Plasma-Etching Endpoint Detection*

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Because plasma-etching processes generally lack the selectivity of their wet-processing counterparts, and because the trend toward smaller geometries severely limits the amount of overetch that can be tolerated, the success of any dry-etching technique is highly dependent upon accurate determination of the etching endpoint. Of the numerous endpoint detection methods that have been investigated, each of which measures some property of the process that exhibits a change when etching has been completed, optical emission spectroscopy appears to offer the greatest potential for satisfying present and future requirements of plasma technology.

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For semiconductor wafer fabrication, the potential of plasma-etching technologies continues to be exploited as minimum lithographic features approach submicrometer dimensions. The control and monitoring of plasma processes must also evolve with this technology. By their nature, many processes require careful process control to minimize the amount of overetch that occurs, resulting in undesirable dimensional loss. As a means to control the process, etch endpoint detection (EPD) has received a great deal of attention [1, 2, 3, 4]. Various EPD methods are currently available, each with its inherent advantages and disadvantages, and each technique must be examined carefully to determine which is most suitable for a given application.

The key to success for EPD techniques (automatic or manual) is the ability to indicate the endpoint and then terminate etching without any unnecessary overetch taking place. The *necessary* overetch is determined by factors such as film or etch variations. Minimizing the amount of overetch is particularly important for batch tools, where it is critical to stop etching at that point where the film has been completely removed (vertically) on *all* wafers. The implication is that dimensional loss is reduced by minimizing the amount of overetch.

Most endpoint-detection methods in use today require operator intervention. In order to take full advantage of plasma-etching technology, operator-free or automatic endpoint detection (AEPD) must evolve. As a result, the various EPD techniques should be reexamined with respect to their applications for automatic process control. Although some equipment manufacturers are beginning to offer first-generation AEPD techniques, their effectiveness at eliminating all unnecessary overetch must be examined carefully.

Because plasma tools and processing are becoming more sophisticated and complex, routine process monitoring is necessary, due to ordinary tool fluctuations, tool-to-tool variations, and tool/process variations after routine maintenance or repair. For it to be effective, routine monitoring should be independent of the tool itself, and it becomes particularly important after an etch-tool repair when an unobserved error in calibration may alter the base process.

Endpoint-Detection Techniques

In its broadest sense, endpoint detection refers to the control of an etch process by measuring some property of the process that changes when the desired etching has been completed. This normally corresponds to the point where the film has been completely removed vertically. Numerous EPD methods have been reported. Among them are:

- Laser interferometry
- Mass spectroscopy
- Pressure
- Mass flowmeter
- Discharge impedance
- Optical emission spectroscopy

Generally, the effectiveness of a given technique is revealed by examining its important features with re-

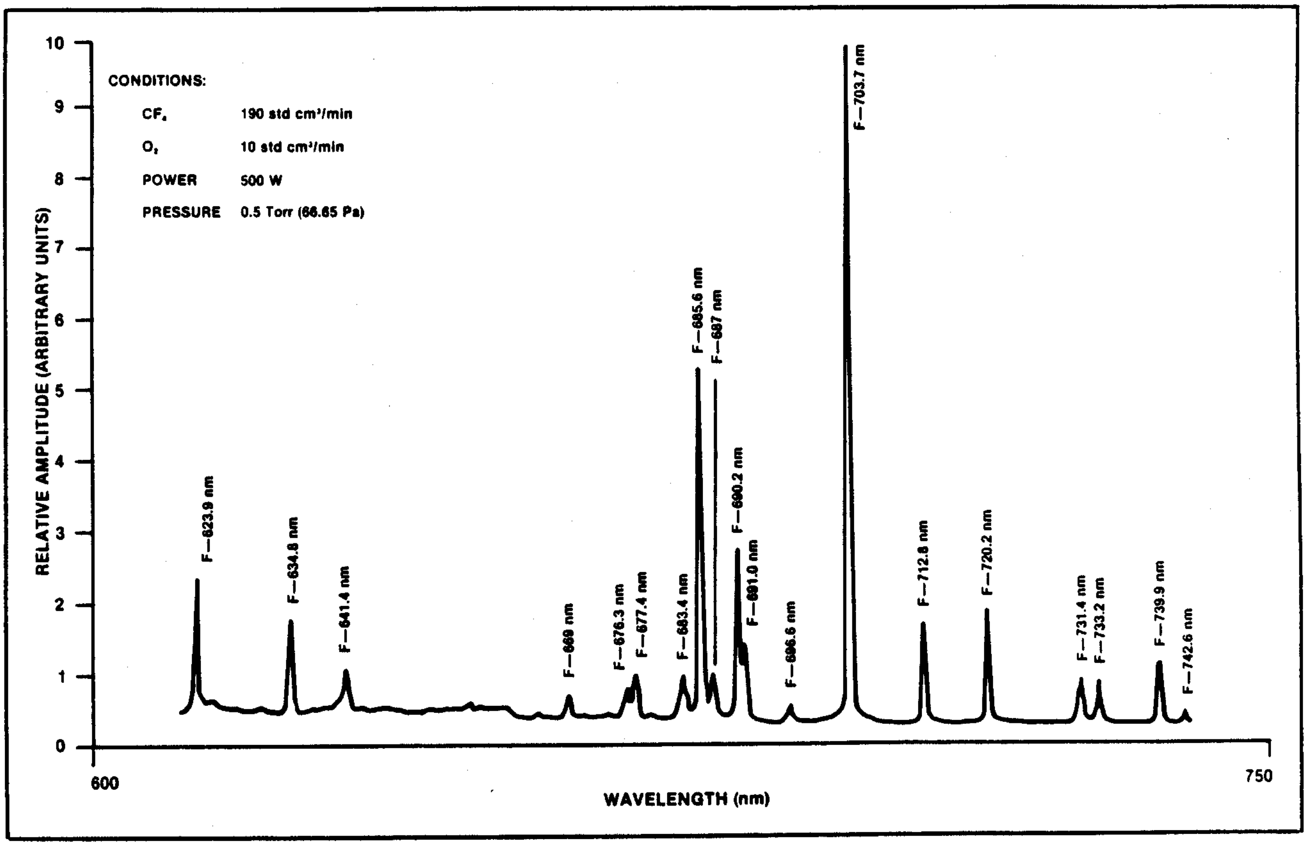

Figure 1. Emission spectrum of CF$_4$/O$_2$ process. Relative amplitude of emission is presented as a function of wavelength over the region of the visible spectrum between 600 and 750 nanometers. Major fluorine peaks are identified. Process employed 190 and 10 std cm^3/min, respectively, of CF$_4$ and O$_2$, with 500 W of power and pressure of 66.7 Pa.

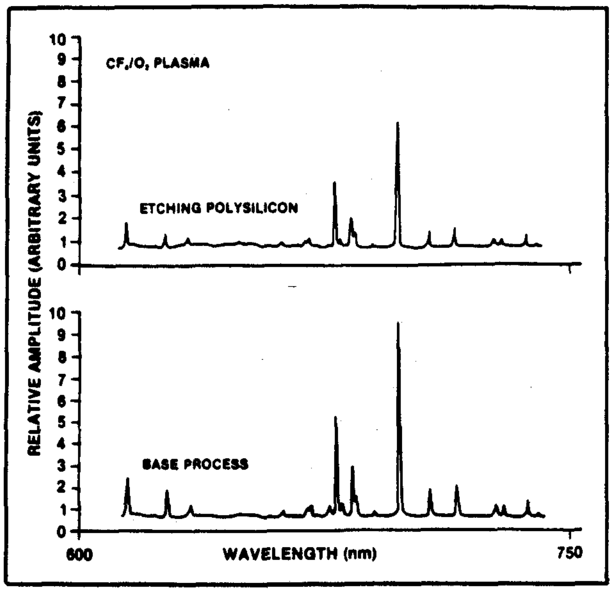

Figure 2. Emission spectrum of $CF_4 / 0_2$ plasma while etching polysilicon, together with that of base process (spectrum shown in Fig. 1). Note changes in peak intensities.

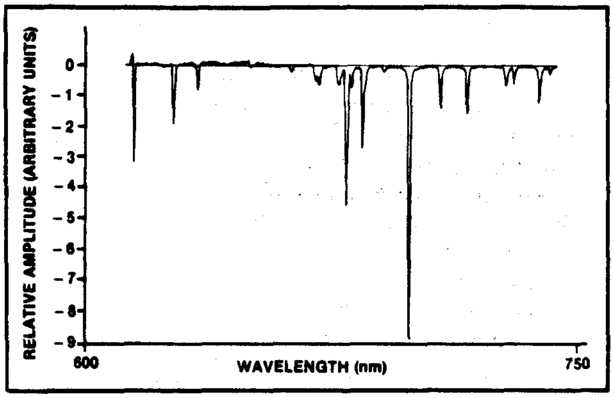

Figure 3. Base spectrum subtracted from etching spectrum (curves of Fig. 2) identifies potential peaks that can be monitored for endpoint detection.

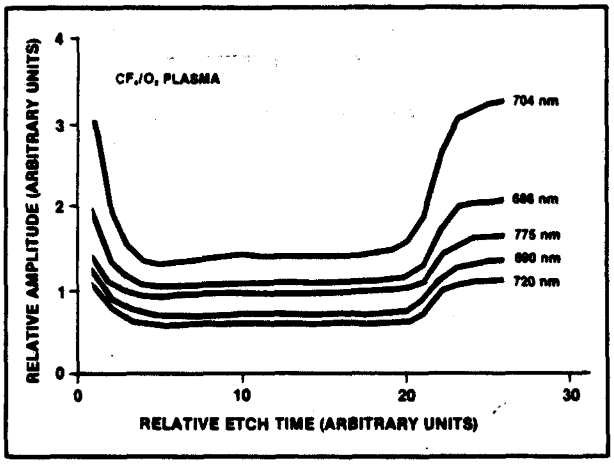

Figure 4. Relative amplitudes of five different wavelengths as monitored for endpoint detection during CF_4 / O_2-plasma etching of polysilicon.

spect to EPD requirements. First, does the technique indicate the endpoint of a batch, or must it be correlated for the batch endpoint? This is important for batch systems and single-wafer tools where poor uniformity exists. Second, does the endpoint's signal sensitivity to the point of transition make the technique successful for one application but not for another? This sensitivity can manifest itself as a dependency on the etchable surface area, film composition, or even the etchant chemistry. In some cases, the technique can be modified easily to suit the film or etchant dependency. Finally, does the technique offer desirable system/process diagnostics?

For batch-endpoint-detection, it is necessary that the etching chemistry for the film to be etched be different from that of the underlying barrier. The magnitude of this requirement is a function of each particular application. Table I summarizes the characteristics of the six EPD techniques to be discussed.

Laser Interferometry [5, 6]

The intensity of a laser beam reflected from a substrate covered by a transparent film is a function of the interference between the light reflected from the top and bottom surfaces of the film. As the film is etched, film thickness is decreased and the intensity passes through maxima and minima corresponding to points of constructive and destructive interference. When the film has been completely etched, the intensity becomes a constant (assuming that no etching of the substrate occurs), thereby signalling etch endpoint.

If the film is reflective, the etch endpoint can be determined by using a fine grating pattern [6] as a laser endpoint site. The light reflected from the etched and unetched surfaces interferes to produce endpoint curves similar to those for transparent films.

This technique actually indicates the endpoint at the single site where the laser light intercepts the wafer. This can be a disadvantage if an indication of endpoint for a batch of wafers is desired. Correlation of this endpoint to the etch completion of all remaining wafers is then required. If a reliable correlation is established, batch-to-batch thickness variations may still result in unnecessary overetch. However, laser interferometry can be useful as an *in-situ* thickness or etch-rate monitor. The signal level for this technique is generally not a function of the etchable surface area, although an EPD site with some minimum lithographic dimensions may be desirable. It should be noted that the etching process being monitored may be enhanced or retarded at the laser site due to perturbations of the plasma by the presence of the laser-light access port, or by laser-light interactions with the local reactant species or the surface of the wafer being etched.

Mass Spectroscopy [7, 8]

The mass spectrometer monitors plasma effluents directly. The ionized molecular fragments, each of which exhibits a specific ratio of mass-to-charge, give rise to identifiable peaks in the mass/charge spectrum. The intensity of each peak reflects the relative abundance of the ion producing the signal. Time-base monitoring of the peak(s) for a particular product or

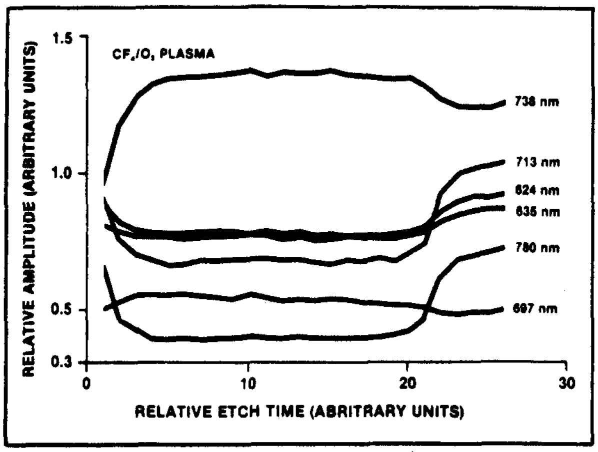

Figure 5. Relative amplitudes of six additional wavelengths as monitored for endpoint detection during the same CF_4/O_2-plasma etching of polysilicon shown in Fig. 4.

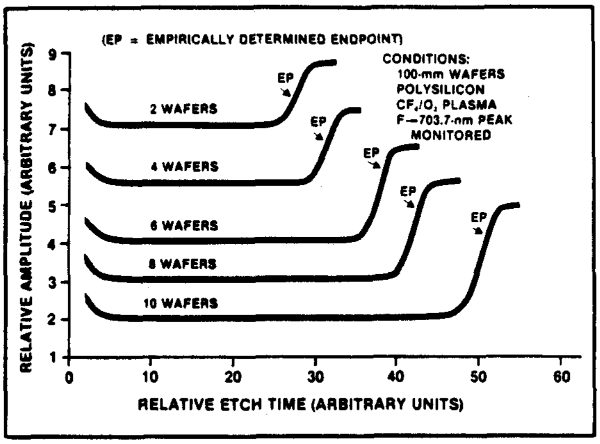

Figure 6. Emission endpoint curves of CF_4/O_2 plasma etching of polysilicon for six different batch sizes. Relative amplitudes of the 704-nm fluorine peaks are shown as a function of relative etch time. EP indicates the point at which the vertical removal of polysilicon is complete.

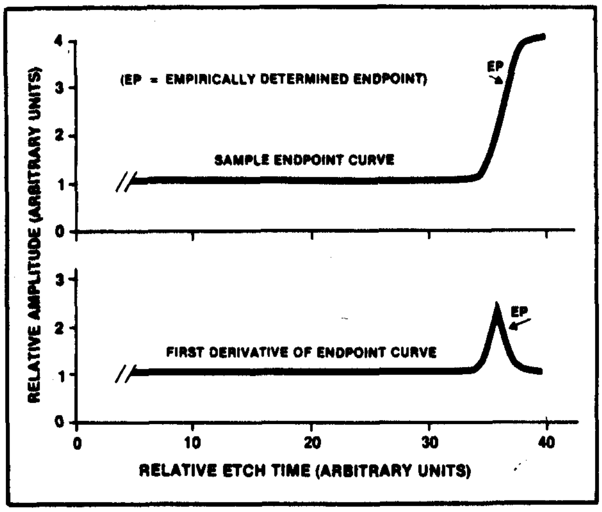

Figure 7. Sample endpoint curve and its digital derivative. The digital-derivative (or slope) technique eliminates endpoint uncertainty caused by routine process variations.

reactant in the plasma during the course of an etch process produces an endpoint curve.

This particular batch endpoint technique offers several desirable features, including detailed diagnostic capability and leak detection. Although the sensitivity of this technique is a function of the film and the etchant, the selection of peaks corresponding to the appropriate species is generally straightforward and easily modified. However, the sensitivity of the technique to the etchable surface area limits its effectiveness for applications such as the etching of contact vias.

Although mass spectroscopy is a potentially powerful analytical tool, several of its inherent features combine to make it less desirable for plasma-processing applications. For example, the need to integrate the detector head with the etching tool's vacuum system makes the technique somewhat inflexible. This is especially true since the detector head must be cleaned periodically after being contaminated by the plasma process species and reaction products. The maintenance of a separate high-vacuum system is an additional disadvantage of this technique.

Pressure [9]

This batch endpoint technique is implemented by monitoring the total pressure in the plasma chamber. Etch endpoint is observed when changes occur in the partial pressure of reactants and/or products, as the etching nears completion. For this technique to be effective, total reactant flow must be held constant, and system pumping speed is generally assumed constant.

Although the technique is generally insensitive to the particular film to be etched, a high sensitivity to etchable surface area has been observed. This sensitivity limits the technique's effectiveness for large etchable surface areas (e.g., photoresist stripping and aluminum etching). The limitation is particularly important when batch sizes are varied. However, this batch monitoring technique is useful as a simple diagnostic tool for monitoring water vapor [9].

Mass Flowmeter

This technique is a simple extension of pressure EPD in which system pressure is held constant by adjusting the mass flow of the process gases, rather than

TABLE I – COMPARISON OF ETCH ENDPOINT TECHNIQUES

Endpoint Technique	Batch	Signal Sensitivity			Changeable for Film/Etchant	Detailed Diagnostic
		Surface Area	Film	Etchant		
Laser Interferometry	No	No	No	No	—	No
Emission Spectroscopy	Yes	Yes	Yes	Yes	Yes	Yes
Mass Spectroscopy	Yes	Yes	Yes	Yes	Yes	Yes
Pressure	Yes	Yes	No	No	—	No
Mass Flowmeter	Yes	Yes	No	No	—	No
Discharge Impedance	Yes	Yes	No	No	—	No

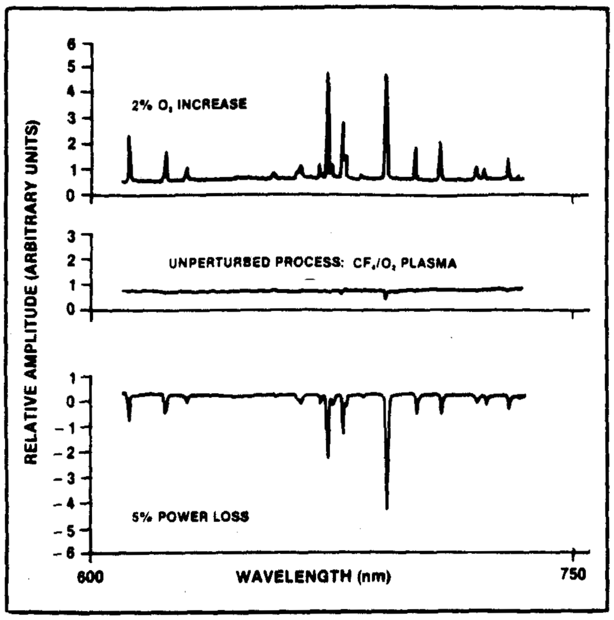

Figure 8. Whole-spectrum subtraction of the base-process spectrum for a CF_4/O_2 plasma from that of: a process experiencing a 5% power decrease, the base-process at a different point in time, and a process with a 2% increase in oxygen. The technique is a sensitive indicator of any change in process environment.

by means of the throttle valve. An endpoint curve is generated by monitoring the mass flow of the process gases (e.g., voltage applied to the mass-flow controller or proportioning valve). Endpoint occurs when reactant and reaction-product partial pressures change as the etching nears completion, requiring a flow adjustment to maintain the total pressure. This technique has the same inherent advantages/disadvantages as those of the pressure technique, but may be preferred over pressure EPD if it is simpler to implement.

Discharge Impedance [10, 11]

As an etching process nears completion, changes in the concentrations of the plasma constituents (reactants and/or products) result in changes in the electrical impedance of the discharge. Therefore, etch endpoint can be determined by monitoring the discharge impedance. For internal-electrode systems, several monitoring approaches are possible, including radio-frequency (RF) peak voltage, direct-circuit (DC) potential, and RF power. The only requirement is that one of these parameters must be controlled while either of the other two is monitored for endpoint. We find the simplest and most effective technique involves measurement of the plasma-induced DC potential of a capacitively-coupled electrode while input power or RF peak voltage is controlled.

TABLE II – EMISSION ENDPOINT PEAKS

Monitored Species	Wavelength (nm)	Monitored Species	Wavelength (nm)
Al^*	308.2	H^*	656.5
$AlCl^*$	261.4	H^*	486.1
CF_2^*	251.9	N^*	674
Cl^*	725.6	N_2^*	337
Cl^*	741.4	NO^*	247.9
CN^*	387	O^*	777.2
CO^*	483.5	O^*	844.7
CO^*	519.8	OH^*	308.9
F^*	703.7	S^*	469.5
F^*	685.4	Si^*	288.2
F^*	712.8	SiF^*	777

The sensitivity of impedance EPD is a function of the film, the etchant, and the etchable surface area. However, the technique does provide some limited process-control information. A change in the absolute value or the shape of the endpoint curve during the etch process reflects a change in the base process. Unfortunately, little information is provided to identify the cause of the change.

Optical-Emission Spectroscopy [12, 13, 14]

In general, for optical-emission spectroscopy, light emitted by the plasma is viewed by an optical detector. Etching endpoint is detected by monitoring the amplitude or amplitude-ratio changes of particular emission lines as etching nears completion. The use of a photocell with either a bandpass or interference filter is considered a simple subset of optical-emission spectroscopy. A more sophisticated technique employs a monochromator arrangement.

Like mass spectroscopy, this technique is sensitive to the film, etchant, and etchable surface area. It can also be adjusted easily for a particular chemistry or film. Although it is sensitive to the etchable surface area, optical-emission spectroscopy is nonetheless effective for very-small-surface-area applications (e.g., contact vias). It can also be used for detailed diagnostics or routine process control by means of plasma-process-spectra matching.

In consideration of the preceding discussion, we have chosen emission spectroscopy as the technique with the greatest potential to satisfy the present and future requirements of plasma technology. Therefore, let us explore in detail the practical applications of emission spectroscopy to plasma technology.

Advantages of Emission Spectroscopy

Emission spectroscopy is a very flexible endpoint-detection method. An endpoint-appropriate peak that is a function of the film being etched and of the plasma chemistry being used can always be found easily. Most tools offer immediate assignment of the peak to be monitored, which can be that of either a reactant or a product of the reaction. A species that does not become involved directly in the etching, but whose emission is diminished or quenched by a product of the reaction, may be monitored. As another example, one can monitor the emission of a species that is quenched by other reactants in the plasma when no etching is being accomplished, but whose emission intensity is increased upon reduction of the quenching-reactant concentration once etching begins.

To demonstrate the ease with which emission spectroscopy can be implemented, let us consider an example of etching polysilicon with CF_4/O_2 in a parallel-plate system. Figure 1 shows the emission spectrum of a CF_4/O_2 plasma process, illustrating the actual process parameters only in the visible region of the spectrum from 600 to 750 nanometers. Assignments for the major peaks are identified. Notice that in this particular region the emission is characteristic of fluorine excited states.

Plasma emission for the same process parameters while etching polysilicon is presented in Fig. 2. The peaks that can be used for endpoint detection are immediately identified by changes in peak intensities. In some cases new peaks representing products of the reaction may appear. Potential endpoint peaks can be identified very quickly by subtracting the etching spectrum from that of the base process.

Figure 3 shows the result of subtracting the spectra in Fig. 2. Any peaks above the zero point indicate either species that are enhanced or emission from products formed during the etching process. Peaks below the zero point generally indicate quenched or reactive species. Any of the peaks that decrease in intensity could be monitored to indicate endpoint. The peak with the greatest signal-to-noise ratio should be selected for routine monitoring.

Representative endpoint curves for etching polysilicon with CF_4/O_2 plasma are shown for various wavelengths in Fig. 4. Notice that the F — 704-nm peak provides the greatest signal-to-noise ratio. Figure 5 is a continuation of Fig. 4 for wavelengths exhibiting lower signal levels than those of Fig. 4. Notice the curve for 738-nm wavelength. This peak is assigned to a N_2 species attributed to the background nitrogen in the system. It is interpreted as representing the absence of background-N_2 quenching during the etching reaction.

The 738-nm curve is an example of a case where an enhanced species could be monitored to determine etch endpoint. Other examples include monitoring the characteristic emission from carrier gases such as Ar, N_2, or He. Several important points to remember are: (1) many wavelengths can be monitored for endpoint; (2) it is not necessary to know a wavelength's actual assignment in order for it to be a useful endpoint peak; and, (3) the species emission monitored need not take place directly in the reaction in order for it to be a useful endpoint peak.

Selection of an appropriate peak can be made by considering the film to be etched and its etching chemistry. For example, if aluminum is etched in chlorine chemistry, the emission of Al could be monitored directly at 308.2 nm [15]. Oxide etching might necessitate monitoring a CO line at 483.5 nm or 519.8 nm [12]. Table II lists the peaks that could be monitored for endpoint detection. Obviously, based on the previous discussion, this chart presents only a few of the available peaks.

Careful examination of the commercial equipment available suggests that a substantial effort has been made in this area. Equipment ranges from a simple photocell implementation to full emission spectrometers employing microprocessor control — a feature that is very important for automatic endpoint detection. Many systems are also beginning to include automatic endpoint-detection algorithms. The effectiveness of these algorithms depends upon the chemistries used and the amount of overetch that is acceptable.

To fully utilize the advantages of emission spectroscopy for plasma process technology, full emission spectrometers are needed. Although these instruments are certainly more expensive than their photocell counterparts, their cost can soon be recovered through applications beyond simple endpoint detection. Process control through spectra matching and *in-situ* leak detection become routine. Emission spectroscopy can also be of assistance toward process optimization.

Automatic Endpoint-Detection Algorithms

As stated previously, the full potential of plasma processing can be achieved only by developing operator-free or automatic endpoint detection. The EPD algorithm — a key component in the success of any AEPD method — becomes more important as the allowable amount of overetch is reduced, due either to more stringent dimensional-control requirements or to relatively poor selectivity of the etching process between the film to be etched and the underlying barrier layer. For the algorithm to be most effective, it should determine endpoint and stop the etch completely, eliminating any unnecessary overetch.

The two most widely used algorithms are the sample-hold-difference and the transition-threshold value. Less common, but more effective, is the digital-derivative algorithm, that addresses the problems of the first two. A subset of the digital derivative is slope determination. All of these techniques act upon the amplitude of the emission signal, either by direct analog or digitally converted means.

To demonstrate the differences among these algorithms, let us consider some representative endpoint curves. Figure 6 is a graphical representation of polysilicon-etching endpoints, using CF_4/O_2 while monitoring the F — 704-nm fluorine line, chosen because it provides the greatest signal-to-noise ratio. The curves for various batch sizes are indicated. Also identified on each curve is the empirically-determined endpoint — that point at which the vertical removal of polysilicon is complete. Notice that the endpoint is not at the point of stabilization, and that the stabilization points for various batch sizes are not equal. It is important to evaluate the manner in which each endpoint algorithm operates on these data.

The sample-hold-and-difference algorithm determines the stabilization point for each curve. However, it is already known that endpoint occurs prior to stabilization. Therefore, the use of this algorithm would result in unnecessary overetch.

The transition-threshold-value algorithm assumes that the fluorine emission returns to a specified value or a threshold value after the transition begins. However, this transition-threshold value is dependent upon batch size, detector dark current, viewport etching, and normal process variations of power, pressure, flow, etc. Upon careful examination, it is clear that the transition-threshold-value algorithm can be quite ineffective, especially for processes that exhibit loading when etching with gases such as CF_4 and O_2. Even if the process is limited to a given batch size, false endpoints can occur due to routine process variations.

However, if the digital-derivative or slope technique is used, these dependencies are removed. An example of the digital-derivative algorithm operating on a typical endpoint curve is presented in Fig. 7. This

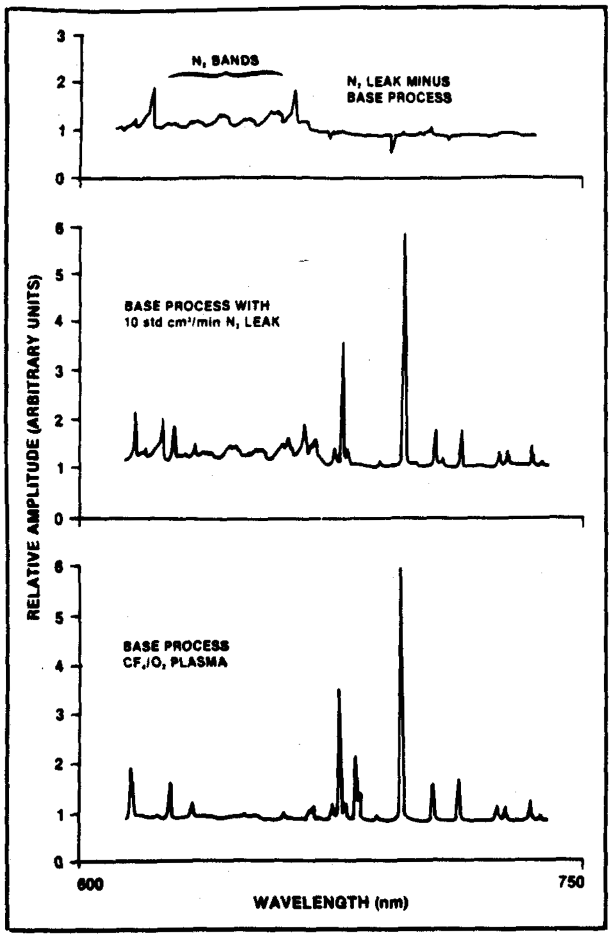

Figure 9. Optical spectrum of a CF_4/O_2 base process and of the base process with a 10 std cm³/min nitrogen leak (leakage of N_2 *into* the system), and then the result of subtracting the two spectra. Note the N_2 lines that appear in the spectrum. Technique provides a sensitive means of *in-situ* leak detection.

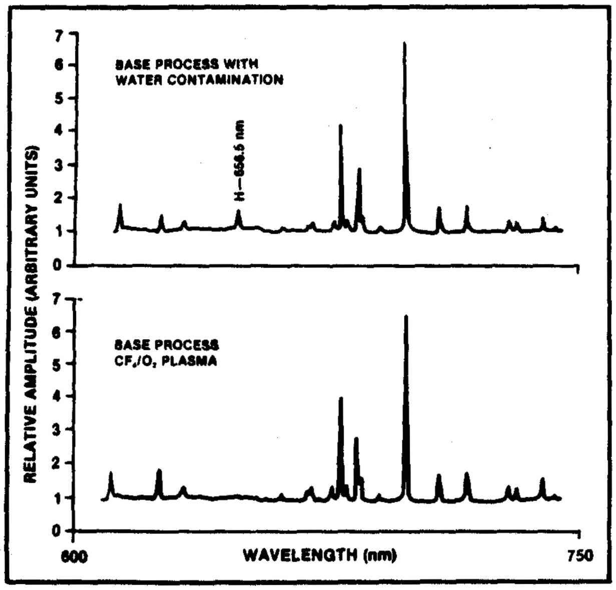

Figure 10. Optical spectra of a CF_4/O_2 base process and of the same process with water contamination. Note appearance of the hydrogen line at 656.5 nm, which is indicative of the presence of contamination.

technique is easily programmed, very reproducible, and is considered to be one of the best for automatic endpoint detection.

Plasma Process Characterization

Other applications of emission spectroscopy are very useful for quality-control purposes in a manufacturing environment. These applications generally require the more sophisticated emission spectrometers. The ultimate goal is to ensure that the wafers being etched experience the same plasma environment routinely. Because this technique monitors the plasma environment itself and not the process parameters, the measurements are independent of the etch tool.

Emission spectroscopy could be used for routine control of the process, which could include establishing limits for tool parameters, evaluating new gas cylinders, and testing the process after a tool repair, as well as comparisons among several tools in a manufacturing environment. All of these functions may be performed on the plasma process without any etching taking place. A subset of routine process control, that can be performed during the etching process, is *in-situ* leak detection.

In the following discussions, process perturbations are applied to the base process shown in Fig. 1. The first application, which must be to the base process without any etching occurring, is to establish process-control limits for the tool parameters that affect the process. These parameters might include pressure, power, gas composition, flow, etc. Wafer-electrode temperature-control limits cannot be defined using this technique, since it is highly unlikely that wafer temperature would affect the plasma significantly. (It may, however, affect the etching properties, and should not be ignored.) Indicated in Fig. 8 is the difference (actual whole-spectra subraction) between the base process and a process with 2 percent O_2 increase, the base process at a different point in time, and a process that experienced a 5 percent power loss.

Notice that the two base processes are not identical. This is the result of normal process variations, and is to be expected. The other two perturbed processes illustrate the sensitivity of the technique and indicate that a different plasma environment is being presented to the wafers. Experience may then be used to determine whether or not the variations are acceptable, or whether further action is required.

A second measurement that may be performed, with or without etching taking place, is *in-situ* leak detection. Figure 9 illustrates the introduction of a 10-standard-cubic-centimeters-per-minute (sccm) N_2 leak into the plasma. The appearance of the nitrogen bands, identified in Fig. 9, is apparent in the resulting spectrum. By closer examination, or by subracting the two spectra, it can be observed that the N_2 has also quenched the fluorine emission. These changes indicate that the base process has been perturbed, and corrective action should be taken.

Some plasma processes are sensitive to water vapor. Figure 10 illustrates another example of *in-situ* leak detection. Here the base process has been purposely contaminated with H_2O. If there is no other source of hydrogen in the process, then one could monitor the 656.5-nm hydrogen emission line to detect the contamination.

In all of the applications cited, process control has been accomplished by comparing the base-process spectrum to that of the perturbed process. This is a general technique that is defined as "process control through spectra match".

Future Developments

Enhancements in plasma technology must be accompanied by further development of endpoint-detection techniques. Many techniques are available to the engineer, and careful examination of those that have been discussed suggests that a given EPD method must be matched properly to a particular application in order to achieve successful etching results.

The continued evolution of plasma processing must be accompanied by further development of automatic EPD. Moreover, since processes and tools continue to become more complex, routine process control must also evolve to monitor tool variations.

Emission spectroscopy, which has been used primarily as a laboratory tool, can also provide a very flexible EPD method for manufacturing applications. In addition, the technique's applicability to automatic EPD makes it an effective approach to the satisfaction of future technology requirements. As the technique continues to evolve, its potential for process optimization will also be used to advantage. ■

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