Tribology issues in CMP

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ABSTRACT

Chemical-mechanical planarization, or CMP, has become the process of choice for modern semiconductor devices. Though this complicated technology has been known for a quarter of century, its large-scale proliferation into the fabs has happened recently. Within the last five – seven years the industry of CMP polishers has grown from less than a quarter billion to over a billion dollars a year, with over four thousand polishers installed in the fabs. There are reputable predictions that in 2004 the polisher market will be more than twice of its size in 2001 – 2002, with over twelve thousand polishing heads (spindles) working in the fabs. Metrology is one of the key technologies for the control and optimization of CMP processes and materials. In this article, the in-situ monitoring of both the pad and wafer is discussed.

INTRODUCTION

The dramatic growth so far has been achieved by producing more and more polishers and consumables, with no much improvement in processes. Based upon earlier determined process windows, the industry has succeeded in the remarkable increase in number of wafers being planarized with currently acceptable yields. The further growth, however, and even the very existence of the CMP industry in the highly competitive environment where new technologies are developed all the time, will depend on the degree of progress it will achieve in terms of process accuracy, reproducibility, yield and cost. There is no surprise that a number of CMP related issued US patents increased from just a few hundred several years ago to about 1,500 in 2000 and almost 2,000 in 2001, with the flow of patent applications intensifying.

This technological progress shall be based on the theoretical fundamentals that CMP technology still lacks. There is neither common basic understanding of the mechanical and chemical processes involved nor a practical and theoretically sound computational model to be based on such understanding. Thus, to ensure its continuous growth and competitiveness, the CMP industry has no choice but to invest in research and optimization of CMP processes and consumables.

CMP TRIBOLOGY

Though quite young, CMP industry has not been developed from scratch, and has deep and established roots in such traditional surface treatments as mechanical polishing, grinding, lapping. These processes have been studied or many years, and a vast wealth of knowledge has been accumulated and shall be utilized.

Studies of mechanical and chemical-mechanical surface finishing treatments have been a part of the science of tribology. Tribology is a science of friction and wear, or material removal. Surfaces of both object being treated (for example, semiconductor wafer) and the finishing tool (for example, polishing pad), together with polishing slurry between them, constitute a rather classical tribological system. This is sometimes referred to as a three-body interface, because it includes two solids in relative motion and the slurry. Modern CMP machines may have an abrasive pad conditioner rubbing the pad either during wafer polishing or between the polishing cycles, which makes the four-body picture more complicated. Any tribological system is characterized with classical parameters of coefficient of friction between the surfaces and their wear rate. A part of the later parameter has been widely used in the CMP industry as the removal rate of wafer material; the parameters of friction and pad wear have not become common yet.

The friction coefficient is defined as a ratio of the tangential friction force, resisting relative motion of the surfaces, to the normal load pressing the surfaces together. In a case of high adhesion of wet smooth surfaces, the normal load shall be considered as a sum of the externally applied down-force and the internally developed adhesion (stiction) between surfaces. For simplification, the normal load is usually considered equal to the external down-force.

The total wear of the interface, typically measured in the direction perpendicular to the rubbing surfaces, consists of wafer and pad linear wear. The former one is the useful goal of the process, the later one is a negative accompanying effect. In the wafer-pad interface, there is negligible pad linear wear (though there may be large pad glazing and deterioration) and supposedly substantial wafer material removal (up to the target level of wafer layer thickness). In the conditioner-pad interface there is a significant pad linear wear with no conditioner wear (except for unavoidable dulling and deterioration of a conditioner surface, as well as seldom loss of its abrasive particles).

The science of tribology has developed a number of correct theoretical models for various materials and interfaces. Based on these models, the formulae for calculations of both friction and wear have been derived. Unfortunately, these equations cannot be used by process and equipment design engineers due to the unknown empirical coefficients. Indeed, friction and wear properties of a tribological interface depend on macro-, micro and nano-geometry of rubbing surfaces, speed and acceleration of relative

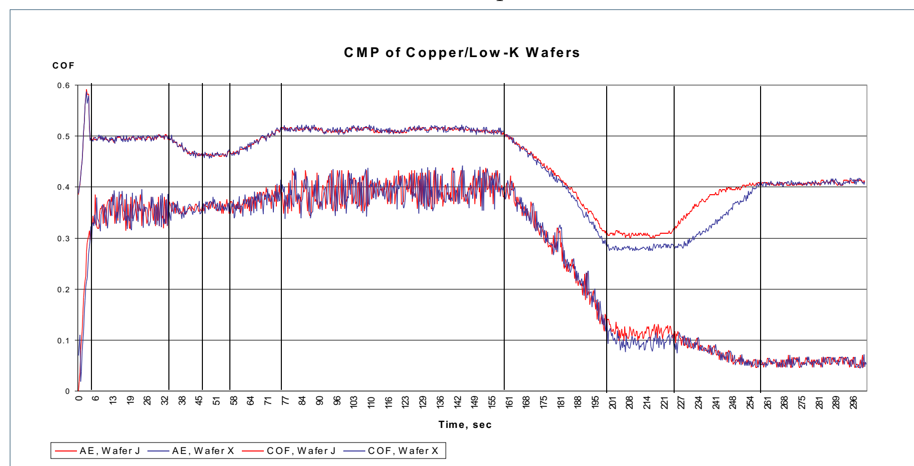

Figure 1. In-Situ CMP Monitoring On Copper/Low-K Wafers.

motion, stiffness and dampening characteristics of the mechanical system, physical and mechanical characteristics of ultra-thin surface layers, organic films spontaneously formed on the surfaces, lubricating films formed by the polishing slurry, temperature and humidity, etc. The related fields of physics, mechanics, chemistry and physical chemistry do not provide the exact knowledge of all these parameters. As a result, the only practical way of knowing the crucial tribological parameters of the CMP interface is their in-situ measurement during polishing.

CMP TRIBO-METROLOGY

Tribo-metrology is a science of precise, repeatable and reproducible measurements of friction and wear (material removal). To monitor friction, it is preferred to measure its coefficient instead of just measuring the force resisting the relative motion of rubbing surfaces. Indeed, there are cases when changes in down-force cause substantial changes in the friction force, while the coefficient of friction remains constant. Alternatively, sometime important changes in the coefficient of friction cannot be observed by monitoring the friction force due to periodic fluctuations of down-force.

To monitor wear, it is preferred to measure the linear geometrical wear of each of the rubbing surfaces. As wafer material removal is of the order of nanometers, its measurements are very complicated during polishing, and are often performed after polishing. The pad wear of interest is of the order of micrometers, its measurements are rather straightforward.

Another important parameter of friction and wear is the acoustic emission from the contact of rubbing surfaces. Its spectrum may have numerous frequencies, corresponding to such different processes as plastic and elastic deformations of sub-surface material layers, micro-scratching and micro-fatigue, micro-corrosion and other electrochemical reactions, delamination of material layers. At given speed, higher frequencies reflect the processes on smaller micro-areas that spread into smaller depths. Thus, the mega-Hertz acoustics is more informative of the specific micro-tribo-processes on tiny micro-contacts, in comparison with a kilo-Hertz range reflective of integral characteristics of the interface and deci-Hertz range reflective of integral characteristics of the entire mechanical system.

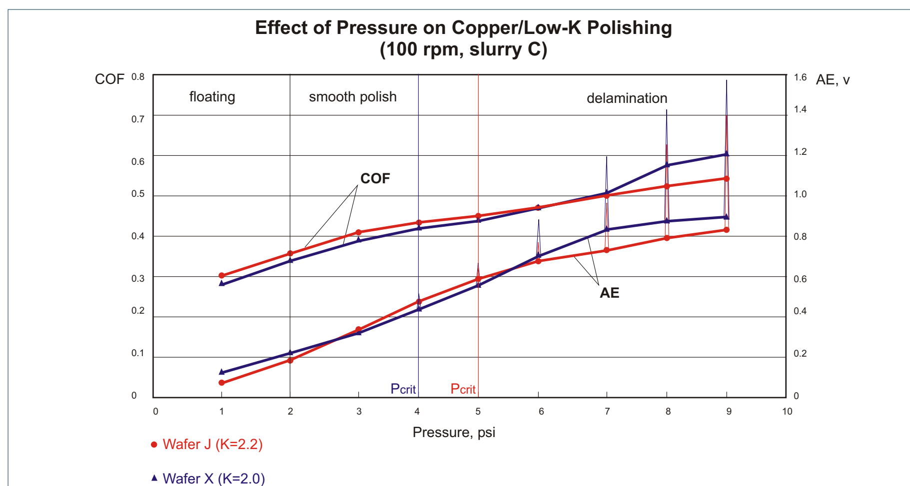

Figure 2. Effect Of Down-Pressure On Copper/Low-K Delamination.

Computerized real-time measurements and analysis of the coefficient of friction, contact high frequency acoustic emission and pad wear allow for the effective evaluation of dynamic characteristics of the polishing process, including rate and non-uniformity of material removal.

Indeed, it turns out that for the given combination of consumables and polishing conditions, the value of the coefficient of friction measured in the wafer-pad interface during polishing reflects the top layer on the wafer surface (Figure 1). This allows for realtime in-situ monitoring of the wafer surface without optical observation. Either in-situ or post-polish analysis of the friction coefficient data allows for calculations of the time to remove wafer layer and so rate of material removal (though these calculations can take place only after the layer is removed). Moreover, as the transition from an upper layer to a lower layer does not happen instantaneously and takes some time, this time is a direct characteristics of the non-uniformity of material removal: the longer is the time of transition, the higher is the polishing non-uniformity.

There are two other promising ways of measuring friction in CMP. The coefficient of friction measured in the conditioner-pad interface during conditioning allows for monitoring the conditioning process and state of the conditioner. The coefficient of friction measured in the probe-pad interface reflects the state of the pad surface as a result of pad conditioning and so allows for predictive monitoring of wafer polishing.

The parallel acoustic emission measurements compliment the friction coefficient ones (see Figure 1) in detecting the end point of polishing. For example, in some cases the difference in friction coefficients of the upper and lower wafer

Figure 3. CMP Bench-top Tester Mod. CP-2.

layers may be insignificant, but their acoustic response to CMP may be sufficient to detect the transition from one layer to the other. Also, in determination of the end point of planarization, the high frequency acoustics may sometimes be more informative than friction. Among the main benefits of the acoustic measurements in CMP are monitoring the intensity of polishing processes and detecting polishing regimes and conditions when wafer layers, for example low-K polymers, delaminate (Figure 2).

The cumulative pad wear measurements allow for accurate determination of the time for pad replacement. Also, the pad wear measurements help monitor the abrasiveness of the conditioning process and time for conditioner replacement or cleaning.

BENCH-TOP CMP MACHINE

Some of the first friction and wear measurements in CMP were done on the novel unique bench-top polisher shown in Figure 3. The CMP tester provides a fully controlled, instrumented CMP process on up to 4″ (for mod. CP-4) or 2″ (for mod. CP-2) wafers or wafer coupons and 8″ (for mod. CP-4) or 6″ (for CP-2) pad coupons. Wafer and pad

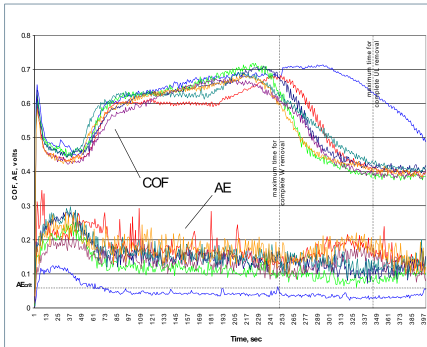

Figure 4. Quality Control Testing of Tungsten Slurry.

Coupon cutters are provided with the machine. The tester has precision translational (for wafer and conditioning disc) and rotational (active for pad and wafer, passive for conditioning disc) motions, with programmable speeds from 0.1 to 750 rpm. A down-force is applied via a closed-loop servomechanism and can be either kept constant or changing in the range from 1 mN to 1 kN. Static and dynamic friction force, torque and coefficient, contact high-frequency acoustic emission and pad wear depth can all be measured in-situ (real-time) at a total sampling rate of 20 kHz, displayed and recorded for further analysis. This polisher has been effectively utilized for both process development and functional testing of CMP materials: pads, slurries, conditioners, retaining rings. Among its advantages are low cost of both the instrument and the facilities required for it, small footprint, low cost of operation (due to the use of small coupons from wafers and pads and smaller amount of slurry). Most importantly, it allows for dramatic reduction in test time (minutes instead of hours, hours instead of days) and thus in time-to-market, as well as for an increase in wafer yield by pre-screening and eliminating non-optimal or defective consumables. An example of utilizing the CMP Tester for testing polishing slurries is illustrated in Figure 4 below. A semiconductor manufacturer has accumulated 7 batches of supposedly the same common slurry for tungsten polishing, but it had suspicions that 2 of them had deteriorated. Several expensive multi-wafer tests on production polishers have neither fully confirmed nor disproved the suspicions. For a quantitative fast and inexpensive estimate of their functional properties, the slurries were then tested on the CMP Tester, with continuous acquisition of the frictional and acoustic signals that allow for determination of three important functional parameters, namely: time of complete tungsten removal, time of complete under-layer removal, and intensity of polishing (characterized by the level of acoustic signal). It turned out that six of the tested slurry batches removed both the tungsten and under-layer before the maximum times allocated on it, while one batch (batch 1, blue lines) was unacceptable due to both longer time for material removal (the under-layer did not get fully removed during the test duration) and lower level of polishing intensity. The other batch under suspicion (batch 2, red lines), though exhibited slightly rougher acoustic profile and slightly different rate of tungsten removal, still fit the three criteria and so got accepted for production. A number of tests can be done on the CMP Tester with polishing pads. Deformation tests (with an upper indenter of either flat or spherical shape, moving up and down, no wafer, on the stationary pad) are used to evaluate elastic, plastic and creeping properties of either complete pads or their working (polyurethane) and supporting (foam) layers separately. Wear tests (with an upper conditioner either rotating or stationary, no wafer, on the rotating pad) are used to characterize pad wear resistance. Scratch tests (with a sharp upper indenter moving both vertically and horizontally on the stationary pad) are used to measure pad scratch resistance. Functional polishing tests (with either in-situ or ex-situ conditioning) allow for the quantitative estimate of pad functional properties, by determination of four important functional parameters, namely: time of wafer layer removal (characterizing the removal rate), transition time from one wafer layer to another (characterizing the polishing non-uniformity), acoustic level (intensity of polishing) and pad wear (durability). Plots on Figures 5 and 6 below show tungsten polishing results for two pads, pad 1 with more intensive polishing and faster tungsten removal (Figure 5) and less pad wear (Figure 6) versus pad 2 with slower tungsten removal (Figure 5) and higher pad wear (Figure 6).

PADPROBE

A simple and cost effective way of insitu monitoring the pad friction and wear parameters in the Fab is by utilizing a small novel PadProbe™, developed for CMP machines of all rotational, orbital and linear types. This completely non-invasive instrument can be easily installed anywhere on a production polisher within minutes, with neither design integration into the polisher nor any changes in already developed planarization processes. The only requirement is for the sensor to touch the pad. The PadProbe™ allows for either continuous or periodic insitu, in-process control of two crucial CMP parameters:

- Pad Life (dynamics of Pad Wear) and
- Pad Condition (dynamics and level of Pad Friction).

This reliable inexpensive probe is very effective in the Fab environment for the following:

- shows when to start and when to finish ex-situ pad conditioning,
- shows when either more or less conditioning is required,
- shows when pad is worn out and has to be replaced,
- helps improve wafer-to-wafer uniformity of polishing by maintaining the pad in the same optimal condition.

Examples of the typical experimental data correlating Pad Wear (shown as pad thickness change), Pad Condition, Wafer Removal Rate (RR), and within the wafer non-uniformity (WIWNU) are shown in Figure 7 for wafers polished with ex-situ pad conditioning. The experiment included polishing of four groups of wafers, each group consisting of three blanket PTEOS wafers, with pad pre-conditioning (T0 - T1), regular conditioning (T2 – T3 and T6 – T7), shortened conditioning (T4 – T5) between the groups and without conditioning within the groups. An initial portion of the graphs from the beginning T0 to moment T1 on the time scale corresponds to the preconditioning of a just-installed pad with a conditioner. During this procedure the Pad Thickness reduces, the Pad Condition increases and reaches its initial working level, designated as 100%, at the time T1', after which it practically does not change. The second portion of the graphs from T1 to T2, as well as the portions T3 to T4, T5 to T6, and T7 to T8 correspond to polishing procedures, not accompanied with in-situ conditioning. During these periods of time the pad surface gets clogged with particles and gradually loses its quality, but not its thickness. Therefore, the Pad Thickness stays substantially constant, while the Pad Condition gradually drops to the level close to 70% of the initial working level. The ex-situ conditioning procedures (periods T2 to T3,T4 to T5, and T6 to T7 on the time scale) restore the polishing properties of the pad, and

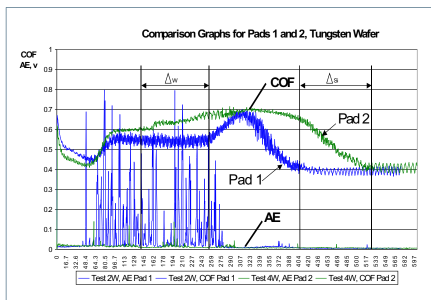

Figure 5. In-Situ Pad Friction and AE Measurements Allow to Evaluate Time of Tungsten Removal.

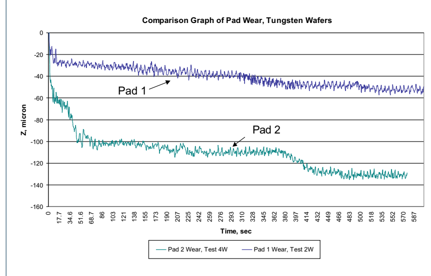

Figure 6. In-Situ Pad Wear Measurements.

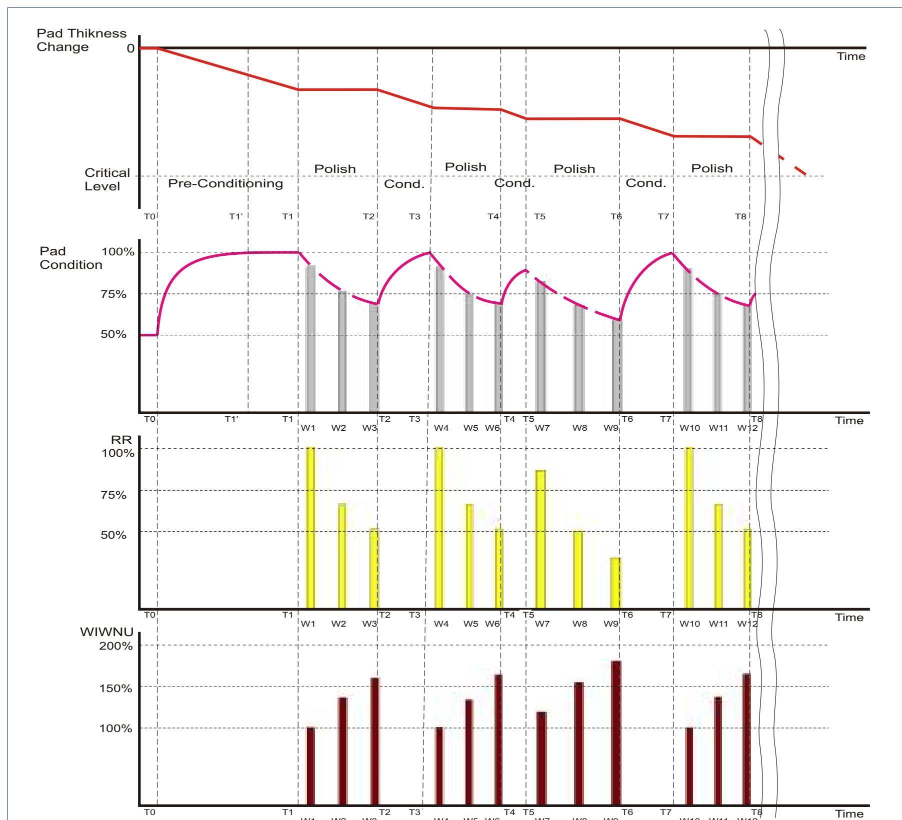

Figure 7. Correlation of PadProbe™ Output with CMP Parameters of RR and WIWNU.

corresponding areas on the graphs are similar to the one described above for the interval T0 to T1. Thus, Pad Thickness reduces (Pad Wear increases) during every conditioning procedure, while Pad Condition rises during conditioning and then falls during polishing.

When the polishing pad is worn out, its thickness reaches a certain level when the pad has to be replaced. This is defined as the critical wear level. The graphs also reflect how the wafer RR and WIWNU change in the course of the above described polishing and conditioning periods. The RR and WIWNU measurements were performed ex-situ and represented with bars. Pad surface conditions define the removal rate (for the given combination of materials and process parameters), with the latter increasing when pad is conditioned and decreasing when pad loses its quality during polishing. Pad surface conditions also define WIWNU, which substantially increases during polishing and drops after conditioning. During the experiment, after polishing the second group of wafers the pad was under-conditioned (period T4 to T5) and the Pad Condition didn't reach the level of 100%. As a result, both RR and WIWNU for the group 3 were worse than for other groups. Thus, there is a strong correlation between Pad Condition, RR, and WIWNU.

With time, Pad Condition level can gradually decrease, e.g., due to pad surface erosion, despite continuous conditioning. After Pad Condition reaches certain critical threshold, when conditioning cannot bring pad surface back to the state, which provides allowable RR and WIWNU, the pad has to be replaced. The data measured with the PadProbe™ has very good correlation with the removal rate and WIWNU, which are the most important characteristics of polishing.

CONCLUSIONS

Tribo-metrology is one of the key technologies for the control and optimization of CMP processes and materials.

The CMP bench-top tester is capable of fast, repeatable and accurate characterization of polishing pads, slurries, conditioners and other materials, as well as of cost-effective accelerated process development. The PadProbe™, which can be easily installed on any CMP machine, allows for substantial cost savings in the Fab due to less frequent pad replacements, dramatic reduction in the usage of test wafers, shortening pad conditioning cycles, and preventing making defective wafers during CMP.

ABOUT AUTHOR

Dr. Gitis obtained his Ph.D. in Tribology from the USSR Academy of Sciences (Moscow), 1983. He worked as a Scientist for the Tribology Center of the USSR Academy of Sciences (1979-83) and as a Senior Scientist for the Institute of Machine Tools and Robotics in Moscow (1983-88). After moving to California, he was an Advisory Engineer at IBM (1989-1992) and a Tribology Manager at Maxtor (1992-1993). He founded and has been President of Center for Tribology since 1994. He is Chairman of the STLE Technical Committee on Tribotesting, Vice-Chair of the ASTM G-2 Sub-Committee on Wear, Honorary Member of the Japanese Society of Tribologists, Guest-Professor of JiLin University (China). He authored 3 books, over 70 technical papers, over 30 patents.

ENQUIRIES

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