RF MEASUREMENTS AND THEIR ROLE IN THE MANUFACTURING ENVIRONMENT

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Plasma etching is a complex process to control, and it can account for one-third to one-half of the total wafer scrap in the fab. An RF impedance monitor, placed between the matching network and the cathode, provides data that can speed troubleshooting and detect the etch endpoint.

The semiconductor manufacturing industry is characterized by the need for ever-tightening process control, to achieve increasingly difficult device structure geometries and higher yields. The work being done by the AEC/APC (Advanced Equipment Control/Advanced Process Control) Committee, sponsored by SEMATECH, is one of the drivers for equipment process control improvement. At the October, 1996 AEC/APC workshop, Texas Instruments reported that up to $135M annually could be saved in each of their factories in such areas as improved wafer yield and increased OEE (Overall Equipment Effectiveness), both of which are substantially driven by process control. In order to meet these goals, it is imperative that each process be closely monitored, and if failures occur, that they be properly diagnosed and corrected. The diagnostic tools to achieve better control should be in-situ and robust as well as easy to install and interpret. A new generation of RF plasma impedance measurement probes may meet these requirements for plasma processing equipment.

PROCESS MEASUREMENTS FOR PLASMA ETCHING

Plasma etching is potentially one of the most costly areas in any wafer fab. As chip complexity increases, it is more difficult to control ever-decreasing dimensions and to stop on ever-thinner underlayers. In response to requirements for increased aspect ratio and greater etch selectivity, equipment manufacturers are responding with tools that provide more machine controls; these, coupled with increasingly exotic etch chemistries, have enabled great strides in manufacturing control of etched features. Still, it is not uncommon for the plasma etch processes to account for between one-third and one-half of the total wafer scrap in a fab. Additionally, etcher downtime is often the cause of serious bottleneck conditions. Therefore, understanding the elements that determine plasma etch tool performance is of critical importance to reducing scrapped wafers and costly downtime.

Geometry Requirements	Timeframe/ Reactor Design	Chemistries	Strengths	Limitations and Problems	Process Controls
4 to 5 microns isotropic etch	Pre-1977 Wet etch	$HNO_3/HF/I_2$ (Wet etchant)	Batch process; high throughput	Resist lift; bath aging; temperature sensitive	Operator judgement
3 microns	1977 Barrel etcher	CF_4/O_2	Batch process; high throughput	Nonuniformity; isotropic etch; large undercut	Manometer
2 microns	1981 Single wafer plasma etch	CF_4/O_2	Single wafer; individual etch endpoint	Low oxide selectivity; isotropic process	Endpoint detection
1.5 microns	1982 Single wafer RIE	SF_6/Freon$_{11}$, SF_6/He	MFC's; independent pressure/gas flow control	Low oxide selectivity; profile control	MFC's; separate gas flow and pressure control
to 0.5 microns	1983 Variable gap; load-locked	CC_{14}/He, C_{12}/He, C_{12}/HBr	Load-locked chamber; variable gap	Microloading in high aspect ratios; profile control	Control of electrode gap; computer controls
to 0.25 microns, may go lower	1991 Inductively coupled plasma (ICP)	C_{12}, HBr	Low pressure; simple gas mixtures	Complex tool; many variables	Independent RF for plasma generation and wafer bias

Table 1. Polysilicon Etch Technology Evolution

An example of increased etch tool capability in response to the need for tighter process control is illustrated in the progression of polysilicon etch technology that has occurred over the past two decades, as shown in Table 1. The advances from wet etch technology of the 1970s to the reactive ion etch (RIE) of the 1980s and to the inductively coupled plasma (ICP) etchers with independent RF wafer bias of today demonstrates the dramatic increase in tool capability over the last 20 years. This, of course, has not been limited to polysilicon etch; most other tool sets have undergone a similar evolution.

With each new generation of tools came a solution to a previous process-limiting problem. However, the solution to an old problem typically came at the expense of a new level of complexity that carried with it a new set of problems. With this increase in complexity, there was also an increase in the number of parameters that could be controlled to optimize the etch process. For example, old barrel etchers were simple tools with very limited controls. However, they were easily constructed, inexpensive, and operated reliably within their process window. As etch requirements grew more stringent, more controls were added. Now, modern etch tools for state-of-the-art processes have at least two RF power supplies used concurrently for separate control of ion current and of energy delivered to the etched substrate.

Having a plasma etch process in control once meant that daily etch rate and uniformity tests would "pass" fairly arbitrarily-set specifications. As device complexity increases and continues to push plasma etch tools toward the limit of their capabilities, understanding all of the sources of variability that can exist within the etch process becomes imperative. For example, etch rate and uniformity are often used as tool-performance indicators. However, it is actually factors such as etch selectivity to photoresist and underlying films as well as the formation and longevity of etched feature sidewall polymers that determine proper device functionality. Checks of these critical results are often complex and time consuming, and, therefore, not done on a routine basis. If found to be out of normal operating range, the list of possible parameter interactions that can cause an undesired outcome may well be beyond the ability of process engineers to analyze.

TRADITIONAL MEASUREMENTS DON'T TELL THE WHOLE STORY

Process and maintenance engineers generally understand effects of the traditionally monitored variables of plasma etch tools, such as process gas flow and pressure, substrate temperature, and dc bias. However, RF power delivery to the plasma has historically been monitored only to the extent that the power delivered from the RF power supply to the matching network is known. The system readouts typically display only forward and reflected power; in some cases, the relative positions of variable match network components are given. These may allow inferences about the state of the etch system, such as the degree of the ionization, electrode condition, and presence or absence of chamber wall coatings. While the construction of RF matching networks varies greatly, matching network losses are generally unaccounted for, and they can be quite high and variable. Traditional air dielectric variable capacitors and wound inductors typically result in match network power losses of from 25% up to 75%. Changes in variable capacitor settings and inductor tap positions can change the RF power loss in the match network, even if other conditions such as RF generator power and process gas pressure remain the same. Therefore, it may be difficult to know the actual RF power delivered to the etch chamber, and, hence, the state of the etch plasma.

RF PLASMA IMPEDANCE MEASUREMENTS DELIVER PREVIOUSLY UNAVAILABLE DATA

By adding an RF plasma impedance sensor to the plasma etch system—between the match network and plasma electrode—new electrical variables may be monitored and controlled. This gives both process and maintenance engineers a new tool, providing additional insight into plasma etch problems. All electrical loads have a characteristic impedance consisting of an Ohmic, or real, part, and a reactive, or imaginary (capacitive or inductive), part. An etch plasma is no exception. As such, the RF impedance characteristics of the etch plasma system can be measured and used as both a troubleshooting aid and a simple system status monitor. By monitoring the plasma RF parameters, changes in the plasma etch chamber impedance can be noted and problems, such as poor RF connections, worn electrode coatings, and changes in process gas mixture, can be more easily detected and solved. Most plasma impedance sensors measure the RF power delivered to the plasma load. Thus, even if the resistive losses of the match network are changed by, for example, moving a tap on an inductor, the etch plasma can be returned to its original state. Etch endpoint may be detected using changes in RF impedance during the etch cycle, without the problems associated with optical endpoint detection, such as optical window clouding, detector drift, and optical set-up. The RF sensor is in-situ and need not be adjusted like optical components.

RF SENSOR PROVEN VALUABLE FOR SYMBIOS LOGIC'S PROCESS TROUBLESHOOTING

In recent years, several manufacturers have introduced RF sensors. Included in this group are Advanced Energy, Comdel, ENI, and Fourth State Technology. Each offers a variety of features over a wide spectrum of price. They all are installed at the point of power delivery to the etching chamber and can give valuable information about a portion of the etch tool data previously unavailable.

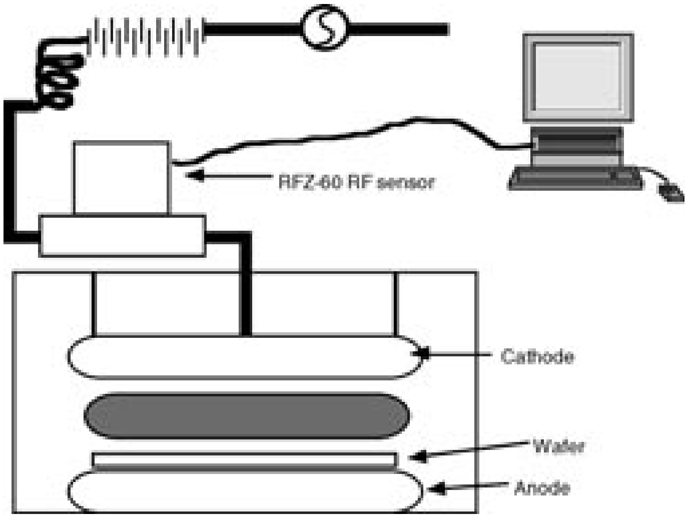

Figure 1. The positioning of the Advanced Energy RFZ-60 RF sensor in the Lam 490 etching tool

At Symbios Logic, we installed an Advanced Energy RFZ-60 Probe sensor to help us get a handle on this data. Figure 1 shows the installation of the RF sensor, in this case on a Lam 490 AutoEtch. The sensor was installed between the matching network and cathode.

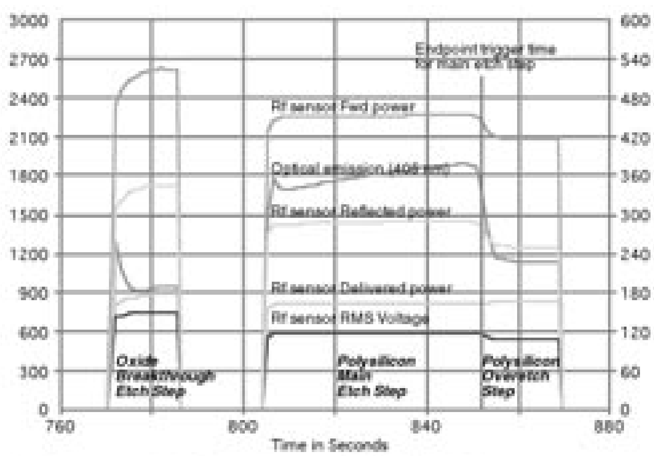

Figure 2. A set of waveforms gathered during the etch of a polysilicon wafer on a Lam 490 AutoEtch. Shown are a portion of the RF parameters available, plotted along with a standard optical emission parameter for reference

Figure 2 shows a part of the RF data gathered by the plasma impedance sensor. Only a few of the parameters are plotted here, for clarity. The RFZ-60 probe sensor monitors the RF power delivery to the plasma chamber and calculates several RF parameters, which give important information about the state of the tool and the plasma. For example, since the power delivered to the etch chamber is known, unaccounted losses in the match can be compensated for. Also, several of the RF parameters undergo parallel changes at endpoint; this can be useful in determining proper process termination.[1, 2]

RF SENSOR KEY IN ETCH PROBLEM SOLVING

Recently, in the wafer fab at Symbios Logic, we had an example underscoring the usefulness of the RF parameters for problem solving. In this case, there was a sporadic underetching of polysilicon wafers. The problem would appear quickly, almost at random, and then disappear in the same manner. The poly etch rate and uniformity test, a standard indicator used to determine system health, was within specification and control limits. After generating much inconclusive data, some oxide wafers were etched to test the hypothesis that the problem was being caused by an incomplete strip of oxide formed during the POCl3 doping operation. The optical emission waveform seemed to suggest that this might be a valid problem mechanism. The monitored optical and RF parameters from this test are shown in Figure 3. Figure 4 shows the same waveforms for a "bad" etch occurring between two normal etch cycles.

At this point (Figure 4), the match network was disassembled and two problems were discovered. First, we found a bent fin on an air capacitor, which would occasionally touch another fin, depending on tune position. Second, we found a loose gap drive motor wire, which was very close to the series air capacitor. With such severe RF problems, we would have expected to see excursions of the reflected power signal, as sensed by the Lam controller. It is not clear why, but there were no such excursions. Instead, when these problems occurred, the tool actually tuned faster on the problem wafers, and there was no appreciable reflected power between the match and the generator. No indicators, other than the RFZ-60 data, were useful in diagnosing these problems. After identifying and fixing both problems, we were able to return the tool to normal production, and the underetch problems have not since returned.

Steve Hyer, a Senior Maintenance Technician at Symbios Logic says, "We have a lot of older equipment that we're pretty familiar with. Still, when we come across a new RF problem, it can sometimes take a couple of days to figure out. The results we saw with the RF sensor can help me determine the root-cause of a wide variety of maintenance problems."

RF SENSORS MAY HELP SOLVE PROBLEMS INDUSTRY-WIDE

The results we saw at Symbios Logic may have wider application. Tim McGaughey, Service Manager for Aspect Systems of Chandler, Arizona, is very familiar with elusive RF problems. Aspect Systems remanufactures and services AutoEtch tools, and Tim says, "Even my best techs really wish they knew more about RF. About 90% of the difficult service calls we have are RF-related."

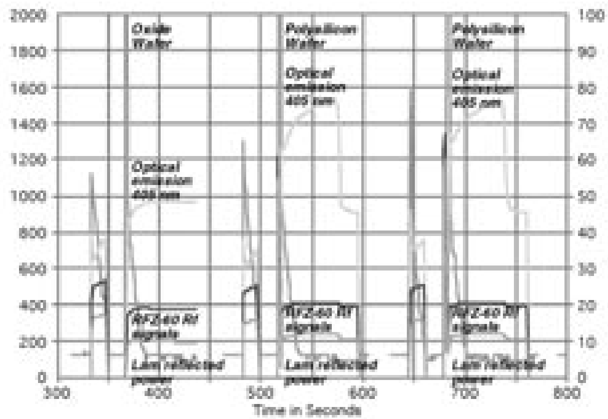

Figure 3. Polysilicon etch on a Lam 490. This was an attempt to recreate a recurring problem, with the thought that it was due to an incomplete oxide strip after POC13 deposition. This test was not successful, as residual oxide was not the problem mechanism. But, the oxide wafer gave an optical trace signature similar to that seen during previous problem etches.

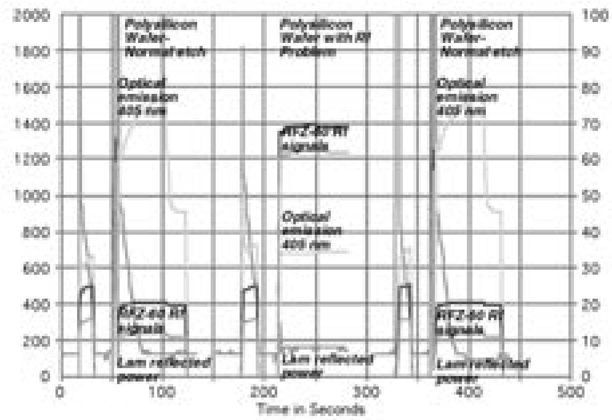

Figure 4. Polysilicon etch problem on a Lam 490. Note the similarity of the optical data trace on the problem wafer to the oxide wafer in the Figure 3 graph. However, the RF signals clearly showed us that the problem was not the oxide scenario proposed, but rather an RF problem.

CONCLUSION

The potential to implement RF sensor technology into tools is now widely available. It is clear that getting more data about RF parameters can greatly aid in system troubleshooting. As tools get ever-more complex, the task of clearly distinguishing process cause and effect also gets more complex. Process and maintenance engineers need robust sensors to help them correctly and easily interpret the anomalies in their particular processes. In-situ RF plasma impedance sensors have proven valuable in meeting these troubleshooting requirements.

RF sensors may also give manufacturers important process control benefits. The technology is now available to control the actual delivery of RF to the chamber. This may become an important competitive advantage on the new-generation tools with complex RF systems. These additional controls may well allow tools to be used beyond their designed capabilities, extending their lifetimes, and promoting device evolution. And these gains need not be limited to the etching area; any tool that uses RF power can experience similar benefits.

ABOUT THE AUTHOR

Carl Almgren is a Consultant Engineer at Symbios Logic Inc., in Fort Collins, Colorado. He has 16 years experience in plasma-etch processing. He is currently completing an advanced degree in Electrical Engineering at Colorado State University. His area of study is using real-time parameter data to detect and diagnose faults in processing. Mr. Almgren has been with Symbios Logic for five years.

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