Task ID: 425.020
Task Title: An Integrated, Multi-Scale Framework for Designing Environmentally-Benign Copper, Tantalum and Ruthenium Planarization Processes

Deliverable: Integration of force-frequency sensing with wafer/chip/feature scale modeling for physically based interpretation of signals.

## I. Summary/Abstract.

This report summarizes recent experimental results of force-frequency sensing during Ta/TaN CMP process and physically based interpretation of signals. The results indicate that coefficient of friction, variance of shear force and variance of down force increase sharply during layer transition from Ta/TaN to $SiO_2$ and reach maximum value after total Ta/TaN clearing. In addition, unique and consistent force spectral fingerprints emerge showing significant changes in several fundamental frequency peaks before, during and after layer transition from Ta/TaN to $SiO_2$ polishing. To help interpret these signals, a physically-based version of a feature/chip/wafer scale CMP model is used. The model relates the evolution of surface topography during the planarization process, and the exposure of different materials during clearing, to the effective friction. Future extensions which also consider the height and lateral spatial distribution of pad surface asperities to observed variance of COF and shear force are suggested.

## II. Technical Results and Data.

All polishing experiments were performed on an Araca APD-800 polisher and tribometer which is equipped with the unique ability to acquire shear force and down force using load cells in real-time. The force acquisition was set at a frequency of 1,000 Hz. The stacked films for the patterned wafers consisted of 700 nm electrodeposited copper on top of 80 nm PVD copper seed layer and 40 nm PVD Ta/TaN and 300 nm thermally grown $SiO_2$ on silicon substrate. Prior to the actual Ta/TaN polishing process, the overburden copper layer was removed. Ta/TaN polishing was done on a RHEM embossed Politex REG pad at a pressure and sliding velocity of 1.5 PSI and 0.6 m/s, respectively. The total polishing time for each wafer was 50 seconds. Hitachi Chemicals HS-T815-B1 slurry was used at a flow rate of 300 ml/min. Blanket TaN and $SiO_2$ wafers were also polished. The film in the blanket TaN wafer was 100 nm PVD TaN on silicon substrate. The film in the blanket $SiO_2$ wafer was 300 nm thermally grown $SiO_2$ on silicon substrate.

Figure 1 shows how shear force and down force vary with polish time for one of the three patterned wafers (all three patterned wafers exhibited similar characteristics). The polish time was intentionally lengthened for all three wafers to ensure that over-polish happened. Three different polishing regimes occurs during the Ta/TaN clearing process, as follows: 1) the bulk removal of Ta/TaN layer (i.e. less than 30 seconds), 2) the subsequent layer transition to $SiO_2$ polishing (i.e. between 30 and 40 seconds), and 3) the over-polish regime (i.e. after 40 seconds).

Figure 2 shows the coefficient of friction (COF) as a function of time. COF was calculated by dividing the shear force by the down force. During the transition from Ta/TaN to $SiO_2$ polishing (between 30 and 40 seconds), the COF increases gradually from 0.10 to 0.15 and reaches its steady value in 10 seconds after the onset of transition. This phenomenon indicates that the Ta/TaN clearing occurs gradually. During the transition from Ta/TaN to $SiO_2$ polishing, the Ta/TaN film is partially removed hence exposing $SiO_2$ film that intrinsically induces higher shear force or COF than Ta/TaN. Shear force and COF continues to increase as the exposed $SiO_2$ film becomes larger and reach maximum value when the Ta/TaN film is cleared completely.

During blanket TaN and $SiO_2$ wafer polishing, the measured COF for blanket $SiO_2$ wafer polishing (0.22) is higher than the COF for blanket TaN wafer polishing (0.10). Such COF trend is qualitatively similar to the COF trend exhibited in Ta/TaN clearing during patterned wafer polishing. This observation clearly indicates that the shear force measurement is capable of detecting the transition from Ta/TaN film to the subsequent $SiO_2$ film.

Fast Fourier Transformation (FFT) was performed on the shear force and down force data to convert them from time domain to frequency domain. Frequency spectra associated with the evolution of wafer topography (between 20 to 50 seconds) are shown in Fig. 3. Results indicate the presence of unique and consistent spectral fingerprints associated with polishing of the patterned wafers. There is a peak in the shear force spectra that dominates at 0.77 Hz before the transition region (i.e. 20 – 30 second). During the transition region (i.e. 30 – 40 second), fundamental peak at 0.43 Hz rises significantly and then finally increases by an order of magnitude after the transition has taken place. From this data, we can deduce that changes in the topography of the layers being polished and their interaction with the contacting bodies (i.e. the abrasive particles and the pad) are manifested in the dynamic evolution of the frequency spectra described above.

During the transition region, the peak at 0.1 Hz increases substantially. The shear force exhibits a major increase from approximately 7.5 $lb_f$ to 11.3 $lb_f$ at a relatively long period of time (i.e. starting from 30th second to 40th second) as shown in Fig. 1. Such slow fluctuation results in a low frequency spectrum of 0.1 Hz. After the transition is complete (i.e. 40 – 50 second), the peak at 0.1 Hz drops accordingly.

In contrast, the down force spectra shown in Fig. 3(b) do not share similar dynamic evolution as the shear force spectra. There is no systematic trend observed in the down force spectra.

Our model relates the surface topography on the wafer, together with the area-fraction mix of thin film material that is exposed on the wafer surface, to the resulting effective friction between pad and wafer. The MIT chip-scale models for CMP predict the time-evolution of surface topography during the process step, and provide surface step-height information for this component of friction. The model also tracks when clearing occurs, exposing different material types. We assume a friction force given by

$f \propto \mu_{avg} \cdot (1 + \beta \cdot \sigma_{Long-Range})$, where $\mu_{avg}$ is the average material COF based on the relative portion of different materials on the wafer surface, and is calculated by averaging the material COF weighted by that material's exposed area. We denote the long range standard deviation of the raised area height by $\sigma_{Long-Range}$; here $\beta$ is a model fit parameter.

This model is consistent with the Ta/TaN polish step trends observed in Fig. 2. Initially, the incoming topography of the wafer has some height variation, resulting from the earlier polish step removing and clearing the overburden copper. During the initial stages of the barrier removal CMP step, pattern density differences across the chip result in slight increases in the standard deviation of feature step-heights. Thus by the model above, there is a slight rise in the effective COF during the initial stage of barrier polish. As the barrier removal step proceeds, however, this chip-scale variation is indeed planarized and the standard deviation of heights begins to decrease, resulting in a gentle reduction in the effective COF. The more dramatic effect, consistent with the chip-scale pattern evolution model, occurs during the "transition" step, when the underlying SiO2 layer begins to be exposed in some fraction of the chip (and wafer). As the barrier clears, the mix of exposed Ta/TaN and SiO2 layers changes, resulting in the increased averaged COF. Finally, when the barrier is fully cleared, a relatively constant COF is predicted. The model suggests that with extreme overpolish times, however, pattern dependent erosion of the oxide will begin to increase height variance; this increase in $\sigma_{Long-Range}$ for very long overpolish times predicts a gentle increase in the average COF.

The feature/chip/wafer scale model does not explain or encompass the higher frequency peaks in the observed time traces or spectral analysis of Fig. 3. Future work might extend the CMP model to include wafer scale nonuniformity in the pad surface roughness (asperity height and lateral spatial distributions), to relate the pad/wafer kinematics with the effective observed COF.

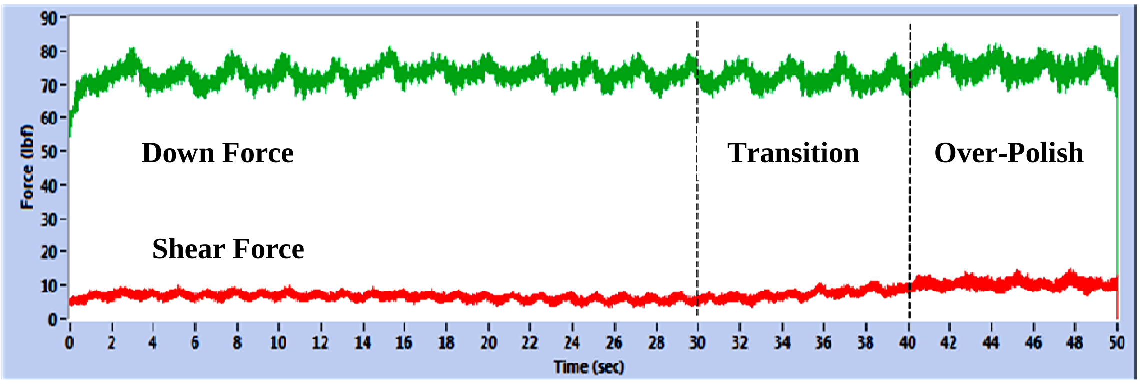


**Figure 1: Shear force and down force as a function of polish time during Ta/TaN clearing process**

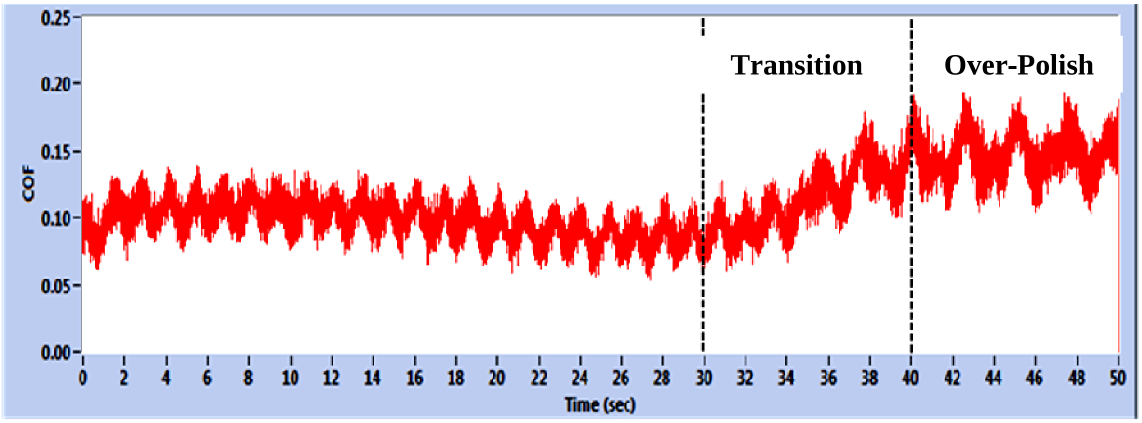
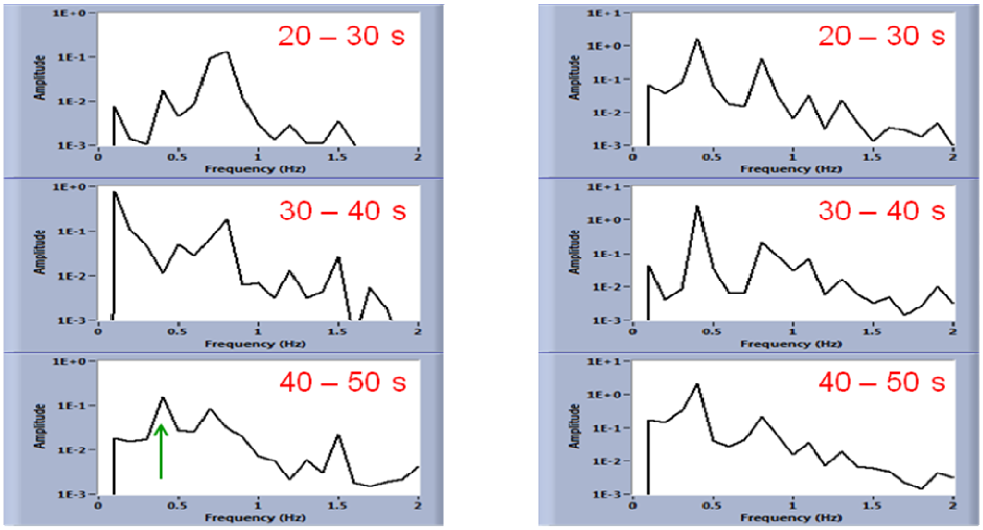


**Figure 2: Coefficient of friction as a function of polish time during Ta/TaN clearing process**



(a) (b)

**Figure 3: (a) Shear force and (b) down force spectral analysis before, during and after the Ta/TaN clearing process**