Model of Particle Contact Area for Friction in Oxide Chemical Mechanical Polishing

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Friction from Chemical Mechanical Polishing (CMP) of integrated circuits can cause damage to surface and sub-surface layers. To understand potentially damaging CMP friction, a model is presented which separates the contributions of: 1) bare pad asperity to substrate junction contacts, 2) slurry nanoparticles in the pad asperity contacts, and 3) a proposed substrate area where slurry particles adhere to and are swept along with the moving asperity contact. The model is used to interpret data from pin-on-disk friction experiments performed with a fused silica wafer and various polymer polishing pad materials, flooded with 100 nm diameter silica nanoparticle slurries. The results showed that only 18% of the pad asperity junction contact area had active particles and contacts outside of the asperity area were 38 times of the asperity junction area. This suggests that 93% of CMP material removal activity results from particles outside of the asperity/substrate contact.

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Chemical mechanical polishing (CMP) is a polishing technology used with precision applications such as integrated circuit (IC) surface polishing. CMP uses a soft, polymeric polishing pad pressed into contact with a substrate with a normal load and relative motion in the presence of chemically active slurry of nano-scale abrasive particles Steigerwald. A typical CMP polishing pad is a porous, hydrophilic polyurethane (PU) with large diameter (~50 μm) pores (see Figure 1). CMP is an integral part of the fabrication of advanced IC materials such as porous insulating materials with lower dielectric constants (low k). These porous materials have lower shear strength than solid films such as dense SiO2. Zantye noted a “mechanical integrity” factor for state of the art SiOC of less than 20% of dense SiO2 and a mechanical integrity of less than 5% of dense SiO2 for some more advanced aerogel or air bridge materials. Friction is an inevitable consequence of the rubbing action of CMP, and shear stresses from this rubbing friction may damage delicate surfaces of substrates being polished.

Balakumar observed that high shear stresses from the friction of CMP could cause delamination of deposited films of copper and dielectric with an advanced low dielectric constant (low k) surface layers on the silicon wafer polishing substrate. Kondo noted that damage could be lowered by decreasing the normal load on the substrate with a less economical decreased polishing rate. Yuan noted that reducing the friction coefficient of CMP or the normal force could both reduce the likelihood of damage. This suggests that finding a lower friction CMP process could enable polishing of advanced materials with lower mechanical integrity without sacrificing an economically high polishing rate.

By its very nature CMP has a chemical and mechanical component. The chemical component has been studied by Brown, Tomozawa, Sikder (this work was for low k films) and others. It is generally agreed that the surface of SiO2 materials is softened by hydrolysis. This layer is on the order of 10 nm deep and is more easily removed from a SiO2 substrate surface by a SiO2 particle without scratching or other surface damage. Liang noted that the SiO2 polishing particles adhere strongly the SiO2 polished substrate. The study of the mechanical component of removal has led to a number of rather varied models.

Sundararajan and others proposed a hydrodynamic lubrication (HL) CMP model, where the wafer is fully separated from the pad by a hydrodynamic film of slurry. Viscous shearing of the slurry moves particles across the substrate surface as slurry flow brings abrasive particles into contact with the substrate. Mori proposed that an EHL slurry film could move the slurry particles along the substrate surface effecting a very fine polishing. Analysis predicted an EHL film, but no fluid film thickness or friction measurements were done which could corroborate the analysis, though it is possible that asperity boundary lubrication contact occurred that moved slurry particles along the substrate to effect polishing. An EHL model by Zhou which analytically predicted an average slurry fluid film thickness of approximately 50 nm, would provide a gap small enough to enable a three-body abrasion mechanism of 100 nm diameter polishing particles. Experimental RR results compared well with the model, though no friction data or analysis was included. A relatively low coefficient of friction would be expected with the EHL model, though typical oxide CMP is effectively between 0.23 and 0.33 [Levert(1), Levert(2), Sikder] making a purely EHL model unlikely.

Xin proposed a model which predicted the predominant contact is EHL and there should be minimal boundary lubrication at the pad asperity-substrate interface. A non-Newtonian flow introduced in the small gap at the pad asperity to substrate interface increases the effective viscosity by 5 to 7 orders of magnitude thereby enabling motion of slurry particles across the substrate surface by viscous shear to effect polishing. This suggests that the CMP friction coefficient should change substantially with speed, though small but not substantial changes in CMP friction coefficient have been measured with speed [Sikder]. A multi-physics modeling approach to predict CMP

Figure 1. 3-D optical profilometry of commercial polyurethane pad material noting the asperity regions which contact the polished substrate.

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using particle modified hydrodynamics and boundary lubricated sliding of pad asperity junctions has shown promising correlations to CMP data sets using PU pads [Terrell[16]]. The authors present measurements of friction coefficients which are strongly dependent on the pad material which strongly suggests a different CMP friction mechanism may be present.

Pad asperity contact at the regions between pores, considered surface "mesas", can lead to boundary lubrication between the pad asperity and substrate surface. Sampurno[17] measured values of friction coefficients between 0.31 and 0.38 for various PU pads as a function of the Somerfield Number. Small variations in the Somerfield Number, between $7 \times 10^{-3}$ and $3 \times 10^{-2}$, with the friction coefficient, and the relatively large friction values suggest that CMP is likely in the boundary lubrication regime. Direct mechanical contact of pad asperities to the polished substrate is necessary for CMP based on experimental evidence of RR and coefficient of friction [Levert(2)[18]]. Friction measurements under boundary lubrication conditions ($\sim 0.001 \text{ m/s}$) ranged from 0.29 to 0.33 [Levert(3)[18]]. Liang[9] showed there is a chemical boundary lubrication layer present during oxide CMP, at the pad asperities-substrate contact.

Indications of the pad asperity-substrate contact significance have been observed by variations in polishing RR as a function of the wear and changes in the pad asperity contact areas [Lu[19], H. Lee[20]]. The RR is found directly proportional to the coefficient of friction [H. Lee[20], Homma[21]] and a decrease in friction as the pad "glazed" with adhered slurry debris after one hour of polishing. The pad wear and glazing lead to decreased roughness on the pad asperity surfaces and lower values of RR and friction.

A common assumption in CMP models is that active abrasive slurry particles are located at the pad asperity-substrate junction [Wang[22]], with either full particle coverage of the asperity junction or a proportional coverage as a function of the slurry particle % weight concentration. Embedment of particles at the pad asperities may be possible since hydrated SiO2 slurry particles adhere strongly to a hydrated substrate surface [Liang[9]], and that PU CMP pads, when wetted, plastically deform at very low stresses [Saka[23]]. Rimai[24] observed microscale SiO2 spheres can be engulfed in a viscoelastic polyurethane surface as a result of adhesive forces only, indicating that the abrasive slurry particles may not always reside at the pad asperity-substrate junction, and embedded particles on the pad asperity junction could become inactive due to engulfment.

Micro and nanoscale friction measurements using the atomic force microscope [Taran[25], Choi[26]] at typical oxide CMP chemistries have shown that SiO2-SiO2 friction coefficients range from 0.03 to 0.1. Choi’s[26] measurements on PU pads have recorded values of 0.15, nearly three times larger. If the pad asperity-substrate junction surfaces were fully covered with SiO2 particles, one could expect a macroscopic coefficient of friction between 0.05 and 0.15 based on Choi’s[26] data, though this does not correlate with the macroscopic data from Levert(3)[18] in which the CMP friction coefficient was between 0.30 and 0.33. This data suggests that the friction of CMP from SiO2 particle interaction is significantly less than that of the PU pad with respect to the SiO2 substrate, and that the majority of CMP friction could be arising from pad contact.

Here, the authors propose a model to address these considerations based on both macro scale friction experiments for various pad materials integrated with the latest single particle experimental friction data. The model uses both nano and macroscale friction data with varying pad materials as the basis. Significant particle engulfment has been assumed but engulfment mechanics has not been incorporated in models, where particle scale experiments have shown that it is possible. Slurry polishing particles could be active in locations outside of the pad asperity junction which has not been fully addressed by contemporary models. Most current models have not considered varying polishing pad materials. The proposed model is unique in that it predicts both the location and the activity of the polishing particles in active contact during CMP. The model applies to oxide CMP with nanoparticles polishing oxide surfaces, but may have wider application to other CMP systems.

![Figure 2](image-url)

**Figure 2.** Cross-sectional schematic diagram of a typical pad asperity junction with the polished substrate - showing regions of slurry particle and pad asperity interaction with the polished substrate.

### Model Development

A model of the friction generated during oxide CMP is developed, which identifies the friction on the substrate from the following real contact areas:

1. The pad asperity junction where no particles are present,
2. The particles trapped in the pad asperity junction which have a large normal load,
3. The particles outside of the pad asperity junction which are adhered to the substrate and are removed and swept along with the motion of the asperity (the swept region).

Figure 2 shows a cross-sectional schematic diagram of a typical pad asperity junction with the polished substrate, with the regions of slurry particles which could interact with the polished substrate labeled. Friction forces on the polished substrate can arise from particle interactions in the areas of the pad junction and swept regions. It is also important to point out that friction can also arise from bare pad interaction with the polished substrate.

Several assumptions are applied in this model including:

1. A quasi-static force analysis,
2. Perfectly-plastic asperity deformation,
3. An 80% coverage of particles adhering to the substrate in the swept region,
4. A 0.5% real pad asperity contact area, and
5. A parabolic pad asperity profile with an experimentally determined average radius of curvature.

The lateral force to remove a particle in the swept region is equal to the vertical adhesion force.

The asperity deformation assumption was chosen as Saka[23] has observed micron scale pad asperity junctions to behave perfectly plastically. The typical 20 MPa hardness of the wetted PU pad was used to calculate the 0.5% real contact area based on an average unit normal force of 0.1MPa measured from the friction experiments done in this paper. The 80% coverage was assumed based on micrographs from Basim.[27] Comparatively, a square packing arrangement would yield 78.5% coverage.

**Quasi-static force balance.**—The friction forces in CMP are modeled by taking into consideration each component of force for the three real contact areas of friction. Figure 3 shows a schematic cross-sectional diagram of the forces on the three areas of real contact.

The model is a representation of an average asperity which reflects the cumulative particle and asperity contacts over the entire apparent contact between the pad and the substrate. Relative motion at a constant speed between the pad asperity and substrate is assumed in the x-direction. Performing a force balance in the x and y directions gives:

$$
\sum F_x = 0 = \left( \mu_{cmp} \right) \left( N_{ta} \right) - \left( \mu_{pad} \right) \left( N_{pad} \right) + \left( \mu_{pp} \right) \left( N_{pp} \right) - F_R \tag{1}
$$
μction, was assumed to be equal to the normal force of adhesion for a single particle in the Y region and as such will not be balanced with the macroscopic force Equation 2. This FR term is the lateral force to overcome the adhesive force of the particles in the Y region and as such will not be balanced with the macroscopic normal load Ntot. Solving for Npp in Equation 2 and substituting into Eq. 1, Eq. 1 can be re-written as:

\[ 0 = (N_{pad}) \left( \mu_{cmp} - \mu_{pp} \right) + (N_{pp}) \left( \mu_{cmp} - \mu_{pp} \right) - F_R \]  

Interaction ratios (X & Y) are related to loads by applying a plastic pad asperity model to describe the fraction of overall pad asperity contact junction area, as follows:

\[ X = \frac{A_{pp}}{A_{pad}} \]  
\[ Y = \frac{A_{pad}}{A_{pad}} \]

The normal loads are defined by:

\[ N_{pad} = A_{pad} (H_{pad}) (1 - X) \]
\[ N_{pp} = A_{pad} (H_{pad}) (X) \]
\[ F_R = 4A_{pad}Y \frac{f_kPF}{\pi D^2} \]

In this model, the value for the lateral force to remove a single particle, \( f_k \), was assumed to be equal to the normal force of adhesion for a single particle in the Y region, \( N_{pp} \).

Finally, the global CMP friction, \( \mu_{cmp} \), was related to the pad friction, \( \mu_{pad} \), by regression analysis of experimental data, presented in the results section of this paper, as follows:

\[ \mu_{cmp} = \mu_{pad} \left( 1 + (0.0406) (\mu_{pad})^{-1.118} \right) \]

**Solution of X & Y contact areas.**—Substituting Equations 6, 7, and 8 into Eq. 3 gives:

\[ 0 = X (H_{pad}) \left[ \mu_{pad} - \mu_{pp} \right] + Y \left[ F_R \right] + (H_{pad}) \left[ \mu_{cmp} - \mu_{pad} \right] \]

Where \( F_R \) is given by Equation 8, and \( \mu_{cmp} \) is given by Equation 9.

The data in the results section of this paper has CMP friction, \( \mu_{cmp} \), as a function of pad friction, \( \mu_{pad} \), for a variety of pad materials. If one equation is written by substituting a given pad material friction, \( \mu_{pad} \), and hardness, \( H_{pad} \), into Eq. 10, a second equation can be written by substituting a second pad material friction, \( \mu_{pad2} \), and hardness, \( H_{pad2} \), into Eq. 10, these two equations would be:

\[ 0 = X (H_{pad}) \left[ \mu_{pad} - \mu_{pp} \right] + Y \left[ f_k PF \right] + (H_{pad}) \left[ \mu_{cmp} - \mu_{pad} \right] \]

\[ 0 = X (H_{pad}) \left[ \mu_{pad2} - \mu_{pp} \right] + Y \left[ f_k PF \right] + (H_{pad}) \left[ \mu_{cmp} - \mu_{pad2} \right] \]

With data substitutions for the above variables, one can solve Equations 11 and 12 simultaneously to uniquely predict values of the true contact areas of the pad asperity junction and the swept regions as a ratio of the pad asperity junction contact area, (variables X and Y).

**Experimental Methods and Materials**

The following experimental section describes the methods used to obtain macroscale CMP and nanoscale CMP slurry particle data to enable numerical solutions from the model. Global CMP and global pad friction data are experimentally determined using a small, bench top, custom “pin on disk” tribometer as described by Levert(3). It uses an inverted architecture (relative to typical CMP tools) where the flat substrate is mounted to the turntable and the pad is mounted at the location of the carrier. Fused silica wafers or singulated Copper low k wafer samples were used as the substrate sample to be polished, and they were mounted on the turntable. Pad samples were mounted to a “pin” in place of a carrier. Sheets of various polymeric materials were used as pad samples, and these were curved to form a 6 mm contacting radius on the pin - where the pad interfaces with the flat substrate. Experiments were run at 1 mm/s speed with a 0.39 N normal load on a 5 mm radius wear track on the substrate samples which were mounted on the turntable of the tribometer. The small normal loads kept the pad contact stress within an order of magnitude of 0.1 MPa which is within the range of commercial CMP (0.05 MPa), and the very slow speeds eliminated any confounding of the data from hydrodynamic effects. A series of experiments were performed using six polymers and two substrate materials (see Table I).

A variety of pad materials were selected with similar hardness to the typical IC 1000 but with different values for their coefficient of friction. This novel selection of pad materials was necessary to enable the model to discern the location of the active slurry abrasive particles. The PU pad was used as received and was not conditioned (intentionally roughened). This surface of the PU pad mesas was skived (sliced with a sharp metal blade). The SBR was also not conditioned. The surface of the LDPE, PTFE, HDPE, & UHMWPE pads were all machined with a tool steel end mill cutter to best simulate the skived surface of the PU pad mesas. Typical commercial conditioning tools (e.g. diamond grit) were not used as the area of pad contact was very small (less than 1 mm diameter), and the widely spaced conditioning tool grit may not enable a consistent texturing of such a small surface.

**Table I. Matrix of pad and substrate material couples for tribometer friction measurement experiments.**

| Material | Description | Substrate Material |
|----------|-------------|--------------------|
| LDPE | Low density polyethylene | Fused Silica |
| PTFE | Polytetrafluoroethylene (Teflon) | Fused Silica |
| PU | Commercial polyurethane (Dow Chemical IC 1000) | Fused Silica & Cu low k IC |
| SBR | Silicone elastomer (Rogers HT1200) | Fused Silica |
| HDPE | High density polyethylene | Fused Silica |
| UHMWPE | Ultrahigh molecular weight polyethylene | Fused Silica |
All pad materials were then prepared cleaning with isopropyl alcohol followed by drying followed by soaking in distilled water for at least 3 days. The minimum 3 day soaking was to ensure equilibrium hydration of the PU pad as determined by Ng.28 Fused silica wafers and singulated Cu low k integrated circuit specimens were used for the two substrate materials. The fused silica wafer was cleaned with a heated ammonia and hydrogen peroxide solution (SC-1 step of RCA clean). The integrated circuit was used as received without any surface treatment or cleaning. The slurry was made by ultrasonically dispersing 1% weight of 100 nm silica spheres (from Fiber Optic Center) in a 10.5 pH ammonia solution. The 1% weight of 100 nm silica spheres was chosen based on previous experiments done by Levert.18 These experiments showed that 1% and 5% solids loading led to statistically significant increases in friction. The 1% value was chosen, as it was the minimum level for which an increase in friction would be expected. The 10.5 pH was chosen to best simulate typical silica slurries where the basic solution creates a negative charge on the silica abrasive particle surface thereby inhibiting agglomeration as noted by Khanna29 and others.

The experiments first measured pad friction on the substrate with a 10.5 pH ammonia solution after a run-in to stabilize the friction. This gave μpad data. Slurry was then added and CMP friction was taken for 7.5 minutes. This gave μcmp data. Data was not taken after 7.5 minutes to limit the effects of slurry agglomeration on pad surfaces which commercial “conditioning” practices limit. Normal load and tangential (friction) force data were continuously measured at 7.5 Hz with a personal computer based data acquisition system which enabled real-time calculation of the coefficient of friction. A 90 second block of data was averaged to one coefficient of friction data point. Multiple data points were averaged and estimates of the statistical confidence interval were calculated.

As noted by Hyunseop Lee30 both pad and CMP friction initially increased. The pad CMP data was taken after an extensive run-in period which was equivalent to approximately a minute or two of commercial CMP. Once the pad had stable friction, CMP friction was data extracted for analysis was generally in the latter half of the 7.5 minute period where slurry particles were applied. This enabled stable friction data without the issue of declining friction from pad wear and glazing as noted by many authors including H. Lee.30

The values of single particle friction and adhesion have been determined using nano-measurements. Thoresen31 performed pull-off measurements for small SiO2 particles down to a few microns in diameter. Extrapolation of this pull-off data suggested that wetted SiO2 particles may have an adhesive force on the order of 20 nN for the 100 nm particles which were used by the authors for this paper. This data was only for dry adhesion. Taran26 measured the adhesion and friction force of wetted 20 μm diameter SiO2 particles in low and high pH solutions against a SiO2 substrate. It was observed that the friction was substantially lower at high (10.6 pH) than at lower pH. At 10.6 pH, the coefficient of friction ranged between .12 and .03 depending on the sliding speed. Although the particle size was too large to correlate directly with the 100 nm diameter particles used by the authors in this paper, it strongly suggests that the CMP coefficient of friction should be rather low within the range of .10 when it is typically near .30. Choi26 did particle analog measurements with oxide coated AFM tips wetted with the 10.5 pH NH4OH solution which is typically used in oxide CMP slurries. It was observed that 100 nm SiO2 particle analogs with a SiO2 substrate had an adhesive force of 0.5 nN, a coefficient of friction of 0.03 at light loads (~10 nN) and a coefficient of friction of .04 at heavy loads (~200 nN) which would be expected during CMP with a PU pad asperity. Basim27 calculated 500 nN of normal force which commercial “conditioning” practices limit. Normal load and tangential (friction) force data were continuously measured at 7.5 Hz with a personal computer based data acquisition system which enabled real-time calculation of the coefficient of friction.

Figure 4. The change of CMP friction coefficient after adding slurry abrasives vs. friction coefficient of the six different polishing pad materials. Note the roughly uniform increase of friction coefficient after SiO2 abrasives are added.

Figure 5. Plot of percent change of CMP friction data after addition of slurry particles versus pad friction is shown in Figure 5.

### Experimental Results

In all cases the macro scale CMP friction with slurry particles was greater than macro scale pad friction. This friction increase with slurry particles occurred whether the pad had a very low friction (such as PTFE with μpad = 0.046) or a very high friction (such as SBR with μpad = 1.1). The increase in friction from the addition of slurry particles (μcmp - μpad) was roughly uniform as can be seen in Figure 4.

The average increase of CMP coefficient of friction was 0.07 across a wide variety of pad materials. This same data set was analyzed to better enable its use in the proposed CMP friction model by examining the percent change of friction after slurry abrasives were added. The percent change of CMP friction data after addition of slurry particles versus the pad friction is shown in Figure 5.
The model used a power law numerical regression of the data shown in Figure 5. This regression had an $R^2 = 0.68$.

$$\mu_{\text{cmp}} = \mu_{\text{pad}} \left[ 1 + (0.0406 \left( \frac{\mu_{\text{pad}}}{1.18} \right)^{-1.18} \right]$$ \[9\]

This correlation was used in the model.

The following values were based on AFM experiments performed using an oxide coated silicon tip as a particle analog:

- $\mu_{pp} = 0.04$ when sliding against SiO$_2$ substrates
- $N_{\text{ad}} = 0.50 \text{nN}$ for single particle adhesion to SiO$_2$ substrates

Pad asperity profilometry determined that the average asperity had a $27.3 \mu$m radius of curvature. The asperity peaks were on the order of $10 \mu$m apart and $1 \mu$m high.

Modeling Results

With the $0.5\%$ true pad asperity contact ratio, a typical true pad junction contact area was calculated for a typical asperity over a repeating $10 \mu$m X $10 \mu$m square area as a circular junction $0.8 \mu$m in diameter or $A_{\text{pad}} = 5 \times 10^{-11} \text{m}^2$.

A pad hardness value $H_{\text{pad}} = 20 \text{MPa}$ was used for a typical wetted PU pad asperity based on nanomechanical testing by Saka. The values of pad hardness for other materials were correlated from vendor provided information. Given the above inputs, Equations 11 and 12 were solved simultaneously for all 21 possible pad combinations giving 21 estimations for both $X$ and $Y$. These were averaged to give the following solution:

- $X = 0.18$ or $18\%$ of the pad junction true contact area,
- $Y = 38$ or $3800\%$ of the pad junction true contact area.

The value of $Y$ predicts that the swept region has a radius of $6.2 \mu$m as shown in the schematic diagram in Figure 6 – assuming that the particles are collected on the “leading edge” of the asperity motion. In this region, particles adhered to the substrate are swept along with the pad asperity junction and polish the substrate as their adhesive connections are broken.

A schematic cross-sectional diagram, approximately to scale, showing the size of $X$ and $Y$ particle contact areas is shown in Figure 7.

Figure 7. Schematic cross-sectional diagram, approximately to scale, showing the relative size of the true particle contact areas: pad asperity junction (X), swept (Y). Active slurry particles (initially) adhered to the substrate in the Y region are shown as hollow circles and active particles with high normal load in the X region are shown as solid circles. Approximate scale show in $\mu$m.

Discussion

The experimental data of CMP coefficient of friction convincingly showed that it is strongly dependent on the polishing pad material. Figure 5 shows that the increase in CMP coefficient of friction, above that of the bare pad material, was an average of 0.07 for a variety of pad materials. These pad materials had a very wide range of coefficient of friction, 0.05 to 1.1, (for experiments without slurry particles (wetted only with 10.5 pH NH$_4$OH solution). The increase in CMP coefficient of friction, when adding SiO$_2$ slurry particles, was modest (0.07 average) when compared to the typical $\sim 0.30$ coefficient of friction for typical PU pads. This strongly indicated that most of the friction in CMP is a result of the pad itself and not the polishing action of the particles. The implication of these experimental observations is that a pad with a low coefficient of friction would be the most effective route to reducing friction in a CMP process.

Most CMP models focus on and predict removal rates (RR). As H. Lee and Homma have observed a correlation of RR with friction, it suggests that friction is integral in understanding RR if not a good predictor of RR. CMP models which depend on fluid flow – either EHL or non-Newtonian shearing – should have equal values of friction for any pad material. The experimental friction data shows that this is obviously not the case. Fluid shearing may be an important aspect of CMP, but currently constructed models do not reflect the experimental data presented here.

The experimental data shows that CMP is in the boundary lubrication regime. The low speed experimental friction coefficient data in this paper is in the same range as that of CMP at typical speeds. The average low speed ($0.01 \text{m/s}$) coefficient of friction for many data points of typical PU pad material was 0.29. This is virtually the same as the 0.30 to 0.40 reported by Levert(2) and close to the 0.3 − 0.45 reported by Sikder for CMP with typical PU pads at typical speeds ($\sim 0.5 \text{m/s}$). Although the pad asperity to substrate contact is under boundary lubrication, the activity of the particles must be considered further.

Slurry floods all surfaces prior to asperity junction contact, and continues to flood the areas around the junction during CMP. As Basim noted, particles are densely distributed on slurry wetted surfaces. Assuming near-full asperity junction coverage with slurry particles, a coefficient of friction similar to that of the slurry particles would be expected if all of the active particles were only in the asperity junction. A coefficient of friction of 0.04 for a SiO$_2$ particle on an SiO$_2$ substrate was measured by AFM wetted particle analog experiments. This suggested that the coefficient of friction for bare PU pad (which was measured at 0.27) should have dropped to approximately 0.04 after slurry particles were added. The actual coefficient of friction change for the PU pad increased to 0.29 after that slurry particles were added. This typical result revealed that most of the pad asperity junction is bare during CMP. This result also suggested that most of the active particles are not at the asperity junction, but elsewhere outside of the junction. This experimental evidence, of modestly increasing friction with slurry particle additions, matches the proposed model’s result.
that only 18% of the pad junction is covered with active SiO₂ particles since the other 82% of the junction would be generating friction from pad to substrate contact. The authors propose the many of the SiO₂ particles at the padasperity junction are being quickly embedded or engulfed into the pad surface thereby becoming inactive. Others including Rimai have shown that embedment or engulfment is indeed possible.

The model also predicts a large Y region of 3800% the size of the padasperity junction area (\(A_{pad}\)). It is proposed that the activity and friction of particles in this Y region contribute to the total friction (\(\mu_{cmp}\)) and subsequently removal rate. Liang noted that SiO₂ particles adhere strongly to SiO₂ substrates. These Y region particles adhered to the SiO₂ substrate and are swept ahead by the leading edge of the padasperity. Breaking the junctions of these particles generates friction. These Y region particles increase the friction beyond that of the bare pad and the particles in the X region. The much lower effectiveparticle contact stress (~20 MPa beneath the padasperity junction versus 0.051 MPa in the Y region) suggests that the polishing in the Y region should be very fine.

The model predicted a swept (Y) region has a gap between the pad and the substrate ranging from 0 nm to 700 nm. This result suggests that particles adhered to the pad surface may interact with the particles on the substrate surface to sweep them along with theasperity. This is illustrated in the cross-sectional diagram in Figure 7.

These results of particle friction have important implications for models to understand removal rate. Removal rate has been measured by H. Lee and Homma and observed to be proportional to overall CMP friction. It would be expected that the bare padasperity junction material polishes SiO₂ substrates very little and that the removal rate (RR) for the SiO₂ particles should be related to the friction of those particles. Preston first documented the observation that wear rate is proportional to the particle to substrate friction forces. Given this argument and Lee and Homma’s observations that removal rate is proportional to friction, a modified Preston equation was used to estimate the anticipated removal rate from the X and Y region particles. In this modified equation, the normal load was replaced with the friction force.

\[
RR_{tot} \propto (F)(v)
\]  

Where F is the friction force and v is the speed. Since the speed was held constant, this reduces to:

\[
RR_{tot} \propto F
\]  

The normal load for the X region SiO₂ particles is proportional to their contact stress and their true contact area. The friction force for the X region particles is the product of that normal force and friction coefficient, or:

\[
F_{pp} = (\mu_{pp})(X)(H_{pad})(A_{pad})
\]

Where \(F_{pp}\) is the friction force for X region particles trapped between theasperity junction and substrate.

The friction force, \(F_{R}\), for the Y region particles is given by Equation 8. Multiplying Equation 8 by the area of the swept region, (Y)(A_{pad}), and combining this equation with Equation 15, gives a total volume removal rate, RR:

\[
RR_{tot} \sim \left\{ (\mu_{pp})(X)(H_{pad})(A_{pad}) \right\} + \left\{ (Y)(A_{pad})(f_{R})(PF)(4)(/\pi)(D^{2}) \right\}
\]

Dividing by \(A_{pad}\) gives a unit, total removal rate of depth per unit time:

\[
RR_{tot}/A_{pad} \sim \left\{ (\mu_{pp})(X)(H_{pad}) \right\} + \left\{ (Y)(f_{R})(PF)(4)(/\pi)(D^{2}) \right\}
\]

The relative removal rate for the X region can be estimated by dividing the first term of the right hand side of Equation 17 by the entire right hand side of the equation. Likewise the same can be done for the Y region by dividing the second term. This gave:

Relative RR of X Region =

\[
= \frac{\left\{ (\mu_{pp})(X)(H_{pad}) \right\}}{\left\{ (Y)(f_{R})(PF)(4)(/\pi)(D^{2}) \right\}}
\]

and:

Relative RR of Y Region =

\[
= \frac{\left\{ Y)(f_{R})(PF)(4)(/\pi)(D^{2}) \right\}}{\left\{ (\mu_{pp})(X)(H_{pad}) \right\}}
\]

The results of this RR model predict that most, 93%, of the removal rate is performed by particles outside of the padasperity junction in the Y region while only 7% of removal rate is done in the X region particles in the padasperity junction. These results suggest that the accuracy of CMP models of removal rates may be improved by applying this proposed model.

Conclusions

A model for oxide CMP containing boundary lubrication between the padasperity and substrate junction with additional particle contacts outside of the junction was presented. Experimental coefficient of friction data for oxide CMP supports that friction is the sum of the bare padasperity friction and a small 0.07 average increase from slurry particle friction. This suggests that a pad with a low coefficient of friction would be the easiest route to reduce damaging friction. The location and contribution of particle friction in CMP may be estimated by the new model incorporating experimental data for oxide CMP with a variety of polishing pad materials.

The slurry particle interaction with the polishing substrate can be summarized as follows:

- An area 18% of the padasperity to substrate real contact (X ratio) between the padasperity contact and substrate where the particles have a high (~200 nN) normal load, and
- An area 3800% of the padasperity to substrate real contact (swept Y region) where particles are adhered to the substrate and are swept ahead of the padasperity contact. The lateral force required to move these particles enables them to perform polishing of the substrate.

It is proposed that many of the SiO₂ particles at the padasperity junction are either embedded or engulfed below the pad surface and rapidly become inactive.

The implication of this particle interaction is that only 7% of polishing is performed by particles with high (~200 nN) normal load in the padasperity junction and 93% from particles with lower, adhesive normal load in the swept (Y) region on the substrate swept along with theasperity. Most (93%) of polishing is performed by particles outside of the padasperity junction.

A further implication is that a wide variety of novel pad materials may become useful in oxide CMP while offering other advantages over current pads such as low coefficient of friction.

List of Symbol

- \(A_{pad}\): Area of pad in contact inasperity junction
- \(A_{pp}\): Area of trapped particles inasperity junction
- \(A_{Y}\): Swept area annular region (Y region) outside of padasperity junction
- \(D\): Diameter of slurryparticles
- \(f_{R}\): Lateral force to remove a single adhered particle in the swept (Y) region
- \(F\): Friction force
- \(F_{pp}\): Friction force of trapped particles inasperity junction in contact with SiO₂
- \(F_{R}\): Lateral force to remove all adhered particles in the swept (Y) region
\( F_x \) Forces in the x or lateral direction
\( F_y \) Forces in the y or vertical direction
\( H_{pad} \) Hardness of the pad material
\( N_{pad} \) Normal force of an individual adhered particle in the swept (Y) region
\( N_{pad} \) Normal force of pad asperities in contact
\( N_{tot} \) Normal force on particles trapped in asperity junction
\( R \) Average radius of pad asperity from profilometry data
\( R_{tot} \) Volume Removal Rate of CMP from all contributing slurry abrasive particles
\( v \) Sliding speed of CMP
\( x \) Lateral distance from asperity tip center
\( X \) Ratio of \( A_{yp} / A_{pad} \)
\( y \) Vertical distance from substrate to pad asperity surface – outside of the asperity junction
\( Y \) Ratio of \( A_y / A_{pad} \)

Greek
\( \mu_{cmp} \) Coefficient of friction of macro scale tribometer CMP experiments
\( \mu_{pad} \) Coefficient of friction for pad without slurry from tribometer experiments
\( \mu_{pp} \) Coefficient of friction for trapped particles in asperity junction in contact with SiO₂

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