Review of In Situ & In-line Detection for CMP Applications

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ABSTRACT

The reason for continued development of metrology techniques for chemical mechanical polishing (CMP) applications is clearly a cost of ownership (COO) issue. Test wafers can reduce throughput by 35% using off-line techniques and increase production costs considerably, yet the necessity to monitor machine performance to reduce potential yield loss is critical. Figure 1 shows the impact that the mean time to test (MTTT) has on the COO. The ideal situation is one whereby if a problem should occur during process, only one wafer at most is at risk. Techniques for end-point detection (EPD), including both in situ and in-line methods are being developed to improve the COO of CMP tools. In situ methods involve EPD while the wafer is being polished without requiring the CMP process to be modified. In-line methods involve measurements made after the wafer has been polished, but before it is removed from the CMP tool. Other advantages that can be gained from close monitoring of a CMP process are improved PM schedules based on improved statistical process control (SPC) data, hence leading to increased machine up-time. Improved process control means less deposited material is required and less polish time. All these factors lead to increased throughput and reduced COO.

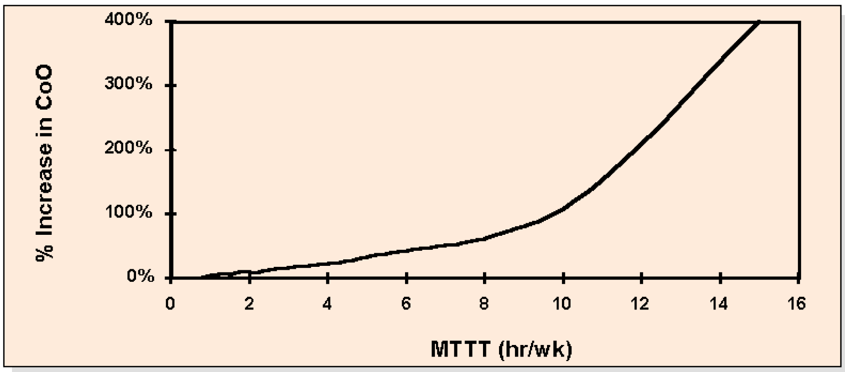


Figure 1. Plot of the percent increase in the COO as a function of MTTT for a standard tungsten CMP process.

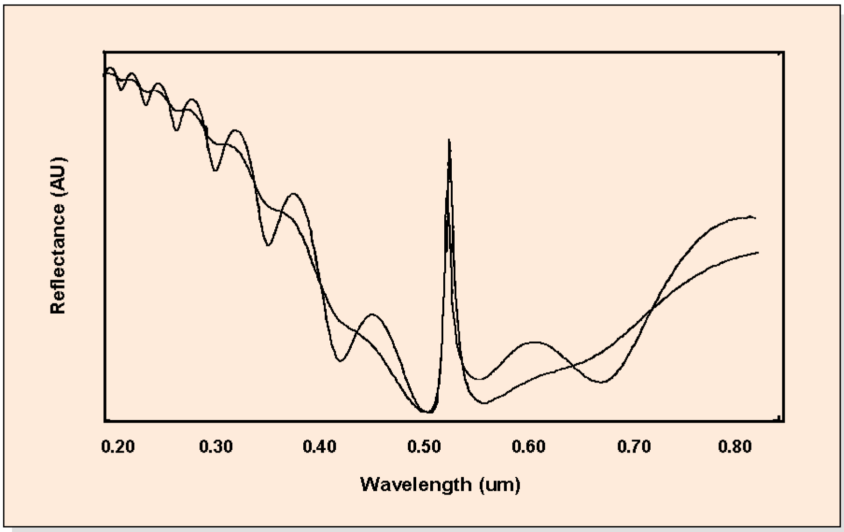
IN-LINE CMP METROLOGY

There are two major methodologies in use for in-line metrology: wet and dry. Wet measurements involve immersing the wafer in DI water immediately after polishing it and measuring the amount remaining at specified sites using pattern recognition software. Dry measurements are done in a similar manner, except that the wafers are measured after going through an integrated cleaner, and the measurements are done in air.

The advantages of making wet measurements are that the delay in obtaining measurements is minimized and that there are essentially no contamination issues. Since dry measurements are done following post-CMP cleaning, there is a delay of a couple of minutes between the time a wafer is polished and the time it is measured

The advantage of approaches using dry wafers is that the index of refraction difference between the top oxide layer and the air is much greater than that between water and the oxide, and consequently the signal to noise ratio is larger than is the case with wet measurements. If the thin films are deposited under tightly controlled conditions, there will be minimal variation. Unfortunately, it is common practice in semiconductor fabs not to control tightly the thickness, and the optical values of refractive

Figure 2. Plot of reflectance as a function of wavelength for a SiO_2 / TiN / Al film stack in both air and in water.



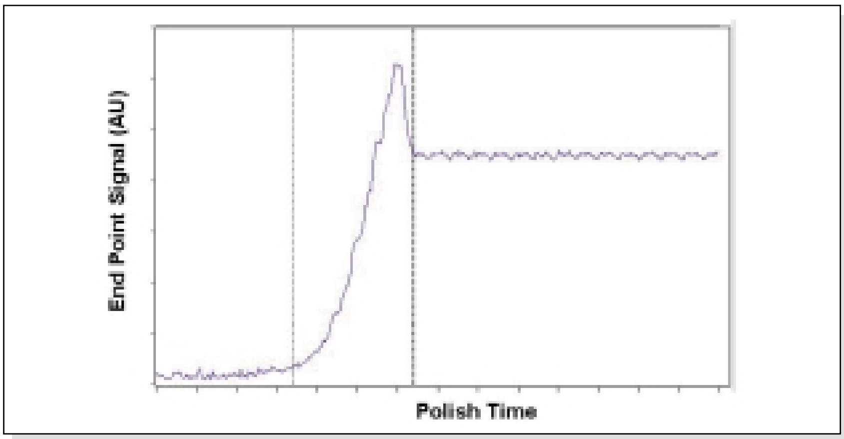


Figure 3. An example of endpoint detection using optical methods for tungsten CMP. The dotted lines indicate the separation between the tungsten and the barrier layer and between the barrier and the underlying oxide.

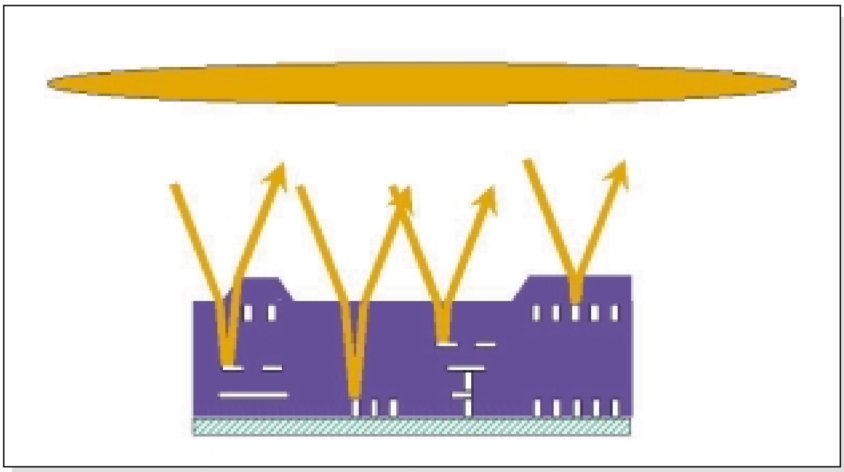
index n and the extinction coefficient k of the anti-reflective coating. Therefore, if an anti-reflection coating such as TiN is not tightly controlled then subsequent measurements of oxide layers on top of the TiN may be more difficult to measure when the wafer is wet. Figure 2 shows a plot of the spectral reflectance of a SiO_2 / TiN / Al film stack in air and in water. It is clear that the spectral signature in both cases lends itself to determining the oxide thickness, but that the amplitude of the oscillations is considerably less in the case of measurements made in water than those made in air. As for contamination, if properly designed, dry systems pose minimal risks. Also, they use no DI water, so there is additional ongoing cost.

The point is that both approaches can work. Nova manufactures a wet system, and IPEC Precision produces a dry wafer measurement system. Run-to-run control systems using integrated metrology are beginning to exploit the potential of in-line measurements. For proper control, both pre- and post-measurements must be made. With rising through-put requirements on CMP tools, the necessity of measuring wafers twice per wafer pass imposes stringent requirements on in-line metrology tools.

ENDPOINT AND IN SITU CMP METROLOGY

Numerous approaches have been proposed for use in CMP for in situ EPD. They include optical, electrical, and acoustic sensing. Given the benefits of EPD, it is no surprise that many of these methods have been awarded patents. Some of these methods, most notably current sensing, have been developed to become commercially viable products while others remain laboratory curiosities. In the following we will briefly review some of these approaches, and list the patents currently in existence. [1].

Figure 4. Schematic representation of reflection sources in optical measurements in multilevel optical endpoint. Scattering arises from diffraction at feature edges.



OPTICAL METHODS OF END-POINTING

The primary optical techniques in use are: Interferometry, reflectance, and spectral reflectivity, ellipsometry (including spectroscopic). Currently, by far the most common optically based off-line film thickness tools being used in fabs uses spectral reflectivity. Spectral reflectivity uses interferometry in which reflected light is measured over a broad spectrum of wavelengths, typically ranging from 400 nm to 800 nm.

In situ metrology for metal CMP can lead to endpoint signals such as the one shown in figure 3. This figure shows an endpoint signal for a tungsten CMP process in which the transition from bulk tungsten to the barrier layer and from the barrier layer to the underlying oxide layer is quite distinct.

For in situ metrology on patterned ILD wafers optical methods present additional challenges. If an optical signal contains diffracted light, then the spectral shape can be tremendously affected, and the subsequently reported thickness value can be completely erroneous. Figure 4 shows a schematic representation of some of the challenges associated with attempting to resolve top layer ILD film thickness information from in situ spectral reflectance measurements. A nominal 10 um spot is incident upon a variety of features. In the case where there are multiple layers and typical dimensions of the order of a micron (or less), there will be reflection from each layer as well scattering as from the edges. These difficulties are compounded by the fact that the optical probe is being used in an exceptionally challenging optical environment, viz. slurry. A pad moving at 50 cm/sec with respect to the wafer means that an optical sensor covers far more than the nominal 10 um spot size, thus collecting scattered light from a much larger surface area. An additional complication is that many post CMP optical measurements are made over anti-reflective layers such as TiN. Consequently, some measurements can be erroneous. These measurements can be further complicated by variations in the surface roughness of the underlying Al which change the reflected signal.

An example of the application of interferometry to CMP end pointing is described in patent # 5,081,796 assigned to Micron. [2] In this patent, a portion of the wafer overhangs the edge of the platen, and an unpatterned die is used for the measurements. A column of water acts as an optical waveguide to bring the laser beam to the surface. It also acts to keep slurry from depositing on the surface of the wafer, and to form a uniform reference beam for the interferometer. The laser must be pulsed synchronously with the rotation of the wafer (in the preferred embodiment) to avoid backscatter from the patterned portion of the wafer. Signal stability is not normally the greatest problem since the two reflecting surfaces (oxide surface and oxide-substrate) are intimately coupled. The Speedfam system monitors off the edge of the pad using a large beam area of the order of square millimeters, broad spectrum light source. [3].

An alternative EPD using interferometry for in-situ oxide measurements is being pursued by Luxtron. [4]

This approach involves inserting small interferometers into a CMP carrier. Infrared illumination penetrates the silicon substrate and reflects from the interfaces on the device side. In metal CMP the reflected signal remains constant until the metal clears at which point the reflectance changes. In oxide CMP, polishing changes the thickness of the topmost layer which changes the optical path. Consequently, the reflections mix and interference takes place. A plot of the intensity as a function of time is periodic. Knowing the index of refraction of the material being removed and the wavelength of the light, one can calculate the amount of material removed. This method has been demonstrated successfully on blanket films.

A variation on the Luxtron approach is to monitor the absorption of the material being polished. In a patent awarded to Toshiba, a method of monitoring the absorption peak of SiO$_2$ is described. [5] Infrared light (2.5 µm to 25 µm) passes through a wafer where it is detected by a photodetector. Since SiO$_2$ has an absorption peak between 9.0 and 9.4 µm, measuring the light in that range allows one to monitor the reduction in the SiO$_2$ thickness during CMP. Endpoint is indicated when the absorption signal reaches a predetermined level corresponding to a prescribed thickness. After detecting a specified reduction in thickness of one material, one can monitor another absorption peak. For example, one could monitor the change in thickness of Si$_3$N$_4$ by switching to the wavelength range 11.4 to 12.5 µm.

Another significant patent is U.S. patent #5,433,561, assigned to IBM. [6] In this patent an optical window, embedded in the rotating polish pad and platen as well as in the pad, enables in situ viewing of the surface being polished. Specular reflection from a test surface strikes a detector. In the patent description, the film being polished is metal, so the reflectivity is high, but the patent itself is not restricted to metals. As long as the thickness of the film is sufficiently great that essentially all of the incident light is reflected, the intensity signal remains constant. As the film thickness approaches zero during polishing, the intensity of the reflected signal changes markedly. To avoid leaving stringers, additional polish time is included. This patent is particularly significant because it covers just about any optical approach that depends on shining light through a hole in a pad on a rotating platen directly at the wafer while it is being polished. The ISRM of AMAT uses a transparent pad and a large area laser. [7] Luxtron also has announced a through the wafer IR technique.

Measuring multiple levels of metal with an optically large area spot (2 or 3 times metal pitch) creates a problem with respect to interpreting the reflected or transmitted signal. If the measurement is made from either the back or front of the wafer, as much as 90% of the wafer surface will have at least one step of metal coverage if not more. Since each metal layer will cover up to 50% of the wafer surface, after 3 or 4 layers very little of the surface is left without metal. The problem of measuring dry wafers with a large spot is indeed great, this is compounded significantly if the wafers are measured wet (see figure 2). In fact for very complex processes large area measurement techniques are going to be very difficult to implement, or not work at all. Patterned wafers will continue to therefore present a challenge for the foreseeable future.

An example of the diverse approaches of optical methods is the use of thermal imagery to monitor the surface temperature of a wafer. [8] In principal, knowing the surface temperature can provide information to refine the polishing process. With the removal of the topmost layer, i.e., metal, the surface temperature changes, and endpoint can be detected.

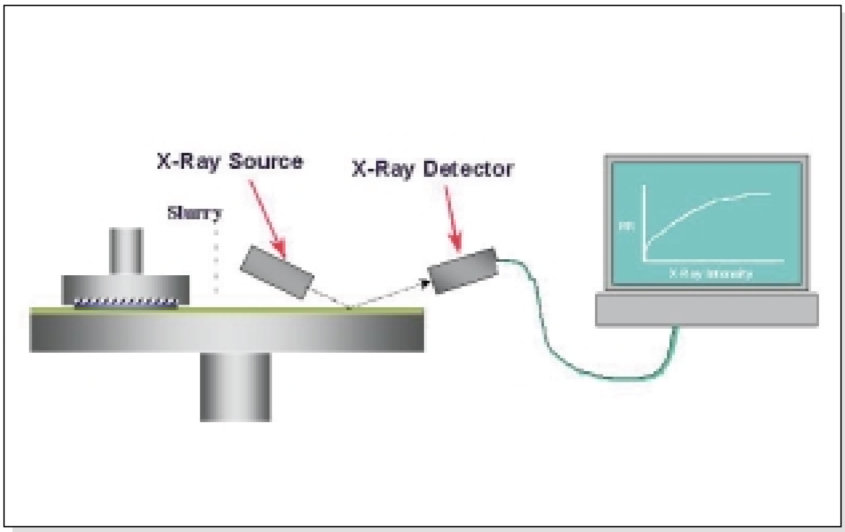


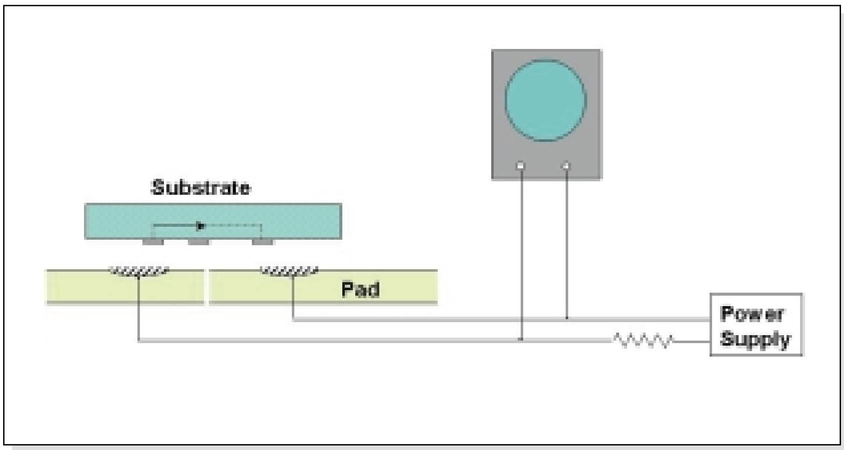
Figure 5. Endpoint detection using x-ray florescence (after U. S. Patent # 5,483,568).

A patent involving the analysis of a thermal image of the wafer in situ was awarded to Micron.[9] Though not strictly a measurement of friction, this method detects heat produced as either a by-product of friction or from a chemically exothermic reaction (e.g., from exothermic processes in Si polishing). In this method an IR camera slightly below or flush with the top of the polish pad senses the temperature at the surface of the wafer. As the friction changes in passing from one material to another, the temperature also changes so one can detect endpoint. Also, knowing the temperature distribution, one can, at least in principle, adjust the process parameters to improve the uniformity. A major challenge with this approach is in the implementation. Embedding an IR camera in a platen would certainly affect the process.

The primary challenge of this method is to obtain a suitable quality image in a production environment. The camera must either be extremely fast, or rotating synchronously with the carrier. In addition, the camera must image through the platen and the polishing pad. The platen could contain an embedded window, and a transparent polishing pad could be used, but obtaining an adequate level of detail remains a challenge. Complicating matters is the fact that if a thermally diffusive material lies between the camera and the object, then lateral diffusion of the thermal signal causes the signal to diminish.

A simpler approach to end point detection using thermal

Figure 6. Conductivity based EPD method (after U. S. Patent # 4,793,895).



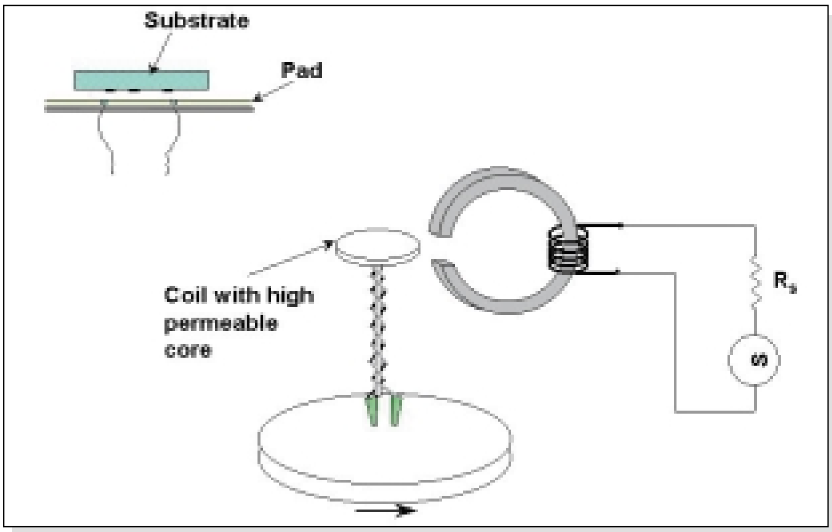
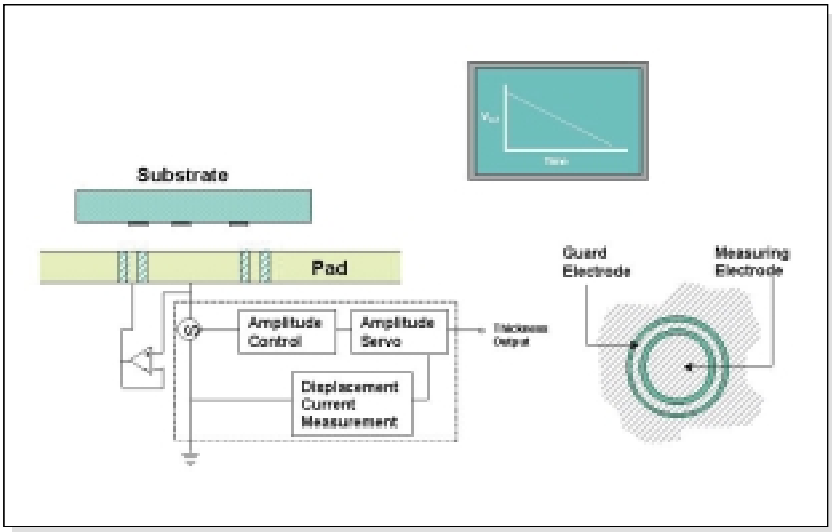


Figure 7. Endpoint detection based on impedance measurements on a modified tool. The rotating coil perturbs the flux field of the stationary coil which in turn induces a change in the output voltage. The amount of voltage change depends on the film a the wafer surface. (After U. S. Patents # 5,213,655 and # 5,242,524)

sensors is given in U. S. Patents # 5,643,050 and # 5,647,952, assigned to the Industrial Technology Research Institute. [10] In this method sensors are used to measure the temperature in discrete locations on the wafer. Heat is generated during CMP, and the rate of production depends on the materials being polished, the polish pads and consumables being used, and the pattern density on the wafer. Since the temperature is a measure of the heat being generated, the integral of the temperature is then proportional to the heat. The coefficients of proportionality are determined for the consumables and the specific pattern being used. Knowing these coefficients then allows one to determine the amount removed.

Most of the methods discussed so far involve monitoring a signal which contains a signature indicative of an appropriate stopping point. An alternative approach, as is the case with interferometric methods, is to monitor the removal rate. If this can be done with sufficient accuracy, then even variations in the removal rate within a wafer let alone within a lot can be accommodated. U. S. Patent # 5,483,568 purports such a method. [11] In this method an X-ray beam, as depicted in figure 5, is mounted on the CMP tool and the beam is directed at slurry downstream from the wafer. A detector monitors the induced fluorescence. Both the fluorescence and the removal rate depend on the density of the abrasives in the slurry, so at least in principle the removal rate can be monitored.

Figure 8. Endpoint detection based on capacitance measurements. The guard electrode enhances S/N ratio. (After U. S. Patent # 5,081,421)



ELECTRICAL METHODS OF END-POINTING

Numerous patents have been awarded for EPD based on electrical measurements of one sort or another. These methods fall into two general categories: those that sense friction in one way or another and those that do not. Typically, the electrically based methods which do not sense friction have not proven successful outside development laboratories. The primary reason for this lack of success is that these methods typically are intrusive: they require electrical connections to the wafer during CMP or modifications to the platen/carrier assembly which affect the basic performance of the tool. On the other hand, methods based on sensing friction have proven to be viable, and several commercial implementations are available. Perhaps the most significant reason for this success is that the measurements are passive; the basic operation of the tool remains unchanged.

Because of the viability of the friction sensing approaches, a few comments are in order. During CMP work is done to move the wafer along the pad. The work is against the force of friction between the pad and the wafer. Part of the result of this work is the removal of material. In metal CMP this sequence leads eventually to the exposure of the underlying ILD layer which has a considerably different coefficient of friction than the metal. Consequently, a method which senses a change in friction will give a clear transition as the underlying material is exposed. In contrast, planarization of the topography on an ILD layer does not involve a transition to an underlying layer with a different coefficient of friction. What does change is the roughness of the surface, but this change is much less than that of the metal to oxide transition. For both approaches, but especially for oxide CMP, pad conditioning plays a critical role.

CONDUCTIVITY AND IMPEDANCE EPD METHODS

One of the earliest CMP EPD patents awarded to IBM for a conductivity sensor for CMP. [12] This method is depicted in figure 6. For metal CMP, current is passed through the overburden of metal, and as long as metal is present a current will pass. As the metal clears, the conductivity decreases. The use of multiple electrodes reduces the risk of prematurely triggering endpoint due to a locally cleared portion of the wafer. For oxide CMP the reverse is true. As the underlying conductive network is exposed, current can pass and the change in conductivity can be detected. This method has not been used in recent years because of concerns about risk to devices when current is passed through unprotected devices. The reliability of the connections was also an issue, too.

Alternative approaches to detecting the presence of metal remaining on the surface of a wafer during CMP are cited in U. S. Patent # 5,213,655 and U. S. Patent # 5,213,655, both awarded to IBM. [13] In these patents endpoint is determined by monitoring the change in impedance that takes place during CMP. This method is a global

EPD system, and is suitable for metal CMP only. This method, depicted in figure 7, relies on electrical contact being made to the conductive surface being polished. These leads are connected to a coil which rotates with the platen. The coil passes through a second coil which is energized. Like the conductivity sensor, the need for connections to be made to the platen render this approach subject to reliability problems.

In U. S. Patent 5,081,421, issued in 1992 and assigned to AT&T Laboratories, Miller, et al. proposed a method and apparatus for monitoring dielectric thickness using measurements of capacitance. This method describes operation in the low frequency regime ($f << 1/\tau_D$ where $\tau_D = \kappa\rho/4\pi$ is the dielectric relaxation time, and κ is the dielectric constant and ρ is the resistivity). As shown in figure 8, it involves forming a constant current source and monitoring the associated voltage across the dielectric film. [14] The invention uses a carefully designed sensor built into the polishing platen to eliminate the shunting effect of the conductive slurry. Though adequate for geometries that are large by today's standards, the 3-5 Volts required are excessive for ULSI circuitry. In addition, the variation in consumables over time adds a significant degree of complexity.

In 1994, IBM was awarded a patent extending the method of Miller et al. to the high frequency regime. This method is based on electronic circuitry designed to produce an output that was inversely proportional to the dielectric layer thickness [15]. This method also claims to be able to monitor non-uniformity variations. Although this method enjoyed considerable success on blanket films, it proved unsuccessful on patterned films.

FRICTION SENSING

There have been several patents related to measuring friction, and in particular, changes in friction. These patents are important because endpoint methods based on these approaches have been successfully implemented for production use. In patents awarded to Micron in 1990 [16] (for the method) and in 1991 [17] (for the apparatus), endpoint detection based on monitoring changes in the motor current to infer the state of the friction between the wafer and the pad. This concept is based on the idea that the current changes as one polishes through one material with a given coefficient of friction into an underlying material with a different coefficient of friction changes.

Patent 5,308,438, assigned to IBM, pertains to monitoring the motor current of the platen to track the power required to rotate the platen.[18] When polishing relatively low friction surfaces such as metal, the friction is relatively low. Consequently the motor current is also relatively low. As thickness of the metal film goes to zero, the polishing pad begins to polish the oxide polish stop. At this time the motor current rises. By monitoring the motor current this point can be detected.

This concept is being used in the Luxtron Model 2X50 series and Model 9300 Endpoint Detection System as well as by the Brookside EPD system. Figure 9 shows the endpoint data from a Brookside EPD system. Changes in the endpoint signal trigger state changes, and the final endpoint trigger must be tailored to each process. Figure 10 shows the endpoint trace from a Luxtron system for a copper CMP process.

U. S. Patent 5,595,526, assigned to Intel, depicts CMP as the use of energy to remove surface topography. Thus, by integrating the amount of energy used during CMP, the process can be stopped when the appropriate amount of material has been removed The amount of energy required is determined empirically. The merit of this approach is that as the friction between the pad and the wafer changes due to pad degradation the amount of energy required to remove material does not change, but power at any time during the polish cycle (compared to similar times for wafers polished earlier) decreases. Thus, by fixing the total amount of energy (for a given layer), the total polish time is automatically extended. A similar approach, using an alternative configuration is described in a patent issued to Chartered Semiconductor.[19]

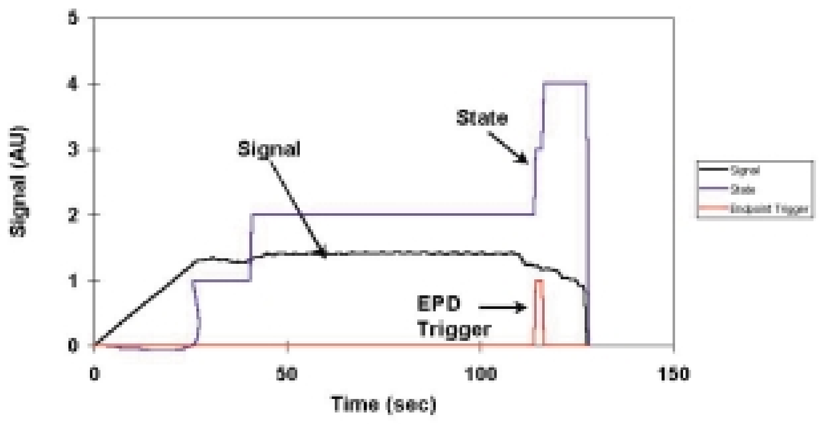
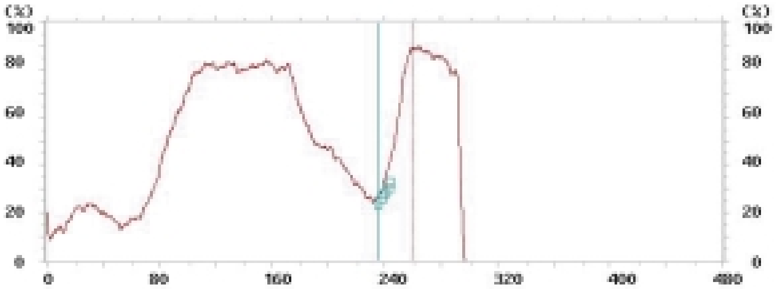


Figure 9. Tungsten endpoint signal from a Brookside EPD system. The state signal is determined by changes in the detected signal, and the endpoint relay is activated by the designated state transition.

ACOUSTIC METHODS

The underlying concept behind acoustic endpoint detection methods is that the grinding action that takes place during polishing generates an acoustic signal which, if demodulated properly can yield information about the polishing process. There are several patents that have been awarded that address aspects of acoustic end pointing. Patents awarded to Micron [20,21] describe various methods for detecting and analyzing acoustic

Figure 10. Copper endpoint signal from a Luxtron EPD system.



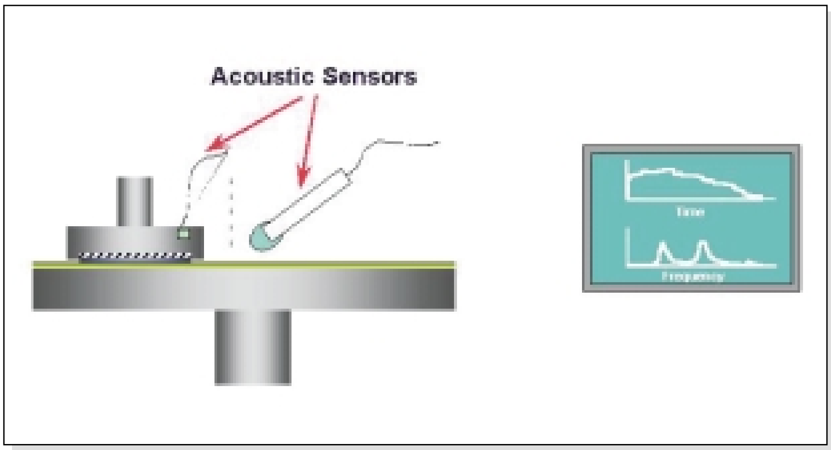


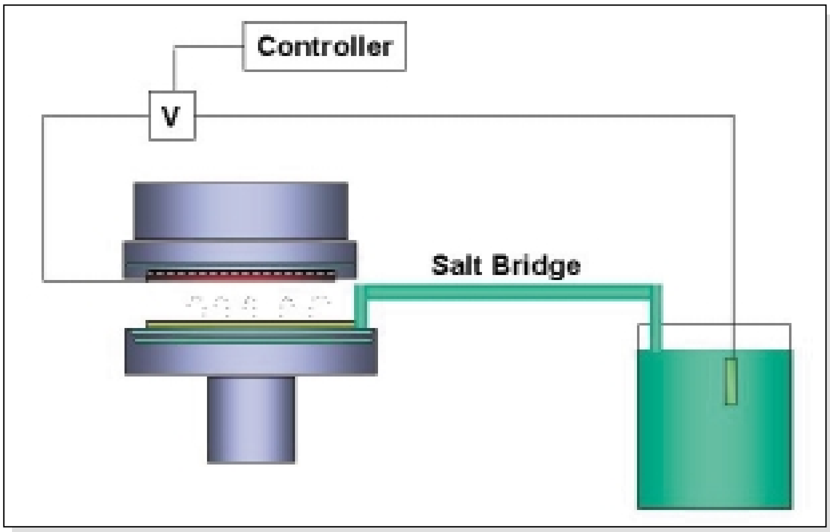
Figure 11. Global EPD using acoustic detection. Feature erosion causes an acoustic signature to change with time. (After U.S. Patents # 5,222,329, #5,240,552, # 5,399,234, Mar. 21, 1995, # 5,254,794, and European Patent Application EP 0 739 687 A2)

signals. These methods, shown schematically in figure 11, involve monitoring the change in amplitude and frequency of spectral peaks. These patents also describe the means of determining the change in thickness of the layer being polished by sensing the change in the amplitude and resonant frequency of the wafer. Additional methods such as integrating the acoustic energy, are described in the European Patent Application EP 0 739 687 A2.[22] When polishing dissimilar materials such as metal over oxide (and vice versa), exposure of the interface will change the acoustic signature in a measurable way. Other work by Salugsugan of AMD describes a low frequency analysis of the acoustic signature.[23]

A variation on these methods, suitable for metal CMP, is described in U. S. Patent 5,399,234. This Micron patent describes the analysis of the acoustic wave velocity. When there is a transition into another layer, the acoustic wave velocity changes and this change can be detected and used for EPD.

These methods, though simple in concept, face significant obstacles. Foremost among them is the large noise component of the acoustic signal generated by wafers undergoing CMP. The complexity of the signal processing is the most likely reason why these methods have not been commercialized to date. Furthermore, it is not clear that advanced signal processing methods will prove useful for a manufacturing environment.

Figure 12. Electrochemical endpoint detection method based on U. S. Patent # 5,637,185.



ELECTROCHEMICAL METHODS

We conclude this summary of proposed methods of detecting the endpoint of a CMP process with a brief discussion of a recently patented electrochemical method assigned to RPI.[24] This patent discloses a method for detecting endpoint in which the electrochemical potential of the system is monitored. As suggested in figure 12, the measurement consists of measuring the difference in potential between a measurement electrode and a reference electrode. The measurement electrode can be, for example, the surface being polished or a probe inserted in the slurry near the wafer being polished. The reference electrode can be a saturated calomel electrode or a standard hydrogen electrode, etc. Since the electrochemical potential depends upon the properties of the materials involved, transitions from bulk metal to barrier metal(s) and from barrier metal to underlying oxide can be detected.

ISSUES CONCERNING THE ABOVE TECHNIQUES

Optical in-situ methods have become very common and have some obvious advantages in that there is real time feedback on each wafer. However, optical techniques may have problems measuring oxide thicknesses over multiple layers of metal. As shown in figure 13, the pattern density affects both the removal rate and the amount remaining: the removal rates tend to converge while the remaining thicknesses diverge. The constant problem of measuring through air, glass and water to obtain a result presents a serious issue especially for those fabs involved in ASIC products where the process parameters may change with each type of device. For applications where it is possible to successfully monitor the process using this technique, it undoubtedly offers the most detailed process feedback.

Monitoring the motor current is a very popular technique where for many applications a very measurable end-point can be seen. Examples are shown in figs. 10 for the Luxtron EPD system and in figure 9 for the Brookside EPD system. However, there are still numerous issues not the least of which is reducing the signal to noise problem. Interpretation of the data during process is also not normally possible as the technique relies more on transition points.

Other techniques for in-situ measurement mentioned above are mostly in the development stage and only time will reveal whether any will be applied on a production level. The number of patents given to various EPD techniques is rapidly changing and expanding, and is expected to increase rapidly over the next few years.[1]

In-line wet and dry process techniques both offer advantages and disadvantages. The dry process techniques are not that much removed from the off-line methodologies and hence have both their advantages and disadvantages. However it is only with this technique that one can use measurement spot sizes of the order of microns. Hence it is unlikely that off-line techniques will ever be completely removed from the process flow. The drawback to this technique is the length of the feedback loop. This results in reduced throughput potentially larger losses. The wet process technique reduces the feedback loop substantially as well as potentially increasing wafer throughput. The problem with the wet process method is that it uses are large spot and has significant signal to noise problems. It should be mentioned that both techniques can be adapted to check for residual metal.

One of the greatest concerns with the closed loop feedback systems that are now being introduced has been implied but as yet not detailed. If a measurement system returns either a correct measurement or a null result, interpretation of the results is very clear. Where the problem occurs is in low signal to noise environments that may yield erroneous data. The most common form of error to date is that of order skipping. A significant problem especially when the film is measured through additional media such as water. Incorrect measurements can potentially lead to significant yield loss and a serious increase in COO. To date this particular aspect of metrology misinformation has not been effectively modeled and thus is often ignored when determining the COO of a system.

SUMMARY

In terms of key parameters that an in-situ or in-line detection system must meet, the following can be specified:

1) Ideally the methodology should be flexible and meet both mass production and ASIC type demands.
2) The methodology should in no way slow the tool performance i.e. reduce the wafers per hour.
3) The measurement technique should ideally yield less than 1 in 10,000 bad measurement points.
4) The cost of the metrology should not add substantially to the cost.

The incremental cost of a complete metrology package is approximately 10% to 15%. The COO calculations will play a major role in purchase decisions.

In this paper we have summarized many approaches that have been considered for integrated in situ and in line metrology for CMP. Some of these methods, such as motor current sensing for endpoint detection of metal layers, have proven to provide acceptable performance. Other methods have not been demonstrated to be production worthy. The contrast between these methods clearly demonstrates that an important characteristic of any in situ or in line CMP metrology system is that it be non-intrusive.

Current sensing as well optical monitoring techniques are now commonly found in many production pieces of equipment. These first generation metrology systems are now starting to be replaced with a second generation . Whether the new generation of end-point , in situ and in line systems will overcome the weaknesses of the first generation tools remains to be seen. The only certain factor is that the COO aspects will become even more critical in a very competitive market.

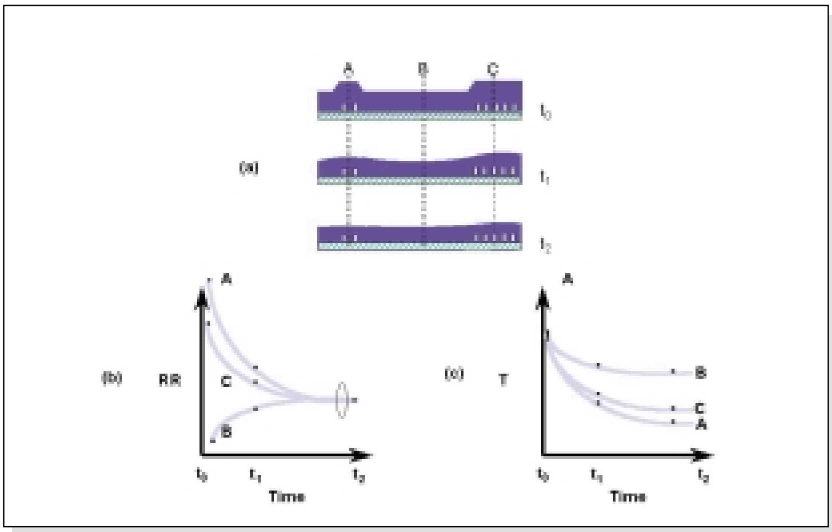


Figure 13. Effect of pattern density during CMP on the removal rate and remaining thickness. (a) shows representative pattern density variations. (b) shows the removal rate, RR, converge over the course of the polish cycle. (c) the remaining thicknesses, T, diverges during polish.

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