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Multi-Sensor Monitoring System in Chemical Mechanical Planarization (CMP) for Correlations with Process Issues

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Abstract
In this paper, three different sensors were used to measure multi-scale phenomena in chemical mechanical planarization. A piezoelectric force sensor, Hall effect sensor and acoustic emission sensor (AE) were installed in CMP equipment and the signals were measured simultaneously during the polishing process. The results showed that the sensors measuring frictional behaviour, such as the Hall effect sensor and force transducer, produced a clear end point signal in the case of the friction characteristics are distinguishable for each material. Also, if there is difference in hardness between materials, then a sharp end point signal is detected with the AE sensor even though the friction characteristic is similar between the two materials. Therefore, using multi-sensors having different bandwidths is complementary for not only process monitoring but also end point detection.

Keywords:
Monitoring, Sensor, CMP

1 INTRODUCTION

As the integration density of devices increases, more stringent planarization of semiconductor devices to satisfy the depth of focus (DoF) margin of the lithography process is needed [1]. Chemical mechanical planarization (CMP) enables local and global planarization over a wafer surface by the combined effects of chemical and mechanical interactions. Process monitoring is becoming an increasingly important in-situ methodology to control the process [2].

The main function of an in-situ measurement system is monitoring of process consistency and end point detection (EPD). The most important and widely used monitoring system is EPD where a process should be stopped based on a trigger signal to prevent over-polishing and excessive loss of materials. Among various EPD methods, the representative systems for EPD are optical [3, 4] and motor current method [5]. In the optical method, direct measurement of thin film thickness, scattering intensity and reflectance [2] of wafer surface are the most commonly used techniques and provide direct information of the wafer surface. The advantage of an optical system is that the signal is less affected by other CMP parameters since it focuses only on the change in surface condition of the wafer. By contrast, monitoring of the process itself, such as pad topography change, is relatively limited by its nature. Monitoring of motor current is the measurement of global frictional behavior resulting from mixed signals of the tribological condition, pattern evolution or material transition of wafer surface. This method is relatively less expensive to implement and can be used as a system to monitor process physics. However, because of its slow response [6], the ability to monitor process physics is restricted.

The other important function of an in-situ monitoring system is monitoring of process consistency. Process inconsistency in CMP is from several sources, such as variation of material property of the incoming pad, aging of slurry, pad profile change, slurry filter life, and so on. Such variations directly affect CMP performance leading to inconsistency of the planarization result, non-uniform removal, under-polishing of metal lines, erosion of dielectric material and scratch issues. Thus, an important function of an in-situ measurement system should be monitoring of process consistency.

In this paper, three different sensors were used to monitor the CMP process: i.) a Hall effect sensor to detect low frequency signal, ii.) a piezoelectric force transducer to detect middle range frequency signal, and iii.) an acoustic emission (AE) sensor, which has been widely used in industry [7, 8], to acquire a high frequency signal. The feasibility of these sensors as part of a multi-sensor monitoring system will be discussed.

2 SOURCE OF SIGNAL

In the CMP process, nano-sized particles abrade a wafer surface with the aid of atomic level chemical interaction by contacting with micrometer scale asperities of the pad which is pressed by a wafer scale down force. These interactions produce physical or chemical signals which can be measured by appropriate sensing technology. Also, depending on the types of slurry, wafer, pad or process conditions, the process produces different signals. Hence the process consistency can be monitored if the appropriate sensor system is chosen.

During polishing, a wafer slides against the pad surface under pressure in the presence of the slurry. The applied pressure on a wafer is supported by the balance between solid contact pressure of pad asperities and dynamic pressure of the slurry fluid, well described by the Stribeck curve [9]. The gap between a pad and a wafer increases with decrease in applied pressure or increase in relative velocity or viscosity of the slurry. This leads to the variation of friction force as determined by the real contact area and shear stress over the contact area.

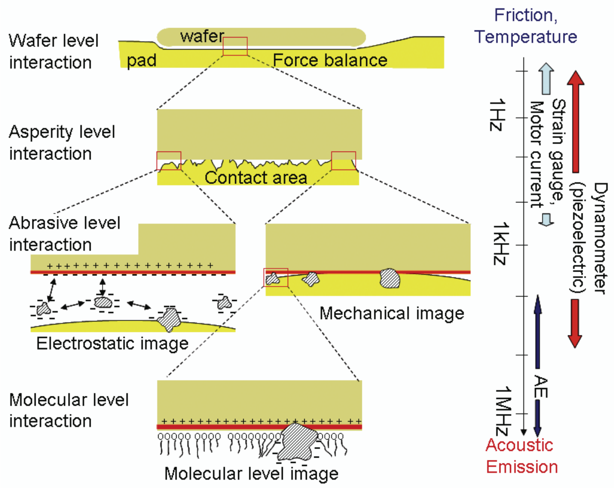


Figure 1: Source of signal depending on scale.

So, the friction force is measurement of wafer level interaction in which the complex interaction between micro to macro level phenomena is averaged. Therefore, global scale interaction could be monitored by measuring the low frequency friction signal.

As the scale becomes smaller and smaller, higher frequency signals are induced because the number of contacts by asperities or the number of abrasive particles is increasing, accordingly, as shown in Figure 1. Therefore, a sensor with higher bandwidth is preferable to study fundamental process physics generated from micro scale phenomena.

3 SENSOR IMPLEMENTATION

In this paper, three different sensor systems are implemented in the CMP equipment to detect multi-scale phenomena during the polishing process. As depicted in Figure 2, the piezoelectric force transducer is attached on the polishing head axis by a shunt method. Therefore, the friction force acting along the wafer surface is mechanically amplified by the lever mechanism. The second sensor is to detect motor current flow. Since the rotational inertia of the polishing platen is relatively large, it is difficult to measure sensitive changes in the friction signal. Therefore, the Hall effect sensor is installed in the head motor. The location of the Hall effect sensor is between the servo controller and servo motor to measure accurate current flow. Additionally, an AE sensor is directly attached to the backside of the wafer carrier.

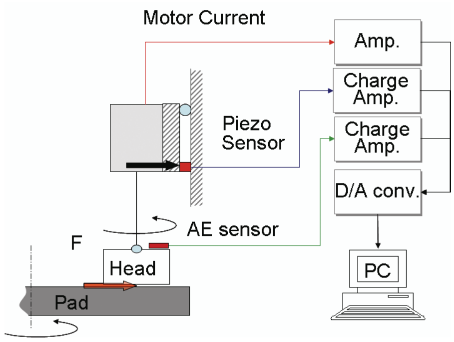
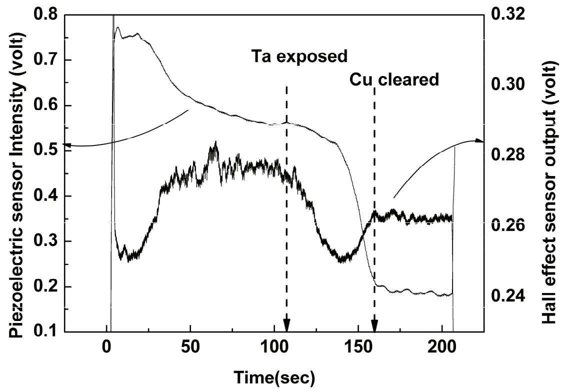


Figure 2: Schematic of monitoring system set-up

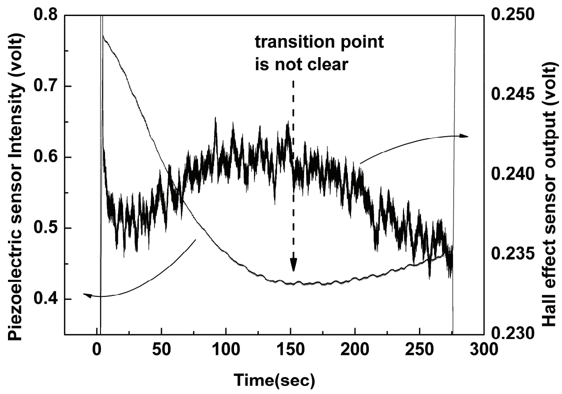
4 SIGNAL TRANSITION

A successful EPD system can be realized with the combination of a sensitive monitoring system and distinguishable process physics. The monitoring system should be sensitive enough to measure the variation during polishing and the signal coming out of the process should have enough discrimination of the physical or chemical conditions during the transition from one stage to another.

The signal transition is evaluated with a copper patterned wafer and STI (Shallow Trench Isolation) patterned wafer. Motor current and piezo sensor signals were measured simultaneously during the CMP process. During copper polishing, the patterned area is removed followed by bulk copper removal. Finally the tantalum layer is exposed at the end point of the process, as shown in Figure 3(a). The motor current signal and force transducer signal showed clear transitions at each stage. However, the signal from STI CMP showed very slow transition even after the Si_3N_4 layer was completely exposed (see Figure 3(b)). In this case, the time for EPD signal triggering is difficult to determine. Therefore, the process should be modified to create a clearer transition signal by using a different slurry or pad.



(a) Monitoring result of copper patterned wafer CMP



(b) Monitoring result of STI patterned wafer CMP

Figure 3: Comparison of signal between motor current and piezo sensor. (a)Cu patterned wafer 60rpm, 300g/cm^2, (b)STI patterned wafer 60rpm, 300g/cm^2

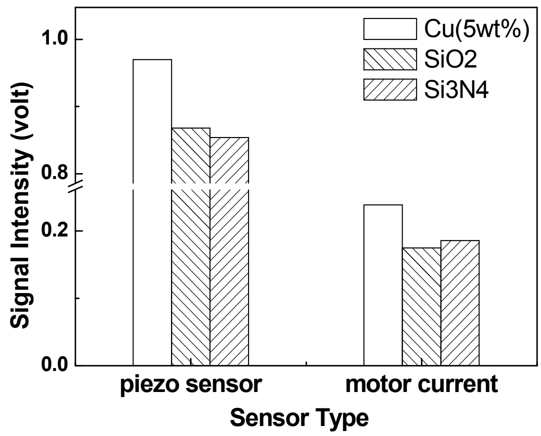


Figure 4: Comparison of friction intensity between different materials.

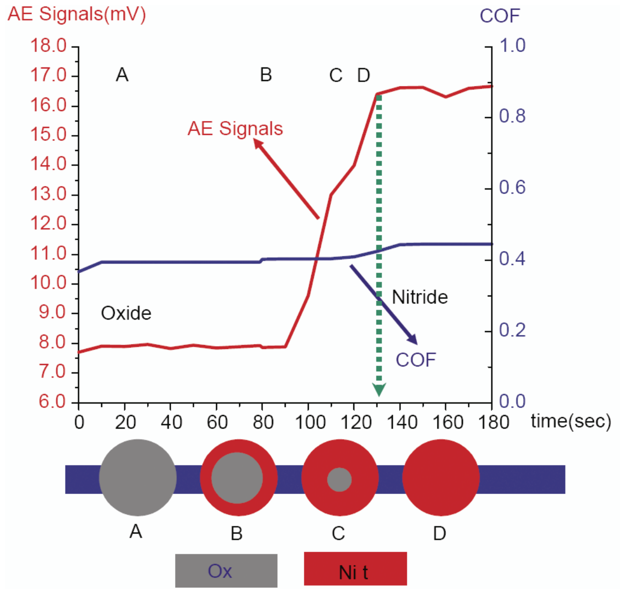


Figure 5: AE RMS and COF (Coefficient of friction) measurement result with STI test wafer.

The friction characteristics of each material are tested with 100mm copper, oxide and nitride wafers to find out the source of the measured difference between two processes. The results are shown in Figure 4. The fundamental source of signal is the same for both the motor current and piezo sensor, i.e. friction. As shown in the graph, the friction characteristic of Si_3N_4 and SiO_2 is very close whereas the difference of friction characteristic between Cu and SiO_2 or Cu and Si_3N_4 is clearly distinguishable. Therefore, the end point could be clearly detected in the case of transition from copper to oxide material. The detection of transition signal from oxide to nitride, however, could be more difficult compared with the previous case due to the similar friction characteristics of the two materials. Therefore, in this case, a monitoring system measuring averaged wafer level friction is not effective to determine the end point.

The AE signal was measured to detect a transition signal from oxide to nitride (the hardness of Si_3N_4 is almost three times that of SiO_2.) A sharp transition in AE RMS signal was observed during polishing of the STI test wafer when the oxide completely cleared (Figure 5). The transition is believed to be directly related to the variation in material properties of each of the films, with harder materials (such as nitride) demonstrating an increase in AE RMS signal during polishing due to the increase in energy required to initiate material removal [10]. Therefore, the EPD ability could be improved by using these two complementary techniques of force transducer and AE sensor. However, the installation of an AE sensor without disturbing the CMP tool is restricted due to the relatively big signal attenuation characteristic of AE across mechanical interfaces.

5 FFT ANALYSIS RESULTS

The force transducer attached on the polishing head assembly seems to act as an accelerometer due to the mass of head assembly. Figure 6 shows FFT peaks of different processes where different sets of pad, slurry and wafer were used. As shown in the graph, the FFT results have a rich and broad band of peaks but all of the individual processes have similar characteristic peaks around 80~100Hz and 140Hz. This implies that the detected peaks are not only the characteristic of the process itself but also the vibration characteristic of sensor/machine assembly.

Although the effective band width of the piezo sensor is up to 72kHz, the measurable range was found to be much lower since the sensor is assembled as part of the heavy polishing axis. Therefore, most of the polishing signal transmitted to the piezo sensor is low frequency range, which means low frequency friction is in the dominant composition of the measured signal.

Although the FFT peaks are induced by the head/sensor assembly, the signal originates not from motor rotation or reduction gear which have nothing to do with process physics, but from friction force which should be measured for further analysis.

At a fixed RPM, the FFT result of the motor current signal does not change even if the consumable condition is changed, as shown in Figure 7. However, the peak points shift with rotation speed of the carrier. The results suggest that the control current seems to have a characteristic frequency related to control of the rotation speed of the carrier at a constant value. This means that the analyzed FFT peaks relate to the control algorithm of the servo controller itself rather than process physics.

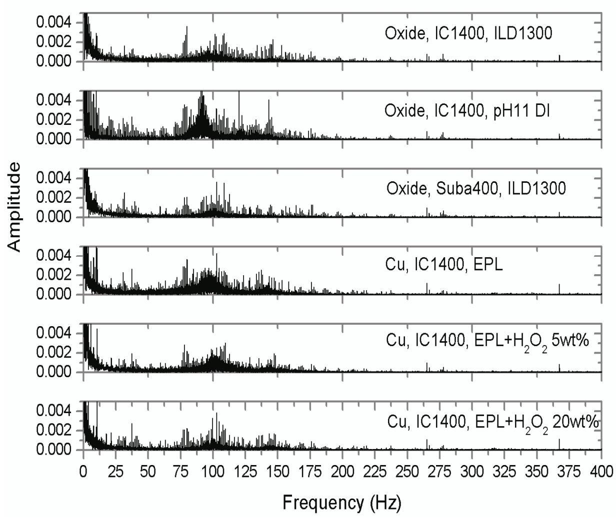


Figure 6: FFT results of different process measured by piezoelectric sensor.

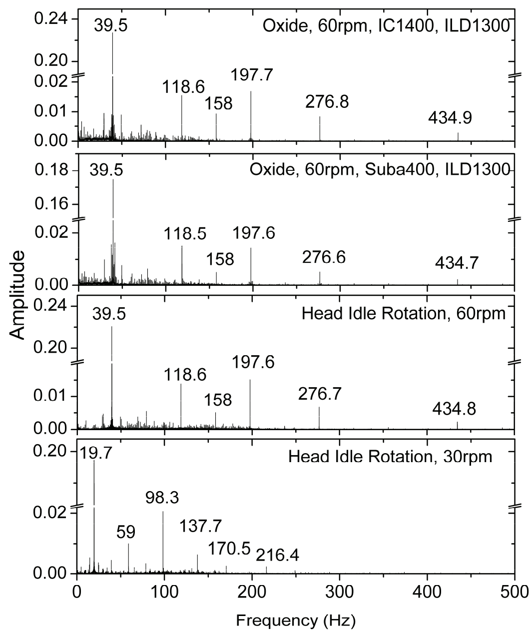


Figure 7: Representative FFT result of motor current signal. FFT of motor current signal of different process showed peak point at the same position and has the same relative height.

Based on the FFT result of copper CMP which has a strong peak around 90Hz in the piezo signal, the raw signal is band pass filtered between 80-100 Hz followed by 1s RMS. With this signal processing, a distinct signal transition is observed at 90sec and 140sec where the copper film is removed to partially expose the Ta layer (1). Also after the copper is completely removed (2), the EPD signal of the tantalum is observed (3) (see Figure 8). However, the RMS of the original motor current and piezo signal did not show a clear variation when the copper was completely removed. This suggests that apart from the change in the magnitude of friction force acting along the interface between pad and wafer, detection of change in vibration or stick-slip could be a precise source of the end point trigger signal. However, the vibration signal is barely measured by the motor current due to its slow response. Therefore, the piezo sensor has broader application to detect the process end point than the motor current method.

The source of vibration signal seems to originate from an unstable friction response at the interface due to nonuniform removal of thin film layer. Therefore, the signal is oscillating as the copper surface clears. A similar phenomenon is found in transition of oxide to silicon surface, as shown in Figure 9. In Figure 9, the band pass filtered piezo signal shows a distinct EPD peak compared

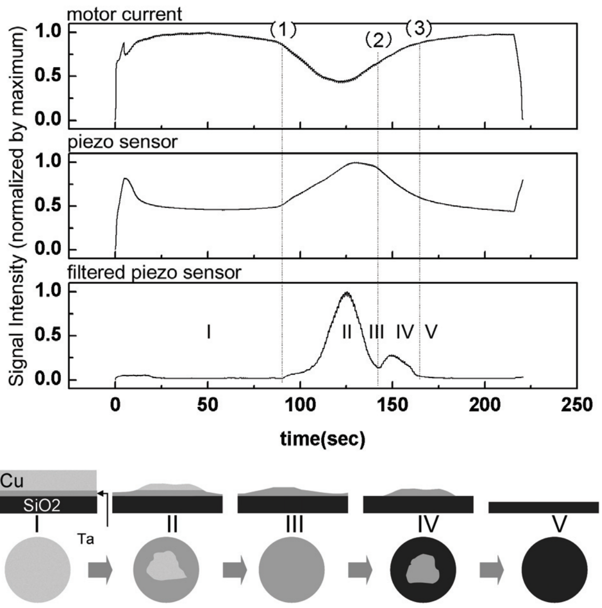


Figure 8: Comparison of measured signal; 1s rms of raw signal of motor current (upper), 1s rms of raw signal of piezo sensor (middle) and 1s rms of 80-100Hz band pass filtered piezo signal (lower). (1) Partially Ta exposed, (2) Cu cleared, (3)Ta cleared.

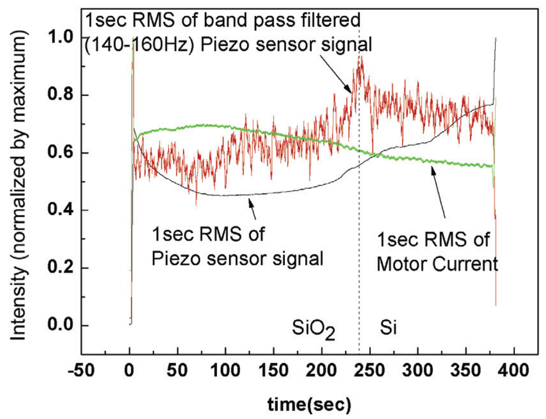


Figure 9: Material transition signal from SiO_2 to Si measured by piezo sensor.

with both the RMS filtered raw signals. The RMS filtered raw signal shows slow transition from oxide to silicon which makes it difficult to determine the end point of the process.

6 CONCLUSION

As the CMP process becomes more sophisticated, process monitoring is essential in order to have reliable process results. For this purpose, process monitoring systems should provide not only end point detection but also reliable process monitoring capability. Therefore, a sensor system should be able to detect variation in process physics from micro to macro scale phenomena for the purpose of process monitoring and to support research to understand the fundamental mechanism of CMP.

In this paper, multiple sensors were used to evaluate their characteristics and their ability for end point detection. The results showed that the band pass filtered signal from a force transducer and Hall sensor produced distinct end point trigger signals in cases of copper and oxide CMP. Also, if the friction characteristic of thin film materials is similar then the RMS filtered AE signal showed a much sharper transition signal than the force signal in case of oxide to nitride transition. Therefore, a complementary strategy of using sensors with different bandwidths could be a good solution for fundamental research and process monitoring in CMP.

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