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A PLASMA PROCESS MONITOR/CONTROL SYSTEM*

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ABSTRACT

Sandia National Laboratories has developed a system to monitor plasma processes for control of industrial applications. The system is designed to act as a fully automated, stand-alone process monitor during printed wiring board and semiconductor production runs. The monitor routinely performs data collection, analysis, process identification, and error detection/correction without the need for human intervention. The monitor can also be used in research mode to allow process engineers to gather additional information about plasma processes. The plasma monitor can perform real-time control of support systems known to influence plasma behavior. The monitor can also signal personnel to modify plasma parameters when the system is operating outside of desired specifications and requires human assistance. A notification protocol can be selected for conditions detected in the plasma process.

The Plasma Process Monitor/Control System consists of a computer running software developed by Sandia National Laboratories, a commercially available spectrophotometer equipped with a charge-coupled device camera, an input/output device, and a fiber optic cable. The instrument monitors the plasma recipes and steps needed to complete all phases of production. During normal operation, the tool notes process steps as they occur, stores a representative set of spectral details for future analysis, and keeps an accurate product count. If the plasma experiences an abnormality, the tool notes the abnormality, signals appropriate personnel, and/or attempts to correct the abnormality *in situ*. The tool is designed to be a versatile, multipurpose piece of equipment allowing automated process verification and error detection/correction as well as a research tool.

We have used the monitor for gauging the "state-of-health" of plasma processes. System 1 has been at Texas Instruments in Austin, TX since February, 1996 monitoring the health of printed wiring board plasma desmear and etch-back. System 2 has been at Advanced Micro Devices in Austin, TX since July, 1996 monitoring integrated circuit multivariate oxide etch. These systems and possible benefits derived from *in situ* monitoring of plasma processes will be discussed.

INTRODUCTION

Plasma processing is an integral part of manufacturing not only for the printed wiring board (PWB) industry, but also for the semiconductor industry and others.^[1,2] Plasma treatment has been used throughout industry for many processes, including surface cleaning, roughening, activation, film deposition, and patterning. Historically, the plasma treatment portions of many production procedures have proven difficult to predict and control.^[21] Therefore, plasma processes are often under-utilized or only used in less critical applications. The nonuniformity of most plasma processes and sensitivity to environmental changes make it difficult to maintain process stability from day to day. Any manufacturer that relies on plasma as a process step, whether for cleaning, etching, surface enhancement, patterning, etc. is vulnerable to process nonuniformity. Plasma processes are susceptible to external factors such as environmental humidity and internal factors such as power, pressure, gas purity, mechanical failures, and electrical failure.

Plasma processes often fail to perform as expected. A small deviation in any internal factor can cause large shifts in plasma performance. Often the cause can be

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directly traced back to the source upon inspection of the system after failure. Depleted gas cylinder, wrong feed gas, power supply failure, and air leak are some typical failure modes in which plasma performance may be affected. These occurrences can be easily identified and corrected, but often a load of PWBs or semiconductors is lost before the failure is detected. Product rework or further processing of improperly plasma cleaned product is costly. Other failure modes are not as easily identifiable. At times, a plasma operation will fail for no discernible reason. These failures, although infrequent, are a costly source of lost product. Process stability is absolutely necessary for reproducible results.

Plasma cleaning, etching, and desmear processes are routinely used in the manufacture of PWBs and electronic components. Photoresist removal, plasma etch-back and plasma desmear of drilled thru-holes are representative production processes in a carefully monitored and controlled production environment. Customers, such as the Defense Department, sometimes require very secure electrical connections to internal copper layers. In those applications, the military specification is a minimum polymer etch-back of 0.02 mils, and anything less is not acceptable. However, too much polymer removal can result in serious plating problems such as plating voids, solution entrapment, and exposed fibers.

Commercial customers also require reliable internal connections. Although not as tightly controlled as components for military applications, commercial customers generally prefer etch-back of polymer to depths of 0.01 mils to guarantee complete desmear of all of the exposed internal copper features. A consistent plasma process is essential in obtaining good electrical connections. For this reason, careful attention to detail must be maintained throughout the production process of plasma cleaning.

To date, plasma process control has occurred using production controls (i.e. PWB handling before and during plasma treatment, precise plasma chemistries and process parameters). A failure in the plasma desmear or plasma etch-back step of production is costly and time consuming. To diagnose the nature of the plasma failure, repair the reactor, and recycle the PWBs requires costly personnel hours and results in reduced yield. Often the plasma failure results in defective boards that cannot be recycled and must be replaced. Replacing product due to plasma failure is extremely costly. Nonuniform plasma field and process variation with each cycle require some method by which to test the integrity of the components treated. Most plasma users in industry rely on one of two common test methods. Many users incorporate both techniques into their quality control procedure.

One test method measures the material removed from one or more weight loss coupons placed in the plasma chamber during the cycle. The coupons are placed in the areas in which average plasma performance is expected (i.e. strategic placement throughout the plasma chamber is required). The success or failure of the run is based upon whether the amount of material removed falls within

some range of acceptable values (based on data from past plasma performance). The difficulty with this method is that if post-process microsectioning of the coupons reveal some abnormality, often the run and all components within the run must either be scrapped or undergo more rigorous testing before being accepted or failed. Further testing is costly and time consuming. If the parts are rejected, either based on the weight loss value or on the results of the postmortem inspection, enormous cost can be incurred and a delay in production is likely.

Another disadvantage is the lack of reliable data from the weight loss coupons. Plasma fields are extremely sensitive to small variations from cycle to cycle. Chamber cleanliness, chamber temperature, sample number, sample placement, and relative humidity are only a few factors that affect process performance. Predicting the areas in which to sample plasma performance via weight loss coupons may be difficult if not impossible. By misplacing coupons, data may indicate a failure when none has occurred. Data may also indicate that the cycle performance falls within guidelines when, in fact, the parts are substandard.

Another test method is destructive testing of a fraction of parts from each production run. With this method, a fraction of parts from each lot is removed, sectioned, and optically examined for plasma performance. Many of the problems experienced with the weight-loss coupon test method are similar to the problems encountered with the destructive testing method. A batch is accepted or rejected based on post-plasma results; again, this is costly and time consuming. Poor selection of test parts can yield false positive or negative results leading to scrapping of acceptable parts or acceptance of substandard products. Since some portion of the parts are sacrificed for testing, the overall price per part is increased to cover the expenses of a reduced yield.

Both of the techniques discussed above evaluate plasma performance after the fact, when any damage to product has already occurred. Neither of these techniques is very reliable, often yielding false information. An *in situ* test that could diagnose plasma problems, correct the malfunction, or abort the process until the problem has been fixed could reduce the time and expense of failed plasma etch or desmear. A real-time technique to monitor plasma progress *in situ* could indicate process failure as it occurs, before damage to the parts has occurred. This would allow for correction of the problem, salvage of the parts, and less down time. By monitoring the plasma health and progress, decisions can be made regarding plasma gas mixtures, pressures, powers, etc. that allow for a more uniform system without the need for post-plasma examination. Process anomalies should be detected and corrected before the parts being treated are damaged by inadequate or overly aggressive plasma treatment. Real time monitoring would allow for near-instantaneous corrections. A system that could monitor several areas of the plasma for performance mapping would also be a useful tool for plasma users.

In the semiconductor industry, a "stop-etch" condition in plasma etch tools prevents the complete etch of contacts and vias in microelectronic devices, resulting in decreased yield and product throughput. One of the goals of this study is to demonstrate that *in situ* real-time monitoring can be used to predict when stop-etch will occur in a semiconductor manufacturing environment.

In this paper, optical emission spectroscopy for non-intrusive, *in situ* process monitoring will be explored along with applications of this technique for process control, failure analysis, endpoint determination, and stop-etch detection.

BACKGROUND/HISTORY

The lack of *in situ* sensors in plasma process equipment has been identified as a major hurdle facing the semiconductor industry.^[29] Numerous researchers are investigating sensor-based manufacturing and control of semiconductor tools.^[28] Many methods for plasma monitoring have been studied, including mass spectroscopy, emission spectroscopy, optical reflectometry, impedance monitoring, pressure monitoring, Langmuir probe monitoring, Fourier transform infrared (FTIR) spectroscopy, and laser induced fluorescence (LIF).^[19]

One method that has been heavily investigated is optical emission spectroscopy (OES). OES has been used for endpoint determination,^[2,5,11,19] chemical species identification,^[13,14,26,27] and general etching performance.^[6,25,34] Automated closed-loop feedback systems have also been developed using OES.^[3,8,9,14,23,24,32] Numerous analytical techniques have been applied to the analysis of OES data.^[1,4,7,10,12,15-17,20,30,31,33]

With commercial equipment (a monochromator or spectrometer), one can observe non-intrusively and identify the species present in a glow discharge. In a cleaning process, the spectral peaks of a contaminant can be isolated from the cleaning gasses. By identifying the peaks due to the contaminant, the process can be monitored for an endpoint. This is a relatively straightforward process. A reference set of spectra may be obtained by recording the emission of the cleaning gasses without any sample present and then compared to the emission observed when the contaminated samples are present. The differences observed are due to the presence of the contaminant in the plasma. When the plasma has consumed the contaminant, these differences no longer exist and an endpoint is determined. If the samples are themselves consumable, such as polymers, the reference spectra should be accumulated with clean samples present and then compared to the spectra of dirty samples. Another advantage to this process is the ability to accumulate spectra from known failure modes such as incorrect gas mixture, air leakage, etc., and then to store those spectra as a reference library. With a spectrophotometer linked to a computer; system monitoring, diagnostics, and automatic self-correction or shutdown could occur, allowing for a fully automated

system. OES has been used to monitor plasma cleaning processes for many years.

Optical monitoring of plasma etching and desmear is not as easily accomplished. In an etching or desmear process, plasma is used either to roughen the existing surface for enhanced adhesion or polish a surface to obtain a smooth finish. Since the material being removed is part of the sample and not a contaminant such as grease, oil, or photoresist, no easily identifiable endpoint can be obtained. Spectral peaks due to the material being removed will always be present as long as the samples are present. Process monitoring for system failures such as air leaks or wrong gas mixture can still be performed by accumulating spectra during a successful cycle and comparing it to spectra of subsequent cycles, but reliable endpoint determination has been thought extremely difficult, if not impossible.

To define an endpoint for a plasma etching or desmear operation using OES, some aspect of the plasma would have to change with time (more or less of the etchant gasses would be consumed or more or less of the etch product would be present). If these phenomena were occurring and detectable, a comparison to etch rate with plasma event could be made and some estimate of endpoint could be predicted. The difficulty with such an approach is that these time related events rarely occur and are not trivial to detect and identify. An endpoint indicator that would rely on such events would have to be uniquely derived for each desmear or plasma etch process. This is a time-intensive process but the potential advantage of greater process control and product reliability has justified the endeavor.

APPROACH

Sandia National Laboratories, in cooperation with the National Center for Manufacturing Sciences (NCMS), Texas Instruments, SEMATECH, and Advanced Micro Devices, has developed a tool to monitor plasma operations. This tool was developed at Sandia National Laboratories in response to the initial request of the PWB industry and a subsequent request from the semiconductor industry for a method of ensuring product quality. The monitoring tool uses OES to gauge the "state-of-health" of plasma processes. We currently have two prototype systems in the field. System 1 has been at Texas Instruments in Austin, TX since February, 1996 monitoring the health of printed wiring board (PWB) plasma desmear and etch-back processes. System 2 has been at Advanced Micro Devices in Austin, TX since July, 1996 monitoring integrated circuit (IC) multivariate oxide etch processes.

The tool gathers information about the health of the plasma process (obtained by OES) and performs tasks based on real-time analysis of the information. By utilizing a library of spectra including normal plasma operation, common plasma failures, and unique differences correlated with different product types, the tool is capable of diagnosing system abnormalities.

Software constantly compares current plasma state against the library. If any deviation from normal occurs, the software initiates a series of hierarchical commands. The exact set of commands are outlined by the customer based on particular needs and preferences. The resulting tool is a real-time plasma monitor with logical pattern recognition ability.

When monitoring plasma systems, one must take care not to perturb the plasma field by introducing a new variable into the complex plasma environment. Remote monitoring, external to the plasma reactor, is more desirable than a probe that resides in the plasma field. OES is an excellent technique for external monitoring since it non-intrusively examines the optical emission of the plasma discharge and separates the emission into its spectral components. As the plasma condition varies from optimum, optical indicators can be seen in the visible, UV, and infrared spectra of the glow discharge. By comparing current plasma state against a library of normal and abnormal plasma spectra, information is obtained about the plasma's current performance. By becoming familiar with normal plasma features, any deviation from normal can be identified. Information about the plasma is gained via OES monitoring through an external view port or window allowing for real time plasma diagnostics with resulting error identification and correction, while not disturbing the plasma environment. Since this tool monitors the plasma external to the reactor, it does not perturb the plasma field or affect the performance of the reactor in any way.

Figure 1 shows a typical use of the Plasma Process Monitor/Control System. The plasma is created in a capacitively coupled plasma reactor (2). Two reactors are shown as part of a plasma unit (1) and controlled by instruments housed in a rack (8). A plasma unit may have multiple plasma reactors, sample handling equipment, loading/unloading ports, etc. A view of the plasma can be obtained through the viewport (3). Light from the plasma is carried to a spectrophotometer (5) via a fiber optic (4). The spectrophotometer splits the plasma light into spectral components or wavelengths. The spectrum is imaged onto a CCD camera (6) and read into software on the computer (7) that in the automation mode controls the spectrophotometer and camera, performs pattern recognition routines, identifies processes, counts samples and lots, diagnoses errors, performs corrective actions, notifies personnel, and writes daily activity reports. In the research mode, the software interacts with a user to perform functions as desired by the researcher.

The program, in performance of the above mentioned tasks communicates with discrete components via an input/output device (12). This device is capable of communicating with 64 independent devices. Some devices that the unit can control include pressure sensors, flow controllers, throttle valves and solenoid valves (9). If operator notification is necessary, the device can sound an audible alarm (14), flash a beacon (13) or page appropriate personnel with alert codes or phone with synthesized voice messages (11).

The Plasma Process Monitor/Control System is designed to operate independently of human interaction. The unit receives a plasma-on signal from a node (10) within the instrument rack. With this signal, the Plasma Process Monitor/Control System awakens and performs the tasks selected by the user. When the plasma cycle has been completed, the Plasma Process Monitor/Control System places itself into standby mode, awaiting the next signal. A recent advance allows the monitor to wake (even in the absence of a signal) if it detects an event of interest.

Figure 1. Schematic of the Plasma Process Monitor/Control System demonstrating typical usage of the system.

The Plasma Process Monitor/Control System is comprised of a computer running a LabVIEW 4-based software program, a spectrophotometer equipped with a charge-coupled device (CCD) camera, an input/output control center, and a fiber optic cable. The instrument automatically monitors the various plasma recipes and steps needed to complete all phases of production. During normal operation, the tool notes process steps as they occur, stores a representative set of spectral details for future analysis, and counts number of products and

lots being treated. If the plasma experiences an abnormality, the tool notes the abnormality, signals appropriate personnel, and attempts to correct the abnormality *in situ* if so directed. The tool is designed to be a versatile multipurpose piece of equipment allowing automated process verification, notation and correction, as well as a research tool.

The Plasma Process Monitor/Control System receives information regarding plasma performance via a fiber optic cable placed in contact with a view port on the plasma reactor. Using OES, details of plasma performance, etch rate, or deposition rate can be obtained. The spectrophotometer and CCD camera send spectral details to software for analysis and action.

The software system is an object oriented, multi-tasking system which allows a variety of activities to be executed concurrently. The software controls the operation of the spectrophotometer and CCD camera, sending instructions to these pieces of equipment for spectral range, resolution, exposure times, etc. The system also instructs the spectrophotometer and CCD camera to perform self evaluations allowing for self calibration for intensity and grating position.

The typical operation mode may follow a specific plan of action (plan of action and error correction protocol are user selectable with endless possibilities for performance demands). The system makes decisions and takes corrective actions based on a protocol established by the user. For example, the Plasma Process Monitor/Control System remains on at all times but is dormant until the plasma reactor begins a cycle. At that point, the Plasma Process Monitor/Control System receives a signal from a node within the reactor via an electro-optically isolated line. The tool sends commands to the spectrophotometer to initiate and scan a region of the spectra centered about an area containing information regarding plasma recipe. The spectrophotometer performs the scan and returns information to the Plasma Process Monitor/Control System. Upon receiving the spectral information from the spectrophotometer and CCD camera, the tool identifies the recipe and recipe step then makes decisions based on information detailed in the spectra. The tool may instruct the spectrophotometer to scan a second, third or nth region for additional information. If an error is detected, the tool may take any number of actions based on an error handling protocol selected by the user.

In an example situation, assume the Plasma Process Monitor/Control System detects a failure in the form of inadequate process gas from gas type B in a two gas recipe. The error protocol preferred may include the following actions as shown in Figure 2. The tool accomplishes this task by controlling replacement modules. Modules, such as flow controllers, power supplies, gas cylinders, etc., can be arranged in a bank and may be accessed by the input/output device of the Plasma Process Monitor/Control System. The I/O device can send and receive information from 64 individual devices from alarms and communication devices (synthesized voice messaging or paging) to power supplies, pumps,

and gas cylinders via solenoid valves. The components are addressed using electro-optically isolated control lines. Electro-optically isolated control lines allow instrument control without the possibility of errant signals due to random electrical impulses that may be experienced with RF fields, power surges, electrical storms etc.

Figure 2. An example error protocol that the Plasma Process Monitor/Control System can implement.

The Plasma Process Monitor/Control System is able to diagnose plasma failures and identify plasma recipe and step by referring to a table of known spectra. Initially, normal plasma conditions and some known engineered failures such as air leak or gas failure can be scanned and recorded on a chamber-by-chamber basis for future reference. These reference spectra act as a guide for pattern recognition subroutines within the software package. If plasma conditions arise that have never before been encountered, the Plasma Process Monitor/Control System can be instructed to abort the process, contact appropriate personnel, and save the new condition into the library as "Unknown Condition X" where X is the number of unknown error conditions logged to date. As the cause of the unknown condition becomes apparent from service diagnostics, the unknown file can be renamed to reflect the nature of the failure. From service reports, error correction protocols for this new condition can be assigned, making the Plasma Process Monitor/Control System more useful.

Since the software is truly multi-tasking, error conditions can be identified immediately after the plasma-signal has been received. A multiplicity of corrective actions can be taken soon thereafter, ensuring that the

product can be saved before damage has occurred. The unit can abort the process and hold products in stasis until corrective actions are complete when the process can continue without damaging products. During normal operation, with no error condition present, the tool serves as a process check and record keeping tool. The tool can also be used to identify endpoint for process verification and quality control. The amount of control the tool has is dependent upon the desires of the user. The tool may be used for indication only with alarm notification or a fully functioning process controller that adjusts recipes to maximize etch rate or deposition.

Not only would this tool be able to save many runs by immediately correcting failures under its control, but it would also reduce reactor down time on aborted runs by performing some of the diagnostics needed to repair the instrument. Parts being treated in the reactor would be saved by the automated process correction, and in scenarios where the plasma was aborted, parts would not be ruined by errant conditions and could be re-run after repairs to the reactor. This tool is technically superior to current PWB test mechanisms which include weight loss coupons and/or destructive testing. Since this method of testing is performed *in situ*, corrective actions can be taken as the failure occurs rather than after the cycle is complete. This test method would provide an accurate evaluation of the plasma performance and document the quality of the product exiting the plasma chamber.

RESULTS & DISCUSSION

Printed Wiring Board (PWB) Application

Plasma etch-back and desmear operations are performed in a capacitively coupled, or parallel plate, reactor. In a reactor of this type, a series of parallel electrodes is used. The electrodes are positioned to form alternating ground potential and RF powered planes. The powered electrodes are at approximately 2500 Watts at an RF frequency of 13.56 MHz. PWBs are placed directly on these electrodes for plasma treatment.

For typical plasma etch-back or desmear operations, carbon tetrafluoride (CF_4) and oxygen (O_2) are flowed through the chamber at reduced pressures at an approximate 2:1 ratio. The presence of the fluorine containing molecule in the plasma discharge enables the production of atomic oxygen which is the aggressive polymer attacker in systems of this type. By monitoring the etch-back rate of a specific polymer while varying the percentage of CF_4 to O_2 , one can optimize the etch rate for any given organic susceptible to oxygen attack. Depending on reactor geometry, product loading, available power, obtainable pressures, and other process specific parameters, the overall performance of any given gas mixture may vary. For optimum results, it is suggested that a series of survey experiments be conducted, prior to placing any new reactor into service, to identify ideal operating parameters and limits.

Handling of the product before plasma treatment and during the plasma cycle is extremely important for maintaining quality and uniformity. Plasma etching performance is dramatically effected by environmental factors and condition of PWBs. For example, large variations in environmental humidity can severely reduce the performance of the plasma etch-back or desmear operation. The amount of available water in the system can negatively impact the expected etch rate leading to inconsistent product from day to day. Likewise, improper handling can increase surface water contamination or large molecule oil deposits on PWB prior to plasma treatment. Both types of surface contamination are harmful and potentially destructive to PWBs.

Oil residue, such as from fingerprints, locally slow the etch-back process by presenting a barrier or mask to be overcome by the plasma before actual product etch can occur. To prevent contamination due to oil residue, caution must be taken to prevent unnecessary handling during production. Workers should limit direct contact with the PWBs during assembly and any unavoidable contact should be performed with proper protective equipment such as gloves. Proper storage and handling of the PWBs prior to plasma processing will help reduce cross contamination from external sources.

Surface water contamination is increased by exposing the PWBs to humid environments. To limit exposure, PWBs should be stored in dry areas away from high humidity locations. Also, processing of the PWBs should be performed within a timely manner without unnecessary delays between process steps. Although surface water contamination is unavoidable, proper handling can reduce unnecessary water absorption.

To eliminate the effects of all unavoidable water contamination, pretreatment before plasma treatment is necessary. The PWBs must be baked to remove the water before effective, predictable, and uniform plasma treatment can occur. Industry uses two methods to help drive off water.

A prebake in a separate oven before plasma treatment at approximately 225° F for a period of an hour or more can drive off excess water. However, without vacuum assistance, water comes off more slowly and drying times may vary. Another consideration is the transport between the oven and the plasma reactor. When transport through air is necessary, some water pick up is expected. The boards must be transported as quickly as possible and should be at or near the bake temperature during travel and subsequent loading in the plasma reactor. If the PWBs are transported in a timely fashion, while still at an elevated temperature, additional water pick up will be minimized. One consideration for this type of pretreat is the safety issue of handling hot boards between oven unloading and reactor loading. Severe burns can occur if operators are not familiar with proper handling techniques or appropriate safety equipment.

A second method for water removal is a vacuum bake in the plasma reactor. The reactor plates can be retrofitted to accommodate heating elements. By evacuating the

chamber to normal operating pressure and heating the electrodes and PWBs to approximately 180° F, the water contamination can be removed in 20 minutes or less. Furthermore, since the operation is performed within the plasma reactor, no further water pickup can occur if the reactor is not opened prior to the plasma cycle. If the PWBs are repositioned mid-cycle for more uniform etch, as is standard procedure in many plasma processes, additional baking may be necessary to eliminate any water contamination that may occur at that time.

Plasma systems are typically nonuniform. Reactor geometry, number and type of PWBs in the system, and inherent plasma nonuniformities such as the boundary sheath region, all affect the uniformity of the plasma processing. The effects of this nonuniformity can be minimized by holding load size consistent and by adjusting the load at mid-cycle. By varying the load size and type, charged regions build in an unpredictable manner. By always using the same amount of exposed polymer (number of holes and thickness of panel) and type of polymer (i.e. epoxy, polyimide), the effects can be predicted and controlled. To accommodate loads of varying size, filler boards may need to be used. A filler board, also referred to as a dummy panel, is a PWB of similar material with a known number of drilled thru-holes. By using filler panels along with actual product, consistent load size can be maintained.

Nonuniformity in the plasma can be predicted with the use of consistent load size. To minimize the effects of plasma nonuniformity, mid-cycle board adjustment is necessary. A typical plasma desmear and etch-back operation is approximately an hour in length comprised of two 30 minute cycles. At the mid-point between the two cycles, the boards are unloaded from the system and reloaded in a different order. Depending on the reactor, the center set of electrodes may demonstrate a faster etch rate than those spaced farther from center. At mid-cycle, the operator may choose to exchange the boards from the top of the machine with those in the lower half. The boards may also be replaced in reverse order so that the board exposed to the center region of the discharge is now near the edge of the discharge. By repositioning the boards in this fashion, the average etch rate experienced by all boards is the same, resulting in a more uniform etch throughout the load. During the mid-cycle adjustment, filler boards are handled like any other product in the load and also repositioned within the system.

Over the course of the PWB test, the monitor has diagnosed serious problems with the plasma process. One error detected and corrected as a result of information obtained by the plasma monitor was the effect of placing mismatched dummy boards in the system with product.

For more uniform plasma performance, it is standard practice to fill incomplete lots of boards with dummy boards. A dummy board is a board matched to product by size, shape, and type of material. A dummy board may be reused many times before it has been destroyed. A recent change in production material (new supplier) resulted in product being made with a slightly different chemical

content than earlier product. The dummy boards were made with the original materials. The facility assumed that the materials were identical. Because of slight differences in chemical content, the dummy boards and product boards did not etch at the same rate causing asymmetry in the process. The plasma monitor detected the difference in plasma performance. New dummy boards were manufactured in response to this discovery.

Other problems detected by the monitor include impending failures of power supplies and pumping systems. The monitor can also detect air leaks and fluctuations of either of the two process gasses used. The performance of the monitor for these failures has been tested by engineering tests of these conditions. To date no actual failures of this nature have been observed.

Endpoint detection of plasma desmear and etch-back was also conducted. The spectra of various types of PWBs were monitored with time. The PWBs were treated in a typical CF_4/O_2 etching plasma at an approximate 2:1 ratio. Cycle times were extended up to 80 hours to observe the peaks of interest. The behavior of the etchant gas as well as etch products were compared throughout the run. Postmortem examination of the samples was performed to insure that the accumulated data were for average cycles with expected etch rates.

Careful inspection of the accumulated spectra revealed a time-related behavior at 325 nm and 333 nm. The peaks observed at these wavelengths appeared to change intensity relative to each other throughout the cycle in an oscillating fashion (Figure 3). The period of these oscillations is not regular, but appeared to decrease in frequency with time. The peaks are primarily due to the etchant gasses and are present in the spectra when there is no sample present. However, their intensity does not change with time. These two peaks only begin to toggle when samples are being etched in the chamber. This phenomenon was observed both in the laboratory with a scaled down plasma apparatus and in the production facility on an industrial plasma treatment system. Efforts are in progress to correlate etch rate with peak oscillation by comparing real-time spectra with test coupons.

The most intriguing question is by what mechanism could an oscillatory behavior of spectral peaks occur when etch gas and etch product should be a constant. One explanation might be that the plasma is encountering some mechanical barrier so that, from time to time, etch rate is slowed until the barrier is overcome. The barrier in this scenario may be the glass fiber micro-weave fabric used within the interlayers of the PWBs. The PWBs are constructed of alternating layers of copper sheet and epoxy filled glass fabric (Figure 4). The voids between the warp and weave of the fabric form relatively large pockets of epoxy which are easily removed by the plasma. As these pockets of epoxy become depleted, the plasma is primarily exposed to the glass fibers which do not etch and therefore become a barrier. These barriers are not impenetrable to the plasma. Even though the large pocket of epoxy has been removed, the adjacent pockets of epoxy are now exposed by a small gap in the glass fabric caused

by one fiber being placed across another. The plasma etching process has been slowed but not halted. As the plasma opens the gap between fibers by etching away the epoxy that seals it, again a large pocket of epoxy is revealed and the etch process continues at a faster rate. With each barrier the plasma overcomes, the path through which the plasma must travel becomes longer and more geometrically complex, slowing the processes with time. This may explain why the period of oscillation seems to decrease in frequency with time.

Figure 3. Variation in relative peak height observed in printed wiring board etching using OES. The X-axis is plotted in wavelength (nm) units. The Y-axis is plotted in intensity (counts) units.

Figure 4. Multilayered printed wiring board

Integrated Circuit (IC) Application

Plasma etch tools, such as the Applied Materials (AMAT) Centura High Density Plasma (HDP) 5300 Dielectric Etcher, exhibit a phenomenon known as "stop-etch" which results in an incomplete etch of contacts and vias in microelectronic devices manufactured in IC fabrication facilities. This results in decreases in both yield and product throughput, both of which have negative impact on productivity. Using OES, we have developed a plasma process monitor and controller for determining the "state-of-health" of IC plasma processes. By extending our initial tool for monitoring PWB plasma desmear and etch-back processes, we have been successful in monitoring IC multivariate oxide etch processes. We have used OES to acquire spectral information during typical IC plasma etching and cleaning cycles during a beta test where an automated plasma process monitor is collecting data at the Advanced Micro Devices facility in Austin, TX.

The OES sensor has worked extremely well during the first phase of the beta test where spectra were collected over the 250 - 1000 nm range during all phases of the oxide etch process. The calibration and long-term stability of the OES sensor were found to be acceptable. OES spectra collected from two AMAT 5300 High-Density Oxide Etchers during the polymer removal portion of the etch process show clear differences in several regions, demonstrating that the relative age of reactors may be determined from OES analysis (Figure 5). This type of analysis can provide useful information in the design of reactor cleaning schedules.

Figure 5. OES spectra recorded during polymer removal portion of semiconductor oxide etch process. The top graph is from a clean tool and the bottom graph is from a dirty tool. Note the differences in peaks at 913, 916, and 928 nm. The Y-axis is plotted in intensity (counts) units.

Figure 6. Representative spectra from semiconductor oxide etch process showing three of the many process steps that can be distinguished using OES.

Preliminary results also show clear differences in the spectra for processes that were identified by Advanced Micro Devices as being different from one another (Figure 6). Chemometric analysis is currently being applied to the data for improved sensitivity compared to single peak and peak ratio analysis. The OES data is also being correlated with XSEM, etch rate, contact resistance, and microprocessor functionality results. These preliminary results are being explored in the second phase of the beta test, where the automated plasma process monitor is being augmented to collect data from eight reactors at the Advanced Micro Devices facility in Austin, TX. The Plasma Process Monitor/Control System is being reconfigured to automatically switch from one reactor to another, thereby collecting OES data from the full suite of etch tools. This study will provide information and insight on chamber-to-chamber variations within the etch bay. We will also characterize these OES spectra for cycle to cycle variations as indicators of stop-etch condition.

When the tool is finalized, predictions of impending stop-etch conditions or other malfunctions will be made before product wafers are damaged. The tool could ultimately notify key personnel, take corrective action, etc., as prescribed by the customer. The monitor continues to perform wafer and lot counting, recipe and recipe step identification, as well as general process monitoring. The proprietary nature of the experiments being conducted and the data being collected at this facility precludes a detailed discussion at this time.

SUMMARY & CONCLUSIONS

Plasma processes for etching and desmear of PWB and electronic components are critical fabrication steps which are difficult to predict and control. To ensure product excellence, care must be taken to optimize plasma processes and to eliminate sources of inconsistent or nonuniform plasma results. In the case of PWBs, reactor performance can be adversely affected by environmental factors and by board condition. Board handling prior to plasma processing and during mid-cycle board adjustment must be done with care and consistency. Water absorption is a serious problem and must be eliminated. Either prebake in a separate oven or vacuum bake in the plasma reactor can reduce the amount of water in system. It is suggested that vacuum bake in the reactor is the better method for eliminating water since transport between oven and reactor can lead to recontamination. Currently, quality control is maintained through proper processing protocol and post-process testing. The accepted method of testing is performed using weight loss coupons and post-process destructive testing. The unreliability of such testing has led to the development of a new tool using OES to monitor plasma performance *in situ* and correct problems as they occur before the product has been damaged.

The Plasma Process Monitor/Control System, developed by Sandia National Laboratories uses OES to detect real-time plasma failures. The technology utilizes a commercially available spectrophotometer and camera to view the plasma. Error detection and signaling is performed by software developed at Sandia National Laboratories. In an industrial process, the plasma system technology can compare normal and actual operation and note any deviations. If any deviation from normal occurs, the software initiates a series of hierarchical commands. The exact set of commands are outlined by the customer based on particular needs and preferences. An important capability of this real-time plasma monitor is that it can allow control of support systems known to influence plasma behavior. The resulting tool is a real-time plasma monitor with logical pattern recognition ability. The system is designed to act as a stand-alone process monitor or as a research tool for investigating plasma performance.

The benefits of identifying the end of a plasma process, prescribing the amount of material to etch-back or identifying and correcting failures are apparent. In this competitive age, industry needs to work faster and more efficiently. Post-process testing to insure that a part is acceptable is time consuming and costly. *In situ* testing for process integrity and immediate error correction is preferable. Endpoint determination of cleaning processes and known failure analysis are relatively easy to perform and require little to implement. Identifying spectral clues for endpoints of processes such as plasma etching or desmear is more difficult. The potential payoff, however, is enormous with fewer failed parts and greater process reliability. It is promising that of the several types of products examined to date, all have shown some time related behavior and other distinguishing characteristics.

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