress field associated with a conical indenter does not present any stress concentration similar to those associate with the edges of a pyramidal indenter. The second indenter is a stainless steel flat punch with a 60 \(\mu m\) diameter. The geometry of the indenter is selected to understand the contribution of the elastic cell membrane deformation on the macroscopic response of the pad. In addition, a circular flat punch can be easily approximated by the analytical response of a rigid axisymmetric flat-punch into elastic half space.

Experimental Results

Conical indenter response (particle scale).— From the conical tip indentation, two distinct trends are observed. A typical load-indentation depth of conical tip for each trend is shown in Figs. 4 and 5. Trend-P1 (Fig. 4) shows three domain of deformation. (i) An initial soft response with a 200–350 N/m contact stiffness at a low applied load of 20–75 \(\mu N\). (ii) An increased contact stiffness of 400–550 N/m as the applied load is further increased up to 90–225 \(\mu N\). (iii) Much higher contact stiffness is observed beyond this load limit and it approaches 500–650 N/m. Trend-P2 (Fig. 5) showed also three distinctive domains of deformations but at different level of indentation loads. (i) An initial soft response of 450–600 N/m for a range of loads of 50–200 \(\mu N\) is observed. (ii) An increased contact stiffness of 600–800 N/m up to a load of 200–400 \(\mu N\). (iii) A softer contact stiffness is followed of about 500–600 N/m. The observed creeping deformation at maximum load is due to the hold period before unloading. The final reduced modulus obtained from unloading curve is about 1.7 GPa, which is consistent with that of dense polyurethane.

The observed modulus of the dense polyurethane is not a surprise during unloading. According to the Sneddon’s analytical solution,\[^26\] the local contact field immediately unload underneath the indenter, before any far field deformation takes place. Additionally, the observed irrecoverable deformation after fully unloading is a visco-elastic
deformation that would relax at a time scale, which is much longer than the time scale of the experiment. The observed trend is quite repeatable. To clarify this trend, a series of multiple loading and unloading were conducted with a relaxation period of approximately 5 minutes on the same cell membrane. The response was repeatable as shown in the third to fifth cycle of loading, shown in Fig. 6. However, several spatial location on the surface showed very compliant initial response as observed from the first loading cycle in Fig. 6. This trend was found to correlate with the existence of a local fine roughness with a higher frequency, leading to a local radius of curvature much smaller than the indenter radius. The soft response in the first and second cycle is attributed to the crushing of these initial nano-asperities. Thereafter, a steady state response is achieved.

**Flat indenter response (cell level).**—Multiple indents are performed at different regions of the pad using the flat punch and a consistent trend of pad response is observed. A typical load-indentation depth of the flat punch during one complete cycle of loading and unloading at different load levels is shown in Fig. 7. A three domain of deformation can be identified. (i) An initial soft response with continuously varying contact stiffness of about 500–1000 N/m at an applied load of 300–800 μN. (ii) The contact stiffness approaches 1000–2000 N/m up to loads of about 2000–3000 μN. (iii) A harder response is observed with a contact stiffness of about 3500 N/m. For clarity, the equivalent pressure on the equivalent macroscopic area of wavelength λ (area of 0.8 × 0.8 mm) is also noted on the graph in PSI units. With such conversion, the maximum applied indentation load on the cell level is equivalent to a macroscopic applied pressure of 1.25 psi. It is also worth mentioning that the initial stiffness is about 3–5 times those observed in the conical indenter and marked by local indent for Trends-P1 and P2 as shown in Figs. 4 and 5. Moreover the transition load between domains (i) to (ii) is about 3–6 times the corresponding transition loads for the same domains of Trend-P2 in Fig. 5.

**Deformation mechanisms.**—Multiple tests are carried out at different loads by using both the conical and the flat punch indenter. These tests showed the transition in the pad deformation characteristics. The proposed deformation mechanisms of the pad, based on the observed experimental trends are shown in Fig. 8. The deformation mechanism is derived from the observed change of contact stiffness at different applied loads in the nano-indentation experiments.

When a conical tip is used, because of smaller tip radius (≈ 1 μm) the indenter initially touches or slides over a single or multiple asperities at low loads (Fig. 8a). If the local asperity radius of curvature is greater than the indenter radius, the indenter settles over a single asperity, and the indentation field starts to evolve with the increased loading (Fig. 8b). However, if the local asperity radius of curvature is smaller than the indenter radius, the indenter crushes multiple asperities, and thereby showing the reduced initial contact stiffness as indicated in Trend-P1 (Fig. 4) and from the multiple loading in Fig. 6. As the load is increased, a full contact between the indenter and the surface is established and indentation field start to evolve. At this stage, the process zone of the indentation is at least an order of magnitude less than the cell membrane thickness. As the load progress, the contribution of cell bending to the total deformation becomes more pronounced (Fig. 8c).

When a flat indenter is used, high aspect ratio asperities with a wavelength much smaller than the indenter radius are crushed at low loads (Fig. 8d). From the proportionality of the measured stiffnesses and transition loads of the conical and flat indenters, it seems there is about 2–5 high aspect ratio asperities being crushed within a single cell membrane. Such observation is consistent with the local asperity roughness measurements, shown in Fig. 1, where it is estimated...
to be about 4–6 asperities within the 60 μm flat indenter perimeter. Moreover, the initial response of these multiple high aspect ratio asperities are very similar to encompassing the submicron slurry particles, wherein these entrapped particles becomes the contact points between the pad and the wafer in a three-body contact model. As the load is increased further the cell membrane bending contribution becomes significant (Fig. 8e). Upon further increase of load, bulk response of the pad is observed (Fig. 8f).

**Modeling Pad Response**

The experimental data showed a wide range of contact stiffness and transition loads associated with each of the presented deformation mechanisms. Such variation arises from the stochastic nature of the pad structure and its roughness. To understand this effect, the applied load-indentation depth for the range of observation is compared to the elastic indentation response of spherical and conical Hertzian contact (wherein an infinitesimal strain and elastic isotropy are assumed), as well as to the flexing of circular region (cell membrane) having fixed edges and loaded at the center. It should be noted that the utilized conical indenter has an initial round nose up to an indentation depth of about 140 nm, as shown in Fig. 3. Thus, for a shallow indentation depth, the applied load, \( F \) and the depth of penetration, \( h \) would be similar to the response of a spherical indentation with a radius of, \( r \approx 1 \mu m \). Beyond a certain depth of penetration the \( F-h \) curve would follow that of a conical indenter with a semi cone angle, \( \alpha = 60^{\circ} \). In the next section we will present the analytical results for spherical indenter, conical indenter, flexing of a circular plate and then present an equivalent mechanical model for the pad effective stiffness response as shown in Fig. 9. The model predictions will be compared to the experimental data. It should be noted that the bulk response under a singular load is thought to be outside the scope of this work, since in a CMP process, the global response of the long wavelength asperities dominates beyond the cell level.

**Spherical indenter.**—The spherical indentation model for an elastic half space approximates the shallow depth response of the employed conical indenter at low loads, when the indenter is just touching the surface of the sample (Fig. 3). This behavior is expected in CMP when individual slurry particle interacts with the pad. From the Hertz contact theory and assuming an isotropic cell wall response, the elastic contact force between the pad and spherical indenter is given by:

\[
F = \frac{4}{3} E_r \frac{r^{3/2}}{h_{sph}^{1/2}}
\]  

Where \( r \) is the indenter radius, \( h_{sph} \) is the penetration depth and \( E_r \) is the reduce modulus \( \{1/E_r = (1 - \nu_{pad}^2/E_{pad})+(1 - \nu_{indentor}^2/E_{indentor})\} \). Here \( E_{pad} \) and \( \nu_{pad} \) are the Young’s modulus and Poisson’s ratio of the dense polyurethane, from which the pad is formed. For a nearly

![Figure 9. Equivalent mechanical model for the combined deformation modes, assuming full elastic loading.](https://doi.org/10.1021/acs.jpclett.0c03366)
rigid indenter, \( E_s \approx E_{pad}/1 - \nu_{pad} \), Eq. 1 reduce to

\[ F = \frac{4E_{pad} r^{1/2} h_{sph}^{3/2}}{3 \left( 1 - \nu_{pad}^2 \right)}. \]  \[2\]

The Hertzian contact stiffness would follow from Eq. 2 as

\[ K_{sph} = \frac{4E_{pad} \sqrt{r} h_{sph}}{3 \left( 1 - \nu_{pad}^2 \right)}. \]  \[3\]

The contact stiffness is continuously evolving with the indentation depth, since the indentation process zone is expanding to encompass more material. The load vs. depth for \( r = 1 \mu m \) is plotted in Fig. 10 (dashed line for spherical indent) by utilizing \( E_{pad} = 1.7 GPa \) and \( \nu_{pad} = 0.531 \).

Conical indenter.—The conical indentation model for an elastic half space approximates the higher depth response of the utilized conical indenter (Fig. 3). The elastic contact force between the pad and conical indenter is given by, \[4\]

\[ F = \frac{2 h_{con}^2 E_{pad} \tan \alpha}{\pi \left( 1 - \nu_{pad}^2 \right)}. \]  \[4\]

Where \( \alpha \) is the cone semi-angle, \( h_{con} \) is the indentation depth. The corresponding conical contact stiffness is given by,

\[ K_{con} = \frac{2h_{con}E_{pad} \tan \alpha}{\pi \left( 1 - \nu_{pad}^2 \right)}. \]  \[5\]

In contrast with the spherical indentation stiffness of Eq. 3, the conical contact stiffness has a linear dependence on the indentation depth. Physically, the indentation process zone is expanding at a slower rate, compared to the spherical case. The load vs. depth for \( \alpha = 60^\circ \) is plotted in Fig. 11 (dashed line for conical indent) by utilizing \( E_{pad} = 1.7 GPa \) and \( \nu_{pad} = 0.531 \). The conical contact stiffness variation with indentation depth is shown in Fig. 12 (conical indent).

Cell bending.—The porous polishing pad is composed of closed cells with varying cell size and cell wall thickness. Each intact cell-membrane (circled in Fig. 1) is assumed to be a circular plate with fixed edges and loaded at its center. For infinitesimal deformation, the force required to cause maximum deflection at the center of the plate is given by, \[6\]

\[ F = \frac{4E_{pad} t_{cell}^3 h_{cell}}{3 \left( 1 - \nu_{pad}^2 \right) D_{cell}^2}. \]  \[6\]

Where \( D_{cell} \) is the diameter of the circular plate, \( h_{cell} \) is the maximum deflection at the center of the plate and \( t_{cell} \) is the thickness of the plate. The corresponding stiffness due to cell flexing is given by

\[ K_{cell} = \frac{16\pi E_{pad} t_{cell}^3}{3 \left( 1 - \nu_{pad}^2 \right) D_{cell}^2}. \]  \[7\]

The cell bending response, predicted by Eq. 7 is marked on both Figs. 10 and 11 by the dash-dot lines for the average properties of the pad cell geometry of \( t_{cell} = 3.5 \mu m \) and \( D_{cell} = 50 \mu m \), and mechanical properties of the pad of \( E_{pad} = 1.7 GPa \) and \( \nu_{pad} = 0.531 \).

Cell bending response, predicted by Eq. 7 is marked on both Figs. 10 and 11 by the dash-dot lines for the average properties of the pad cell geometry of \( t_{cell} = 3.5 \mu m \) and \( D_{cell} = 50 \mu m \), and mechanical properties of the pad of \( E_{pad} = 1.7 GPa \) and \( \nu_{pad} = 0.531 \). At low
loads of Fig. 10, the cell bending stiffness is of the same order as the spherical indentation stiffness. The combined effect of spherical indentation and cell bending is also marked with the dash-dot-dot line. For comparison, the experimental range of the measured force-depth indentation curve is also marked by the continuous line on Fig. 10. The experimental range is falling between the initial spherical indentation and the combined indentation plus bending response. Figure 11 shows the prediction of the effective pad response model at large indentation depth, wherein the cell bending stiffness dominates the deformation. The observed experimentally measured displacement range at each load increment is also marked on the curve. The model prediction, utilizing the average cell geometry of the cellular pad closely follow the mean of the experimentally measured trend.

Effective pad response model.—The effective pad response can now be presented as the combined response of both the indentation and the cell membrane bending. The effective pad stiffness is evaluated from the equitant mechanical model of a two-spring in series, sketched in Fig. 9. At shallow depth, the effective pad surface motion (total depth) \( h_{\text{tot}} \) is equal to sum of the penetration depth, \( h_{\text{pad}} \) and the maximum deflection at the center of the plate \( h_{\text{cell}} \).

\[
h_{\text{tot}} = \left[ \frac{3(1 - \nu^2_{\text{pad}})}{4E_{\text{pad}}r^{1/2}} \right]^{2/3} + \left[ \frac{3(1 - \nu^2_{\text{pad}})}{16\pi E_{\text{pad}}r^{1/2}} \right]^{2/3} + \frac{D^2_{\text{cell}}F}{F_{\text{pad}}r_{\text{cell}}} \]

The effective pad stiffness, \( K_{\text{eff}} \) would be governed by both the spherical indentation stiffness, \( K_{\text{pad}} \) and the cell membrane flexing, \( K_{\text{cell}} \). The effective pad stiffness is given by,

\[
K_{\text{eff}} = \frac{F}{h_{\text{tot}}} = \frac{K_{\text{pad}}K_{\text{cell}}}{h_{\text{pad}} + h_{\text{cell}}} \]

The plot of indentation load, \( F \) vs. effective depth \( h_{\text{tot}} \) is shown in Fig. 10 (dash-dot-dot for indent + bending). The prediction of Eq. 8 is compared to the experimental data range at low loads in Fig. 10. For this comparison, the employed model plate dimensions were the average pad cell morphology of \( t_{\text{cell}} \approx 3.5 \mu m \) and \( D_{\text{cell}} \approx 50 \mu m \). The property of the dense polyurethane was \( E_{\text{pad}} = 1.7 \text{GPa} \) and \( \nu_{\text{pad}} = 0.5 \). It is quite remarkable that the experimentally measured data range at low indentation loads fall between the effective pad response model employing the combined effects of local spherical indentation and cell bending.

At large indentation depth when the conical indentation field dominates, the effective pad depth (total depth) \( h_{\text{tot}} \) is equal to sum of penetration depth, \( h_{\text{con}} \) and the maximum deflection at the center of the plate \( h_{\text{cell}} \).

\[
h_{\text{tot}} = \left[ \frac{\pi(1 - \nu^2_{\text{pad}})}{2E_{\text{pad}}\tan\alpha} \right]^{1/2} + \left[ \frac{3(1 - \nu^2_{\text{pad}})}{16\pi E_{\text{pad}}r_{\text{cell}}} \right]^{2/3} + \frac{D^2_{\text{cell}}F}{F_{\text{pad}}r_{\text{cell}}} \]

The effective pad stiffness, \( K_{\text{eff}} \) would be governed by the conical indentation stiffness, \( K_{\text{con}} \) and the cell membrane flexing, \( K_{\text{cell}} \). In this range, \( K_{\text{eff}} \) is given by:

\[
K_{\text{eff}} = \frac{F}{h_{\text{tot}}} = \frac{K_{\text{con}}K_{\text{cell}}}{h_{\text{con}} + h_{\text{cell}}} \]

The plot of indentation load, \( F \) vs. effective depth \( h_{\text{tot}} \) is shown on Fig. 11 (dash-dot-dot for indent + bending). The prediction of Eq. 10 is plotted with the range of the experimental data in Fig. 11. Similar material properties and cell membrane dimensions to those in Fig. 10 are utilized. The experimental data is represented by the average of 10 indentation tests carried at different spatial positions for each loading level, with the horizontal scatter bar showing the data range. This scatter bar is due to stochastic variation of the pad cell surface morphology and cell dimensions. Apparently, the effective pad response model (based on the combination of local conical indentation and cell bending) lies well within the experimental data. At higher depth (∼4000nm), a slight deviation is noticed due to the localized large deformation beneath the indenter and deviation from the infinitesimal strain framework of Hertz contact theory.

Mechanistic View of Pad Response

The various experimentally observed trends can be understood in view of the pad surface morphology and the deformation mechanisms depicted in Fig. 8. When a conical indenter is used with a tip radius in the same range of the abrasive particle size employed in CMP, the measured macroscopic response is a combination of the local cell membrane roughness contact and the local cell flexing response. The initial soft Trend-P1 shown in Fig. 4 arises from the interaction of the tip with the local roughness, wherein the tip of the indenter is just establishing the surface contact over sub-micron asperities or sliding over a single asperity. Such interaction would reduce the initial contact stiffness and limit it below 3500N/m. As the load is progressively increased the tip starts to locally indent the pad cell membrane and thereby increasing the contact stiffness to the range of about 5500N/m. The Trend-P2 in Fig. 5 is consistent with an initiation of a local cell indentation at the start of loading, followed by a global cell wall bending at the same range of transition load as those of Trend-P1. As the load is further increased beyond 4000N, the bulk response of the pad starts to influence the macroscopic response and thereby decreasing the contact stiffness further. The two observed trends are consistent with simple Hertzian contact theory, wherein the contact stiffness is having a square root dependence on the indentation depth for a spherical contact (Eq. 3) and a linear dependence for conical contact (Eq. 5).

As the load is further increased, the cell wall starts to globally deflect in bending (Eq. 7). Once the cell bending dominates, the macroscopic observable contact stiffness will be reduced and follow that of the cell wall flexing as shown in Fig. 12. The evolution of the effective pad stiffness \( K_{\text{eff}} \) for the combined cell indentation and bending as given by Eq. 11, is shown in Fig. 12. The local pad stiffness follows initially a linear relation with the indentation depth, which is indication of the dominance of the conical contact stiffness (local indentation).

As the depth increases, the stiffness-measured pad deformation depth becomes highly nonlinear, wherein a gradual transition to cell bending dominance occurs. At higher depth, the curve becomes flat which clearly represents that the cell bending is substantial.

The observed trend from the flat punch of 60μm diameter complements the local measurements by the conical tip. The presented trend in Fig. 7 for a flat punch at high loads represents initial multiple asperity contact with a range of continuously varying contact stiffness of 500–1000N/m. This local level of contact stiffness is consistent with the observed trend of contact stiffness variation from the single asperity indentation induced by the local conical indentation of the cell membrane, Figs. 4 and 5. This can be realized if one considers the local roughness of the cell membrane (Figs. 1 and 2) with about 4–6 asperities below the indenter face. Thus the effective initial contact stiffness of the flat punch would be the sum of contact stiffness of individual asperity (∼ 200–3500N/m), which is equivalent to a set of springs in parallel. The corresponding applied load per asperity would be about 50–100μN, which is consistent with the transition load for the single conical indentation. The following increase of contact stiffness to the range of 1000–2000N/m is consistent with global bending of the cell membrane. Such consistency between the results of the two indenter’s configuration supports the proposed cell bending mechanism. Finally, the contact stiffness reaches that of the bulk of about 1500–3500N/m at a load range of 1500–3500μN.

Accordingly, the response of multiple abrasive particle contacts within one of the long wavelength pad asperities can be modeled as a set of springs in parallel for a pad-particle-wafer three body contact. To highlight this mechanism, the equivalent applied uniform pressure on the top surface of the pad can be estimated from the effective contact area ratio\(^5\) over the long wavelength \( \lambda \). Form the flat punch indenters results of Fig. 7, the equivalent applied pressure on the top surface of the pad, corresponding to indentation load of 5000μN, is about 8.66kPa (∼1.25 psi). At this load, the corresponding macroscopic strain averaged over the whole pad thickness is about 0.5%. This value of average strain is about 25% of the speculated pad compressibility during a standard CMP operation. To put these numbers in prospective of the pad macroscopic deformability, the overall indentation depth is...
Pad Role on Propensity of Scratch Generation

The presented experimental data and the proposed model would lay a foundation for modeling the material removal rate and defect evolution during the CMP process. It is now clear that the whole CMP process is controlled by the evolution of the pad surface deformation, commensurate with the CMP operational parameter, the local contact stiffness is dominated by the pad cell bending. Though, a major portion of the load partitioning and redistribution is controlled by the surface morphology and deformation characteristics of the pad surface. Finally, it should be noted that while all the testing and analysis were carried out on a dry pad, a limited set of testing on wet pad has shown the same observed trend, however the contact stiffness was consistently lower by about 20%. This is in agreement with previous studies that showed the role of pad soaking to slightly reduce the mechanical properties of the polishing pad.

The provided characterization of the pad at the cell level, as well as the proposed effective stiffness model would provide more realistic approach to represent the pad stiffness when accounting for the transfer of the applied pressure to local forces on individual abrasive particles. This effective multiscale response of the pad asperity contact will provide the framework to study the role of the pad morphological effects on the CMP process quality, highlighted next.

Figure 13. Model prediction summary for the scratch propensity Index, $I_s$ as a function of (a) the pad stiffness, and (b) pad cell dimensions.

The effective stiffness model would provide more realistic representation of parallel springs, the local pad deformation can be related to the contact radius $R$ and pad thickness $D_{pad}$ thus the local pad deformation can be related to the applied pressure through:

$$\frac{P_o}{E_{pad}} = \xi_2 \left[ \frac{h_{cell}}{\lambda} \right]^n \approx \frac{1}{\xi_1} \frac{h_{cell}}{\lambda}, \ m \approx 3/4 \ , \ n \approx 3/8$$

At the local scale of the pad asperity/abrasive particle contact, the local pad deformation can be related to the contact radius $R$, such that $R^2 \approx \lambda h_{cell}$ for small pad deformation. Thus the total pad deformation can be related to the applied pressure through:

$$\frac{P_o}{E_{pad}} = \xi_2 \left[ \frac{h_{cell}}{\lambda} \right]^n \ , \ \xi_1 \approx \left[ \frac{1}{\xi_2} \frac{h_{cell}}{\lambda} \right]^m , \ m \approx 4/3$$

The dual scale analysis of the pad deformation at the particle scale (conical indenter) and long wavelength sparsity scale (flat punch indenter) showed that the effective contact stiffness for the long asperity contact is equivalent to the sum of the individual particle contact stiffness. For this equivalent representation of parallel springs, the local pad indentation and the long wavelength asperity deformation, $h_{cell}$ are the same. Accordingly, Eq. 13 along with Eqs. 8 or 10 can be utilized to find the local abrasive grit force, $F$.

Employing the force and stress equilibrium at the grit-wafer interface, the particle-wafer penetration depth can be estimated through the wafer surface hardness $H_w$.

$$h_{scratch \ depth} = \frac{F}{\pi r_{grit} H_w}$$

Now, a scratch propensity index $I_s$ based on the mean abrasive grit radius can be defined,

$$I_s \equiv \frac{h_{scratch \ depth}}{r_{grit}} = \frac{F}{\pi H_w \ r_{grit}^2}$$

For the typical low applied loads encountered in CMP, Eqs. 13 and 15 in conjunction with Eqs. 8 or 10 characterize the role of the pad geometrical and mechanical properties on the design domain for scratch propensity during the CMP process. The design space is controlled by the pad surface morphology parameters $\lambda$ and $\alpha$, pad structure morphology ratios $D_{cell}/h$, and $t_{cell}/h$, pad material property $E_{pad}$, $v_{pad}$, abrasive particle radius $r_{particle}$, and the planarized surface strength, $\sigma_y$. Other process kinematic parameters, while important, are not considered in this short overview. Figure 13 shows the variation of the scratch propensity index, $I_s$, as a function of the pad stiffness and the pad morphology ratio $D_{cell}/h$. Figure 13a shows the variation of $I_s$ vs. $D_{cell}/h$. As the pad stiffness is reduced, the propensity of scratches drops significantly (four fold reduction over the shown range of local pad stiffness). Figure 13b shows the variation of $I_s$ vs. $D_{cell}/h$. As the $D_{cell}/h$ ratio increases, the bending stiffness of the pad drops and

converted to an equivalent pad macroscopic strain through the pad thickness, and is cross-correlated to the indentation depth on Fig. 12 (top horizontal scale). It can be seen that over an extended range of the pad deformation, commensurate with the CMP operational parameter, the local contact stiffness is dominated by the pad cell bending. Though, a major portion of the load partitioning and redistribution is controlled by the surface morphology and deformation characteristics of the pad surface. Finally, it should be noted that while all the testing and analysis were carried out on a dry pad, a limited set of testing on wet pad has shown the same observed trend, however the contact stiffness was consistently lower by about 20%. This is in agreement with previous studies that showed the role of pad soaking to slightly reduce the mechanical properties of the polishing pad.

The dual scale analysis of the pad deformation at the particle scale (conical indenter) and long wavelength sparsity scale (flat punch indenter) showed that the effective contact stiffness for the long asperity contact is equivalent to the sum of the individual particle contact stiffness. For this equivalent representation of parallel springs, the local pad indentation and the long wavelength asperity deformation, $h_{cell}$ are the same. Accordingly, Eq. 13 along with Eqs. 8 or 10 can be utilized to find the local abrasive grit force, $F$. Employing the force and stress equilibrium at the grit-wafer interface, the particle-wafer penetration depth can be estimated through the wafer surface hardness $H_w$.

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radius $R$ evolves with the applied pressure according to

$$\frac{R}{\lambda} = \xi_1 \left[ \frac{P_o}{E_{pad}} \right]^n ; \ \xi_1 \approx 3/4 , \ n \approx 3/8$$

At the local scale of the pad asperity/abrasive particle contact, the local pad deformation can be related to the contact radius $R$, such that $R^2 \approx \lambda h_{cell}$ for small pad deformation. Thus the total pad deformation can be related to the applied pressure through:

$$\frac{P_o}{E_{pad}} = \xi_2 \left[ \frac{h_{cell}}{\lambda} \right]^m ; \ \xi_2 \approx \left[ \frac{1}{\xi_1} \frac{h_{cell}}{\lambda} \right]^m , \ m \approx 4/3$$

The dual scale analysis of the pad deformation at the particle scale (conical indenter) and long wavelength sparsity scale (flat punch indenter) showed that the effective contact stiffness for the long asperity contact is equivalent to the sum of the individual particle contact stiffness. For this equivalent representation of parallel springs, the local pad indentation and the long wavelength asperity deformation, $h_{cell}$ are the same. Accordingly, Eq. 13 along with Eqs. 8 or 10 can be utilized to find the local abrasive grit force, $F$.

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tends to be softer locally. Such trend reduces the propensity for cracking significantly. While it is not the focus of this work, though it is evident that using different conditioning disc might result in a change of the process performance due to pad surface roughness modulation leading and the load transfer ratio for the same pad microstructure.

The proposed model would provide a systematic way to understand the effect of varying the local and global pad stiffness on defect evolution, like scratches at particle scale or dishing and erosion at the die scale. A range of pad morphology optimization can be also performed under different constraints (e.g. constant pad density), while including additional process parameters such as pad wear rate (e.g. the evolution of the long wave asperity heights), the abrasive particle volumetric loading and the corresponding agglomeration rate, as well as the full stochastic nature of the process. For example, when the cellular pad has a lower cell bending response (larger and thinner cells), the local cell deformation (flexing) will provide load redistribution among the local polishing particles and reduce the propensity for scratching and/or defect generation. The converse is also true. That is harder pad with thicker cell walls and smaller cell diameters will reduce the local cell deformation, resulting in an increased localized loading of extreme polishing particle sizes and thereby increased propensity for defects.13,14

While this study is conducted on a preconditioned pad that has been used in oxide CMP for 66 minutes at a pressure of 6 psi and 120 RPM. However, the observed shallow depth response of the pad and the associated mechanical characteristics are equally valid for the new restriction on oxide CMP down pressure of less than 3 psi to protect the low-k dielectrics.35 The quasi-static analysis of a dry pad has provided some understanding of the cell-level pad deformation characteristics; further work is needed to understand the pad dynamics, viscoelastic effects and the role of water adsorption on cell level and macroscopic properties.

Conclusions

The deformation mechanisms at the pad cell level have been studied experimentally. It is found that the macroscopic pad response is controlled by both the local indentation of the pad cells as well as the flexing deformation of the cell wall. The experimentally observed trends from quasi-static tests and deformation mechanisms indicate that the whole CMP process domain is carried out by the local cell level interaction at the contact interface and not by the bulk response of the pad. The force-displacement plot obtained from the elastic response of the pad by quasi-static tests matches well with the equivalent mechanical model for the effective stiffness. The equivalent model combined spherical contact for shallow indentation or conical contact for higher indentation with the cell bending response. The implication of such findings is significant for process optimization to achieve targeted polishing specification.

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References

1. R. L. Rhoades and J. Murphy, MICRO, 24, 51, (2006).
2. International Technology Roadmap for Semiconductors, http://www.itrs2.net (2009-2011).
3. A. Chandra, A. F. Bastawros, X. P. Wang, P. Karra, and M. Haugen, in Micro-Manufacturing, V. K. Jain, Editor, Taylor & Francis Pub., New York (2012).
4. T. Yu, D. T. Asplund, A. F. Bastawros, and A. Chandra, Int. J. Machine Tools and Manufacture, 109, 49, (2016).
5. M. A. Martinez, Solid State Technol., 26, (1994).
6. J. Steigerwald, S. Murarka, and R. Gutmann, Chemical Planarization of Microelectronic Materials, John Wiley & Sons Pub., New York (1997).
7. S. R. Rennels and L. M. Eyman, J. Electrochem. Soc., 141, 1698 (1994).
8. A. F. Bastawros, A. Chandra, Y. Guo, and B. Yan, J. Elect. Mater., 31, 1022 (2002).
9. W. Che, A. F. Bastawros, A. Chandra, and P. M. Lonardo, CIRP annals 55(1), 605 (2006).
10. S. H. Ng, R. Hight, C. H. Zhou, I. Yoon, and S. Danyluk, J. tribology-Trans. ASME, 125(3), 582 (2003).
11. G. Fu and A. Chandra, J. Electronic Materials, 30(4), 400 (2001).
12. G. Fu and A. Chandra, J. Electronic Mat., 31(10), 1066 (2002).
13. Y. Guo, A. Chandra, and A. F. Bastawros, J. Electrochem., 151(9), G583 (2004).
14. A. Chandra, P. Karra, A. F. Bastawros, R. Biwas, P. J. Sherman, S. Arminni, and A. D. Locc, Annals of the CIRP, 57(1), 559 (2008).
15. O. Ouma, D. S. Boning, W. G. Easter, and V. Saxena, IEEE Transactions on Semiconductor Manufacturing, 15(2), 232 (2002).
16. L. J. Gibson and M. F. Ashby, Cellular Solids Structure and Properties, Cambridge University Press, Cambridge (1997).
17. C. Zhou, L. Shao, R. Hight, S. Danyluk, S. H. Ng, and A. J. Paszkowski, Lubrication Eng., August issue, pp. 35 (2002).
18. R. L. Rhoades, S. Murarka, and R. Gutmann, J. Electrochem. Soc., 112 (3), 530 (1965).
19. C. H. Zhou, L. Shao, R. Hight, S. Danyluk, S. H. Ng, and A. J. Paszkowski, Lubrication Eng., August issue, pp. 35 (2002).
20. G. Fu, A. Chandra, and A. F. Bastawros, ASME-J. Mfg. Sc. Eng., 127(3), 545 (2005).
21. X. Liao, Y. Zhuang, L. J. Borucki, J. Cheng, S. Theng, T. Ashizawa, and A. Philipossian, Microelectronic Engineer., 83, 1 (2006).
22. M. F. Doerner and W. D. Nix, J. Electrochem. Soc., 141, 1698 (1994).
23. J. J. Vlassak, J. Mech. Phys. Solids, 52, 847 (2004).
24. I. N. Sneddon, Int. J. Eng. Sci., 47, 47 (1965).
25. W. C. Oliver and G. M. Pharr, J. Mater. Res., 6, 567 (1991).
26. T. K. Yu, C. C. Yu, and M. Oroowski, JEDM Tech. Dig., 385 (1993).
27. G. Fu, A. Chandra, S. Guha, and G. Subhash, IEEE Trans. Semiconductor Manufact., 14, 406 (2001).
28. J. Luo and D. A. Dornfield, IEEE Trans. Semiconductor Manufact., 14, 112 (2001).
29. M. F. Doerner and W. D. Nix, J. Mater. Res., 6, 567 (1991).
30. W. Che, Y. Guo, A. Chandra, and A.-F. Bastawros, ASME-J. Mfg. Sc. Eng., 125(4), 731 (2003).
31. I. M. Ward, John Wiley & Sons, New York (1983).
32. J. K. Sun, Y. Zhuang, L. J. Borucki, and A. Philipossian, Journal of Applied Physics, 95, 06501 (2010).
33. B. Vasilev, S. Bott, R. Rzehak, and J. W. Bartha, Micronanotechnol Eng., 111, 21 (2013).