



Stick-Slip Transitions in Chemical Mechanical Planarization

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As semiconductor device sizes continue to shrink and economic realities drive ever increasing yield targets, achieving wafer scale planarity through the application of chemical mechanical planarization (CMP) has become increasingly challenging. The dynamics of the wafer-pad interface is critical to maintaining this uniformity. Utilizing measured friction coefficients (0.3–0.6), we report on the transitions from a smooth planarization regime to a stick-slip regime and vice versa over a set of two applied vertical loads and three relative velocities during the CMP process. Finally, we note a correlation between time spent in a stick-slip regime and platen velocity.

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On closer analysis, the apparently simple act of sliding two contacting substrates relative to one another reveals a myriad of fundamental physical questions that have a broad technical application. Present semiconductor manufacturing imperatives require that planarization uniformity be maintained over length scales spanning 8 orders of magnitude,¹ from gate lengths of 32 nm to wafer diameters of 300 mm. Economic realities continue to drive yield targets ever higher. In this environment, process engineers seek to improve all manufacturing techniques, including chemical mechanical planarization (CMP). Stick-slip behavior, and the large lateral forces associated with it, is an indication of reduced polish quality.^{2,3}

Stick-Slip

As two surfaces slide past one another, their relative motion can be categorized into two regimes. The smooth polishing regime exhibits a stable, unchanging relative velocity, whereas stick-slip is identified by a relative velocity that alternates between near zero and some nonzero value at a high frequency. Hence, the stick-slip name, the surface alternates between sticking to the substrate and sliding past the substrate.⁴ In many applications, to avoid stick-slip, a thin layer of fluid is introduced between the two surfaces, eliminating contact. This relative motion in which one surface is supported by a thin fluid layer is often characterized as hydrodynamic lubrication.⁵ However, material removal during CMP requires some degree of contact; thus, process engineers must walk a fine line between acceptable contact and removal rates vs unacceptably high contact and the resultant stick-slip.^{6,7} Intuitively, it is easy to postulate an increase in defectivity and reduction in polish quality resulting from stick-slip. Nevertheless, literature is sparse in this regard, indicating a possible avenue for investigation.

CoF

Researchers often report in situ measurements of the coefficient of friction (CoF), a mechanical characteristic defined as the ratio of the lateral forces (parallel to the planarization interface, the F_x and F_y components) to the vertical forces⁸ (perpendicular to the interface, the F_z component), or symbolically

$$\mu = \frac{\sqrt{(F_x^2 + F_y^2)}}{F_z}$$

CoF data can be used to observe polishing regime transitions in CMP.

Experimental

Experiments were performed on an instrumented laboratory-scale polisher (Struers Rotopol model 31). The polisher had a 12 in. (0.305 m) diameter rotating platen and, to maintain the same polishing pad-wafer area ratio seen in the industry, we employed 3 in.

diameter borosilicate wafers. The optical clarity provided by these wafers is required by other concurrent experiments.

Lateral and vertical forces were monitored by a commercially available force transducer table, (AMTI model MC12) capable of decomposing forces and moments in all three spatial dimensions. Custom LabVIEW software allowed us to log datastreams and calculate CoF. The complete setup is described in greater detail elsewhere.⁹ In brief, experimental conditions and parameter settings were as follows:

1. Three relative velocities, platen rotational velocities of 30, 60, and 120 rpm, were chosen. The wafer velocity was set to $1.1 \times$ platen velocity to avoid patterning. These rotational velocities translate to relative pad-wafer velocities of 0.3, 0.6, and 1.3 m/s at the wafer leading edge.

2. Two injection locations: slurry (Cabot SCI 3:2 concentration with pH adjusted deionized water) injection locations were aligned with the wafer inner edge and aligned with the wafer center. In subsequent data, the authors did not find significant variations between injection points. However, further testing is required to verify this conclusion and, for this reason, we segmented the data by injection location.

3. Two downforces: pressure was set to 9.7 kPa (1.4 psi) or 16.5 kPa (2.4 psi).

4. Each experimental run was 30 s long and data were sampled at 2 kS/s.

5. Cabot DC100 AC grooved pads were employed throughout.

6. A 4 in. diameter diamond grit conditioner maintained pad roughness.

Data and Analysis

Due to our interest in a phenomenon (stick-slip) that manifests as a high frequency signal, we estimated the response of the entire system using both simulation (a 10 degree of freedom dynamic model) and experiment (excitation with an instrumented impact hammer).¹⁰ For frequencies below 30 Hz, the magnitude and phase of the forces measured at the force plate accurately reflect wafer-pad interaction forces. Above this frequency, we cannot isolate interfacial forces from the overall response of the experimental setup and therefore must draw only qualitative conclusions. These limitations result from compromises required (mainly size and cost) to perform a variety of simultaneous experiments all requiring access to the planarization interface. Of course, a study more specifically focused on this phenomenon would employ a more optimized setup.

Figure 1 shows an example of smooth polishing: variations in CoF are not large, on the order of 10% of the nominal value, and signal frequency is relatively low (less than 15 Hz). In Fig. 2, we can clearly see a transition from a smooth polishing regime to a resonance (stick-slip) regime. Initially, the wafer is in a smooth polishing regime but, periodically, high frequency (beyond our 30 Hz limit) transients appear and begin to dominate the signal. After some time, the frequency begins to decrease and there is a reverse transi-

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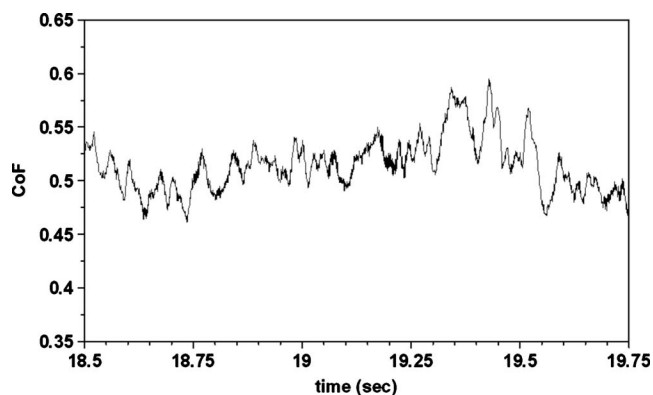


Figure 1. An example of smooth polishing. Conditions for this run were midinjection, 9.7 kPa (1.4 psi), and 0.6 m/s.

tion from stick-slip back to smooth polishing. Simply counting peaks yields an estimate of stick-slip frequency of ~ 100 Hz, though such an estimate is beyond our accuracy limit. Certainly, it would be interesting to know this frequency more precisely, but this imprecision does not qualitatively alter the results.

In Fig. 3, we present a more detailed view of the transition from smooth polishing to stick-slip. At 16.10 s, we are firmly in a smooth polishing regime. At 16.18 s, we see the onset of high frequency transients, but in this case, these do not lead to stick-slip, instead they damp out by 16.24 s. By 16.34 s, however, the transients have

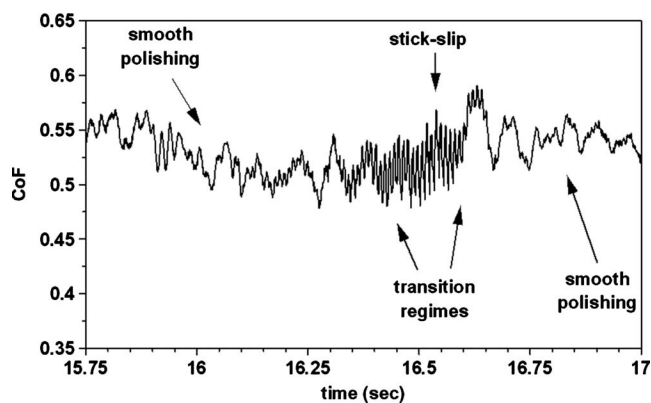


Figure 2. An example of stick-slip exhibiting both a transition to stick-slip and a return to smooth polishing. Experimental conditions were midinjection, 16.5 kPa (2.4 psi), and 0.6 m/s.

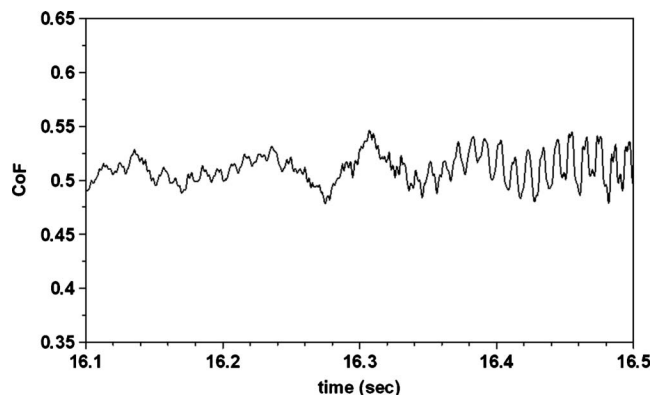


Figure 3. A transition from smooth polishing to stick-slip. Experimental conditions were midinjection, 16.5 kPa (2.4 psi), and 0.6 m/s.

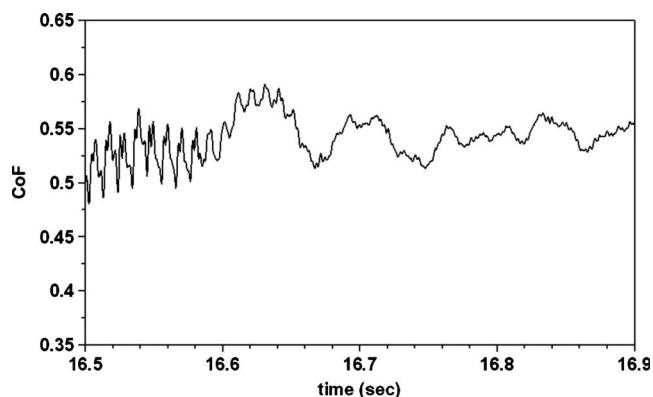


Figure 4. A transition from stick-slip to smooth polishing. Experimental conditions were midinjection, 16.5 kPa (2.4 psi), and 0.6 m/s.

returned, and by 16.45 s, we observe stick-slip, identified by features highly suggestive of period doubling phenomena. Typically, once the high frequency transients begin, a full transition to stick-slip occurs; the “damp out” phenomena observed here are relatively rare.

Figure 4 shows the reverse transition, from stick-slip to a smooth polishing regime. Initially, in a stick-slip regime, the CoF signal frequency decreases, and by 16.59 s, we are in a transition zone. At 16.65 s, these transients have decayed and a smooth polishing regime has been reestablished. For Fig. 2-4, experimental conditions are midwafer injection, 16.5 kPa (2.4 psi), and 0.6 m/s, and one representative stick-slip event is examined.

In an effort to quantify the extent of stick-slip in a given process condition, the average time spent in a stick-slip event, including transition times, has been extracted from the data. Figure 5 shows these average times for low velocity (0.3 m/s) cases. The average event time is nominally 1 s. Recall that this relative velocity is realized at a rotational velocity of 30 rpm. Each stick-slip event lasts, on average, for half a platen rotation. Figure 6 shows the same type of data for 0.6 m/s cases. In this instance, the 9.7 kPa experi-

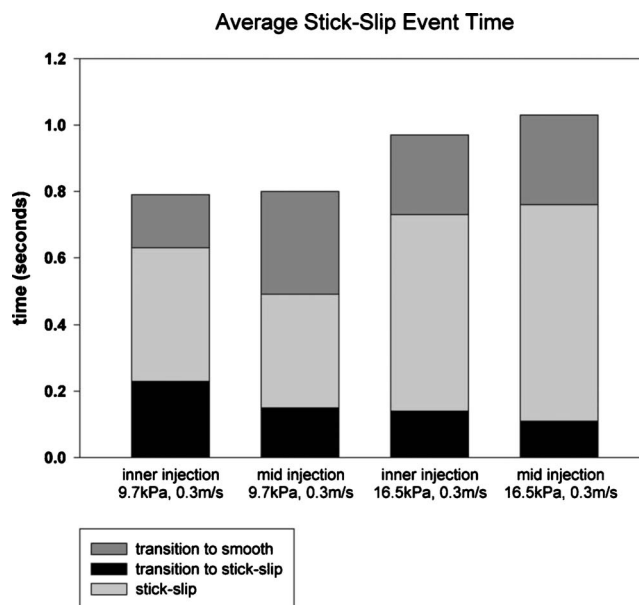


Figure 5. Average stick-slip event time for 0.3 m/s relative velocity. Overall standard deviations for these measurements were ± 0.2 s. We could not discern significant differences due to injection location but did not feel such a conclusion was warranted without further testing and thus segment the data using this variable.

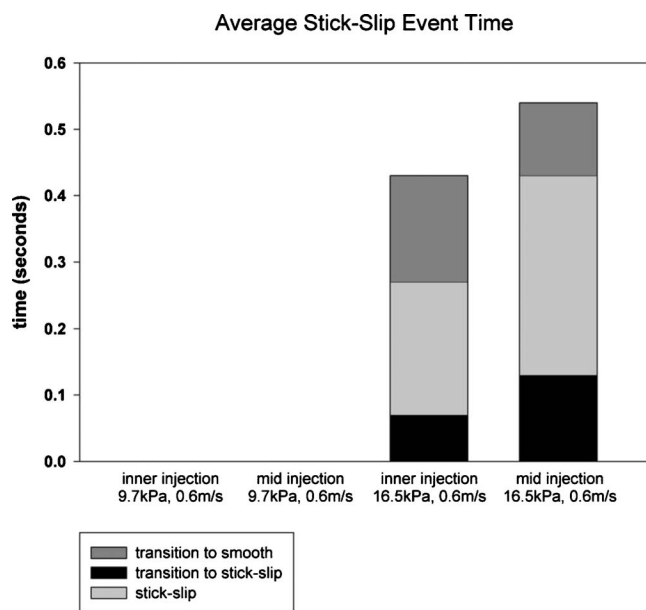


Figure 6. Average stick-slip event time for a relative velocity of 0.6 m/s. The lower pressure cases did not exhibit stick-slip. Overall standard deviations for these measurements were ± 0.1 s.

ments do not exhibit stick-slip. For 16.5 kPa downforce cases, stick-slip is observed with an average event time of approximately 0.5 s, which, for this velocity, is again half a rotation.

Discussion

The correlation between platen rotation rate and stick-slip event duration suggests that stick-slip events may be associated with specific areas of the platen. We hypothesize that two particular areas on the platen, the measured high and low points (which are approximately 180° rotation apart) initiate and then terminate stick-slip events. Consider the wafer as it moves across the platen: as the wafer's leading edge encounters a high point on the platen, one might expect the wafer to "dig in" and initiate a stick-slip event. Conversely, as the leading edge encounters a low point, a relatively

large amount of slurry is introduced into the planarization interface, serving to moderate the stick-slip and triggering a return to smooth polishing. Platen runout was measured to be ± 0.010 in. (± 0.25 mm), typical of industrial quality bearings. Extending this analysis to the 1.3 m/s cases (120 rpm) is not possible. No stick-slip was evident in those cases for either downforce, the increase in slurry flow to the planarization interface that results from an increase in velocity mitigating any tendency to stick-slip.

Overall, this study confirms the processing rule of thumb that stick-slip is more prevalent at lower velocity–higher pressure combinations and raises several possible avenues for future study.

1. How can we quantify the increase in defectivity and reduction in polish quality associated with stick-slip? Studies in these areas seem relatively uncommon.

2. Why do some initial transients lead to stick-slip, whereas others do not? A better understanding of these dynamics could lead to improvements in pad properties and/or polisher mechanics.

3. Is stick-slip associated with specific platen locations? If so, what are the key components of those special positions?

4. Can we identify the onset of transition events in real-time and prevent them from becoming fully realized stick-slip?

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References

1. E. Matijević and S. V. Babu, *J. Colloid Interface Sci.*, **320**, 219 (2008).
2. D. Rosales-Yeomans, T. Doi, M. Kinoshita, T. Suzuki, and A. Philipossian, *J. Electrochem. Soc.*, **152**, G62 (2005).
3. C. Barnes, Personal communication.
4. J. P. Den Hartog, *Mechanical Vibration*, McGraw-Hill, New York (1956).
5. A. Z. Szeri, *Fluid Film Lubrication: Theory and Design*, Cambridge University Press, New York (1998).
6. Z. Li, K. Ina, I. Koshiyama, and A. Philipossian, *J. Electrochem. Soc.*, **152**, G299 (2005).
7. M. D. Hersey, *Theory of Lubrication*, John Wiley & Sons, New York (1938).
8. F. P. Beer and E. R. Johnston, Jr., *Vector Mechanics for Engineers*, McGraw-Hill, New York (1996).
9. J. Vlahakis, C. Rogers, V. P. Manno, R. White, M. Moinpour, D. Hooper, and S. Anjur, *J. Electrochem. Soc.*, **156**, H794 (2009).
10. J. Vlahakis, Ph.D. Thesis, Tufts University, Massachusetts (2008).