

STUDY OF SLURRY SELECTIVITY AND END POINT DETECTIONS IN Cu- CMP PROCESS

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Abstract:

The chemical mechanical polishing (CMP) process end point detection is one of the key aspects of effective process characterization. Due to the inherently deficient knowledge of the exact working of CMP process, experimental methods have been widely used for CMP process characterization. The CMP bench top tribometer is used as metrology and characterization tool to optimize the Cu CMP process. Here three different candidate materials for Cu damascene process namely, Cu (metal), SiLK™ (dielectric) and Ta (barrier) are polished in three different slurries, where one is Cu selective, the other one is Ta selective and third one is non-selective. The high frequency acoustic emission (AE) signal and the dynamic coefficient of friction (COF) during the CMP process are monitored in situ. The change in the tribological properties of the candidate materials can be used for effective end point detection, while the difference in the material removal rate of the testing specimens in different slurries is used to estimate the slurry selectivity.

Introduction:

The process of chemical mechanical polishing (CMP), used to planarize different materials in integrated circuit (IC) fabrication, has undergone rapid development. CMP has now emerged as the most effective method of achieving global planarization in multilevel circuits with feature size less than 0.5-um [1]. CMP synergistically combines the tribological and chemical effects during wafer, pad and slurry interactions to yield excellent local and global planarization. [2] Advanced metallization schemes need to be implemented to obtain performance benefits of device scaling in the sub 0.5 um regime. Controlled chemical etching of Cu poses numerous problems; hence the damascene approach needs to be employed to pattern the wiring material Cu, barrier material Ta and interlayer dielectric (ILD) layers [3]. It is estimated that down the line 25 % of all process steps involved in the device fabrication would be CMP. Thus effective characterization and optimization of the CMP process is of paramount importance in the field of semiconductor fabrication. As the exact mechanism of the CMP process is yet to be well understood, experimental approaches are predominantly employed for process characterization. The challenge is exacerbated by the need to meet the stringent selectivity and associated erosion and dishing specifications that arise from the need to use a barrier layer like Ta or TaN. From a CMP point of view, the problems posted by the hardness and relative inertness of these diffusion barrier layers compared to Cu have so far proven to be insurmountable and a reliable and robust single step or even a two step CMP process remains elusive

An important aspect of effective CMP process characterization is the process end point detection. Over polishing is one of the most significant reasons for surface defects like dishing and erosion. Wafer to wafer non uniformity (WTWNU) is another undesirable effect of ineffective detection of CMP process endpoint. The most commonly used approach for effective endpoint detection is the measurement of the change in motor current from the polishing head or the rotating platen. [4] Other approaches like the optical method [5], infra red radiation [6], pad temperature measurement [7] etc. have also been employed to a reasonable degree of success. Several innovative modifications and improvements like laser beam detection, [8], light reflectance analysis [9], and gaseous reactant product detection [10] have been developed as a supplementary module to the actual CMP equipment. However, due to the repeatability and reliability issues, the field of CMP process end point detection is still wide open for comprehensive research. The difference in removal rate of one material as compared to another in particular slurry gives

the measure of the selectivity of that slurry for those two materials. Higher the slurry selectivity, the more effective is the end point detection for a particular CMP process step as there is a marked change in the tribological properties of the material being polished and the under layer.

In this research, the selectivity of the various polishing slurries is investigated and the change in the tribological properties of Cu, Ta and *low-k* dielectric materials in various slurry environments is used to detect the end point of a particular CMP process step. In situ monitoring of acoustic emission (AE) signal and coefficient of friction (COF) is done for CMP process characterization and end point detection.

Experimental:

The prototype testing of candidate material samples was performed on the CETR™ CMP tester [11, 12], which is a stand-alone bench-top CMP simulator with instrumented process control. It can accommodate actual polishing pad, slurry, conditioning disc and wafer (or their coupons) and perform a CMP process with a number of crucial real time monitored parameters. The salient and the relevant real time measurements provided by this CMP tester are a) force sensor which provides measurement of real friction coefficient by monitoring simultaneously and independently a horizontal friction force or torque and a vertical normal load (above the wafer and beneath the pad); b) high-frequency acoustic emission (AE) sensor provides very high sensitivity to tiny local asperities, debris, micro-cracks, etc. The frequency range allows the detection of much smaller material removal than that observed with commercial AE sensors and it allows monitoring CMP process within the same layer and from layer to layer. Owing to the sensitivity of the AE sensor to various noise and signal frequencies, it can be effectively used for the determine quality of the polishing as well as the delamination of the thin film if any, during polishing and to better detect the transition from one layer to another; c) high-frequency data-acquisition system d) multi-channel computerized motor-control and data-acquisition system that allows simultaneous control of several specimen's motions, including programming of very sophisticated test sequences, with real-time parallel acquisition of up to 8 test output parameters.

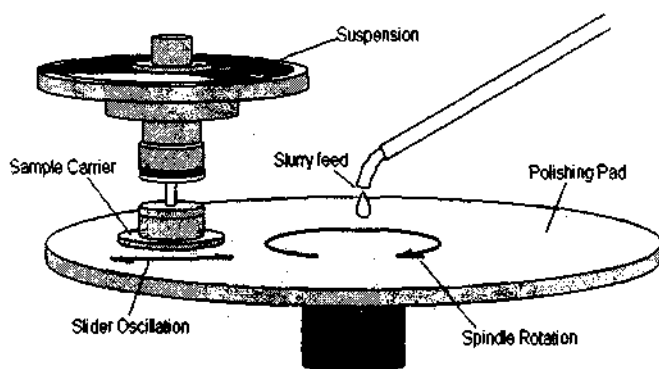


Fig. 1 Schematic diagram of the CMP polishing process on the CETR™ Bench Top CMP tester

The candidate materials were polished in the form of coupons of 1" X 1" dimension. Each type of samples was polished on a 6" polishing pad at two different values of down force, 2 and 4 PSI, and three different values of platen rotation for each value of down force, viz. 150, 200, 250 RPM. The experiments were performed on the following candidate materials:

1. Blanket Cu samples with SiO₂ used as dielectric
2. Blanket Ta samples with SiO₂ dielectric
3. Blanket low K dielectric sample (SiLK™)

The types of slurries used to polish the candidate materials were:

1. Cu selective particle less slurry (Slurry Cu)

2. Ta selective slurry with colloidal abrasives (Slurry Ta)
3. Non-selective slurry (Slurry Cu-Ta).

The sample was pressed down against the polishing pad. In the absence of the rotation of the sample, the polishing head oscillated over a distance of 5 mm at the speed of 1 mm/sec on the rotating pad. The polishing slurry was fed to the interface continuously, at the flow rate of 55 ml/min. Every set of test precluded with polishing of the particular candidate material for extended period of time for complete material removal. The polishing routine was split in to two stages, a) the sample coming down and pressing against polishing pad with no rotation of the pad, until the application of the required down force for 2 sec, b) polishing pad rotating at the predetermined fixed speed and time with the sample placed face down on the pad. On some occasions, as the samples were polished in very highly selective slurries, AE signal could not be measured during the course of polishing due to excessive vibration of the sample during the polishing routine. Also, in case of low-k dielectric polishing using highly Cu selective particle less slurry, the tests for at higher PSI could not be carried out due to unacceptable levels of sample vibration.

Results and Discussion:

The results of the planarization of all three different samples, in three different slurries at 2 and 4 PSI for 150, 200 and 250 RPM are given in Table 1, 2 and 3. It can be seen from Table 1, 2 and 3 that the values for COF for Cu in Slurry Cu are the highest followed by SiLK™ and Ta. This shows that slurry Cu is interacting more with Cu as compared to other materials. The values of COF recorded for Cu are the highest while those of Ta are the lowest among the three candidate materials, when they are polished in Slurry Cu-Ta. Also the values of COF for Cu and Ta are in close vicinity of each other when planarized at

Table 1. The experimental results of AE and COF for Cu samples in three different slurries, namely Slurry Cu, Slurry Ta and Slurry Cu-Ta. The AE and COF have been taken at two different intervals of polishing time.

Sample	PSI	RPM	Slurry selective to	Polishing Time (sec)	AE (0-20) sec	COF (0-20) sec	AE (20-40) sec	COF (20-40) sec
Cu	2	150	Cu	60	—	0.7973	—	0.7647
Cu	2	200	Cu	60	0.7854	0.8055	0.6714	0.787
Cu	2	250	Cu	60	0.9358	0.666	0.81559	0.6745
Cu	4	150	Cu	60	—	0.6681	—	0.7208
Cu	4	200	Cu	60	0.3259	0.6265	0.1661	0.6396
Cu	4	250	Cu	60	3.8017	0.4933	0.4933	0.487
Cu	2	150	Ta	60	0.4471	0.9463	---	0.8119
Cu	2	200	Ta	60	0.4067	0.85	0.2986	0.6711
Cu	2	250	Ta	60	0.9065	0.8164	0.7278	0.6779
Cu	4	150	Ta	60	0.4646	0.6413	0.5529	0.5765
Cu	4	200	Ta	60	2.7385	0.597	2.1665	0.5877
Cu	4	250	Ta	60	2.0385	0.5328	---	0.3792
Cu	2	150	Cu-Ta	60	0.991	1	1.9006	0.958
Cu	2	200	Cu-Ta	60	0.567	0.9382	0.4923	0.8369
Cu	2	250	Cu-Ta	60	0.4913	0.8557	0.4018	0.7127
Cu	2	150	Cu-Ta	60	1.6894	0.8736	0.6189	0.7548
Cu	2	200	Cu-Ta	60	0.8409	0.7701	0.4169	0.7179
Cu	2	250	Cu-Ta	60	1.2234	0.64	—	0.6251

Table 2. The experimental results of AE and COF for SiLK™ sample in three different slurries, namely Slurry Cu, Slurry Ta and Slurry Cu-Ta. The AE and COF have been taken at two different intervals of polishing time.

Sample	PSI	RPM	Slurry	Polishing Time (sec)	AE (0-20) sec	COF (0-20) sec	AE (20-40) sec	COF (20-40) sec
SiLK™	2	250	Cu	60	0.4139	0.6605	0.4268	0.4871
SiLK™	2	200	Cu	60	0.0883	0.3952	---	0.3759
SiLK™	2	150	Cu	60	0.0978	0.6249	0.1615	0.5774
SiLK™	4	250	Cu	60	0.9238	0.4951	---	0.4512
SiLK™	4	200	Cu	60	---	---	---	---
SiLK™	4	150	Cu	60	---	---	---	---
SiLS™	a	150	Ta	60	0.4665	0.654	0.4376	0.6494
SiLK™	2	200	Ta	60	0.288	0.5739	---	0.5626
SiLK™	2	250	Ta	60	0.1025	0.582	0.9355	0.5388
SiLR™	4	150	Ta	60	0.9355	0.4987	0.1016	0.4897
SiLK™	4	200	Ta	60	0.1478	0.4736	---	0.4617
SiLK™	4	250	Ta	60	0.3682	0.5006	---	0.5038
SiLK™	2	150	Cu-Ta	60	1.7638	0.9217	0.1379	0.8037
SiLK™	2	200	Cu-Ta	60	1.5398	0.8275	---	0.6919
SiLK™	2	250	Cu-Ta	60	---	0.7935	---	0.6751
SiLK™	4	150	Cu-Ta	60	---	1	---	0.97
SiLK™	4	200	Cu-Ta	60	---	0.8802	---	0.7863
SiLK™	4	250	Cu-Ta	60	---	0.5922	---	0.5602

Table 3. The experimental results of AE and COF for Ta sample in three different slurries, namely Slurry Cu, Slurry Ta and Slurry Cu-Ta. The AE and COF have been taken at two different intervals of polishing time

Sample	PSI	RPM	Slurry	Polishing Time (sec)	AE (0-20) sec	COF (0-20) sec	AE (20-40) sec	COF (20-40) sec
Ta	2	150	Cu	60	0.3854	0.4653	0.4206	0.3927
Ta	2	200	Cu	60	0.6608	0.4162	0.6947	0.3521
Ta	2	250	Cu	60	0.9096	0.3842	0.9446	0.3087
Ta	4	150	Cu	60	0.6232	0.3717	0.6206	0.3156
Ta	4	200	Cu	60	0.8312	0.3369	0.8326	0.2736
Ta	4	250	Cu	60	1.1604	0.3016	1.1949	0.2383
Ta	2	150	Ta	60	0.3899	0.7351	0.4069	0.686
Ta	2	200	Ta	60	0.4364	0.6935	0.3723	0.5542
Ta	2	250	Ta	60	0.3132	0.6371	0.2568	0.5382
Ta	4	150	Ta	60		0.6134	0.043	0.561
Ta	4	200	Ta	60	0.5612	0.6019	0.4226	0.471
Ta	4	250	Ta	60	0.9328	0.5494	0.6536	0.4459
Ta	2	150	Cu-Ta	60	0.4947	0.7856	0.4135	0.6527
Ta	2	200	Cu-Ta	60	0.2161	0.4683	0.1506	0.4183
Ta	2	250	Cu-Ta	60	0.5421	0.8688	0.2363	0.6652
Ta	4	150	Cu-Ta	60	0.2651	0.5675	0.1305	0.4659
Ta	4	200	Cu-Ta	60	0.538	0.5118	0.2446	0.4235
Ta	4	250	Cu-Ta	60	0.6139	0.6189	0.3557	0.4413

4 PSI. When the films were polished in Slurry Ta, similar trend is seen in the change of COF with Cu having the highest, SiLK™ having the intermediate and Ta having the lowest COF values.

It can be seen from Fig 2, that Slurry Ta selectively polishes Ta and negligible amount of material is removed from both Cu and low-k after an extended period of polishing. The Slurry Cu shows higher material removal rate for Cu while ultra low-k and Ta are polished to a very small extent. The Slurry Cu-Ta polishes both Cu and Ta to a similar extent. However, due the difference of thickness of Cu and Ta, the extent of polishing cannot be determined by visual inspection. The slurry also attacks SiLK™, which can be seen from the image of the polished coupon

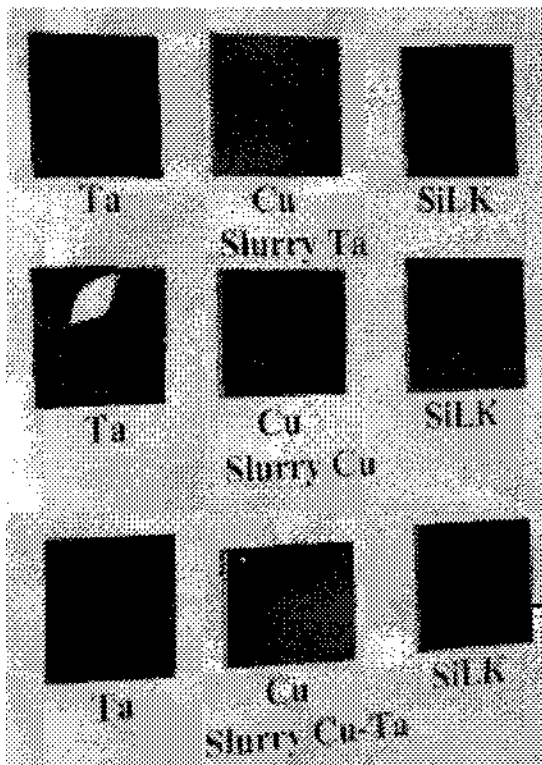
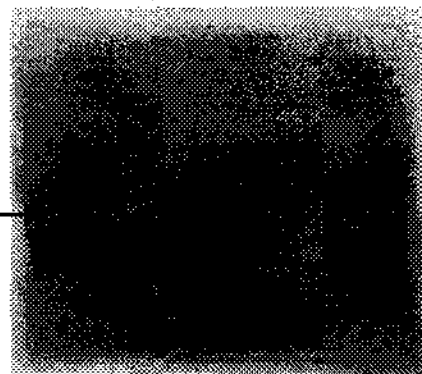


Fig. 2 Picture of the coupons of different samples after polished at different slurries. Enlarged SiLK coupon shows large material removal with Slurry Cu-Ta



In-situ monitoring of the Acoustic Emission signal is used to gauge the nature of the polishing. Every prototype material has a distinctive AE in a particular polishing environment. This is one the most efficient methods of detection of the end point of a particular CMP process. However, in this research, for the study of selectivity of the candidate slurry, the prototypes were polished in different highly selective slurries. Thus the level of vibration during the course of polishing made it very difficult to accurate gauge the change in the AE signals in the different slurries. Therefore, the entire selectivity analysis is based primarily on the variation of COF of the materials in different slurries. However, the data from Tables 1, 2 and 3 are plotted in form of graph from Fig. 3 to Fig 7. The values of AE signal increase with increase in RPM when the Cu, SiLK™ and Ta are polished in Slurry Cu (Fig. 3a) while the values of COF of Cu and Ta decrease with increase in RPM when polished in the same slurry. The distinct difference in the values of COF of interconnect wiring metal Cu and barrier metal Ta give a sound basis for effective end point detection of Cu polishing process in Slurry Cu (Fig. 3b, 5b). The values of AE signal increase with increase in RPM when Ta is polished in Slurry Cu-Ta and Slurry Ta (Fig.6a, 7a) at 4 PSI. From Fig.6b it can be seen that, the COF values of Cu and Ta in Slurry Cu-Ta are very much similar to each other. This could be attributed to the fact that the Slurry Cu-Ta can polish both Cu and Ta with similar removal rate.

It is prudent to mention that Slurry Cu-Ta polishes Cu, Ta and SiO₂ with similar ratio (1:1:1). This research will be continued with a machine having an upper rotational arrangement, where AE sensor will be in-built in the upper carriage. This will be simulation of the real CMP process and will allow to acquisition of AE signal even in an aggressive CMP environment.

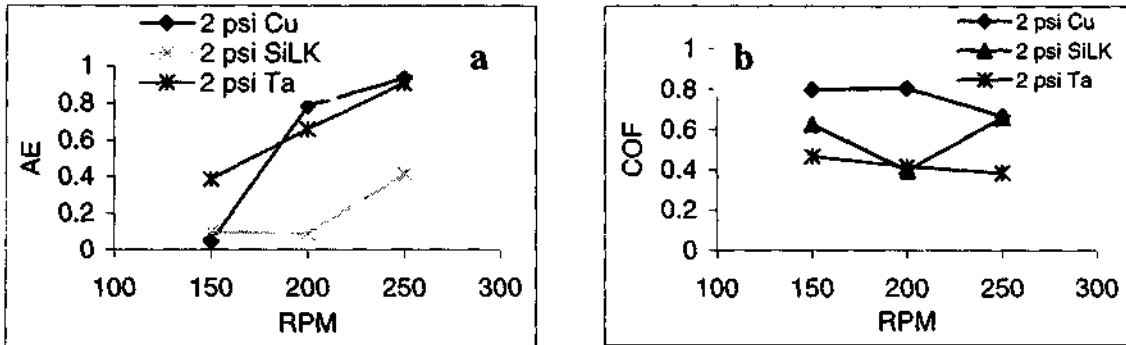


Fig. 3 (a) Variation of AE signal (0-20 sec) at 2 PSI and different RPM for Cu, SiLK™ and Ta samples in Slurry Cu and (b) variation of COF signal (0-20 sec) at different RPM in for Cu, SiLK™ and Ta samples in Slurry Cu

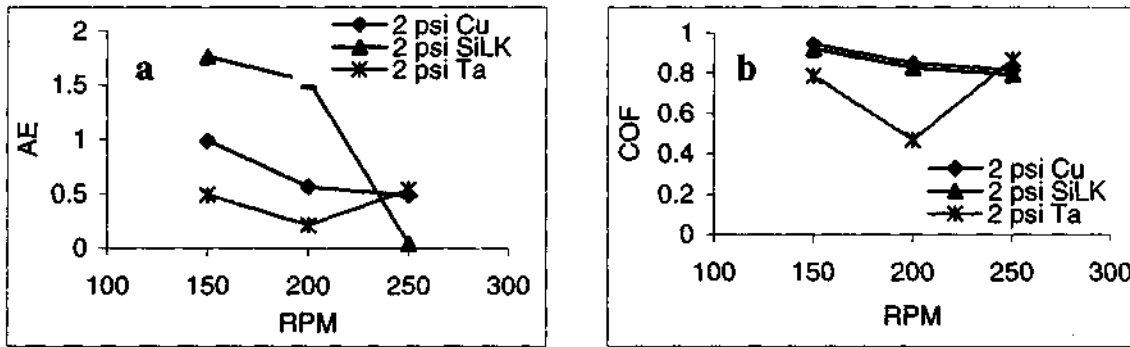


Fig. 4 (a) Variation of AE signal (0-20 sec) at 2 PSI and different RPM in for Cu, SiLK™ and Ta samples in Slurry Ta (b) Variation of COF (0-20 sec) at different RPM in for Cu, SiLK™ and Ta samples in Slurry Ta

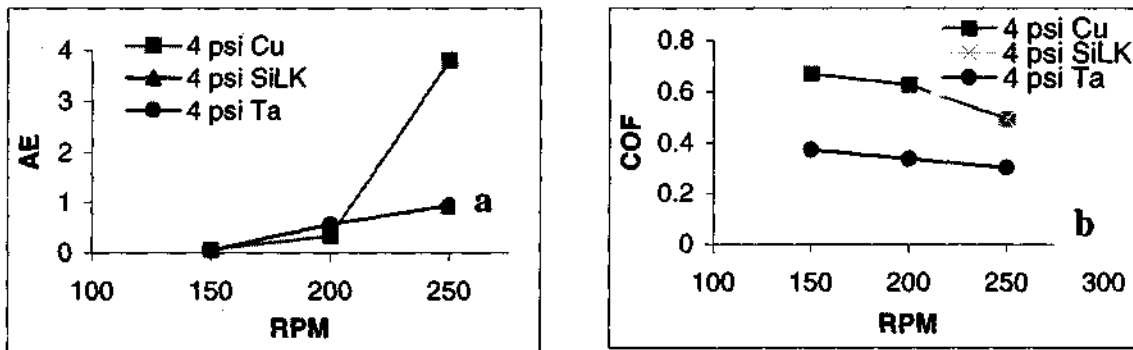


Fig. 5 (a) Variation of AE signal (0-20 sec) at 4 PSI and different RPM in for Cu, SiLK™ and Ta samples in Slurry Cu (b) Variation of COF (0-20 sec) signal at different RPM in for Cu, SiLK™ and Ta samples in Slurry Cu

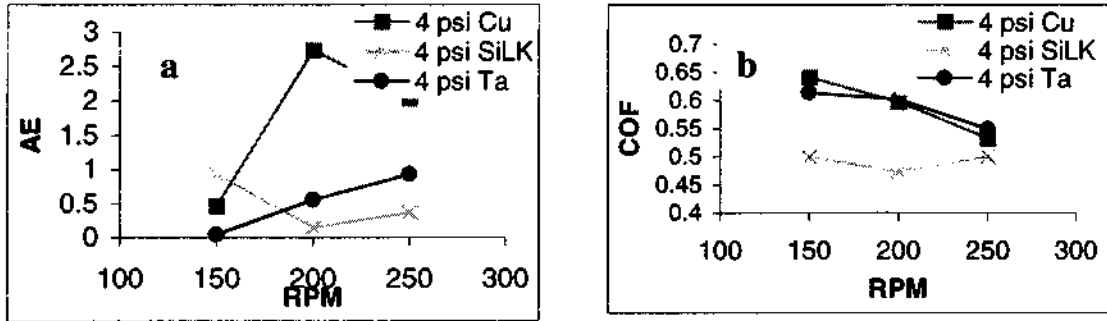


Fig. 6 (a) Variation of AE signal (0-20 sec) at 4 PSI and different RPM in for Cu, SiLK™ and Ta

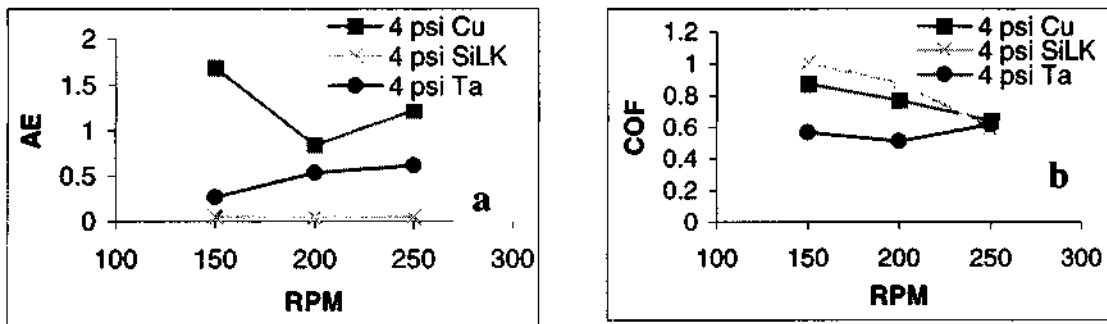


Fig. 7 (a) Variation of AE signal at 4 PSI and different RPM in for Cu, SiLK™ and Ta samples in slurry
 (b) Variation of COF at different RPM in for Cu, SiLK™ and Ta samples in slurry

Conclusions:

The following conclusions can be drawn after the evaluation of the results of the experiments performed:

1. The end point of Cu polishing process can be clearly determined by the change in coefficient of friction of Cu and Ta in Slurry Cu. The Cu shows a higher value of COF in the particle less Slurry Cu due to the enhanced interaction with it owing to its high Cu selectivity.
2. The values of COF of Cu in Slurry Ta are the highest while Ta shows the lowest values
3. At elevated PSI, the values of COF of Cu and Ta in Slurry Cu-Ta are similar. This may be due to the similar level of interaction of the slurry with both Cu and Ta. This shows the non-selectivity of the slurry. The values of COF for the ultra low k dielectric material are also in close vicinity of Cu and Ta hence showing that slurry is non selective to the ILD as well.
4. From the optical inspection of sample coupons after extended polishing, it can be conclusively established that, the Slurry Cu is highly selective to Cu while Slurry Ta is also highly selective to Ta. Both the slurries show negligible removal rate for ultra low-k ILD.
5. Prototype CMP machine can be used for characterization of CMP process

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