NITROGEN PLASMA INSTABILITIES AND THE GROWTH OF SILICON NITRIDE BY ELECTRON CYCLOTRON RESONANCE MICROWAVE PLASMA CHEMICAL VAPOR DEPOSITION

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Nitrogen plasma instabilities have! been identified through fluctuations in the ion current density and substrate floating potential. The behavior of the plasma instabilities was found to be confined to the pressure regime 0.9 mTorr<P<1.6 mTorr. The onset of instabilities in the nitrogen plasmas occurred following the transition from an underdense to overdense plasma, where an overdense plasma is defined for densities greater than the critical density $n_c=7.4x10^{10}$ $cm.^{-3}$ The instabilities are a consequence of the nonlinear dynamics present in ECR plasmas and indicative of a transition between plasma modes as the pressure increases from 0.9 to 1.6 mTorr. The plasma instabilities are suppressed with the introduction of silane for the deposition of silicon nitride, although the plasma still undergoes a transition from an underdense to overdense plasma at 1.0 mTorr. The transition pressure delineated regions of poor and optimum electrical properties of silicon nitride films deposited from a dilute nitrogen-silane ($N_2/SiH_4=5$) plasma. To evaluate growth conditions the flux of energetic ions to deposited atoms was approximated by examination of the ratio of ion current density to deposition rate. This ratio was found to be well correlated to the electrical properties of ECR microwave plasma deposited silicon nitride films for pressures above the underdense to overdense transition at 1.0 mTorr.

1. INTRODUCTION

Silicon nitride (SiN) is of significant technological interest due to its extensive use in semiconductor electronics. Typical properties which make SiN an important dielectric in VLSI technology are low leakage current, high breakdown strength and low interface-state density. Fabrication technologies which promise superior nitride characteristics utilizing deposition conditions compatible with semiconductor processing are of considerable interest. Electron cyclotron resonance (ECR) microwave plasma-enhanced chemical vapor deposition (PECVD) has been investigated in recent years as an alternative to more established nitride CVD techniques. Advantages that have been identified with the ECR system over other plasma CVD techniques are controllable ion energy, high degree of plasma ionization (>10%), thereby yielding the generation of dense plasmas (10^{10}-10^{12} cm^{-3}) and low deposition pressures (10^{-5}-10^{-3} Torr) and temperatures.[1-4] By manipulation of the ion energy, damage to interfaces and devices is minimized. A high plasma density can be utilized for extremely high deposition rates and enhanced material properties. Accessing the low pressure regime may be effective in reducing material contamination, The ability to deposit high quality dielectric materials at low temperatures eliminates possible degradation of devices which can occur at the elevated temperatures required by most other deposition techniques. ECR systems offer a highly advantages deposition regime not accessed by other CVD techniques.

Silicon nitride growth by ECR PECVD has been the subject of numerous recent studies. In general these have focused on specific characteristics of the deposited films, such as hydrogen content, thermal stability and electrical properties. Extensive work has been done describing the bonding of ECR deposited amorphous silicon nitride (a-SiN:H) films through Fourier Transform Infrared Spectroscopy (FTIR).[5-7] The attendant hydrogen content has been estimated from the FTIR spectra and thermal stability evaluated. Some studies have focused primarily on the electrical characteristics of the SiN:H films, delineating properties as a function of microwave power, process gas ratios and deposition pressure.[8-10] The role of excited species in the deposition process has been examined by optical emission spectroscopy (OES).[11,12] However, investigations relating specific plasma characteristics to the properties of the deposited films have been less forthcoming.

Many studies have been undertaken describing various ECR plasma modes, primarily using argon as a source gas. Popov noted the existence of column, hollow and uniform plasma characteristics and transitions from an underdense ($n_e<n_c$) to overdense ($n_e>n_c$) plasma, where n_e is the plasma density and $n_c=7.4\times10^{10}$ cm^{-3} is the critical density.[13-15] Gorbatkin and Shufflebotham were both able to differentiate the existence of plasma modes in pressure-power space by capturing abrupt optical changes in plasma characteristics.[16,17] Aydil observed similar transitions between plasma modes using the substrate floating potential and ion current density.[18] Since these studies are primarily based on argon plasmas they are of limited applicability to nitrogen and silane-nitrogen plasmas and so in determining specific plasma characteristics relevant to silicon nitride processing. It is important to identify mode transition regions and salient plasma characteristics for ECR silane-nitrogen plasmas, which may delineate optimum properties of silicon nitride films.

The purpose of this study is a detailed examination of the relation of nitrogen and silane nitrogen plasmas to the growth of silicon nitride as a function of pressure. The plasma was characterized using the substrate floating potential and ion current density. An analysis was made to determine whether nitride characteristics could be identified with definitive plasma characteristics or variations in the plasma associated with plasma modes. Samples were evaluated using FTIR and standard ellipsometry to determine hydrogen content and the index of refraction respectively. The dependence of the current-voltage characteristics and dielectric constant were also measured as a function of pressure and related to plasma parameters. Optimum nitride characteristics for this study were defined by those conditions which minimized the leakage current as a function of applied field. This is of particular relevance in the fabrication of DRAMs in VLSI technology, where minimizing leakage current densities is essential for optimum performance.[19]

II. EXPERIMENTAL

A. ECR System

A schematic diagram for the ECR PECVD system is given in Figure 1. This system was equipped with a load lock for immediate turn-around of samples and high vacuum integrity of the deposition system (base pressures as low as 10-8 Torr). An ASTeX AX4100 ECR plasma source was used for this study. The microwave power is transmitted in a rectangular waveguide and coupled to the plasma chamber via a symmetric mode converter (T E_{10}-to-TM_{01}) and a quartz window. The plasma is generated through absorption of 2.45 GHz microwaves by the process gases. A microwave power of 800W was used for all depositions of this study. Two coaxial coils mounted approximately 30 cm apart supply the magnetic field in a magnetic mirror configuration. Currents of 180A and 125A were applied through the window and exit magnets respectively. This creates a magnetic field of over 1000G just below the microwave window of the source chamber, allowing for the propagation of a "whistler" mode in the plasma.[19] In this mode the right hand circularly polarized component of the incident microwaves is not absorbed, but propagates through the plasma until reaching a magnetic field region where the ECR condition is satisfied (B=875G). An overdense plasma mode can thus achieved, depending of specific system parameters, with ion densities well in excess of the critical density n_c ($=m\omega^2/4\pi e^2$, where ω is the microwave angular frequency) otherwise identified for microwave absorption,

Directly below and connected to the plasma chamber is a down-stream deposition chamber equipped with a gas injection ring. Samples are mounted on a 7.5 cm diameter molybdenum substrate stage, covered with a silicon wafer, located approximately 15cm below the aperture of the source chamber and 10cm below the gas ring. Nitrogen was introduced into the source chamber immediately below the quartz window, while silane (1 00% SiH_4) entered the deposition chamber through the gas ring. The gas flow rates were controlled by mass flow controllers accurate to approximately 5% of the display flow rate. The pressure was monitored by an MKS

122 B baratron capacitance manometer, with pressure being adjusted by manipulation of the total gas flow rate. The ratio of N_2 to SiH_4 was kept constant at 5 for all pressures. The depositions were made at ambient temperature, with plasma heating resulting in temperatures <100C.

B. Silicon Nitride Characterization

Measurements of the current-voltage characteristics were made with a Hewlett-Packard 4145B Semiconductor Parameter Analyzer. Electrical contacts were made using a Bausch-Lomb probe station, equipped with tungsten probe tips. The infrared spectra of the SiN thin-films, deposited on polished silicon substrates, was obtained using a Perkin-Elmer 1600 Series Fourier-transform infrared spectrometer. The hydrogen content of the films was estimated from the Si-H and N-H absorption bands of the FTIR spectra, which are nominally located at 3350 and 2160 cm-l respectively. The densities of the Si-H and N-H bonds were calculated by estimating the area under the absorption band and weighting this with the absorption cross-sections as described by Landford.[20] The Si-H absorption band was not detectable for pressures less than 4 mTorr.

Measurements of the index of refraction and thickness for the dielectric films were accomplished using a Rudolph Research AutoEL-Ill ellipsometer. Thickness measurements could be confirmed directly utilizing a Tencor Alpha-Step 250 profilometer. A thickness of approximately 0.3μm was used for all samples. 1 he substrates for electrical measurements were RCA cleaned silicon wafers coated with aluminum by e-beam evaporation. A metal-insulator-metal (MIM) configuration 0.5mm in diameter was fabricated by e-beam evaporation of aluminum electrodes through a mask on the deposited silicon nitride. Depositions were also made on double-polished silicon substrates for bonding analysis by Fourier transform infrared spectroscopy.

C. Plasma Characterization

A Langmiur probe was used for determination of the ion current density for the nitrogen plasmas. Langmuir probe measurements were not obtained in silane-nitrogen plasmas due to rapid coating of the probe tip with an insulating nitride layer. The probe was equipped with a tungsten tip 0.8mm in diameter and 2.5mm in length. I-he collection area was approximately $3mm.^2$ Determination of the ion current density was not intended as an absolute measurement of the ion density, but as a means of identifying significant relative changes in the plasma. Measurements of the ion current density were supported by measurements of the substrate floating potential, V_f . It has been demonstrated that V_f is an effective means for determining the existence of plasma modes through instabilities in the measured potential.[18] The floating potential was monitored using an Astro-Med MT95KT2 chart recorder, which allowed for storage of data to disk for later evaluation. The substrate electrical contact was not directly exposed to the plasma, hence V_f could be measured for both plasma compositions, nitrogen and silane-nitrogen.

The addition of silane to the plasma will reduce the nitrogen ion density n+. Saito observed approximately a 20% reduction in nitrogen ion intensity with the addition of silane, as determined by optical emission spectroscopy.[12] The change in n^+ is obviously dependent on the N_2/SiH_4 ratio and specific system parameters, but it is assumed the change is approximately uniform as a function of pressure (with N_2/SiH_4=constant) for the dilute plasmas of this study. This is supported by measurements of V_f as a function of pressure, given in Figure 3 below, where the pressure dependence is qualitatively similar for both plasma compositions. The floating potential and ion (current) density are interrelated, both functions of the electron temperature. This is demonstrated, in part, by the fact that instabilities in the floating potential were accompanied by instabilities in the ion current density. Gross changes in the pressure dependence of n^+ should coincide with significant changes in the pressure dependence of the floating potential. Since the latter was not observed, the pressure dependence of the nitrogen ion density is assumed to have the same relative behavior for the nitrogen and nitrogen-silane plasmas of this study and therefore relevant in evaluating optimum deposition conditions.

III. RESULTS

A. Plasma Instabilities

Instabilities in the nitrogen plasmas were readily observed through abrupt fluctuations in the floating potential, as suggested by Aydil.[18] Figure 2a-2c are representative of how these plasma instabilities vary as a function of pressure. As the pressure increases from 0.9 to 1.5 mTorr the transition potential between modes increases from 0.2V to 2.4V and the residence time in each mode also increases from .2s to 25s. At 1.6 mTorr the instabilities are no longer observed i.e., an infinite residence time. The plasma instabilities observed through fluctuations in V_f were also manifested by abrupt changes in the ion current density. These plasma instabilities were suppressed with the introduction of silane to the plasma. It was also observed that plasma instabilities were dependent on chamber history. Prior to silicon nitride deposition the nitrogen plasma instabilities exhibited a well defined, reproducible behavior. After a significant number of depositions the instabilities were found to be reduced and in some instances were suppressed entirely.

The pressure dependence of the substrate floating potential is given in Figure 3. The substrate potential for the silane-nitrogen plasma is also given for comparison. The floating potential given in the unstable pressure regime is that of the more stable potential i.e., where $|V_f|$ is a maximum. Figure 4 gives the ion current density j^+ as a function of pressure for the nitrogen plasmas. I-he density was found to reach a maximum at 0.8-0.9 mTorr and gradually decrease at higher pressures. The ion current density with pressure closely follows the functional behavior, $a/pe^{[-b/p]}$, where p is the pressure and a and b are constants. T his pressure dependence is qualitatively the same as that previously observed for both argon and nitrogen plasmas.[14,16] The pressure dependence of j^+ has been explained qualitatively as a consequence of the dependence of the electron temperature T_e with pressure.[21] The density of electrons of sufficient energy for ionization and the ionization cross section are functions of the electron energy. As the pressure increases T_e decreases, due to collisions with neutrals, resulting in a rapid decrease in ionization cross section. Simultaneously, the increase in pressure results in an increase in the density of nitrogen gas available for ionization and hence an increase in the electron density. The dependence of the ion current density with pressure is a consequence of the competing mechanisms of increased density of process gas available for ionization and decrease in ionization cross section,

B. Silicon Nitride Characteristics

The deposition rate as a function of pressure is given in Figure 5. The index of refraction and hydrogen content as a function of pressure are given in Figures 6 and 7 respectively. The index of refraction shows a shallow minimum at approximately 4 ml-err, while the increase observed in hydrogen content with pressure is roughly linear.

In Figure 8a typical current-voltage characteristics for the silicon nitride films deposited in this study are given, while in Figure 8b In(l) is plotted as a function of the square root of the electric field $E^{1/2}$. At low fields ohmic behavior is observed, while for high fields (E>3-5MV/cm) the current is found to depend exponentially on $E^{1/2}$. These current-voltage characteristics are typical for a Frenkel-Poole transport process, which is due to field-enhanced "thermal excitation of trapped electrons into the conduction band.[22]

The leakage current density j obtained at a field strength of 1 and 4 MV/cm is given as a function of pressure in Figure 9. Although j is relatively independent on pressure at low fields ($E \leq 1$MV/cm), this changes dramatically with the onset of the Frenkel-Poole transport process at higher fields. This can be seen as due to the variation in barrier height of the trapping centers ϕ_B from the expression for the Frenkel-Poole transport process,

$$j \sim E\exp[-q(\phi_B-(qE/\pi\varepsilon_i)^{1/2})/kT] ,$$

where E is the electric field, ε_i is the dielectric permittivity and ϕ_B is the barrier height. The constant of proportionality is a function of the density of the trapping centers. The dielectric permittivity was found to vary from 6.7 at 1.3mTorr to 6.3 at 10mTorr and so cannot account for the observed increase in leakage current at higher pressures. An increase only in the density of trapping centers would result in an increase in the leakage current at the field required for detrapping i.e., a field dependence should not be observed. This contrasts with the field dependence observed for the onset of the exponential current increase which is associated with the Frenkel-Poole transport process. In Figure 10 the field at which the current increase becomes exponential is given as a function of pressure, The lowest leakage current densities are well correlated to films with high field exponential regions. This strongly supports the contention that the lowest leakage current densities are a result of deeper trap states created at the optimum deposition pressures.

III. DISCUSSION

A. Plasma Transition

The pressure dependence of the nitrogen plasma and silicon nitride characteristics are found to undergo transitions at 0.9 and 1.0 mTorr respectively. At these pressures, the onset of the nitrogen plasma instabilities occurs and silicon nitride characteristics are found to radically improve. Popov found that for system specific parameters of microwave power, pressure and magnetic field configuration, the plasma would reach a critical density $n_c = m\omega^2/4\pi e^2 = 7.4\times10^{10}\,cm^{-3}$. At this plasma density a dramatic decrease in reflected power and increase in visual intensity of the plasma was observed. [13] In this study similar observations were made, with the reflected power as a function of pressure (Figure 11), suddenly decreasing as the pressure is increased to 0.9 mTorr for N_2 plasmas and 1.0 mTorr for N_2/SiH_4 plasmas. The identification of these pressures as transition regions from an underdense to overdense plasma condition is also consistent with the rapid increase in the ion current density shown in Figure 4.

The observation of highly stressed, poor quality nitride below 1.0 mTorr is similarly consistent with growth in an underdense plasma. The deposition rate was much lower in this regime and films were highly stressed compressively, peeling off the substrates. In an underdense plasma condition a substantial fraction of the incident microwave energy will be transmitted through the plasma and absorbed by the growth surface. This would be expected to lead to substantial degradation of thin-film properties. The low deposition rate is a consequence of a low plasma density, but also significant sputtering may be occurring at these pressures from energetic ions, contributing to the compressive stress of the films. The transition to an overdense plasma would substantially eliminate all the deleterious conditions discussed above, leading to the optimum film properties observed above 1.0 mTorr.

B. Plasma Instabilities

Variation in plasma modes have been identified in the vacinity of the transition region from an underdense to an overdense plasma condition, with the exact pressure dependence of this transition dependent on the specifics of the plasma system. The existence of distinct plasma modes has been correlated with the depletion of neutrals and variations in the plasma density, as demonstrated by Gorbatkin utilizing optical emission spectroscopy .23 Plasmas will display nonlinear behavior due to the relationship of the neutral density, ionization rate and plasma density. These nonlinearities may, in turn, stimulate unstable regions of operation. Therefore, it is likely that plasma instabilities will accompany mode transitions.

Although studies of plasma instabilities and mode transitions have been primarily confined to argon plasmas, the instabilities and density transition observed here for nitrogen plasmas are qualitatively very similar and occur in the same pressure regime. As the pressure is increased to 0.9 ml orr the plasma density abruptly increases, consistent with a transition from an underdense to overdense plasma as discussed earlier. Further increases in pressure result in the onset of plasma instabilities (at 1.0 mTorr). It is consistent with previous observations to identify the unstable pressure region (0.9 mTorr<P<1.6 ml-err) as a consequence of a plasma mode transition. This is observed as an increase in residence time for V_f in the alternate mode as the pressure is increased, becoming infinitely long at 1.6 mTorr, where the plasma mode stabilizes. The discontinuity in V_f for the N_2 plasma in Figure 3 is evidence of the plasma having shifted into the new mode. The N_2/SiH_4 plasma which did not display plasma instabilities shows no such discontinuity. The connection of plasma mode transitions to plasma parameters has been suggested by Shufflebotham, through correlating measurements of microwave power to an optically observed mode transition in hydrogen plasmas.[17] Although Gorbatkin has identified neutral depletion as a mechanism for the mode transitions observed for noble gases, it is not possible to make a determination as to the origin of the nitrogen plasma mode transition implied by the data of this study.

It should be noted that the exact nature of the plasma instabilities will be a function of the past history of the ECR system. Goeckner observed variations of several volts in plasma and floating potentials depending on "clean" and "dirty" start-up conditions.[24] Trapped gases may desorb during plasma heating and sputtering of thin-film material off the chamber walls can occur for systems with prior depositions, introducing contaminants into the Plasma. These contaminants can alter or suppress the instabilities, depending on specific system parameters.

c. a-Si N:H Film Properties

The introduction of silane to the plasma eliminates the plasma instabilities. The (nitrogen) ion density is reduced and an abundance of silane neutral radicals are generated in the plasma. These interrupt the mechanisms responsible for the nitrogen plasma instabilities, resulting in a stable overdense plasma. Note that since the ion and plasma density have been reduced a higher pressure (1,0 mTorr) is required for n_c to be achieved and the overdense transition to occur.

At pressures above the underdense to overdense transition identified at 1.0 mTorr the leakage current density at 4MV/cm shows a continuous increase with deposition pressure. The growth process is dominated by neutral silane radicals, but any thin-film growth process is significantly altered by energetic ions. The energy imparted by incident ions can lead to thermal activation of the growth surface, resulting in improved bonding configurations and enhanced electrical properties. l-he ratio of nitrogen ions to the primary deposition species (ions/deposited atoms) should be an effective means of determining optimum deposition conditions, as has been observed for a variety of deposition processes.[25,26] To evaluate this, the ratio of the ion current density of the nitrogen plasma to the deposition rate were used as an approximation to the nitrogen ion/silane deposition species ratio. The pressure dependence of this ratio is given in Figure 12 and plotted with the leakage current density of the SiN:H films, with which it is well correlated. This result suggests an approximate means for determining optimum deposition conditions for ECR silicon nitride thin-films. Obviously the application of external (e.g., RF) bias will alter the energy of incident ions and thus the thin-film characteristics.

This minimum in the index of refraction observed may be due to the presence of oxygen in the films, sputtered from the quartz liner and microwave window. Oxygen contamination of ECR deposited silicon nitride thin-films from a quartz line has been investigated and found to be present in significant quantities in the parameter regime of this study.[27] The relative sputtering yield to deposition rate may reach a maximum at this pressure and subsequently decline at higher pressures as nitrogen ion energies and the plasma density decline.

V. CONCLUSIONS

The plasma characteristics for both nitrogen and silane-nitrogen plasmas are consistent with a transition from an underdense to overdense plasma at 0.9 and 1.0 mTorr respectively. This is supported by visual observations of the plasma intensity, sudden reduction of reflected power and abrupt increase in ion current density. At pressures immediately above the overdense transition in nitrogen plasmas, instabilities in the plasma were observed through measurements of the substrate floating potential and ion current density. These instabilities are consistent with a mode change occurring in the plasma as the pressure is increased from 0.9 mTorr. The new plasma mode stabilizes at approximately 1.6 mTorr, which is observed as a discontinuity in the floating potential as a function of pressure. The nitrogen plasma instabilities were eliminated with the introduction of silane to the plasma. Further, the plasma instabilities were found to be altered following the deposition of silicon nitride thin-films. Variation or even suppression of the instabilities can result from the introduction of background contaminants, particularly from residues of prior thin-film depositions on chamber walls.

The low deposition rates and poor quality of silicon nitride measured below 1.0 mTorr are due to an underdense plasma condition, resulting in excessive sputtering by energetic ions and absorption of microwaves by the substrate. The quality of silicon nitride films measured above 1.0 mTorr, in the overdense regime, are well correlated to the ratio of nitrogen ion current density to silicon nitride deposition rate, in effect the ions per deposited atom. This result gives an approximate means to identify optimum deposition conditions for ECR deposited silicon nitride thin-films.

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FIGURE CAPTIONS

Figure 1. Schematic diagram of the ECR PECVD system.

Figure 2. Instabilities in the floating potential V_f as a function of time for a nitrogen plasma at (a) 1.2 mTorr, (b) 1.4 mTorr and (c) 1.5 mTorr.

Figure 3. Floating potential V_f as a function of pressure for nitrogen and nitrogen-silane plasmas ($N_2/SiH_4=5$).

Figure 4. Ion current density as a function of pressure for the nitrogen plasma.

Figure 5. Deposition rate as a function of pressure for the growth of silicon nitride with $N_2/SiH_4=5$ for all depositions.

Figure 6. Index of refraction as a function of pressure. The observed minimum is primarily due to oxygen content in the films.

Figure 7. Hydrogen content as a function of pressure.

Figure 8. Representative leakage current density measured in an MIM structure as a function of applied field for the silicon nitride films grown in this study. These characteristics are consistent with a Frenkel-Poole current transport process.

Figure 9. Leakage current density as a function of pressure measured at 1 MV/cm and 4MV/cm. The low field density is relatively independent of pressure, while at high fields the increase is approximately exponential. The lines are intended as a visual guide.

Figure 10. Applied field at which the exponential increase in current density occurrs as a function of pressure. Higher required fields are indicative of an increased barrier height f_B for trap states.

Figure 11. Reflected microwave power as a function of pressure for nitrogen and nitrogen-silane plasmas. The sudden decrease in reflected power, accompanied by a dramatic increase in the optical intensity of the plasma, is consistent with an underdense to overdense plasma transition.

Figure 12. Comparison of the pressure dependence of the leakage current density at 4MV/cm and the ratio of deposition rate to ion current density.

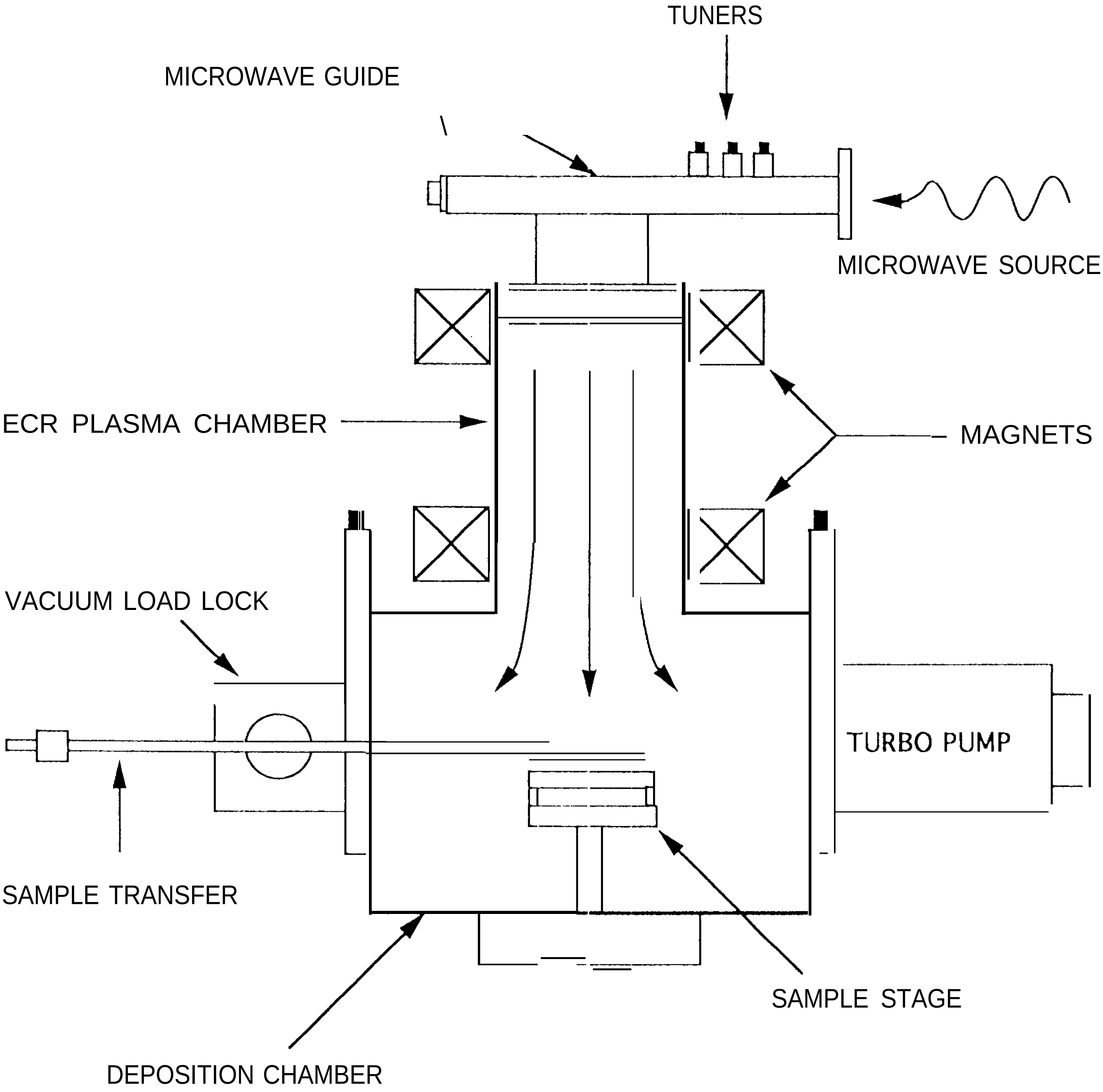

Figure 1. Schematic diagram of the ECRPECVD system.

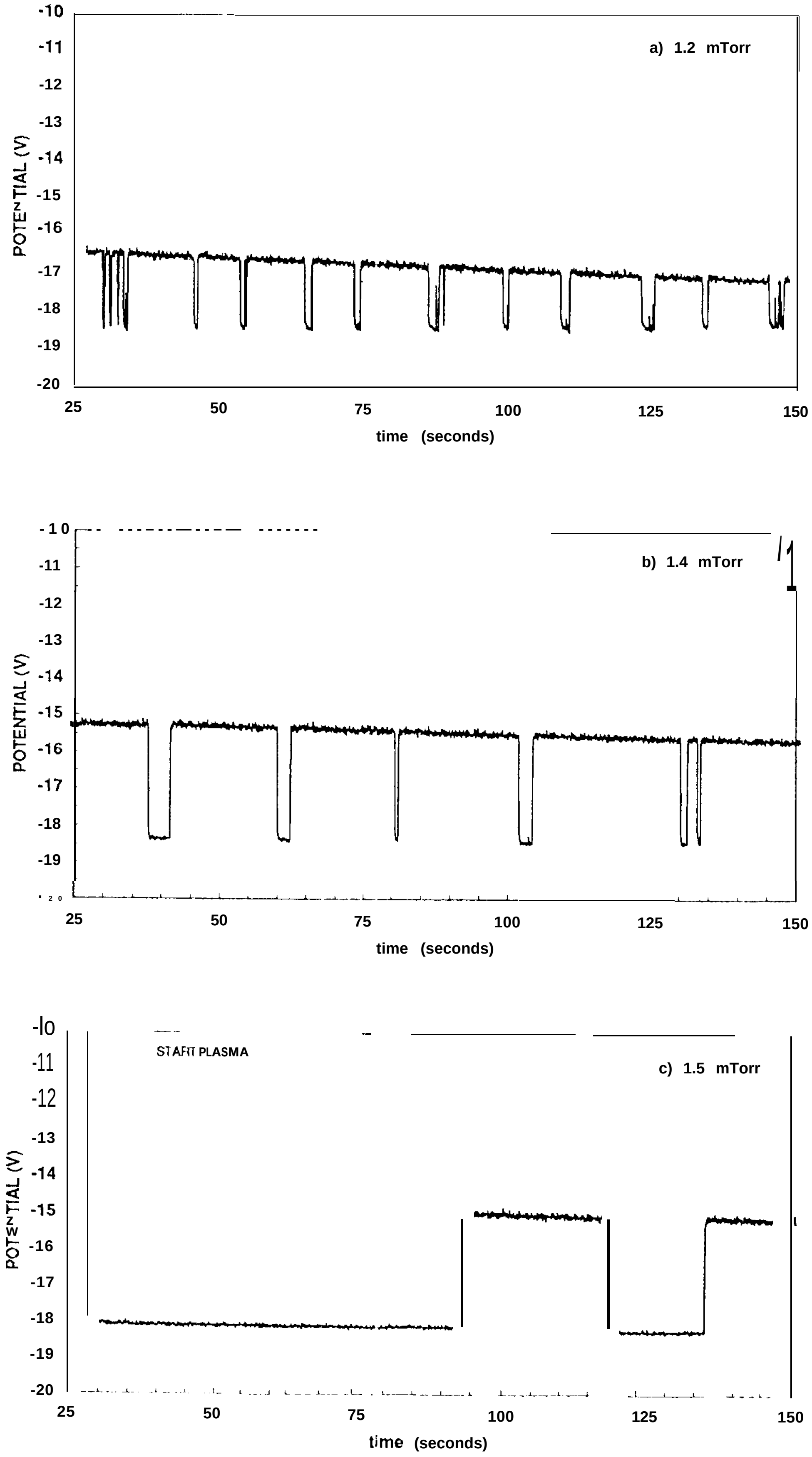

Figure 2. Instabilities in the floating potential V_f as a function of time for a nitrogen plasma at (a) 1.2 mTorr, (b) 1.4 mTorr and (c) 1.5 mTorr.

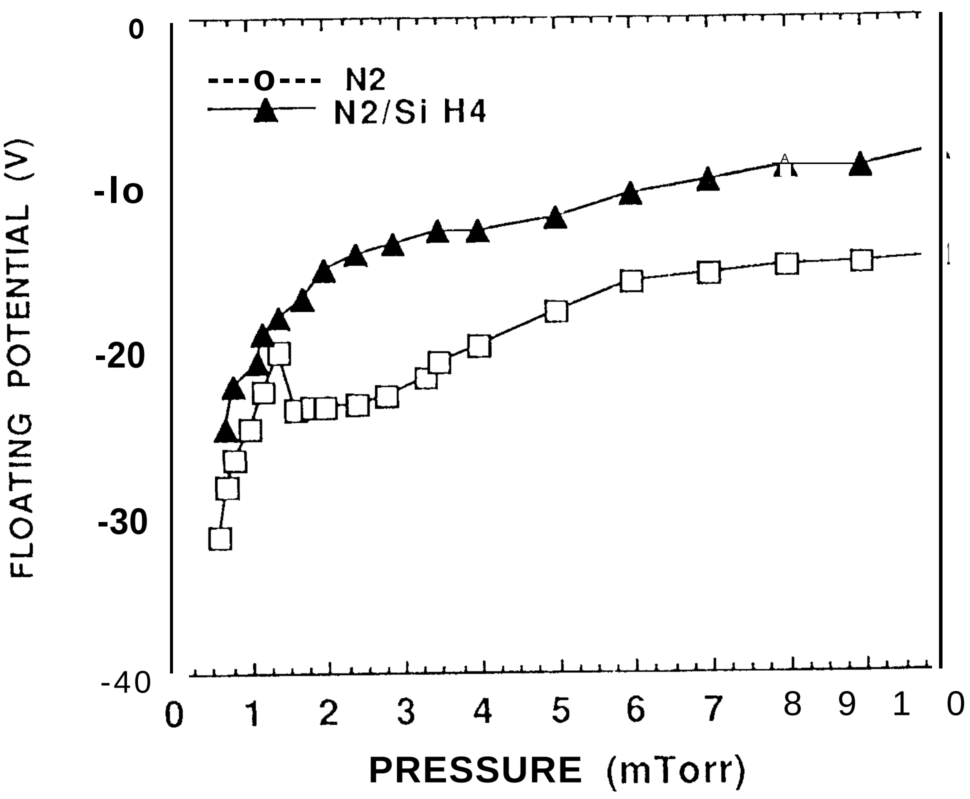

Figure 3. Floating potential V_f as a function of pressure for nitrogen and nitrogen-silane plasmas ($N_2/SiH_4=5$).

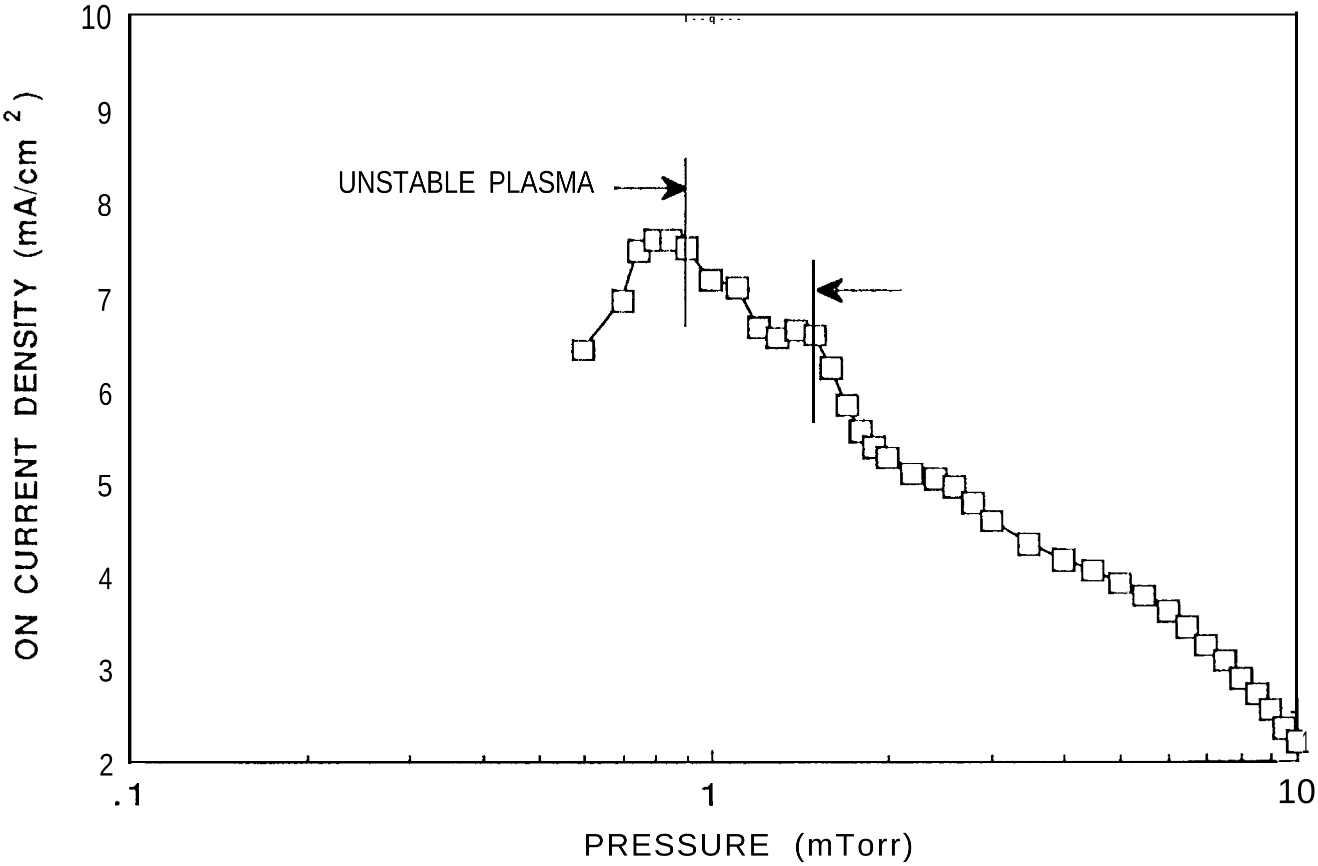

Figure 4. Ion current density as a function of pressure for the nitrogen plasma.

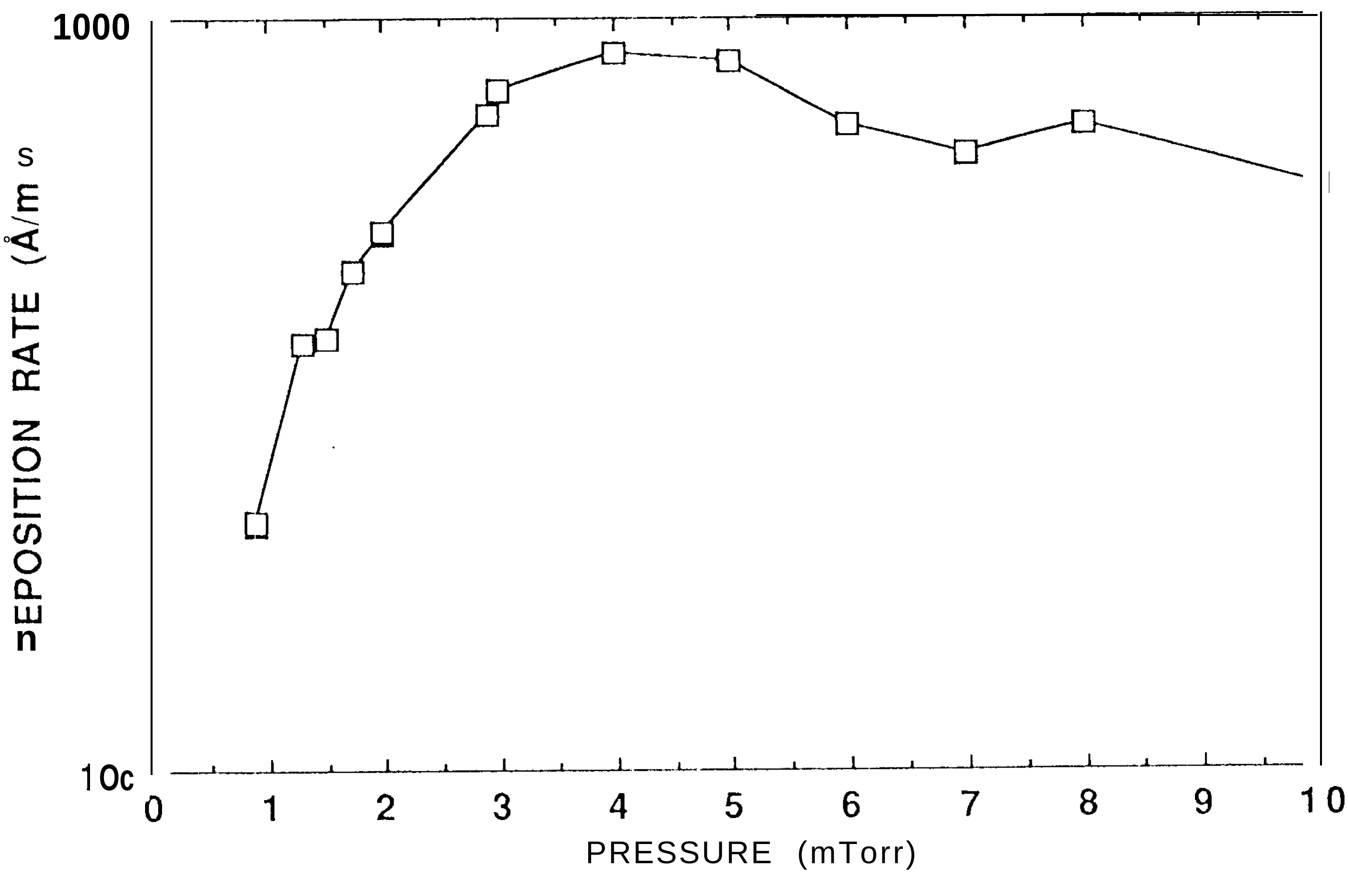

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Figure 5. Deposition rate as a function of pressure for the growth of silicon nitride with $N_2/SiH_4=5$ for all depositions.

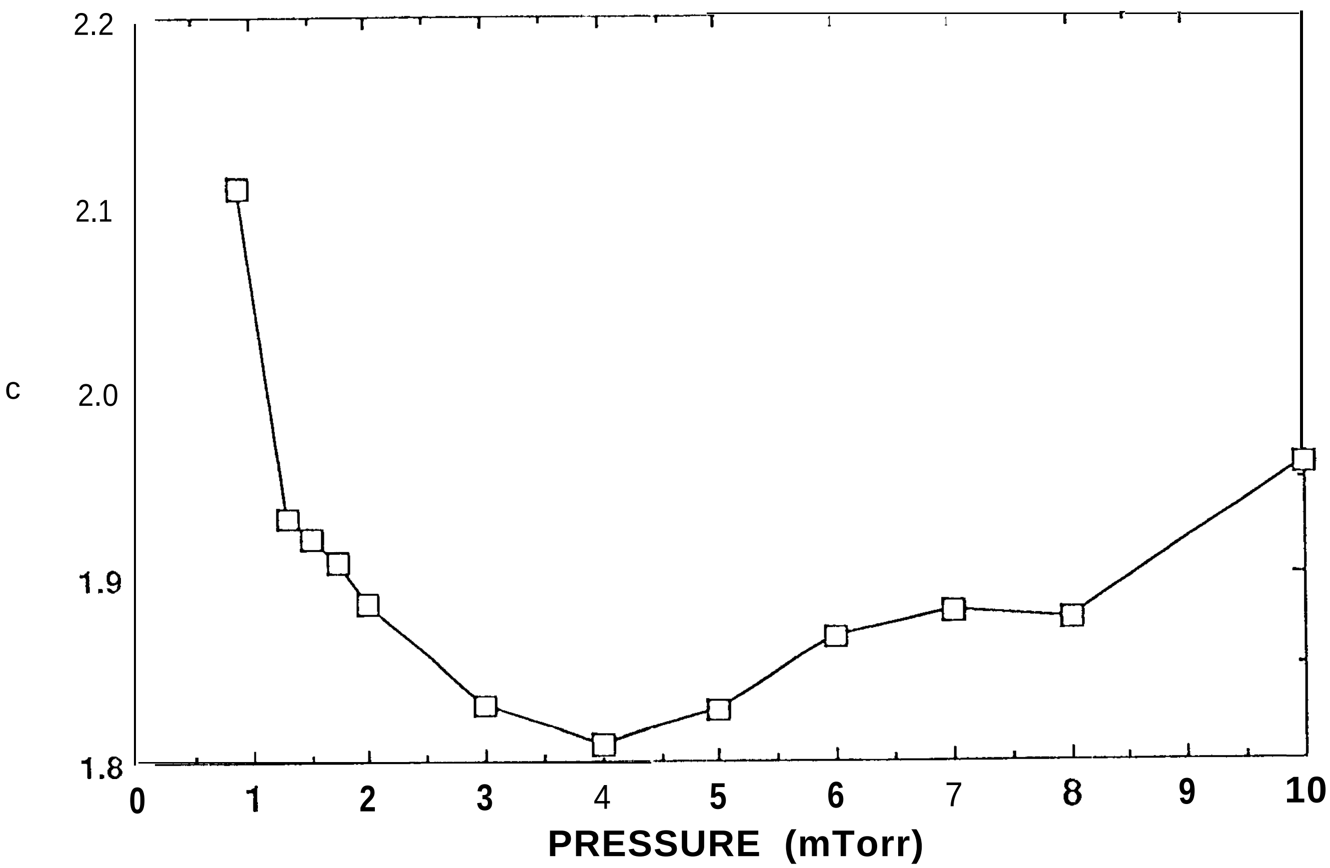

Figure 6. Index of refraction as a function of pressure. The observed minimum is primarily due to oxygen content in the films.

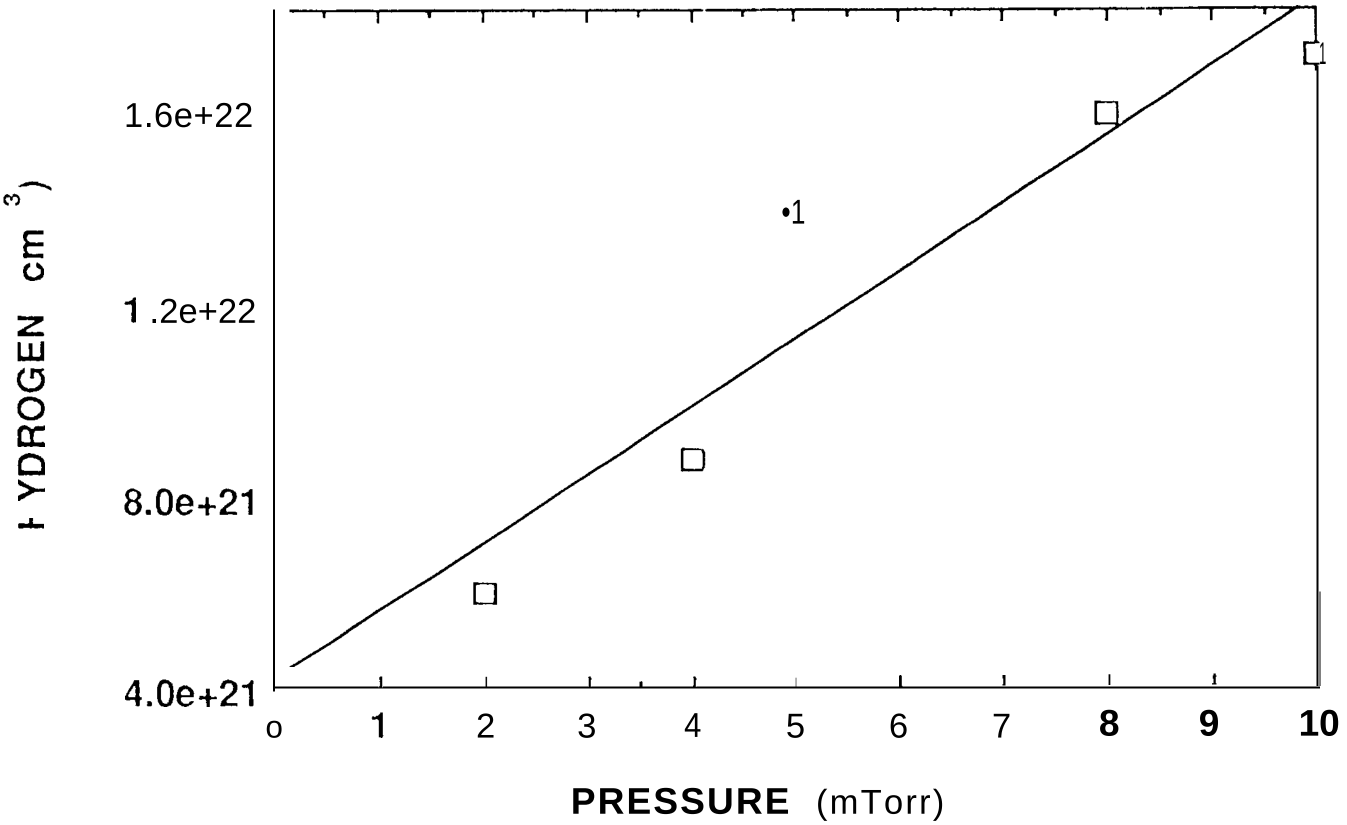

Figure 7. Hydrogen content as a function of pressure

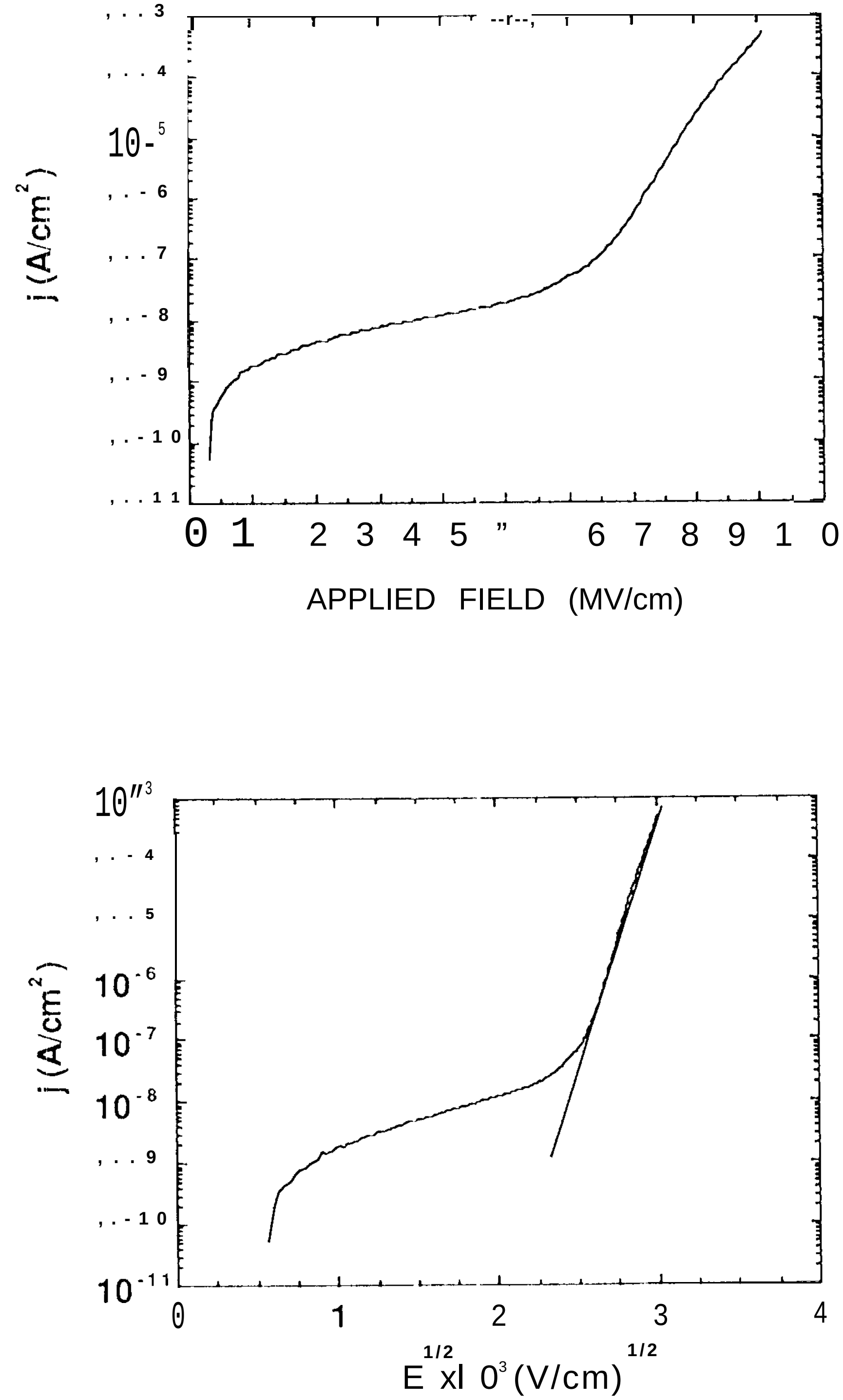

Figure 8. Representative leakage current density measured in an MIM structure as a function of applied field for the silicon nitride films grown in this study. These characteristics are consistent with a Frenkel-Poole current transport process.

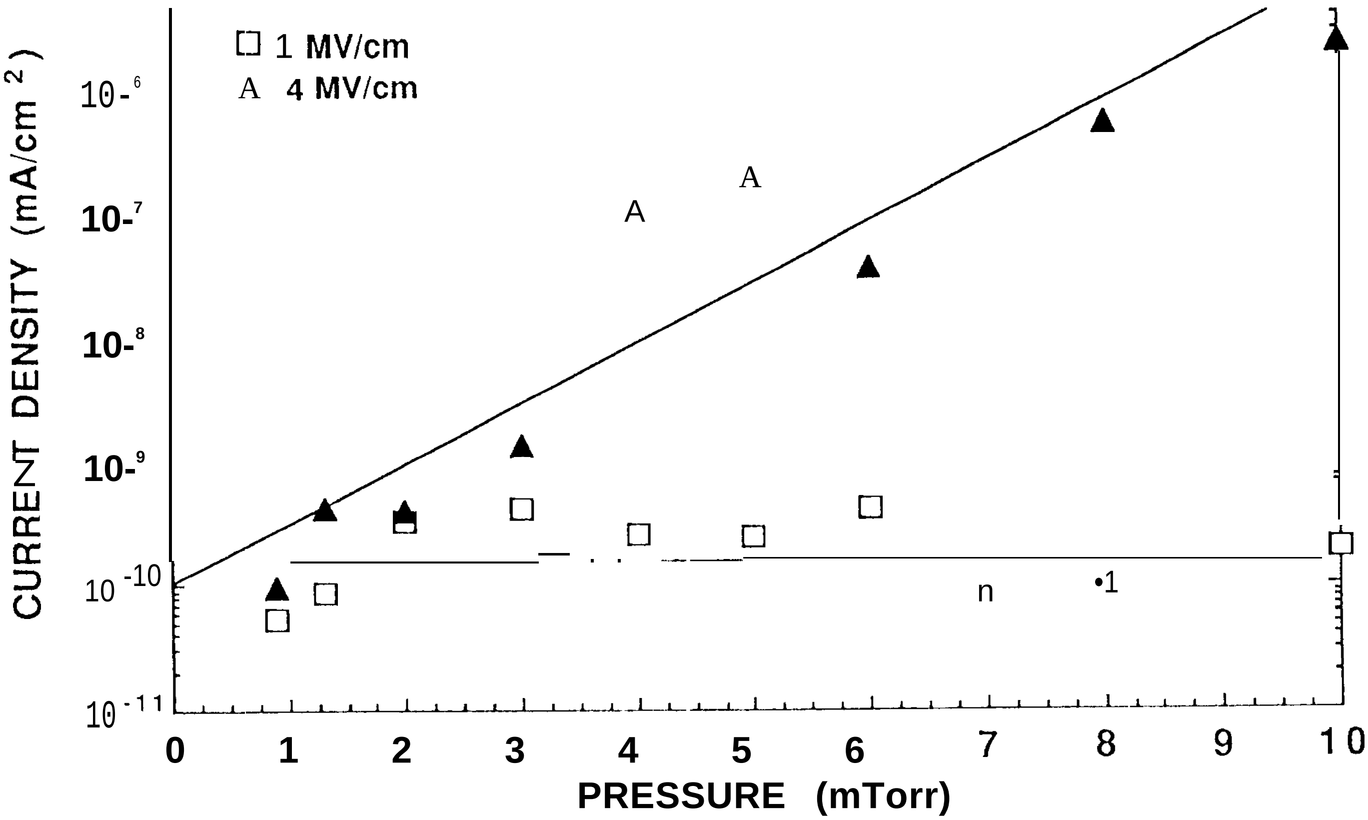

Figure 9. Leakage current density as a function of pressure measured at 1 MV/cm and 4MV/cm. The low field density is relatively independent of pressure, while at high fields the increase is approximately exponential. The lines are intended as a visual guide.

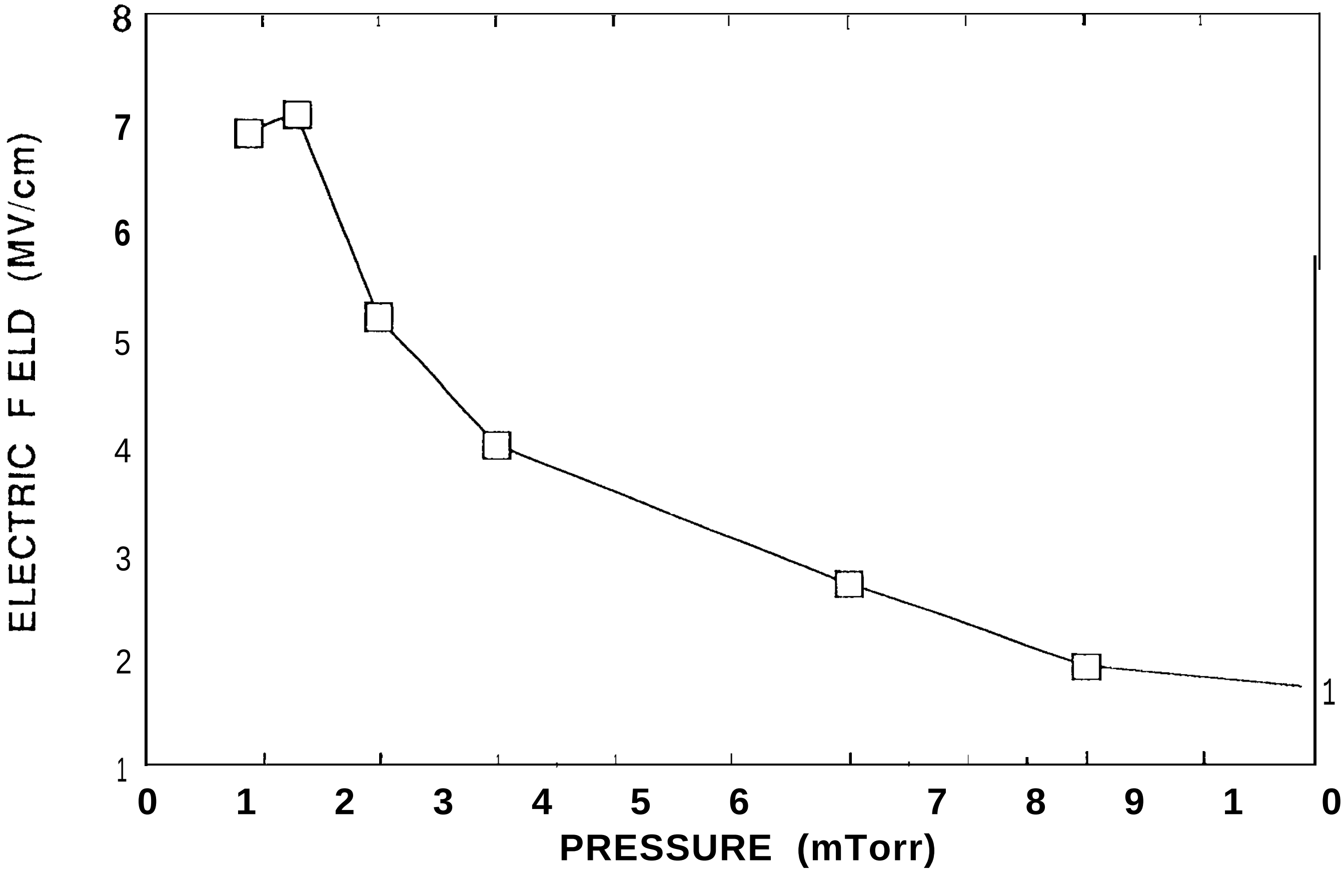

Figure 10. Applied field at which the exponential increase in current density occurrs as a function of pressure. Higher required fields are indicative of an increased barrier height ϕ_B for trap states.

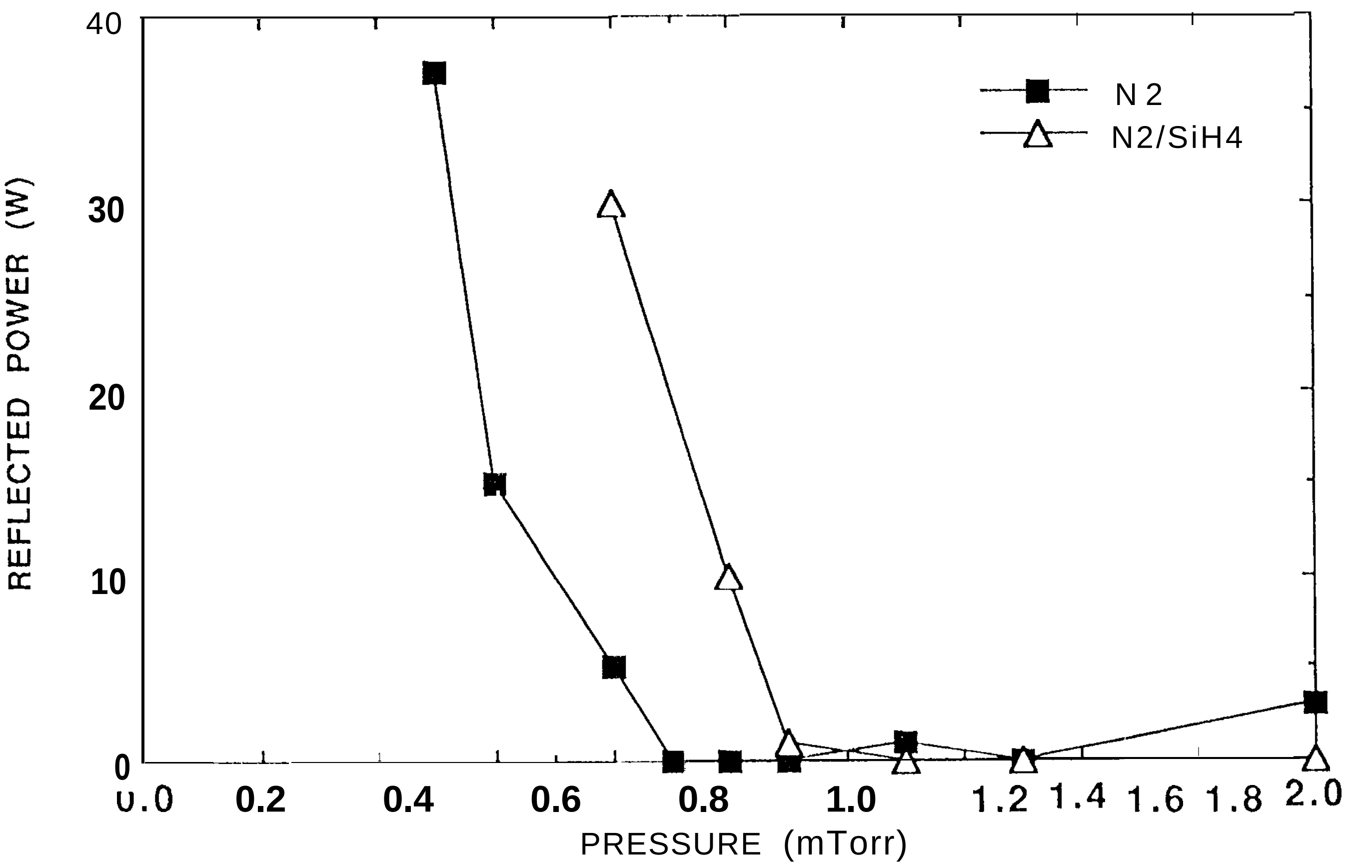

Figure 11. Reflected microwave power as a function of pressure for nitrogen and nitrogen- silane plasmas. The sudden decrease in reflected power, accompanied by a dramatic increase in the optical intensity of the plasma, is consistent with an underdense to overdense plasma transition.

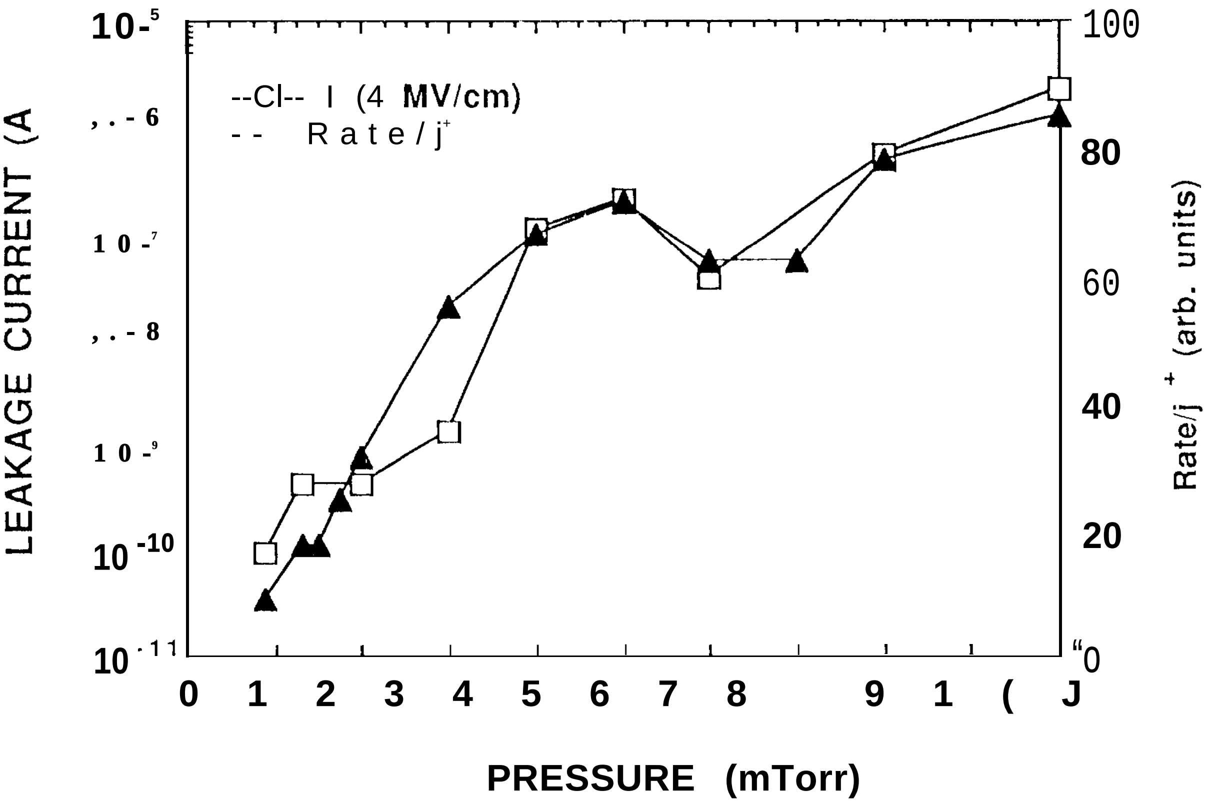

Figure 12. Comparison of the pressure dependence of the leakage current density at 4MV/cm and the ratio of deposition rate to ion current density.