

In Situ Monitoring of Etching Uniformity in Plasma Reactors

Demetre Economou, Eray S. Aydil, *Department of Chemical Engineering, University of Houston, Houston, Texas*
Gabe Barna, *Texas Instruments Inc., Process Automation Center, Dallas, Texas*

ABSTRACT

A spatially resolved optical emission spectroscopy technique was applied to measure etchant concentration profiles in parallel plate plasma reactors. Also, multichannel laser interferometry was used to measure etching uniformity during plasma processing.

Chemically reactive gas plasmas are widely used for etching and deposition in microelectronics [1]. However, predicting the flux and energy of particles striking the wafer (and, in turn, the etching or deposition rates) is still beyond the state-of-the-art. This is largely because, in such processes, equilibrium is not attained and for most of the large number of reactions involved the kinetics are unknown. Although this paper focuses on plasma etching, similar principles apply to plasma deposition.

The ultimate goals of plasma etching are uniform damage-free etching with good anisotropy and selectivity. Etching uniformity is a major concern and uniformity problems often worsen as wafer size increases and new higher rate processes are developed. Nonuniform processes necessitate over-etching which can exacerbate substrate damage and/or undercut masks. Both phenomena adversely affect device yields. In deep trench etching, uniformity is required if the trench structures are to have a tight capacitance distribution.

Nonuniformity can be caused by gradients in etchant concentration, ion bombardment flux, ion energy, and wafer surface temperature. For example, etchant concentration gradients tend to develop at the boundary where two surfaces with different reactivity meet [2]. Such gradients are thought to be responsible for the commonly observed "bull's eye" clearing pattern, in which the etch rate decreases monotonically from the wafer periphery to its center.

In practice, pressure, power, and gas flow rate are iteratively adjusted until the uniformity meets specifications.

This empirical approach is taken because underlying parameters (such as the reactant concentration profiles) are unknown, especially in production reactors. A large number of experiments may be required to find a satisfactory recipe, since uniformity cannot be measured until the wafer is taken out of the reactor. Hence, in situ monitoring of the etch rate and uniformity can be of enormous value for converging on optimum reactor settings and for realtime process control.

In situ plasma diagnostics, such as optical emission spectroscopy (OES) and laser induced fluorescence (LIF) [3], have improved the understanding of plasmas and plasma processes, and they have been used for process monitoring as well. Optical diagnostics are especially attractive because they are nonintrusive. Spatially resolved OES provides valuable information about active species distributions in a plasma reactor, and, from this information, one can draw inferences about uniformity [2]. Laser interferometry is another optical technique which lends itself to realtime monitoring [4]; however, it is limited to materials systems involving transparent films or reflective substrates.

We describe here an OES-based technique that has been used to map etchant concentration profiles for sulfur hexafluoride (SF_6), oxygen (O_2), and chlorine (Cl_2) plasmas. The radial distribution of plasma emission intensity was measured to obtain etchant species concentration profiles in both empty and loaded reactors. These profiles were then compared to etch rates across the wafer. Finally, multichannel interferometry was developed to monitor etch rate and uniformity during processing.

Experimental

Apparatus

Experiments were performed in single-wafer parallel plate reactors including a production PAC 150PC etcher, manufactured by Texas Instruments, Inc. Power was delivered to the upper showerhead electrode by a 13.56 MHz generator via an automatic matching network. Gas flow rates and chamber pressure were automatically regulated.

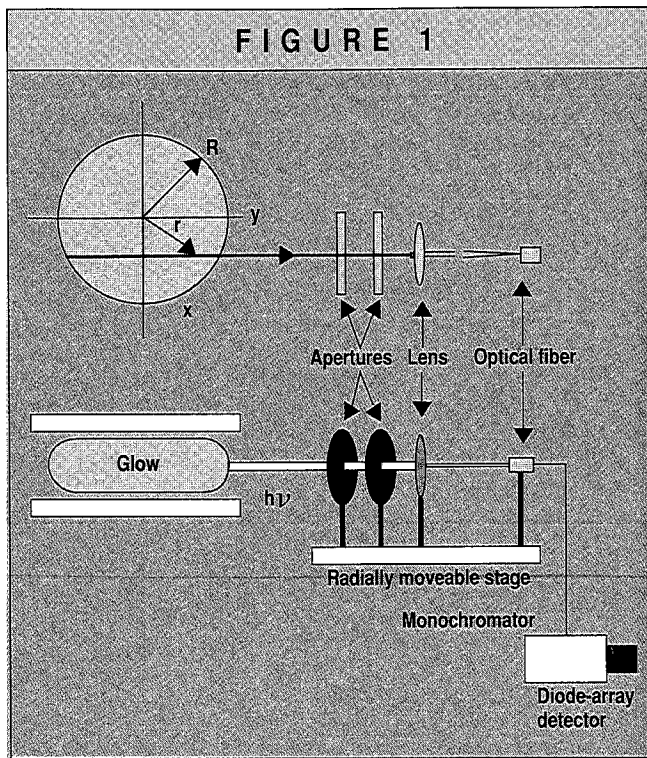


FIGURE 1
An optical train collected spatially resolved plasma emission. A cross sectional view of the plasma glow and the small volume of light sampled by side-on observation are shown at the top.

Actinometry has been used before to monitor oxygen and fluorine atoms in various plasma systems [3,5]. As shown in Fig. 1, light emitted from the plasma passes through a set of apertures and is focused onto an optical fiber coupled to a monochromator. The dispersed light is detected using a photomultiplier tube (PMT) or an intensified diode-array detector (EG&G/PAR OMA III system). The optical train was on a stage which could be translated across the reactor radius. The OMA detector permitted simultaneous monitoring of etchant (e.g., F) and an actinometer gas (e.g., Ar).

Procedure

First, the plasma was ignited under a specified set of conditions in either an empty or a loaded reactor. (The "empty" reactor was charged with a wafer covered by a film that does not consume reactant; the loaded reactor contained a normal process wafer.) In all experiments the wafer diameter was 100 mm and a few percent Ar was added to the gas flow as an actinometer. After the plasma stabilized, optical emission spectra were recorded at 20 different radial locations. The intensities of the 750 nm Ar line and either the 704 nm F line (for SF₆ plasmas) or 845 nm O line (for O₂ plasmas) were determined after subtracting the background. In the Cl₂ plasma experiments the 811.5 nm Ar and 837.6 nm Cl lines were monitored.

Actinometry and Data Processing

In optical emission actinometry, the intensity of light emitted by a species is related to the ground state concentration of that species. If a plasma system contains fluorine atoms and the electronically excited state (F*) is formed by

electrons impacting the ground state (F), then the spontaneous emission intensity, i_F , is proportional to the ground state concentration, [F], i.e.,

$$i_F \approx n_e k_e [F]$$

where n_e is the electron density and k_e is the excitation rate constant. However, in Eq. 1, the so-called excitation efficiency ($\eta = n_e k_e$) varies with reactor operating conditions. To account for this variation, Coburn and Chen [5] introduced a small amount of actinometer gas with an excitation threshold and cross section similar to those of the species of interest. Thus, although η values for the actinometer and the active species may change with operating conditions, their ratio remains almost constant. An equation similar to Eq. 1 can be written for the actinometer gas (say Ar), and a ratio of the two equations results in the following:

$$\frac{i_F}{i_{Ar}} = q \frac{[F]}{[Ar]} \quad (2)$$

where q is a proportionality constant and [Ar] is the known concentration of the actinometer. By measuring i_F and i_{Ar} at suitable wavelengths, the relative change in [F] is obtained. Similarly, Eq. 2 can be applied to monitor atomic O or Cl. Monitoring Cl with actinometry requires care; precautions must be taken to sample the Cl plasma away from the sheaths to avoid emissions from dissociative excitation [6,7].

Figure 1 depicts a cross section of the radially symmetric glow taken at a certain plane parallel to the electrodes (say at $z = z_0$). The optical train collects light from a small plasma volume. The intensity of light from distinct locations $I(x, z_0)$ is measured by translating the optics parallel to the x-axis. This spatially averaged emission includes contributions from different radial positions, but the desired point intensity $i(r, z_0)$ can be computed from $I(x, z_0)$ using the Abel transform [2]. After radial emission intensity profiles $i(r, z_0)$ were obtained for F and Ar, Eq. 3 (analogous to Eq. 2) was applied to find the ground state F concentration profile.

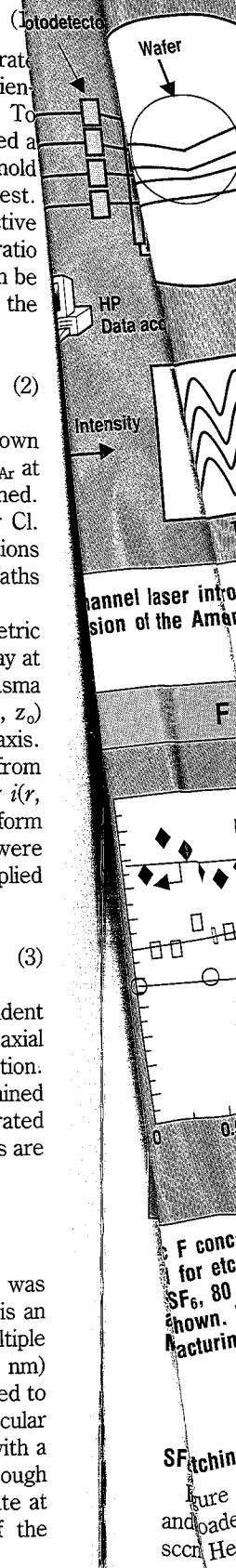
$$C_F(r, z_0) = \frac{C_{Ar}}{q} \frac{i_F(r, z_0)}{i_{Ar}(r, z_0)} \quad (3)$$

Since Ar is nonreactive, C_{Ar} may be taken as independent of position (r, z_0). The procedure is repeated for each axial (z) position to obtain a 3D map of reactant concentration. Unfortunately, absolute concentrations cannot be determined by actinometry unless the relative intensities are calibrated by another technique. This is why etchant concentrations are reported in arbitrary units.

Multichannel Laser Interferometry

Spatially-resolved (multichannel) laser interferometry was used for in situ monitoring of etching uniformity [8]. It is an extension of conventional laser interferometry using multiple laser beams and photodetectors. A He-Ne laser (632.8 nm) subdivided into four beams by beam splitters was directed to different radial positions on the wafer (Fig. 2). The specular reflection intensity from each position was monitored with a silicon photodetector. The reflected intensity goes through maxima and minima as the film is etched away. Etch rate at each radial position is calculated from the period of the intensity variation [4].

FIGURE 2



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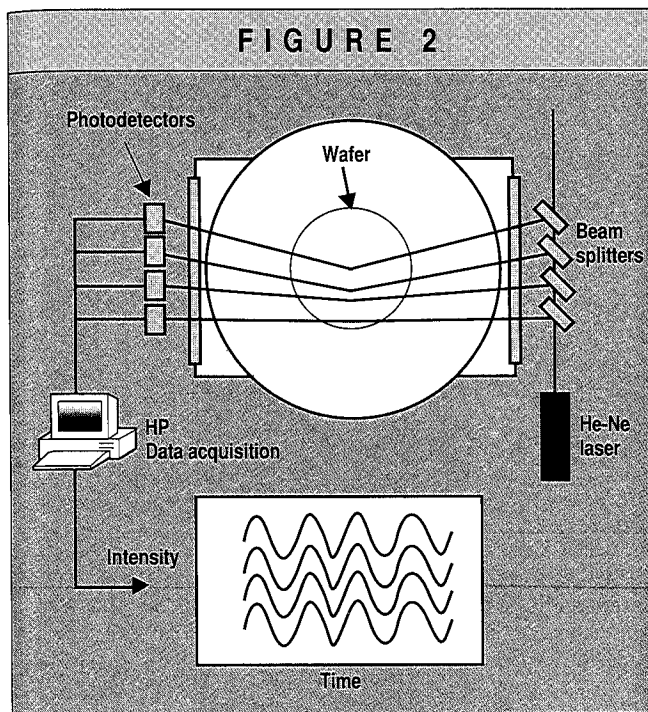
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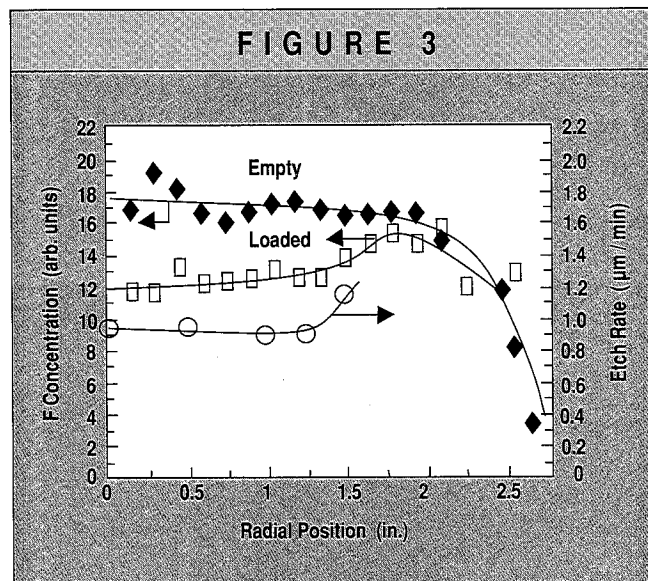
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Multichannel laser interferometry system. From Ref. 8, with permission of the American Institute of Physics.

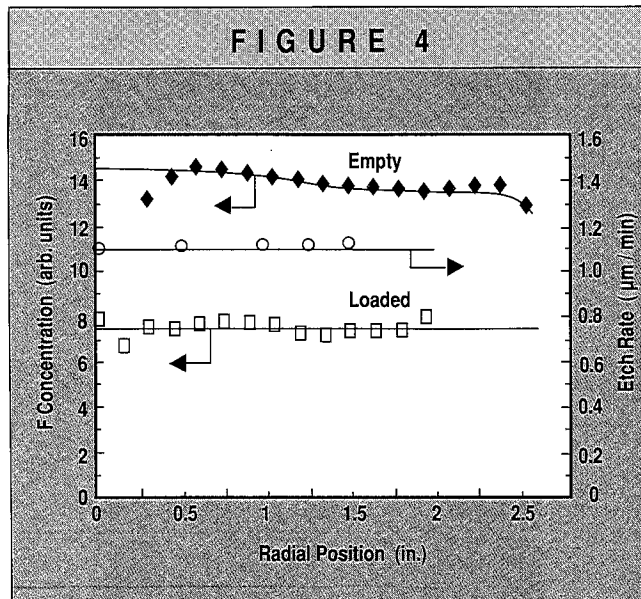


Atomic F concentration profile in an empty reactor and in one loaded for etching poly. Conditions were 0.5 torr, 200 W, 47 sccm SF₆, 80 sccm He, 6 sccm Ar. The poly etch rate profile is also shown. From Ref. 9 with permission of the Society of Manufacturing Engineers.

Results and Discussion

SF₆ Etching of Polysilicon [9]

Figure 3 shows atomic F concentration profiles for empty and loaded reactors at 0.5 torr, 200 W, 47 sccm SF₆, 80 sccm He, and 6 sccm Ar (133 sccm total flow rate). In the



Same as Fig. 3 but with higher flow rate (190 sccm SF₆, 160 sccm He, 12 sccm Ar). From Ref. 9, with permission of the Society of Manufacturing Engineers.

empty reactor (no poly present) F concentration decreases only slightly towards the radial edge of the plasma. However, in the loaded reactor (poly present) there is a *dip* in concentration over the wafer. Also, overall etchant concentration is lower in the loaded reactor because etchant species are consumed. The etching rate profile follows the F concentration profile in the loaded reactor (Fig. 3) confirming that the poly film acts as a sink for atomic F and causes the dip.

Figure 4 shows how uniformity can be improved by increasing the flow rate to 362 sccm. The result is that, although the F concentration is still lower in the loaded reactor, the F concentration profile and etch rate are flat across the wafer. Enhanced convective transport of the fluorine atoms relative to diffusive transport is responsible for the improved uniformity [2].

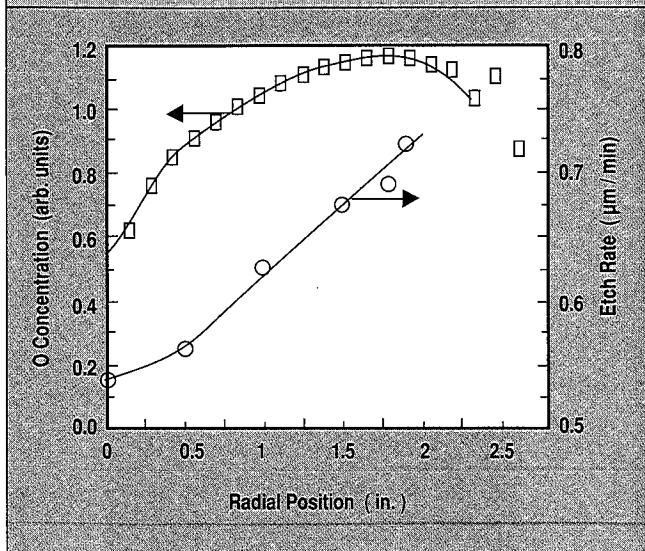
O₂ Etching of Photoresist

Similar experiments using an O₂ plasma to etch photoresist films confirm that the technique can be applied to other plasma chemistries. Measurements of O concentration and etch rate profiles (Fig. 5) showed that both decrease monotonically towards the center of the wafer. This decrease may again be attributed to loading from etchant consumption at the reactive surface.

Cl₂ Etching of Polysilicon

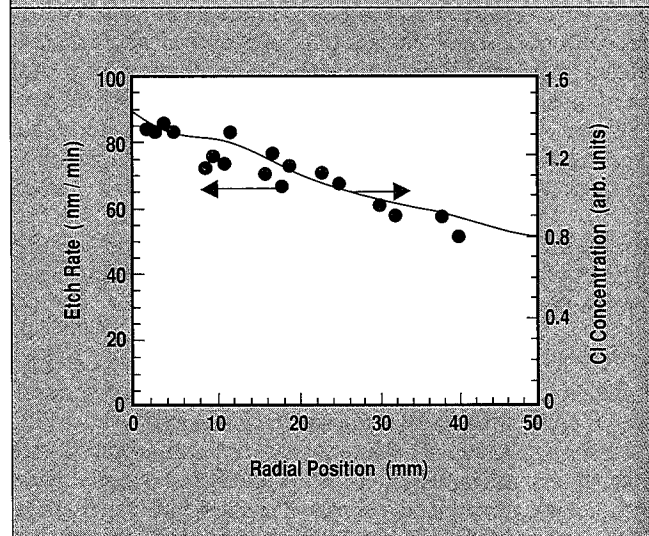
The dip in etchant concentration profile and the ensuing nonuniformity have been reported before [2]. However, other factors can also cause poor uniformity. Figure 6 shows the Cl concentration profile at 0.7 torr, 100 W, and 25 sccm total flow rate. Instead of a dip in the profile, atom concentration *increases* toward the center of the reactor. The discharge under these conditions was radially nonuniform. The plasma had a bright central region known as a plasmoid [8], suggesting that more power is deposited near the center,

FIGURE 5



Atomic O concentration profile during the etching of photoresist. Conditions were 2 torr, 200 W, 130 sccm O₂, 15 sccm He, 12 sccm Ar. The photoresist etch rate profile is also shown. From Ref. 9, with permission of the Society of Manufacturing Engineers.

FIGURE 6

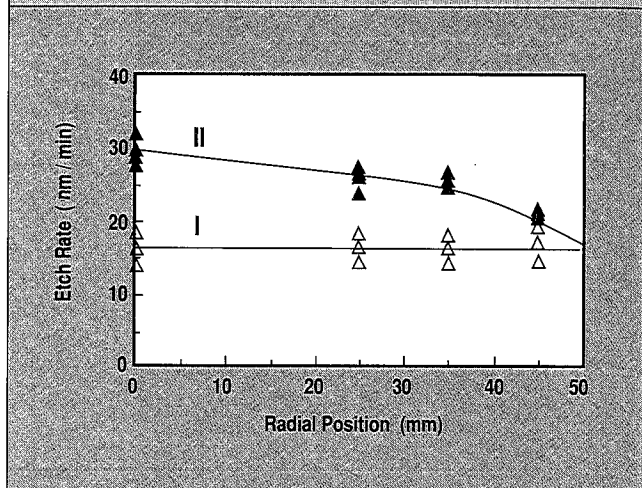


Atomic Cl concentration (curve) and corresponding etch rate profile (points) of P-doped poly. Conditions were 0.7 torr, 100 watts, 25 sccm Cl₂.

and the result is a higher Cl concentration in this zone. The corresponding poly etch rate (Fig. 6) follows the Cl profile.

The measurements discussed so far were made in systems where the etch rate is limited by reactant supply. Consequently, the etch profile tracks the etchant concentration. However, the situation can be more complex when energy driven, ion assisted etching makes a dominant contribution (e.g., the etching of undoped or lightly doped poly in a Cl

FIGURE 7



Poly etch rate profile measured in situ using multichannel laser interferometry. Curves I and II correspond to the presence and absence of a plasmoid, respectively. From Ref. 8, with permission of the American Institute of Physics.

plasma). In such cases, etching uniformity is determined by the flux and energy of ions bombarding the surface, in addition to the etchant concentration profile.

A technique for monitoring uniformity is helpful in any event. Figure 7 shows the realtime etch rate distribution across a wafer as measured by multichannel laser interferometry [8]. Curve I corresponds to operating conditions in which the plasma glow appeared radially uniform, whereas curve II corresponds to a condition where the central zone of the plasma glow was brighter (because a plasmoid formed).

Conclusions

Spatially resolved optical emission actinometry is an effective way to monitor concentration gradients in plasma reactors. The technique was demonstrated for three practical chemistries: SF₆ and Cl₂ etching of poly, and O₂ etching of photoresist. In the presence of etchable films, such as poly in an SF₆ plasma, loading can cause dips in etchant concentration and etch rate profiles. When etching is rate-limited by etchant supply, the etch rate tracks the concentration profile of etchant species.

Changes in reactor operating conditions influence uniformity due to their effects on etchant concentration profiles. Multichannel laser interferometry is convenient for in situ monitoring etch rate uniformity. These techniques may be used in the development and design of plasma processes as well as the monitoring and control of production. ■

Acknowledgments

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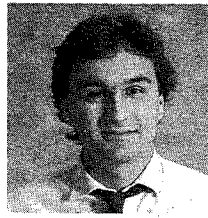
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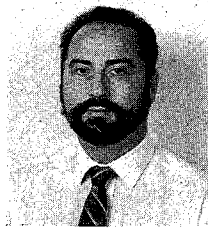
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Demetre J. Economou earned his B.S. degree from the National Technical University, Greece, in 1981, and his Ph.D. from the University of Illinois, Urbana, in 1986, both in Chemical Engineering. Since 1986, he has been an Assistant Professor of Chemical Engineering at the University of Houston. His research interests are in the area of plasma processing of electronic materials. He has published over twenty papers and holds one patent in this area. Dr. Economou is a member of the Electrochemical Society, Materials Research Society, American Vacuum Society, and American Institute of Chemical Engineers.



Eray S. Aydil received B.S. degrees from the University of California at Berkeley, in Chemical Engineering and Materials Science and Engineering in 1986. He then joined the Chemical Engineering department at the University of Houston, where he is a research assistant working towards his Ph.D. degree. Mr. Aydil is a student member of the Electrochemical Society and Materials Research Society.



Gabe Barna received his B.Sc. and Ph.D. degrees in Chemistry from McGill University, Canada, in 1968 and 1973, respectively. Since then, he has been employed at Texas Instruments. For 11 years, he worked in the Central Research Laboratory on Display Technologies first on LCD and electrochromic displays and then on fuel cells as a part of a solar energy research program. Currently, he is a Senior Member of the Technical Staff, having worked

for the last 7 years on plasma processing technology in the Process Automation Center at TI. His interests have been in the automation and control of plasma reactors. He has published 7 papers and holds 2 patents in this field.

CERAMIC CAPACITANCE MANOMETER

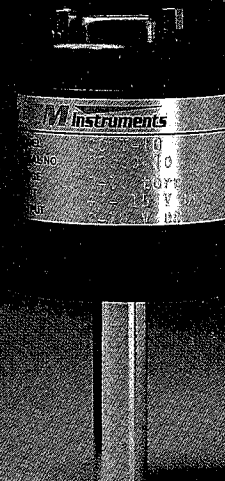
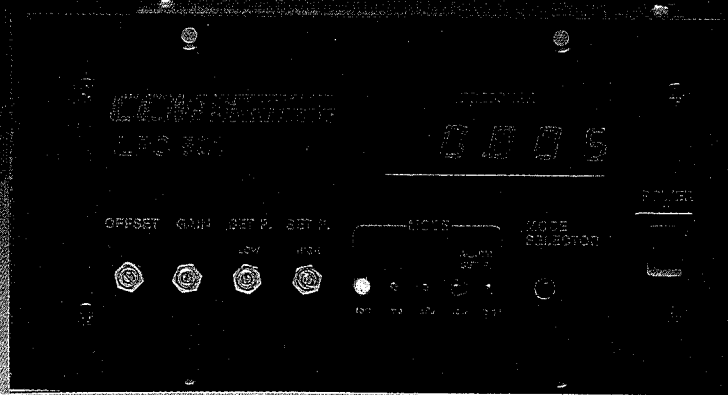
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