APPLICATIONS OF OPTICAL EMISSION SPECTROSCOPY TO SEMICONDUCTOR PROCESSING

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ABSTRACT

Optical emission spectroscopy (OES) has proven to be a valuable tool in the development and production of state-of-the-art semiconductor devices. Application to the plasma etching of a variety of materials necessary for integrated circuit fabrication is discussed, with particular emphasis placed on etch endpoint analysis. The utility of OES techniques in monitoring photolithographic processes is also presented.

INTRODUCTION

The process of transferring complex patterns into and onto the surface of a silicon wafer, in order to produce an integrated circuit (IC) presents a formidable challenge to chemists and engineers alike. It requires the formation of accurate masks, as well as highly controlled etching techniques. Optical emission is an inherent part of both of these process steps; as an exposure source for photolithography in the former, and as a by-product of radio frequency (RF) excitation in the latter. This paper will discuss the characterization of this emission by optical emission spectroscopy (OES), and the use of this technique to monitor and control certain aspects of the semiconductor fabrication process.

PLASMA ETCHING

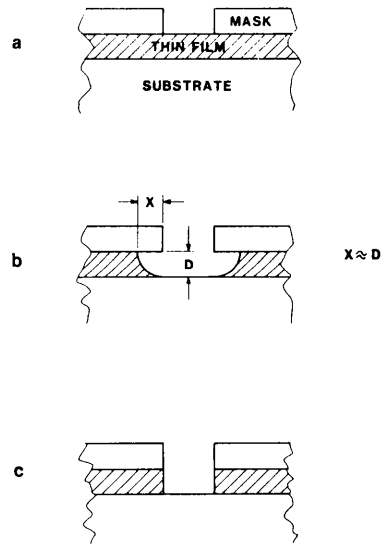
Until recently, wet etching techniques employing nitric and hydrofluoric acid mixtures [1] have been the principle method of pattern transfer. Their widespread acceptance is due primarily to the simplicity of the hardware necessary for implementation and the high selectivity obtainable. Selectivity is defined as the ratio of the etch rate of the film to be etched to the etch rate of the underlying material. Typical selectivities for wet etching are greater than 1000:1.

Unfortunately, wet etching presents several problems, particularly when etching the fine line geometries required by very large scale integration (VLSI) devices. A wet etch proceeds at the same rate in all directions, resulting in an isotropic etch profile which can undercut the etch mask and make it difficult to maintain control of critical dimensions.

In the early 1970's, the use of reduced-pressure, RF discharges or plasmas was investigated for the etching of silicon and silicon-containing materials [2]. These dry etching processes produced an anisotropic etch profile, along with improved cleanliness, both for the device being processed and the local environment. A comparison of typical etch profiles produced by wet and dry processes is presented in Fig. 1. The use of plasma etching also reduced the potential for operator exposure to toxic and corrosive etchants, improving safety in the wafer fab area.

At present, fluorine (CF_4, CHF_3, C_2F_6, C_3F_8 and SF_6) and chlorine (Cl_2, CCl_4 and BCl_3) based plasmas predominate. Often, oxygen is added to the fluorine systems to promote the formation of atomic fluorine [3] and

Figure 1 Comparison of etch profiles:
a) Masked but unetched thin film.
b) Isotropic profile produced by a wet etch, undercut (x) approximately equal to etch depth (d).
c) Anisotropic profile produced by a plasma etch.



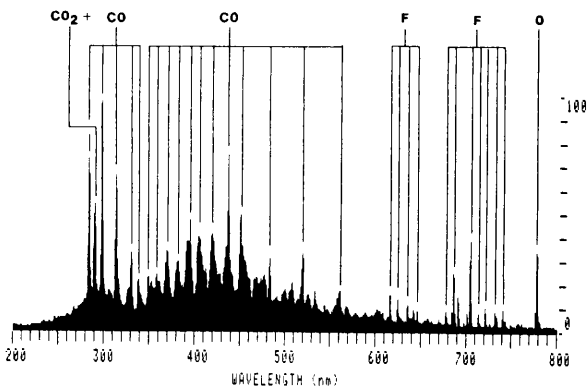


Figure 2 Emission spectrum produced by a CF_4/O_2 plasma maintained under the following conditions: 1000 W at 13.56MHz, 50 mTorr, 40mL/min O_2, 10 mL/min CF_4.

thus increase etch rate. Also, helium is a common additive to reduce wafer surface temperature by increasing the thermal conductivity of the surrounding plasma.

The mechanism of these plasma etching processes is part chemical and part physical. When a plasma contacts a surface, even if that surface is electrically grounded, it takes on a potential which is negative with respect to the plasma [4]. As a result, the wafer surface undergoes positive ion bombardment. The energy of the bombarding ions is established by the difference in potential between the plasma and the wafer. These potentials can be high enough to provide sufficient energy to break chemical bonds and sputter away surface material [5]. This bombardment is directed by the electric field and results in the anisotropic nature of the plasma etch. The chemical nature of plasma etching relies on the formation of atomic fluorine or chlorine through ion and electron collisions in the plasma. Once formed, these active atomic species must diffuse to the wafer surface and be adsorbed. At the surface, a volatile product is formed (i.e. SiF_4 for silicon) and then diffuses away from the surface.

Plasma etching, as described above, is applicable to a wide variety of materials. In general, fluorocarbon/oxygen plasmas are required to etch silicon, polysilicon and doped silicon materials, which are used to form semiconductor junctions and resistors as well as silicon nitride and oxide thin films which are used to form insulating gates, capacitors and a protective cap over the finished circuit. Because of the low volatility of AlF_3, chlorine-based plasmas are preferred for etching aluminum which is used to create conductive interconnections between the circuit components.

MONITORING PLASMA CONDITIONS

Traditionally, plasma etch processes have been controlled by rigorous attention to parameters such as RF power, gas mixture composition and flow, chamber pressure, substrate temperature and load size. Unfortunately, the interaction of these parameters with respect to the plasma chemistry is complex, making process control difficult. OES techniques offer a unique opportunity to monitor plasma chemistry directly and in real time. By viewing the discharge through a window in the chamber, this non-invasive technique can be applied to the many types of etching systems currently employed without any perturbation of the etch process.

The optical emission spectrum of a typical CF_4/O_2 plasma is shown in Fig. 2. This spectrum was collected with the PSS-100 scanning spectrometer system (PT Analytical, Inc.) coupled to a PK-24 plasma etcher (Plasma-Therm, Inc.). The spectral scan was completed in 20 seconds, auto-scaled and displayed on the system monitor, time-stamped, operator and unit identification appended, and finally stored on floppy disk for further manipulation or for future reference. When the spectral emission lines are labeled the utility for process development becomes evident. Notably, the intensity of the O and F lines have been used to identify the etch mechanism for silicon [3]. It is also evident, from the lack of N_2 emission lines, that there are no leaks in the reactor's vacuum system. Typically, a scan such as the one displayed in Fig. 2 can be used to "fingerprint" the plasma under normal operating conditions. Then if a problem arises at a later date, another spectrum can be recorded and compared with the standard. This strategy allows a rapid screening for air leaks, high moisture content and improper or impure process gases.

Spectroscopic techniques can also be applied to monitoring chamber cleanliness. Under some conditions a carbonaceous polymer may form on the electrode and chamber surfaces [6]. This material can alter the etching characteristics of the chamber, outgas adsorbed moisture, or even flake and cause particulate contamination. This material can be removed by initiating an O_2 or O_2/SF_6 plasma in an empty chamber. Fig. 3 documents the course of

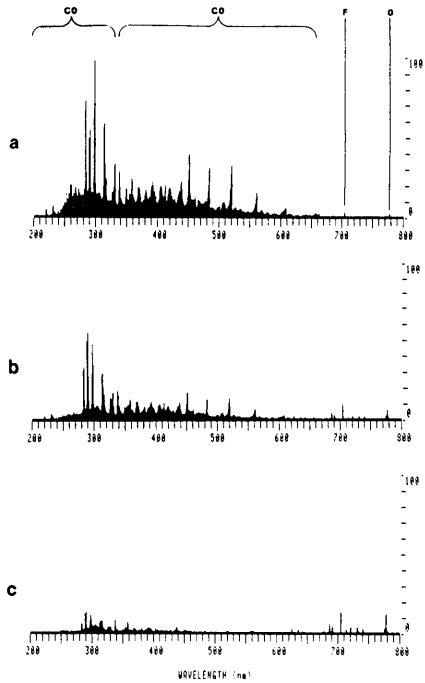


Figure 3 Emission spectra produced by a SF_6/O_2 plasma used to clean an etching chamber; a) at 2 min. b) at 30 min c) at 90 min.

Table I

Common species and emission wavelengths monitored to determine etch endpoint

Material etched	Species monitored	Wavelength (nm)	Ref.
Si, poly-Si	F	703.8	5
	SiF	777.0	9
SiN, Si_3N_4	F	703.8	10
	CN	387.1	10
	N_2	337.1	11
SiO, SiO_2	CO	483.5	
	CO	519.5	
Al	AlCl	261.4	12
	Al	396.2	11
GaAs	Ga	287.4	13
	As	278.0	13
Resist	CO	483.5	14
	CO	519.5	14

such a cleaning plasma. Initially, the CO emission is very intense, as the bulk of the polymer is removed. Also, the O and F lines are suppressed, being consumed by the removal process. When the CO emission intensity returns to baseline, the chamber is clean allowing the etch system to be returned to production as rapidly as possible.

ETCH ENDPOINT DETECTION

Optical emission spectroscopy can also be used to determine when the etching process has been completed. Such endpoint detection does not require that the specific emitting species be identified, only that the spectral feature change intensity when the etch has reached the interface between the film and substrate. Both reactant and product emission have been used for endpoint detection. However, because of the difficulty encountered in measuring a small signal change with respect to the excess of reactants present in the etch chamber, product monitoring is generally considered superior. Table I is a compilation of the species and emission wavelengths which have proven useful for etch endpoint detection.

The development of an etch-endpoint procedure for a thin film of SiO_2 on silicon is presented as an example. Initially, the plasma emission spectrum was recorded both during and after completion of the etch. These spectra were then overlayed, the differences highlighted using software developed for the PSS-100 system. This spectral comparison is shown in Fig. 4. The lines which are shaded correspond to CO, a product of the oxide etch. Of these the 483 and 520nm lines offer the best potential for endpoint determination because of the reduced spectral background in this region. A closer examination of these CO lines, presented in Fig. 5, reveals the absence of any interfering spectral features. Finally, the intensity of the 483nm Co line is monitored as a function of time during the removal of a 1μm layer of silicon dioxide as shown in Fig. 6. The transition at 650 seconds signals the completion of the etch.

Accurate endpoint determination can provide both improved yield and throughput in the production of integrated circuits. The etch rate can increase significantly at endpoint, because the exposed area decreases to a minimum while the etchant concentration approaches a maximum. Terminating the etch promptly at endpoint reduces undercutting of the etch mask, thus reducing damage to the device under construction. Further, the duration of the endpoint transition may be used to monitor etch uniformity, again alerting the operator to a deviation from the desired operating conditions. A broad transition indicates that the etch rate varies across the chamber, making it difficult to avoid some over-or under-etching, thereby reducing yield. Finally, if the etch can be terminated in a timely manner the etching system and the supplies which it consumes can be used more efficiently.

PHOTOLITHOGRAPHY

To take advantage of the anisotropic etch characteristics of plasma processes, a high resolution etch mask is required. Photolithography is an optical process by which a master pattern is used to form a mask which erodes significantly slower than the material being etched. This mask is typically produced by exposing a light sensitive layer of organic photoresist to the emission from a high pressure mercury arc lamp. A chrome mask between the source and the wafer delineates the desired pattern. Once exposed, the resist layer is developed in an organic solvent, such as methyl isobutyl ketone (MIBK) for negative resists, or in aqueous alkali for positive materials. Negative resists are formed from a monomer solution with photon-induced polymerization occurring in the exposed regions. The difference

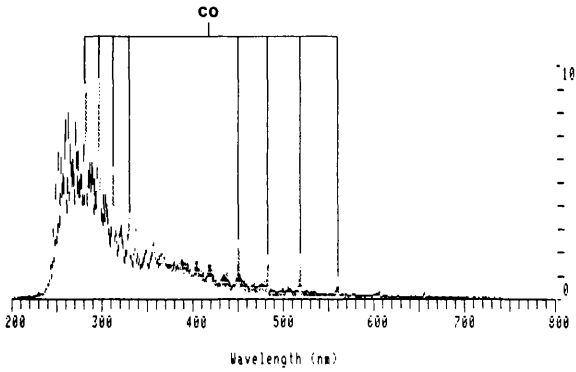


Figure 4
Comparison spectrum of C_2F_6 plasma emission during and after SiO_2 etch. Shaded regions indicate a decrease in emission intensity after etch.

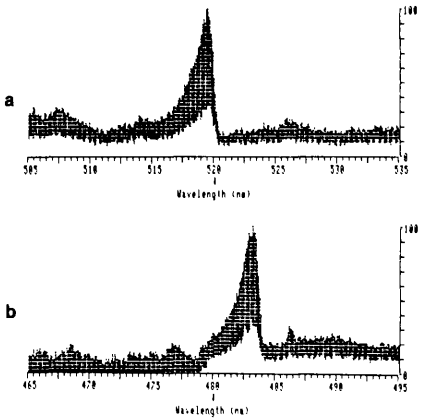


Figure 5
Closer examination of CO emission lines at a) 483.5 and b) 519.5nm from Figure 4.

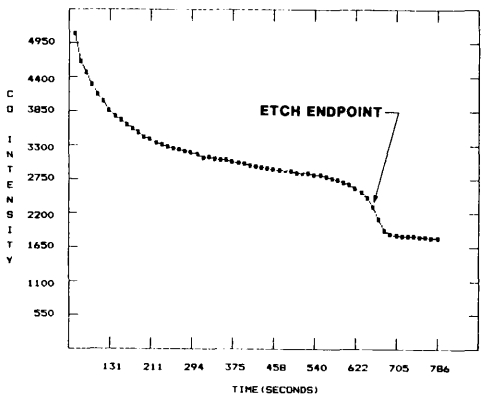


Figure 6
CO emission intensity at 483.5nm as a function of SiO_2 etch time. Transition at 650 sec indicates completion of oxide removal.

in solubility between the monomer and polymer produce the etch mask upon development. On the other hand, positive materials are generally formed from a polymer solution combined with an activator. This activator promotes dissolution of the polymer when exposed to light, and again, differential solubility results in the formation of an etch mask.

The spectrum of a typical high pressure mercury arc lamp is shown in Fig. 7. This output is usually filtered to match the absorbance characteristics of the particular resist being used. Fig. 8 presents two examples of such filtering; a "visible" filter set was employed in Fig. 8A and a "UV" set in Fig. 8B. The current trend is towards shorter wavelength exposure in order to obtain the highest resolution possible. However, careful attention must be paid to radiation at higher wavelengths (>450nm). While this energy does not contribute to the formation of the mask image, it can cause heating and peeling of the photoresist layer. It would appear that exposure at a single short wavelength at which the resist is sensitive would be preferable. Unfortunately, this leads to the formation of a standing wave in the resist layer and an uneven vertical exposure distribution as illustrated in Fig. 9. Consequently, careful mixing of exposure wavelengths is required to obtain the best mask characteristics.

Spectral characterization of the exposure system can also be used to provide a routine check on lamp and filter degration. Such inspections can catch exposure errors before they cause a drop in yield in subsequent production steps.

CONCLUSIONS

The availability of simplified spectrometer systems, designed specifically for the microelectronics industry, has afforded valuable insight into plasma processes, without the need for extensive training in analytical spectroscopy.

The examples presented here serve as a brief introduction to the application of these tools by both chemists and process engineers alike. They have been used to determine reaction mechanisms, diagnose process problems, and for routine process control through etch endpoint determination. This paper has focused on the removal of material in semiconductor device fabrication; however, current experimentation in sputtering and plasma chemical vapor deposition (PCVD) indicate that OES technology may provide significant control and diagnostic capabilities in these processes as well.

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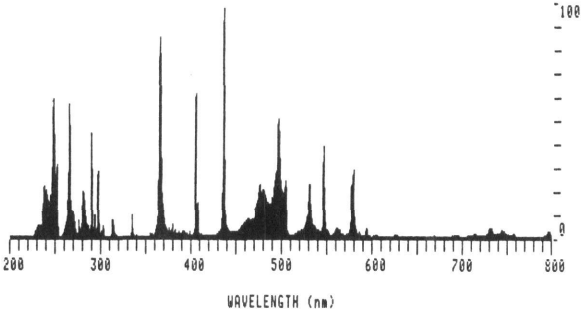
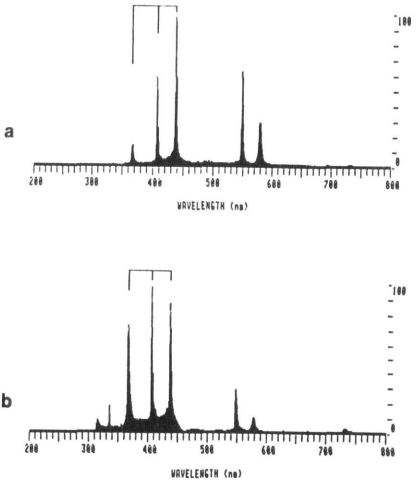


Figure 7
Typical emission spectrum produced by a high pressure mercury arc lamp. (Hybrid Technologies Group)

Figure 8
Filtered mercury emission spectra: a) visible filter set, b) UV filter set.



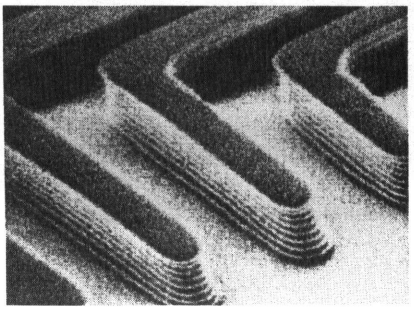


Figure 9
Scanning electron micrograph of developed photoresist mask showing pronounced wall "rippling," 10,000 x magnification.