Optical-Emission Spectroscopy For Plasma Processing

By Marshall J. Cohen, Business Element Manager for Semiconductor Instruments,
EG&G Princeton Applied Research, Princeton, New Jersey

Plasma etching and deposition are complex, dynamic processes that require sophisticated monitoring techniques to support repeatability, reliability, and throughput. Optical Emission Spectroscopy (OES) is a powerful technique that has been used extensively to understand plasmas, and is now finding an increasing number of applications on the production floor in monitoring and control roles.

What is Dry Etching and Why?

The formation of a pattern on the surface of a silicon wafer is a complicated process. In photolithography, a resist material is applied to a wafer and cured. It is then exposed to light through a patterned mask. The light induces a chemical reaction in the resist and upon "development", either the exposed or unexposed portion of the resist is dissolved away, leaving either a positive or negative image of the mask behind. The remaining material "resists" the subsequent chemical process.

In an etch process, the material exposed by the developed resist is chemically removed. Then the remaining resist is stripped away, leaving the desired pattern. Until recently, etching was typically a wet-chemical process.

The advantages of wet-chemical etching lie in its flexibility and in the simplicity and low cost of the neces-
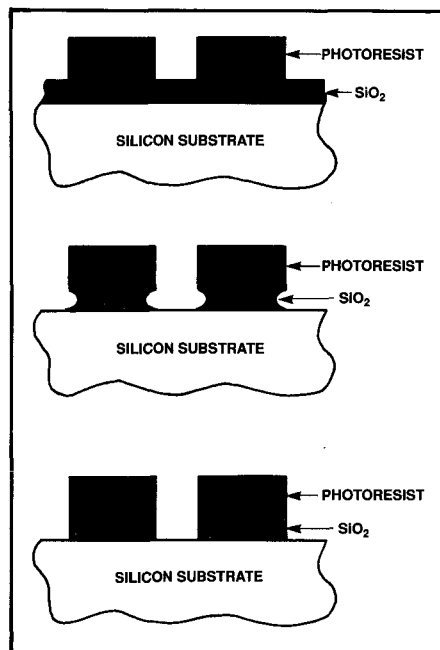

Figure 1. Comparison of wet and dry etching, showing: 1a (top) — oxide-coated silicon wafer with developed resist pattern; 1b (center) — undercutting as a result of isotropic wet-chemical technique; 1c (bottom) — vertical etch pattern achieved using anisotropic plasma (dry) technique.
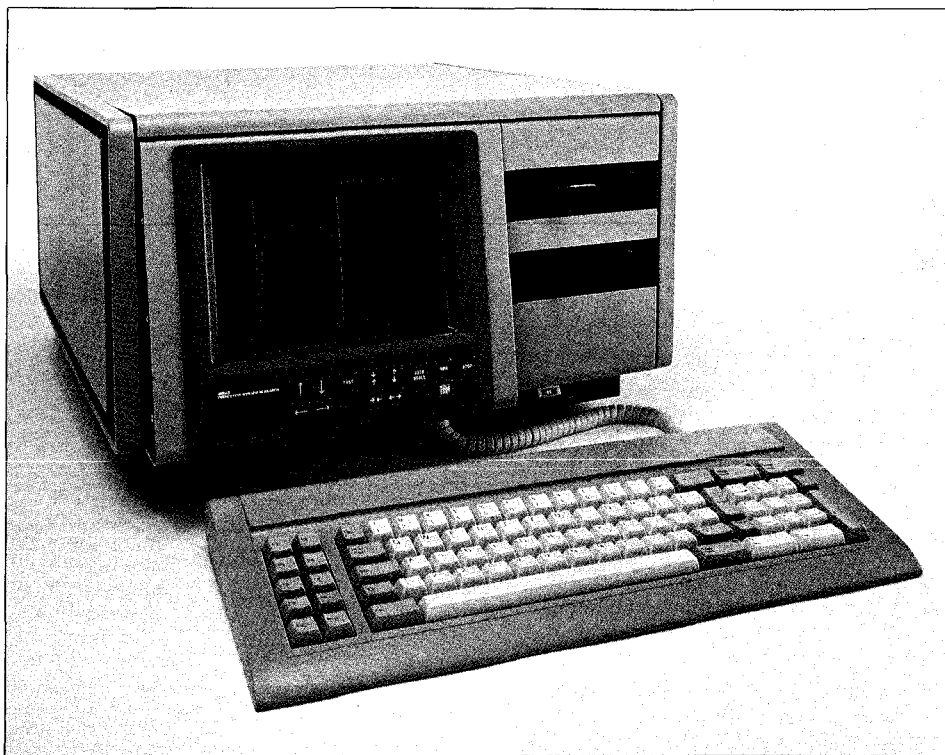

Figure 2. The EG&G PARC Model 1460 plasma monitor that facilitates interactive control of etch chambers to achieve optimum plasma processing.
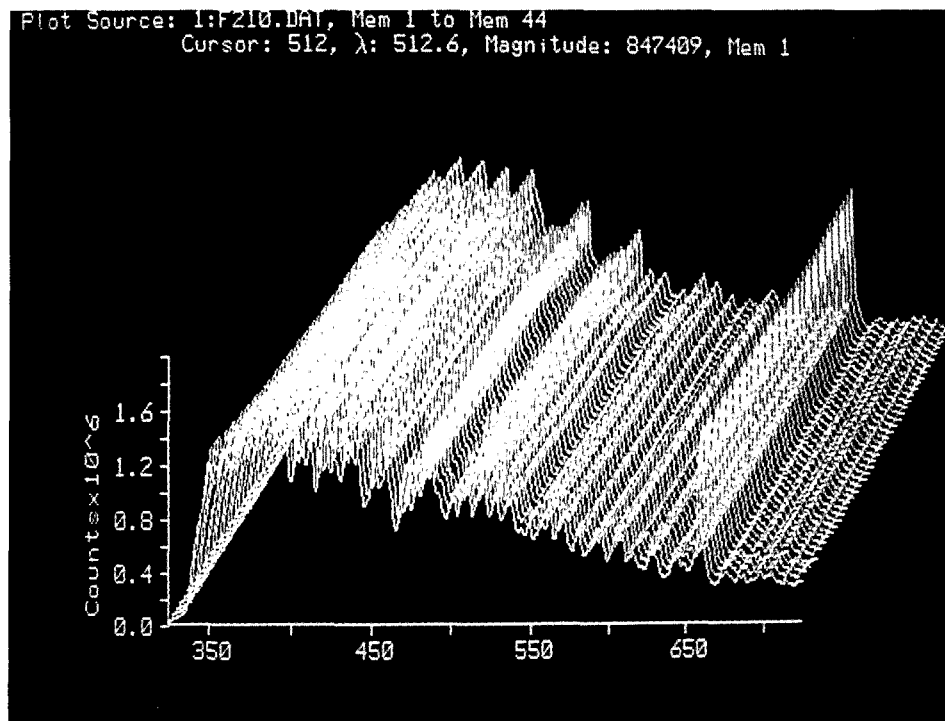
Figure 3. Optical-emission spectra acquired during a CF₄ etch of a SiO₂/Si₃N₄ structure. Each curve represents a time-average of 30 seconds during the 20-minute etch. With the plasma monitor, full spectra can be acquired as rapidly as every 16 ms.
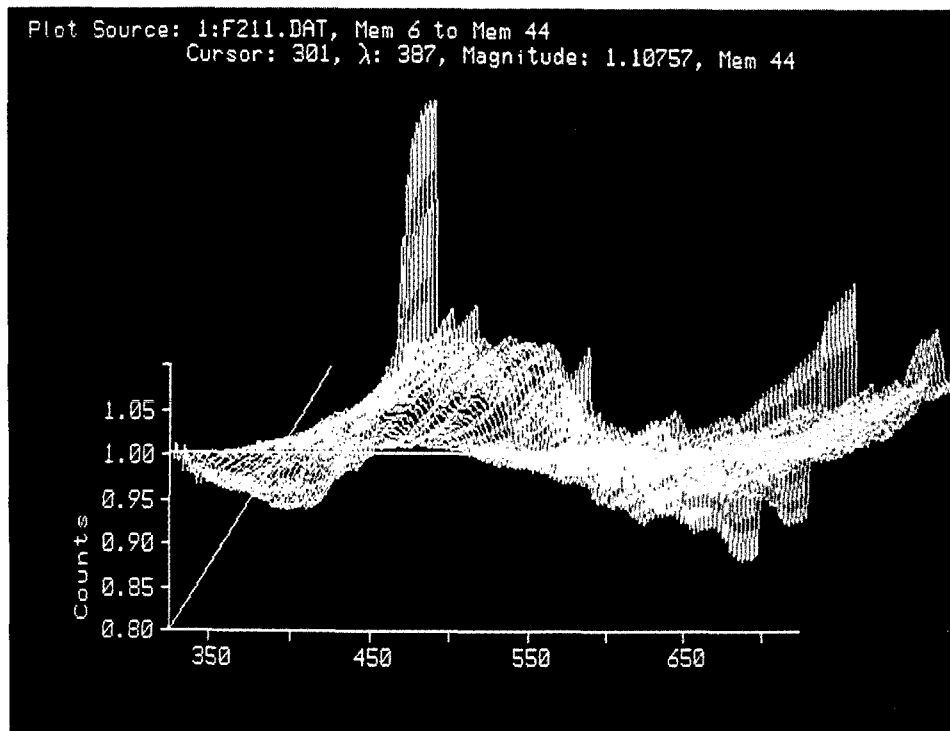
Figure 4. Ratio of each spectrum of Fig. 3 to the spectrum at the beginning of the etch. Note that while the wavelength-dependent intensity varies by about 10 percent during the etch, the most dramatic change occurs at a wavelength of 387 nm, corresponding to emission by the CN radical.

In a dry (or plasma) etch, the wafer is mounted on, and connected electrically to, an electrode within a vacuum chamber. An etchant gas mixture, which is generally inert while neutral, is introduced into the chamber. RF power applied to the electrode then ionizes the gases (i.e., forms a plasma). Because of the difference in mobilities between the positive ions and the electrons in the plasma, a negative self-bias is established on the cathode. This attracts the positive ions, which causes material removal through sputtering. The sputtered material is then swept from the chamber by the gas flow.

The result is a highly directional (vertical) etch, as illustrated in Fig. 1c. Because the sputtering process removes both the resist and the underlying material, gases are used whose ionic species react chemically with the material to be etched (i.e., RIE — reactive-ion etching), but not with the resist. By controlling parameters such as RF power, wafer temperature, partial pressures of the gas mixture, etc., a compromise between directionality and selectivity of the etch can be achieved.

The principal difficulty with plasma etching is generally poor selectivity between the material to be etched and the material immediately beneath it. It is thus critical to be able to monitor the etching process in real time to facilitate recognition of etch completion.

Monitoring the Plasma Process

Although plasma etching is relatively simple in principle, the implementation of a high quality, production-suitable chamber is extremely complicated. Vacuum integrity and background pressure, control of gas flow rates and distribution, control and uniformity of wafer temperature, and RF power level and distribution all contribute to the quality and repeatability of the process.

To be effective, a process-monitoring technique must exhibit a number of key features. It must be:

- Non-Invasive,
- Reliable,
- Repeatable,
- Flexible, and
- Simple.

The first characteristic, non-invasiveness, is most important; the interaction of the process parameters must not be tampered with, and the plasma chemistry must not be disrupted. This criterion is best satisfied by optical techniques. Without disturbing the process in any way, it is possible to

sary hardware. It is possible, for example, to find a chemical that etches a material of interest (e.g., Al, SiO₂, etc.), yet "stops" at the underlying material. The primary disadvantage of wet-chemical etching is that it is largely isotropic — i.e., it etches equally in *all* directions (laterally as well as vertical-

ly), as shown in Fig. 1b. The resist must be thick enough — typically, 1 to 3 μm — to form a continuous film, and to achieve planarization over previously processed features. It is difficult, therefore, *to produce features much smaller* than about 3 μm by wet chemical techniques.
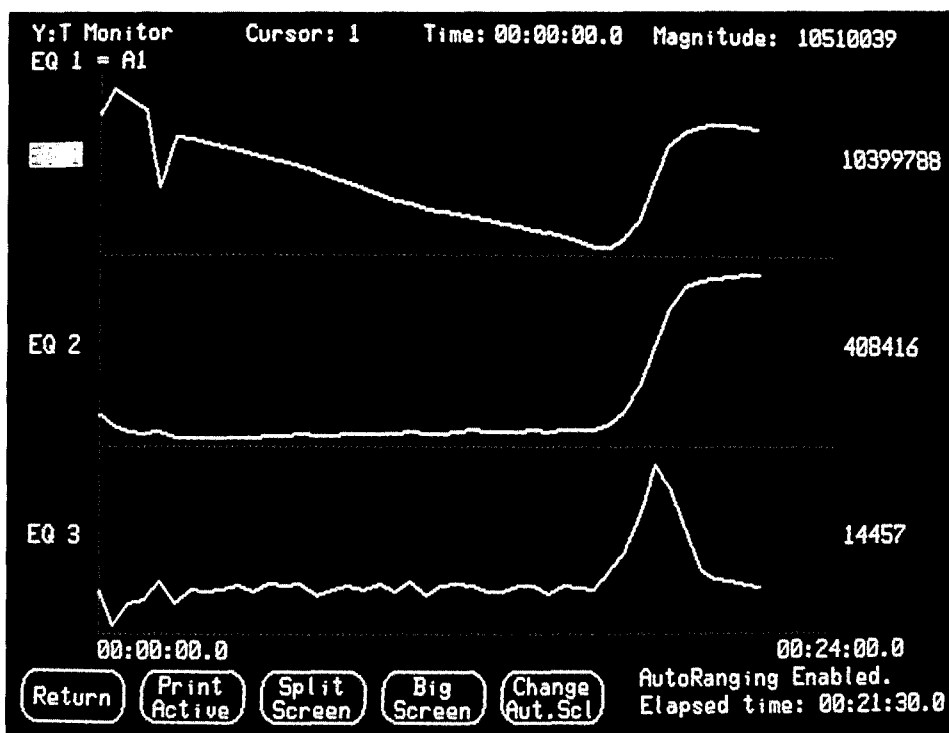
Figure 7. Equation 1 — the time-dependence of the total intensity in the spectral region around 387 nm — shows how the endpoint (increase) is masked by the overall decrease in total plasma emission. In equation 2, the CN emission was corrected for the falling background, creating a clean endpoint signal. Equation 3 is the time derivative of equation 2, that facilitates quantification of etch uniformity.
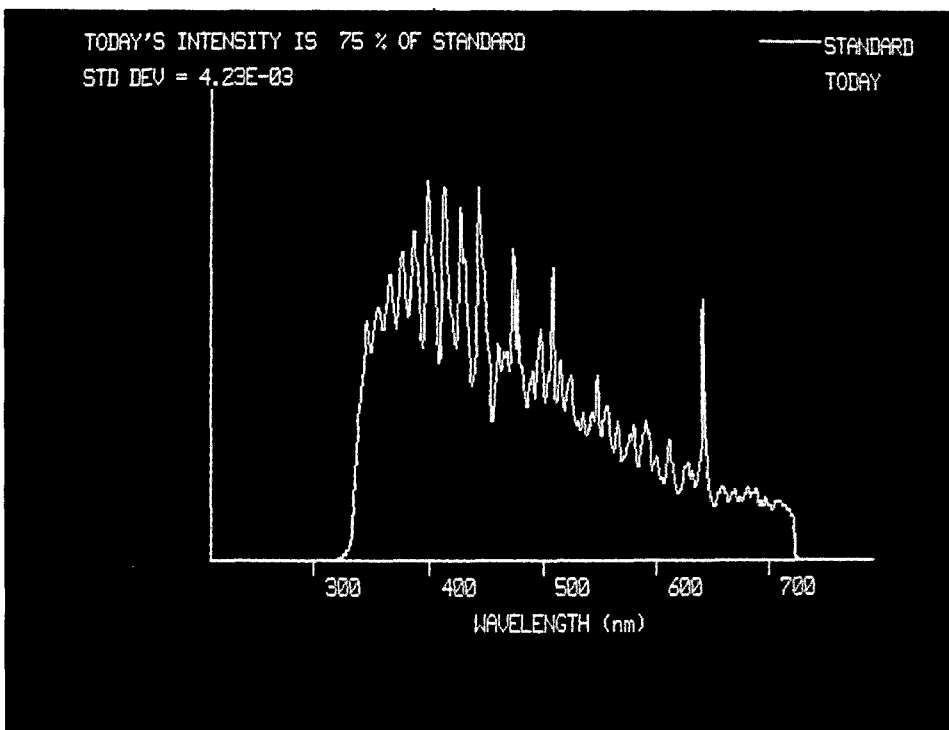

Figure 8. Comparison of a new spectrum with a standard, together with calculated relative intensities and standard deviation (σ).

sured with an Optical Multichannel Analyzer (OMA). The detector is a 512- or 1024-channel photodiode array with on-chip readout electronics. For low-light-level processes, an image intensifier tube is incorporated in the detector to amplify the optical signal.

The detector is controlled by a console that includes both detector control electronics, and rapid processing and display capabilities. The software supplied with the console controls the detector, facilitates analysis of the data (including procedures for the development of new processes), and provides direct communication of the console with the plasma chamber for process control. For convenience in the clean room, a touch screen is provided, as well as a keyboard. A simple Basic programming package allows users to customize the screen for repeated procedures, and "keystroke programming" makes possible the grouping of sequences of commands in the same way that a hand calculator is programmed

Let us consider some of the ways in which optical emission spectroscopy is used to support plasma processes.

Using OES for Development/Control

Figures 3 through 7 illustrate how, with the appropriate software, OES can be used to develop a process – even in the absence of detailed chemical information. The desired process was a CF_4

Without disturbing the process in any way, it is possible to "look" into the chamber through view ports that are already there, to quantify the optical information that is available, and to use that information to control the process.

etch through a thick layer of SiO_2, with the goal of stopping at a thin interface layer of Si_3N_4, even though the CF_4 etches both. The etch took place for a period of 20 minutes, during which a full spectrum was acquired every 30 seconds. For signal-averaging purposes, each spectrum was actually the average of 300 100-ms-duration measurements.

Figure 3 presents the full spectra plotted as a function of time. There is so much spectral information present that it appears to be unusable. The emissions from the reactants and their byproducts are confused by organic emission lines from eroding photoresist, and the entire spectrum includes

terfering spectral lines, it may be possible to monitor the etch with nothing more than a spectral bandpass filter and a photodiode. To quantify more complex optical spectra, however, and to take advantage of the full power of OES, it is necessary to monitor the full changing optical spectrum in real time.

An instrument that is capable of doing this is the plasma monitor shown in Fig. 2. It employs a fiberoptic cable to "look" into the chamber, and to transmit a sample of the optical radiation present to a spectrograph that disperses it into its constituent wavelengths. The output of the spectrograph is mea-
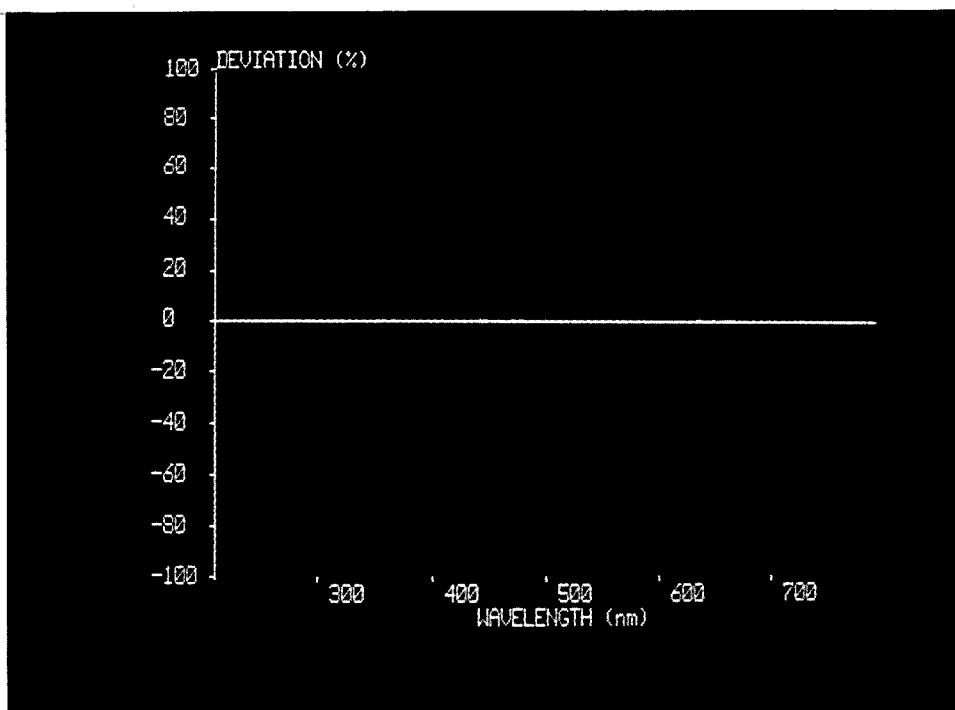
4

Figure 9. Wavelength-dependence of the difference between new and standard spectra, highlighting extra CN (387-nm) and hydrogen (657-nm) emissions.

Wavelength (nm)	Species	Wavelength (nm)	Species
247.9	NO	519.8	CO
251.9	CF$_2$	656.5	H
261.4	AlCl	674.0	N
288.2	Si	685.4	F
308.2	Al	703.7	F
308.9	OH	712.8	F
337.0	N$_2$	725.6	Cl
387.0	CN	741.4	Cl
483.5	CO	777.0	SiF
486.1	H	777.2	O

an interference pattern formed by reflection of the broadband plasma glow from the surfaces of the transparent dielectrics.

Using the software provided with the plasma monitor, each of the spectra was divided by the first spectrum to emphasize changes. The resulting ratios are plotted in Fig. 4, which clearly indicates that the most significant change occurs at a wavelength of 387 nm (the CN emission line). The raw spectral data are replotted in Fig. 5, which emphasizes the wavelength band between 375 and 400 nm. The growth of the new spectral feature at the end of the etch can then be clearly seen.

In Fig. 6, the plasma monitor's postprocessing capabilities are used to identify, graphically, spectral regions for further investigation. As many as 24 spectral regions can be isolated and 8 algorithms defined. In this example, the three algorithms chosen were the total intensity of the 387-nm line, its intensity with the background glow of the plasma subtracted, and the time derivative of the corrected intensity.

The time dependences of these algorithms are plotted in Fig. 7. In the first algorithm, the endpoint is masked by the falling plasma background. Using the ability of a full-spectrum instrument to correct for the background, the true endpoint can be seen in the second algorithm. The time duration of the endpoint – i.e. the uniformity of the etch – can be quantified easily using the third algorithm. Any of these conditions can be used to communicate with the etcher, to control the actual process in real time.

Using OES to "Fingerprint" a Process

We have seen that the ability of optical-emission spectroscopy to monitor the chemistry of a plasma process in real time assists in process parameter development, and can be used for sensitive endpoint detection. Another valuable application is the "fingerprinting" of a process or gas. The emission spectrum in a chamber depends on the gas mixture present, the background pressure in the chamber, and the RF power used to generate the plasma. The presence of spectral lines that do not belong is an indication of potential problems.

The presence of nitrogen, for example, may indicate an air leak. By using the intensity-vs-time feature of the spectrometer, the intensity of the nitrogen peak can be monitored as fittings are adjusted. The spectrometer can thus act as a non-invasive leak detector.

A common problem when etching through photoresist is polymer buildup on the walls of the reactor. This can be detected by the presence of CO emission. Eventually the polymer will begin to flake off the walls, causing catastrophic yield loss. Excitation of an oxygen plasma in the chamber can be used remove the polymer. The CO emission intensity can then be used to verify that the cleaning is complete, thus optimizing the time between teardowns.

Gas bottles are re-used. Faulty valves or regulators can allow leaks that contaminate the contents of the bottle. By exciting a plasma of the gas

> **The presence of spectral lines that do not belong is an indication of potential problems.**

when using a new bottle for the first time, and comparing the emission spectrum to that of a known pure bottle, problems can be anticipated and avoided.

The plasma monitor makes process and gas fingerprinting convenient; specific software can be activated by means of its touch screen. The operator need only touch the screen and the instrument reads the relevant reference spectrum, takes a new spectrum with the same measurement parameters, stores the new spectrum in a dated file for trend analysis, plots both spectra on the screen, and calculates the relative intensity and normalized standard deviation, as shown in Fig. 8.

If the standard deviation is out of limits, an alarm is triggered to alert the operator. With a second touch of the screen, a normalized difference plot such as that of Fig. 9 is generated, to allow the operator to identify missing or extra lines quickly.

Using OES for QC/Troubleshooting

The trend toward integration of the various tools on a fab line by means of a central computer makes OES an even more valuable technique. In a chlorine etch of aluminum, for example, the AlCl line is so intense that repeatable endpointing can be accomplished with nothing more than an optical bandpass filter and a photodiode. For quality control, however, full spectral information is required.

The AlCl emission intensity follows

"look" into the chamber through view ports that are already there, to quantify the optical information that is available, and to use that information to control the process. It is safe to say that, with the exception of simple, noncritical processes in which control by elapsed time is adequate, optical techniques are universally used to monitor plasma etch processes, and to determine their endpoints.

Optical techniques fall into two broad categories: interferometry, and emission spectroscopy. In interferometry, commonly known as laser endpointing, the reflection of a monochromatic laser beam from the wafer surface is measured with a photodiode. As the thickness of the dielectric film changes as it is etched away, the reflection goes through a series of maxima and minima due to constructive and destructive interference between light reflected from the front and back surfaces of the film. This technique is applicable only to the processing of *dielectric* films, and monitors only a small spot on the wafer, thus providing no information on uniformity.

The most powerful and flexible endpoint-detection technique is optical emission spectroscopy. Let us briefly describe OES and the equipment that is necessary for its implementation, together with examples of the uses of OES and a summary of the ability of high quality OES equipment to perform other optical techniques.

Optical Emission Spectroscopy

What is optical emission spectroscopy, and how does it relate to plasma etching? When an atom or a molecule is "excited" by a "pump" (i.e., when it absorbs energy), one mechanism for "relaxing" into its ground state is by the emission of a photon whose wavelength is characteristic of the energy difference between the excited and the ground states. Quantification of the wavelength dependence of this emission *is* optical emission spectroscopy. Examples of the phenomenon of optical emission include LEDs, diode lasers, photoluminescence, laser-induced fluorescence, and plasma emission.

> *The most powerful and flexible endpoint-detection technique is optical emission spectroscopy.*

In a plasma chamber, the gases are in equilibrium between being excited by the RF energy "pump" and relaxing to their respective ground states. They
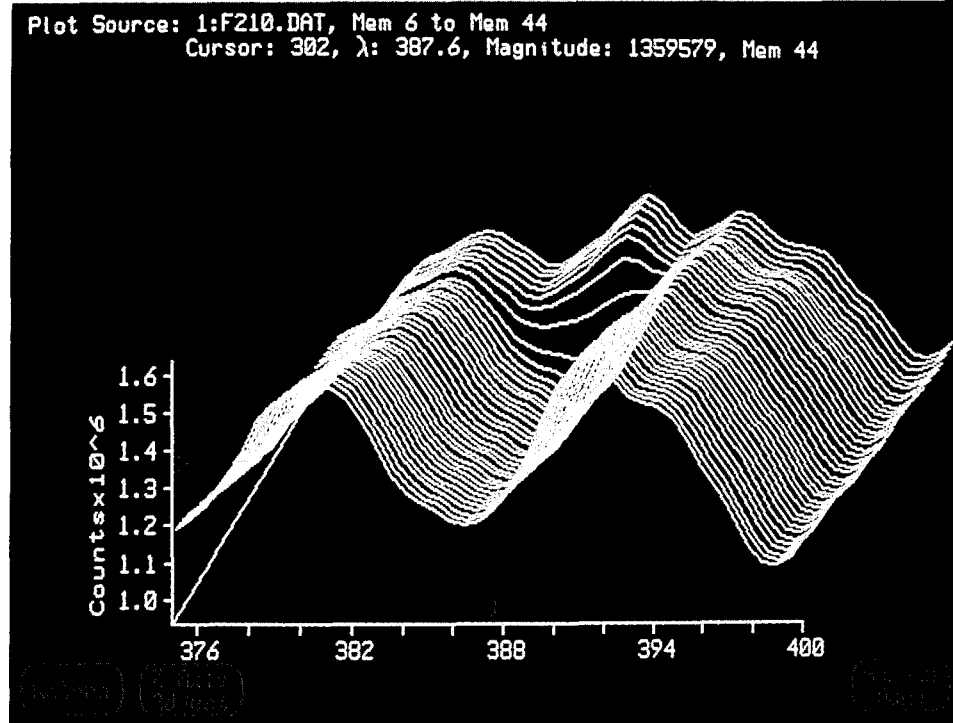

Figure 5. Plot of data from Fig. 3 with the wavelength region from 375 to 400 nm emphasized. The spectral feature at 387 nm is now apparent.
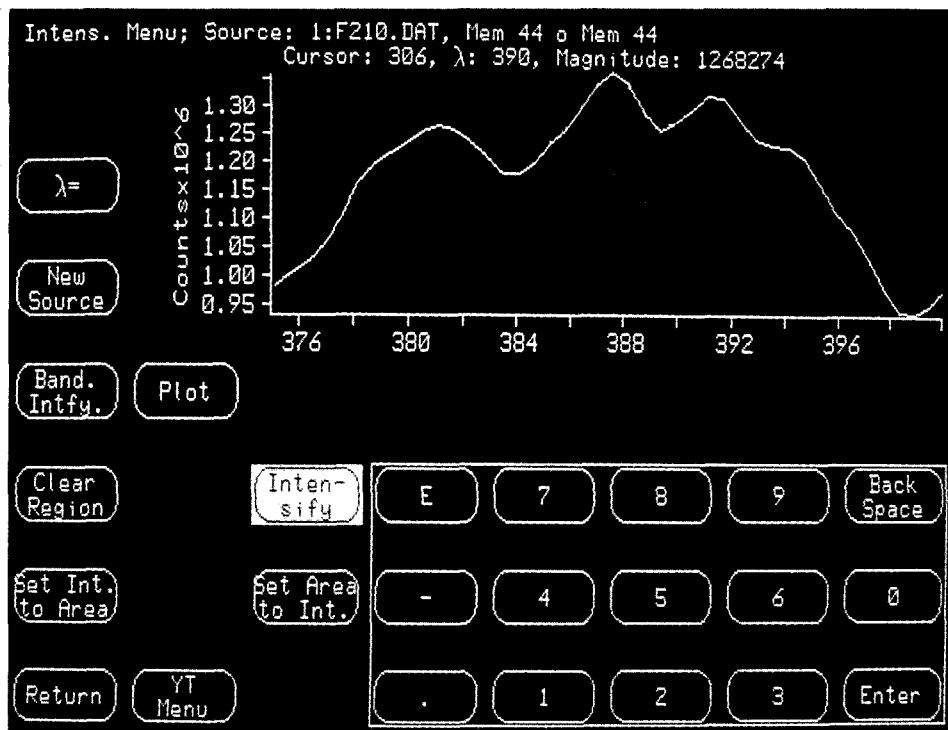

Figure 6. By means of the plasma monitor's post-processing software, spectral regions of interest can be highlighted for use in subsequent analyses.

glow (emit photons of radiation) at a combination of wavelengths that can be used to characterize the plasma.

During plasma etching, the reactants and the byproducts usually emit light that can be used to characterize and monitor the etch chemistry. In a chlorine-based aluminum etch, for example, chlorine radicals combine with the aluminum to form AlCl radicals that relax by emitting light at a wavelength of 261.4 nm. Some commonly used emission wavelengths are listed in Table 1.

If the relevant light emitted is intense compared to the background emission, and is widely spaced from in-

the aluminum etch rate. The CCl emission corresponds to erosion of the photoresist. The process is designed to optimize selectivity between aluminum etching and resist erosion. The ratio of the lines is a monitor of the selectivity that can be used to detect photoresist reticulation. The time integral of the Al-Cl emission intensity measures etch rate, and the width of the endpoint transition measures etch uniformity. It is thus convenient to generate and record trend analyses on spectral purity, selectivity, etch rate, and etch uniformity for each run.

Summary

Advances in silicon processing technology will make the use of OES even more important. The use of ever larger wafers mandates single-wafer processing that must be much faster to maintain throughput, and thus requires more precise real-time control. The structures used to process sub-micron

geometries require processing using complicated chemistries whose monitoring demands full spectral information.

Optical emission spectroscopy has been and continues to be an important technique for the support of plasma processing. It is used to study the fundamental chemistry, to develop new processes, to monitor processes in a production environment, and to anticipate, detect, and diagnose problems.

MMT
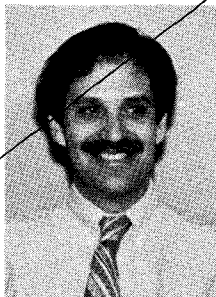
Marshall J. Cohen received the PhD in Solid State Physics from the University of Pennsylvania, where he remained for an additional two years as a research associate. In 1977 he joined Rockwell International's Science Center where, in

1979, he became section manager for GaAs charge-coupled devices. His section developed the first CCD to clock in excess of 1 GHz, and the first heterojunction monolithic CCD imagers. Dr. Cohen was then associated with the Chevron Research Company as a senior research physicist, after which he became director of research at Applied Solar Energy Corporation, where he led an effort in the development and commercialization of GaAs solar cells and other optoelectronic devices. Dr. Cohen is currently Business Element Manager for Semiconductor Instruments at EG&G Princeton Applied Research, where he has responsibility for the application of PARC's products to semiconductor research and process development and control.

For more information concerning any aspect of this article, the author, Dr. Marshall Cohen, can be reached at EG&G Princeton Applied Research, Scientific Instruments Division, P.O. Box 2565, Princeton, New Jersey 08543 (telephone 609/452-2111).