# SINGLE-STEP PROCESSES FOR ETCHING TaSi$_2$POLYSILICON GATE STRUCTURES IN SF$_6$/CCl$_x$F$_y$ PLASMA

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# Single-Step Processes For Etching
# TaSi$_2$/Polysilicon Gate Structures in SF$_6$/CCl$_x$F$_y$ Plasmas

*Ivan L. Wemple*

*Abstract*—One-step RIE processes have been developed for patterning TaSi$_2$/polysilicon thin films. A Plasmatherm ® PK-1250 parallel-plate reactor was modified to improve diagnostic capabilities and to allow 4" wafer processing. Experiments have been conducted on sputtered TaSi$_2$, LPCVD polysilicon, and SiO$_2$ to explore the issues of etch selectivity and anisotropy. Using SF$_6$ in conjunction with chlorine-containing gases allowed adjustment of the fluorine-to-chlorine content of the discharge. CCl$_2$F$_2$ and CClF$_3$ were employed as sources of atomic chlorine. It was shown that the flow rate ratio of SF$_6$:CCl$_x$F$_y$ directly impacted the relative etch rates of the TaSi$_2$ and polysilicon. The influence of gas mixture on the edge profile of the patterned dual-layer film was investigated using scanning electron microscopy. Etch processes exhibiting smooth, anisotropic profiles and acceptable selectivity over SiO$_2$ were developed for SF$_6$/CCl$_2$F$_2$ *and* SF$_6$/CClF$_3$ plasmas.

# I. Introduction

The drive towards implementing higher and higher levels of circuit integration has forced process engineers to explore new alternatives to presently-common polysilicon gate technologies. As linewidths become narrower, the relatively high sheet resistance and its associated contribution to RC circuit delay make polysilicon alone inadequate for use as gate and interconnect material. On the other hand, engineers are unwilling to part with the well-established reliability of the poly/$SiO_2$ gate-insulator interface. One mutually satisfactory solution involves the use of a polysilicon/refractory metal silicide double-layer, or polycide.[1] These composite structures are gaining widespread attention as an acceptable compromise between the high conductivity of silicides[2] and the superior gate integrity of polysilicon.

The utilization of a composite film instead of polysilicon imposes new constraints on the gate electrode etch process. The dissimilarity between the two materials often leads to edge profiles exhibiting discontinuities or "notching" at the silicide/polysilicon interface. A smooth, slightly-tapered or vertical sidewall is desired to allow subsequent step coverage and good device definition. Etching the composite structure anisotropically is not enough. The etch process must demonstrate high selectivity over the underlying gate oxide. Furthermore, safe, easy-to-handle, and cost-effective gases are favored in any dry etch process. Single-step processes are preferred because they eliminate the need for in-situ determination of process "halfway" points and complex gas delivery systems.

This paper evaluates the feasibility of using $SF_6$/$CCl_xF_y$ plasmas for etching $TaSi_2$/polysilicon gate structures in single-step processes. Mattausch, et al.[3] and Clark, et al.[4] used $SF_6$/$Cl_2$ and $SF_6$/Freon-115 discharges to etch tantalum polycides, but neither group was able to obtain strict anisotropy with single-step processes. Herrmann, et al.[5] obtained high selectivity and anisotropic profiles, but a multi-step process was required.

All of the above considerations are relevant to this study. Our initial goal was to determine process parameters for a single-step etch technique capable of patterning $TaSi_2$/polysilicon films anisotropically and selectively over $SiO_2$. $CCl_xF_y$ gases were chosen

based on their dissociative properties and their superiority over $Cl_2$ in terms of safety and ease-of-handling. Following a brief discussion on our laboratory apparatus in Section II, we provide some background on our motivation for choosing gases exhibiting the $CCl_xF_y$ stoichiometry. In Section IV, we describe the results of our preliminary selectivity experiments. Anisotropy and edge profile issues are discussed in Section V.

## II. Experimental Apparatus

All experiments reported in this study were carried out in a PlasmaTherm® PK-1250 parallel-plate etching system. The top and bottom electrodes are circular and of equal diameter (9 1/2"). Their separation is 1 3/4". The rf power is supplied by a 13.56 MHz solid state generator and can be applied to either of the electrodes through a matching network. This network allows maximum power transfer to the discharge. In all of the cases presented here, etch samples were placed on the powered electrode (ie, the system was operated in RIE mode). The other electrode and the chamber walls were grounded. This results in the development of a dc voltage drop from the plasma to the wafer, which accelerates plasma-generated ions toward the wafer surface. It is well-established that this ion bombardment leads to dramatic increases in vertical etch rates of many materials, and can therefore directly contribute toward the attainment of anisotropic etch profiles.

Any three of eight process gases can be delivered to the system after pre-mixing occurs downstream from the chamber. Their individual flow rates are regulated by three mass-flow controllers. The chamber pressure is independently monitored and controlled via a capacitance manometer and throttle valve.

Substrate temperature can also be controlled by heating or cooling the silicone oil which is continuously pumped through a hollow channel inside the lower electrode and a heat-exchanger circuit. The silicone oil and the aluminum electrode are assumed to be in thermal equilibrium, and thus the electrode temperature can be determined by measuring the temperature of the circulating fluid with a thermocouple. The heat-exchanger/thermocouple electronics

are coupled in such a way that the electrode temperature can be constantly maintained at a specific user-established setpoint.

Prior to beginning our investigation, the etch chamber was modified in hopes of improving on the existing design. First, both electrodes were replaced to improve system uniformity and throughput. In the old design, the etch gases entered the chamber through an annular rim on the lower electrode, and the discharge effluent was pumped out through a 1-1/4" manifold at the center of the same electrode. This manifold led to a larger (4" diameter) manifold connected to the pumping system. This configuration was undesirable for three reasons: (*i*) the gas entrance rim near the edge and the 1-1/4" exhaust manifold in the center of the lower electrode reduced its wafer-handling capacity (in fact, wafers with diameters in excess of 3" would not fit on the electrode at all), (*ii*) the smaller exhaust manifold in series with the 4" pump manifold unnecessarily limited the pumping speed, and (*iii*) radially directed gas flow patterns have been linked to etching non-uniformity.

These problems were eliminated by re-designing the chamber electrodes. The process gas delivery line was re-routed to a hollow cavity inside a new *top* electrode. Gas entering this cavity reaches the chamber interior through a carefully-designed[6] concentric hole pattern drilled through the electrode surface. Thus, a "showerhead" delivery system has been implemented. The bottom electrode, freed from the responsibility of supporting any process gas plumbing, was replaced by one with a smooth, solid surface capable of handling up to four 4" wafers. This electrode is supported by three insulated legs, and the 4" pumping manifold is connected directly to the chamber baseplate. Exhaust gas is removed by drawing it around the outside edge of the bottom electrode through the baseplate pumping manifold. Despite major functional modifications, the diameters of the two electrodes were not changed.

Next, a ground shield was installed behind the powered (ie, lower) electrode to confine the plasma to the region between the electrodes. The electrode-to-ground shield spacing was chosen to be 3/32" to eliminate the possibility of striking a discharge in the gap during operation at nominal pressures.[7] Besides the obvious benefit of maximizing power efficiency, confining the discharge to a known region allows easy calculation of the power density. The

top electrode, bottom electrode, ground shield, and new baseplate were all machined from 6061 aluminum.

Other system modifications were made for diagnostic purposes. These included the installation of an electric circuit to measure the time-averaged potential (or "dc self-bias") of the powered electrode with respect to system ground, and an emission spectrometer for analyzing the composition of the plasma. Details of the dc self-bias measurement circuit, as well as diagrams of our experimental system (both before and after modification), appear in Figure 1.

### III. Motivation For The Use of $SF_6/CCl_xF_y$ Plasmas

Interest in polycide structures for VLSI gate and interconnection technology has been spurred by the high sheet resistance of doped polysilicon relative to that of the silicide/polysilicon combination. Although techniques for the removal of $TaSi_2$ via wet chemical etching are well-established,[2,8] the isotropy inherent to these processes makes them unacceptable for use in the VLSI and ULSI fabrication regimes. Dry etching, on the other hand, has demonstrated a superior advantage over wet processing for the definition of fine-line structures. In general, plasma processes can be fine-tuned by careful selection of the process parameters to yield "optimum" results in terms of anisotropy and selectivity.

The reactive ion etching of $TaSi_2$/polysilicon composite films using single-step processes has been reported by Mattausch, et al. and Zhang, et al.[9] Both processes utilize a fluorinated gas ($SF_6$ and $SiF_4$ respectively) in combination with molecular chlorine ($Cl_2$). Although both groups report moderate success with their respective approaches, the fact remains that $Cl_2$ exhibits undesirable properties in terms of its corrosiveness and toxicity. Our approach at Berkeley has involved the introduction of chlorine into our etch system by way of chlorinated Freons, specifically $CCl_2F_2$ and $CClF_3$, which are characteristically more benign and easier to handle than pure molecular chlorine.

Early work in the reactive ion etching of tantalum polycide structures at Berkeley[10] focused on attempts at mimicking the $SF_6/Cl_2$ process gas system used by Mattausch, et al.,

*without using* $Cl_2$. The process reported by Mattausch, et al. relies on the fact that a fraction of the $Cl_2$ molecules are dissociated by electron impact in the plasma releasing Cl radicals. It is clear, however, that other chlorine-containing gas molecules may also generate Cl radicals when subjected to electron impact in a glow discharge. Table 1 below lists the chlorine and fluorine bond strengths[11] in molecular chlorine ($Cl_2$), Freon-12 ($CCl_2F_2$), and Freon-13 ($CClF_3$):

| Table 1. Cl and F Bond Strengths in Selected Chlorine-containing Molecules | | |
|---|---|---|
| Molecule | Bond | $D^o_{298}$/kcal mol$^{-1}$ |
| $Cl_2$ | Cl - Cl | 58 |
| $CCl_2F_2$ | Cl - $CF_2Cl$ | 76 |
|  | F - $CFCl_2$ | 110 |
| $CClF_3$ | Cl - $CF_3$ | 86 |
|  | F - $CF_2Cl$ | 117 |

This data presents two facts: 1) the energy required to remove a chlorine atom from a Freon-12 or Freon-13 molecule is on the same order as the energy required to dissociate the $Cl_2$ molecule, and 2) it is energetically more favorable to remove a chlorine atom from $CCl_2F_2$ and $CClF_3$ than it is to remove a fluorine atom from the same molecules. We realize, of course, that other factors come in to play when discussing the dissociative properties of the Freon and $Cl_2$ plasmas. These include collision cross-sections of the constituent molecules and the electron energy distribution function of the particular plasma in question, among others. However, at first glance, one might suspect that the chlorinated Freons in Table 1 may be an adequate source of Cl radicals in a glow discharge process.

Bearing these issues in mind, we proceeded to etch tantalum silicide/polysilicon/$SiO_2$ stacked films in gas mixtures containing $SF_6$ and $CCl_2F_2$. In all of these preliminary runs, rf power level, chamber pressure, substrate temperature, and total flow rate were held constant at values of 350 W, 40 mT, 70° C, and 40 sccm, respectively. The only parameter that was varied from run-to-run was the $SF_6$:$CCl_2F_2$ flow ratio (ie, the gas mixture). Qualitatively, our results were in agreement with those reported by Mattausch, et al., who used the $SF_6$/$Cl_2$ system. For $SF_6$-rich mixtures, the polysilicon etched faster than the tantalum silicide, creating an undercut edge profile. For mixtures rich in the chlorine-containing gas, the silicide etched faster than the underlying polysilicon, creating a stepped (ie, "overcut" ) profile. Neither is desirable when one considers the linewidth control and step coverage demands required by the level of circuit integration currently used in the electronics industry. However, at some critical $SF_6$:$Cl_2$ or $SF_6$:$CCl_2F_2$ gas flow ratio, a smooth, slightly-tapered sidewall was obtained, which demonstrated good pattern definition and would allow adequate step coverage during subsequent fabrication processes.

Although our preliminary work indicated that the $SF_6$/$CCl_2F_2$ gas system could indeed be used to remove both tantalum silicide and polysilicon, the set of parameters used to obtain a desirable edge profile were inadequate for etching the polycide film *selectively* over $SiO_2$. Careful inspection of the SEM photographs used to examine edge profiles revealed that the underlying gate oxide was being etched quite severely. Furthermore, the $SF_6$/$CClF_3$ system had been neglected altogether throughout the course of our initial investigation. Simultaneously studying both chlorinated Freon systems would be very valuable as an aid in developing insight into the chemical nature of the tantalum polycide etch process. It became evident that a more complete analysis of the $SF_6$/$CCl_2F_2$ plasma process parameter space, as well as that of the $SF_6$/$CClF_3$ system, would be necessary in order to find an "optimum" process capable of satisfying both anisotropy *and* selectivity requirements.

## IV. Selectivity Studies

As mentioned in the previous section, none of our preliminary work provided any indication that the tantalum silicide/polysilicon composite layer could be etched selectively over an underlying gate oxide in an $SF_6/CCl_2F_2$ or $SF_6/CClF_3$ plasma. However, we did prove that varying the relative amounts of $SF_6$ and $CCl_2F_2$ in an $SF_6/CCl_2F_2$ discharge served to vary the relative etch rates of the silicide and polysilicon. At this point, then, we began to focus our attention solely on the issue of etch selectivity.

Our approach would proceed as follows: (*i*) Perform experimental matrices investigating a variety of process parameters (eg, rf power, pressure, gas mixture, etc.) to determine etch rates for polysilicon and $SiO_2$, (*ii*) establish process windows for which the ratio of polysilicon-to-$SiO_2$ etch rates is acceptable *for a range of gas mixtures*, and (*iii*) etch $TaSi_2$/polysilicon double-layers using process parameters which yield adequate selectivity, and simultaneously *tune the gas mixture* to obtain the desired edge profile (as we did in our preliminary experiments). Since the results of the proposed selectivity study (ie, steps (*i*) and (*ii*)) would rely only on information regarding polysilicon and $SiO_2$, it was necessary to assume, a priori, that the gas mixture could indeed be tuned to yield equal polysilicon and $TaSi_2$ etch rates. Based on results presented by Mattausch, et al. using the $SF_6/Cl_2$ system, and our previous work utilizing $SF_6$ and $CCl_2F_2$, we felt justified in making this assumption.

One of the problems associated with plasma process development is the very large number of parameters that are involved. Power, pressure, gas mixture, flow rate, substrate bias and temperature, and other factors may directly or indirectly affect a number of key process "results" (eg, etch rate, anisotropy, etc.). Nevertheless, two user-controllable parameters associated with our etching system were held constant throughout the course of this investigation. First, the *total* flow rate for the gas mixture was fixed at 20 sccm. Given the pumping speed of our vacuum system, and the range of "effective" pump speeds made available by our throttling apparatus, it was determined that a gas flow of approximately 20 sccm allowed us to work in the range of pressures which interested us (10 - 80 mT).[12] Secondly, the substrate

temperature was held at 21° C. This setpoint was motivated by publications by Flamm, et al.[13] and Enomoto, [14] who reported that silicon-to-$SiO_2$ selectivities are greater at lower temperatures in fluorine-based (eg, $SF_6$) plasmas.

Oxide samples were prepared by cleaning 18-22 $\Omega$-cm, p-type or 8-12 $\Omega$-cm, n-type <100> 4" silicon wafers in an HF-based solution. $SiO_2$ was grown to a thickness of approximately 5000 Å in a steam furnace at 1000° C. Similarly-doped 4" <100> silicon wafers were also used as substrates for the polysilicon samples. First, 1000 Å of oxide was grown on the Si surface to facilitate subsequent thickness measurements of the overlying poly. Then, approximately 4500 Å of phosphorous-doped polysilicon was deposited at a pressure of 350 mT in a Tylan® LPCVD deposition tube. The deposition was performed at 650° C, and phosphine gas ($PH_3$) was introduced to the furnace during the process for in-situ doping of the material. Finally, the wafers were annealed at 900° C in $N_2$ for 30 minutes. This was done in an attempt to simulate the poly deposition process used in the fabrication of our composite layers (provided by Sandia National Laboratories), which was performed in an LPCVD system at 900° C. The final polysilicon sheet resistance was approximately 12 $\Omega$ / $\square$. All of the oxide- and polysilicon-coated wafers were then scribed and broken into 1 $cm^2$ pieces, each of which was measured on a Nanospec® AFT thin film system to determine its corresponding layer thickness.

Because of our experience with $SF_6/CCl_2F_2$ discharges as reported in the previous section, we chose this gas system as a starting point in our pursuit of a selective etch process. Figure 2 shows the etch rate dependences on rf power of doped polysilicon and $SiO_2$ for $SF_6$:$CCl_2F_2$ flow ratios of 15:5, 12.5:7.5, and 10:10. The pressure was held constant at 40 mT. Etch rates were determined by dividing the difference in pre- and post-etch thicknesses by the total etch time (30 seconds for poly and 40 seconds for $SiO_2$). It was observed that the $SiO_2$ etch rate was independent of the $SF_6/SiO_2$ gas mixture. Although the etch rates of both materials increase monotonically with increasing rf power, maximum selectivity was obtained at 170 W (.37 W/$cm^2$) for all three gas mixtures tested.

The etch rate curves in Figure 2 seem to imply that the polysilicon etch rate rises as the percentage of $SF_6$ in the mixture is increased. Figure 3, which shows etch rates as a function of the $SF_6:CCl_2F_2$ flow ratio, indicates that this is *not* the case for ratios greater than 17.5:2.5, where the etch rate drops dramatically. Since the $SiO_2$ etch rate is independent of gas mixture, the poly-to-oxide selectivity is directly proportional to the polysilicon etch rate, which is nearly uniform and maximized for all $SF_6/CCl_2F_2$ flow ratios between 12.5:7.5 and 17.5:2.5. For this reason, flow ratios of 12.5:7.5, 15:5, and 17.5:2.5 were used exclusively in all subsequent $SF_6/CCl_2F_2$ runs at 170 W.

At this point, it is appropriate to discuss exactly what polysilicon-to-$SiO_2$ etch-rate ratio is required to achieve "acceptable" or "adequate" selectivity. In many instances, selectivity requirements are complicated by severe wafer topography in underlying films. The tendency for vertical film thicknesses to increase when passing over steps makes it necessary to overetch (sometimes as much as 100%) to ensure complete removal of "stringers" from the base of the steps. Fortunately, our particular process application involves gate-electrode delineation, which occurs very early in the overall device fabrication sequence. The only variations from a *planar* underlying topography are related to the relatively smooth (ie, "birds beak") transitions between the thick field oxide regions and the thin gate oxide regions. Although some overetching of the silicide/polysilicon composite film is in fact necessary, it has been determined that a polycide-to-$SiO_2$ selectivity of 10 is adequate for the development of a viable production process.[15]

Varying the gas mixture at constant pressure and rf power yielded a maximum selectivity of 9.4 at a $SF_6:CCl_2F_2$ ratio of 17.5:2.5 (see Figure 3). According to the discussion in the preceding paragraph, these etch conditions do not provide satisfactory selectivity. In addition, this "best" result is for a single gas mixture only, and good results are desired for a range of mixtures. A more thorough investigation of the parameter space was necessary to obtain higher selectivities. Figure 4 provides data on the polysilicon and $SiO_2$ etch rates as a function of reactor pressure for the three gas mixtures under study. The polysilicon etch rate rises with increasing pressure, while the $SiO_2$ etch rate is shown to decrease. This trend was observed

for all three gas mixtures. Figure 5 shows the polysilicon-to-$SiO_2$ selectivity vs. pressure at 170 W. Sufficient selectivity was obtained for the range of gas mixtures at pressures higher than approximately 50 mT. The trend suggested in Figure 5 prompted us to test pressures greater than 80 mT.[12] At 125 mT, selectivities in excess of 20:1 were obtained for the same range of $SF_6$:$CCl_2F_2$ gas flow ratios.

Experiments to determine etch selectivity were also carried out utilizing the $SF_6$/$CClF_3$ gas system. Bond strength data given in Table 1 supports the hypothesis that $CClF_3$ dissociation in a glow discharge might generate Cl radicals. In addition, Mogab and Shankoff[16] observed substantial amounts of atomic chlorine in $CClF_3$ plasmas using optical emission spectroscopy. These facts, coupled with the clear safety advantages of using $CClF_3$ over $Cl_2$, were enough motivation to include the $SF_6$/$CClF_3$ gas combination in our process development investigation.

Figure 6 shows polysilicon and $SiO_2$ etch rates as a function of the $SF_6$:$CClF_3$ gas flow ratio at 40 mT and 170 W. The total gas flow rate was regulated at 20 sccm. We chose to use a forward rf power of 170 W throughout our $SF_6$/$CClF_3$ selectivity study, because it provided optimum results in prior experiments utilizing $SF_6$ and $CCl_2F_2$. Figure 6 is qualitatively similar to Figure 3. The polysilicon etch rate is low for mixtures rich in the chlorinated species, rises to a maximum for some intermediate combination of gases, and then decreases for mixtures rich in $SF_6$. Although the etch rate "plateau" in Figure 3 is absent from Figure 6, all gas mixtures in the approximate range of 8:12 through 16:4 ($SF_6$:$CClF_3$) remove polysilicon at a rate of 2000 Å /min or greater. Other mixtures etch poly at a lower rate. Once again, the etch selectivity is directly proportional to the polysilicon etch rate because the $SiO_2$ etch rate is mixture-independent.

None of the process set points yielding data in Figure 6 provided selectivities greater than 10, but our experience with $SF_6$/$CCl_2F_2$ mixtures indicated that higher polysilicon etch rates might be obtained by etching at higher pressures. This was also shown to be true for the $SF_6$/$CClF_3$ gas system. Figure 7 is a plot of polysilicon and $SiO_2$ etch rates as a function of chamber pressure for $SF_6$:$CClF_3$ flow ratios of 8:12, 12:8, and 16:4. The matrix was run at

constant values of rf power, substrate temperature, and total gas flow rate as indicated on the graph. Polysilicon-to-oxide selectivities determined from the same experiments are shown in Figure 8. For flow ratios of 8:12 and 12:8 ($SF_6$:$CClF_3$), etching at 80 mT yields selectivities greater than 10. For mixtures containing a higher percentage of $SF_6$ (eg, $SF_6$:$CClF_3$ = 16:4), even greater pressures are required to achieve the necessary selectivity.

For *both* gas systems under study, we have been able to show that acceptable selectivity can be obtained at particular process set points involving a range of $SF_6$:Freon mixtures. Both gas combinations exhibited similar trends in their etching characteristics for changes in gas mixture and chamber pressure. The data clearly indicates that a selective etch process must be performed at a pressure greater than some minimum value which depends on the gas system being utilized. In the following section, we will summarize the process parameters which satisfy poly-to-oxide selectivity requirements, and report on the results of studies directly involving the reactive ion etching of $TaSi_2$/polysilicon composite layers.

## V. Tantalum Silicide / Polysilicon Composite Layers

Analysis of the results presented in the previous section reveals that we have established process windows in which polysilicon can be etched selectively over $SiO_2$. The next step would involve etching polycide samples using those parameters and adjusting the relative amounts of $SF_6$ and $CCl_xF_y$ to obtain edge profiles suitable for use in the fabrication of gate electrodes for small-geometry technologies. Before reporting on the results of this second study, some background and review is appropriate.

Etching double-layer films in a single process step is difficult because any disparity in the etch characteristics of the two films can contribute to an edge profile exhibiting undercut or overcut. A practical production process requires a smooth or slightly overcut taper to allow subsequent step coverage and good device definition. For VLSI processes, a high degree of anisotropy is also required to eliminate linewidth loss during etching and to minimize the distance between features.

Our belief that the $SF_6:CCl_xF_y$ flow ratio can be tuned to obtain optimum sidewall profiles is not unfounded. Mattausch, et al. observed that the shape of the $TaSi_2$/polysilicon sidewall is directly influenced by the $SF_6:Cl_2$ flow rate ratio when other process parameters are held constant.[3] See Figure 9. In pure $SF_6$, the polysilicon etches much more rapidly than the overlying $TaSi_2$, resulting in a silicide overhang. For mixtures rich in $Cl_2$, the silicide etches more rapidly than poly, and the profile exhibits overcut. An optimum result is achieved at some intermediate mixture. We observed similar results in work done prior to this investigation. Mattausch and colleagues point out that $TaSi_2$ cannot be etched in pure $Cl_2$ plasmas, and attribute this to the low volatility of tantalum-chlorine compounds as indicated by their low vapor pressures. On the other hand, $TaSi_2$ *does* etch in fluorine-based plasmas, while silicon is etchable in chlorine- *and* fluorine-based discharges. One possible explanation for the tailorability of the edge profile is based upon these observations. From Figure 9, it is apparent that pure $SF_6$ discharges are incapable of producing an acceptable edge profile; the etch rate of polysilicon is simply too high relative to that of the silicide. Conversely, pure chlorine plasmas are inadequate because they don't etch $TaSi_2$ *at all*. However, when fluorine *and* chlorine are present in the plasma, interesting things can happen. Since Cl and F radicals are capable of etching poly, introducing chlorine into the system offers an alternative reaction pathway for the removal of silicon (ie, via the formation of volatile $SiCl_4$). As silicon consumes chlorine, more fluorine is made available to etch the silicide. Therefore, varying the relative amounts of Cl and F in the discharge varies the relative etch rates of the different materials.

Table 2 outlines process parameters capable of etching polysilicon selectively over $SiO_2$. They were determined solely by the selectivity experiments described in Section IV. We would like to re-emphasize the fact that each process setpoint is capable of achieving adequate results for a *range* of $SF_6:CCl_xF_y$ flow rate ratios, each of which is specified in the table.

| | | | | Table 2. Process Parameters For Etching Polysilicon Selectively Over $SiO_2$ | | |
|---|---|---|---|---|---|---|
| Gases | Power | Pressure | Total Flow | Flow Ratios | Temp |
| $SF_6{:}CCl_2F_2$ | 170 W | $\geq$ 50 mT | 20 sccm | 12.5:7.5 - 17.5:2.5 | 21° C |
| $SF_6{:}CClF_3$ | 170 W | $\geq$ 90 mT | 20 sccm | 8:12 - 16:4 | 21° C |

Utilizing information from Table 2, process parameters were chosen to etch $TaSi_2$/polysilicon double layers for the purpose of examining post-etch edge profiles. Polycide samples were prepared at Sandia National Laboratories in the following manner: (*i*) $SiO_2$ was grown to a thickness of 4200 $\overset{o}{A}$ on 4" Si wafers in a steam ambient, (*ii*) 3000 $\overset{o}{A}$ of phosphine-doped polysilicon was deposited on the $SiO_2$ surface at a furnace temperature of 900 ° C, and (*iii*) 3000 Å of tantalum silicide was sputtered from a composite target on top of the doped poly. The silicide is actually non-stoichiometric, $Ta_xSi_y$, but x and y are approximately 1 and 2, respectively. For convenience, we refer to the material as $TaSi_2$. The sheet resistance of the composite gate layer is approximately 1 $\Omega$ / $\square$ at 6000 Å. To maintain a smooth silicide/polysilicon interface, post-deposition heat treatment (ie, sintering) of the polycide film was avoided. Following silicide deposition, the wafers were vapor-primed in HMDS and coated with 1.6 microns of KTI® 1450 positive photoresist. Lines varying in width from 3.9 to 5.8 microns were patterned in the resist film using standard lithographic techniques. A SEM photograph of a few resist lines prior to etching the polycide is shown in Figure 10(a). Figure 10(b) shows the resist lines following the etch process. Measurement of the resist linewidth in each case indicates that no significant erosion of the resist occurred.

Table 3 lists the process parameters for the individual etch runs involving the composite material. Each run consisted of etching a single 4" wafer in the center of the rf-driven electrode. The last column in the table gives the value of the bias voltage acquired by the electrode during each run. It provides a strong measure of the extent to which positive ions

generated in the plasma bombard the wafer during the etch process.

| Table 3. Process Parameters For Etching $TaSi_2$/Polysilicon Double Layers | | | | | | | |
|---|---|---|---|---|---|---|---|
| Gases | Wafer ID | Power | Pressure | Total Flow[12] | Flow Ratio | Temp | DC Bias |
| $SF_6:CCl_2F_2$ | #UCB06 | 170 W | 60 mT | 20 sccm | 12.5:7.5 | 21° C | -95 V |
| | #UCB08 | 170 W | 60 mT | 20 sccm | 15:5 | 21° C | -75 V |
| | #UCB11 | 170 W | 60 mT | 20 sccm | 17.5:2.5 | 21° C | -85 V |
| | #UCB07 | 170 W | 100 mT | 40 sccm | 12.5:7.5 | 21° C | -40 V |
| | #UCB10 | 170 W | 100 mT | 40 sccm | 15:5 | 21° C | -40 V |
| | #UCB12 | 170 W | 100 mT | 40 sccm | 17.5:2.5 | 21° C | -35 V |
| $SF_6:CClF_3$ | #UCB13 | 170 W | 80 mT | 20 sccm | 8:12 | 21° C | -65 V |
| | #UCB16 | 170 W | 80 mT | 20 sccm | 12:8 | 21° C | -55 V |
| | #UCB19 | 170 W | 80 mT | 20 sccm | 16:4 | 21° C | -55 V |
| | #UCB15 | 170 W | 120 mT | 40 sccm | 8:12 | 21° C | -40 V |
| | #UCB17 | 170 W | 120 mT | 40 sccm | 12:8 | 21° C | -35 V |
| | #UCB18 | 170 W | 120 mT | 40 sccm | 16:4 | 21° C | -35 V |

Endpoint was determined by monitoring the fluorine emission line at 704 nm. As the polysilicon cleared, the fluorine line grew more intense and then stabilized at a constant value when the etch process was complete. A typical endpoint trace showing the F-line intensity vs. time is given in Figure 11.

Extensive use of scanning electron microscopy (SEM) was required to evaluate typical edge profiles obtained with the processes listed in Table 3. The wafers were cleaved perpendicular to the etched lines, and coated with a thin layer of gold to prevent charging by the electron beam. Some of our results are illustrated in Figures 12 and 13. Figure 12 shows SEM photographs of samples etched in $SF_6$/$CCl_2F_2$ discharges at different flow rate ratios. The profile in the first photograph, 12(a), exhibits an overcut profile, while the other, 12(b), shows a smoother interface between the two materials. In light of the previous discussion, this tendency towards silicide overcut at lower $SF_6$ concentrations is exactly what we had anticipated. Qualitatively, our results are in agreement with those found by Mattausch, et al., and illustrated

in Figures 9(c) and 9(d). The photographs in Figure 13 display evidence of a similar trend, but in this case the gas system used was $SF_6/CClF_3$.

It should be pointed out that our results do not totally concur with those presented by Mattausch, et al. For instance, for all of the process set points tested, we never saw any indication that the polysilicon was laterally etching faster than the overlying layer of $TaSi_2$. In other words, none of our SEM photographs revealed an undercut edge profile. This is most likely due to the fact that Mattausch, et al. investigated edge profiles for a *wider* range of gas mixtures. In our study, the flow ratio range was limited by the results of our selectivity experiments. In addition, all of our profiles exhibited a very high degree of anisotropy. Figure 9 reveals that the processes used for polycide removal in $SF_6/Cl_2$ discharges have large isotropic components associated with them. In highly anisotropic processes involving double layers, the relative etch rates of the two materials become less critical in determining the shape of the sidewall. This fact provides further justification for the exclusion of $TaSi_2$ in our earlier study of etch selectivity.

SEM analysis of our edge profiles enabled us to determine which process parameters yielded "optimum" results. In terms of selectivity, *any one* of the 12 operating points listed in Table 3 is adequate. In terms of profile quality, we were able to select two parameter sets based on the results of the SEM evaluation. Figure 14 shows the edge profiles of samples #UCB07 and #UCB16. Both exhibit a very high degree of anisotropy and no discernible discontinuity at the $TaSi_2$/polysilicon interface. It is interesting to note that one process utilizes $CCl_2F_2$ as the chlorinated species, while the other employs $CClF_3$. Thus, either gas can be used in conjunction with $SF_6$ to etch tantalum polycides anisotropically and selectively over $SiO_2$.

## VI. Conclusions

This paper reports on the detailed investigation of the use of $SF_6$ and chlorinated Freon ($CCl_xF_y$) combinations to etch $TaSi_2$/polysilicon gate structures in single-step processes. The

work was motivated by that done by Mattausch, et al., who used $SF_6/Cl_2$ mixtures to etch the same materials. With respect to safety considerations and gas handleability, the $CCl_xF_y$ systems are superior to the one utilizing $Cl_2$. In addition, etch processes using chlorinated Freons exhibited a much higher degree of anisotropy than those employing $Cl_2$.

Two-gas combinations have been used to enable us to continuously vary the relative amounts of atomic fluorine and chlorine in the discharge. Our approach was to first satisfy the requirements of etch selectivity over underlying oxide, and then to adjust the $SF_6/CCl_xF_y$ ratio to obtain edge profiles acceptable for VLSI processes. Some effort has been made to discuss the chemical mechanisms responsible for the "tunability" of the profiles. Etch characteristics of $TaSi_2$ were neglected in our initial experiments, but we were still able to obtain smooth, anisotropic profiles. It was later pointed out that the relative etch rates of the two materials in a composite layer have considerably less impact on the ultimate sidewall profile when the degree of etch anisotropy is high.

Another advantage of our study concerns its use of two different gases for the chlorinated species. The data presented here allows a performance comparison between $CCl_2F_2$ and $CClF_3$. Although both gases behave similarly when mixed with $SF_6$, the $CCl_2F_2$ system exhibits higher selectivity over $SiO_2$. Nevertheless, this variation can be overcome by utilizing the $SF_6/CClF_3$ system at higher pressures. In normal instances, increasing pressure tends to degrade anisotropy, but Figure 14 demonstrates that this is not the case here. Therefore we have shown that *both* $SF_6/CCl_xF_y$ systems studied here are capable of satisfying the process requirements outlined in the paper.

Figure 1. *Details of the RIE parallel plate reactor used in our study...(a) before modification, and (b) after modification.*
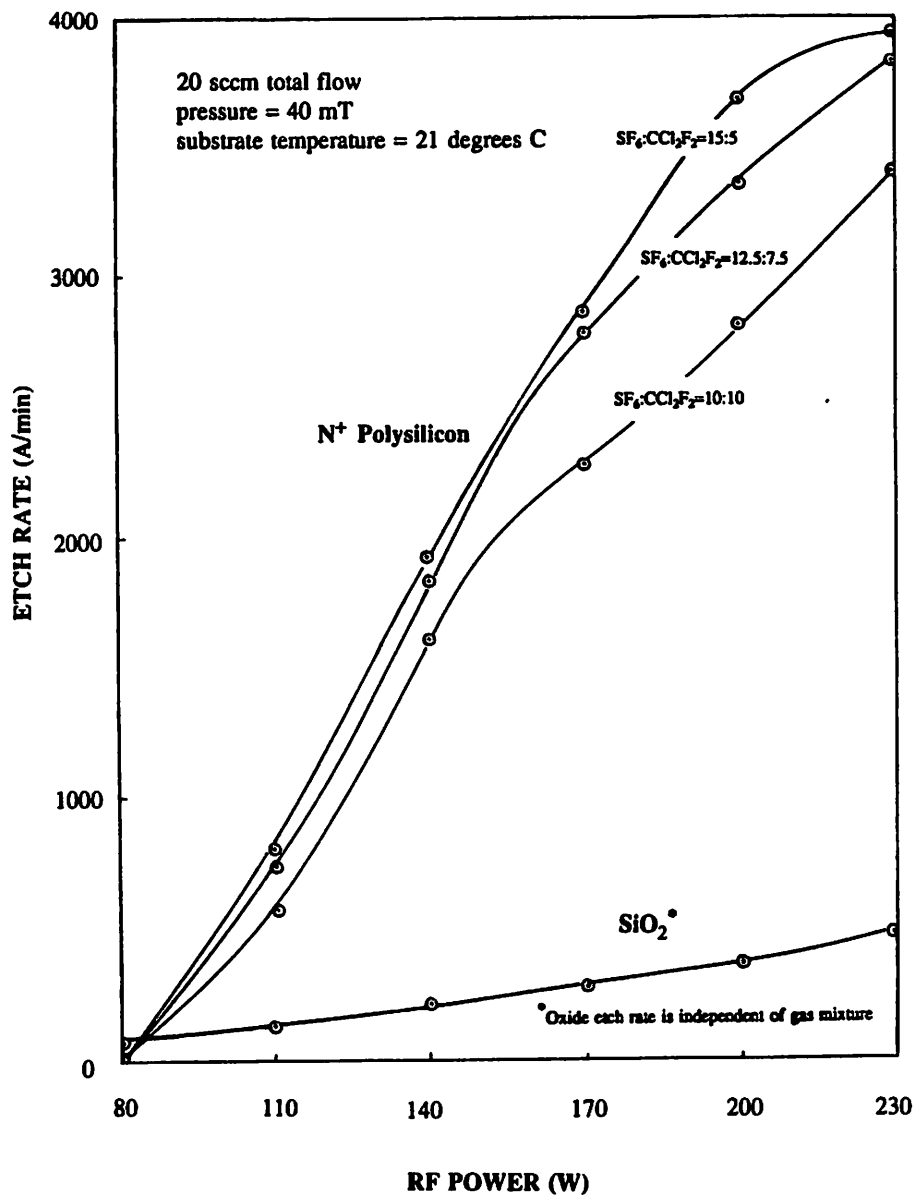


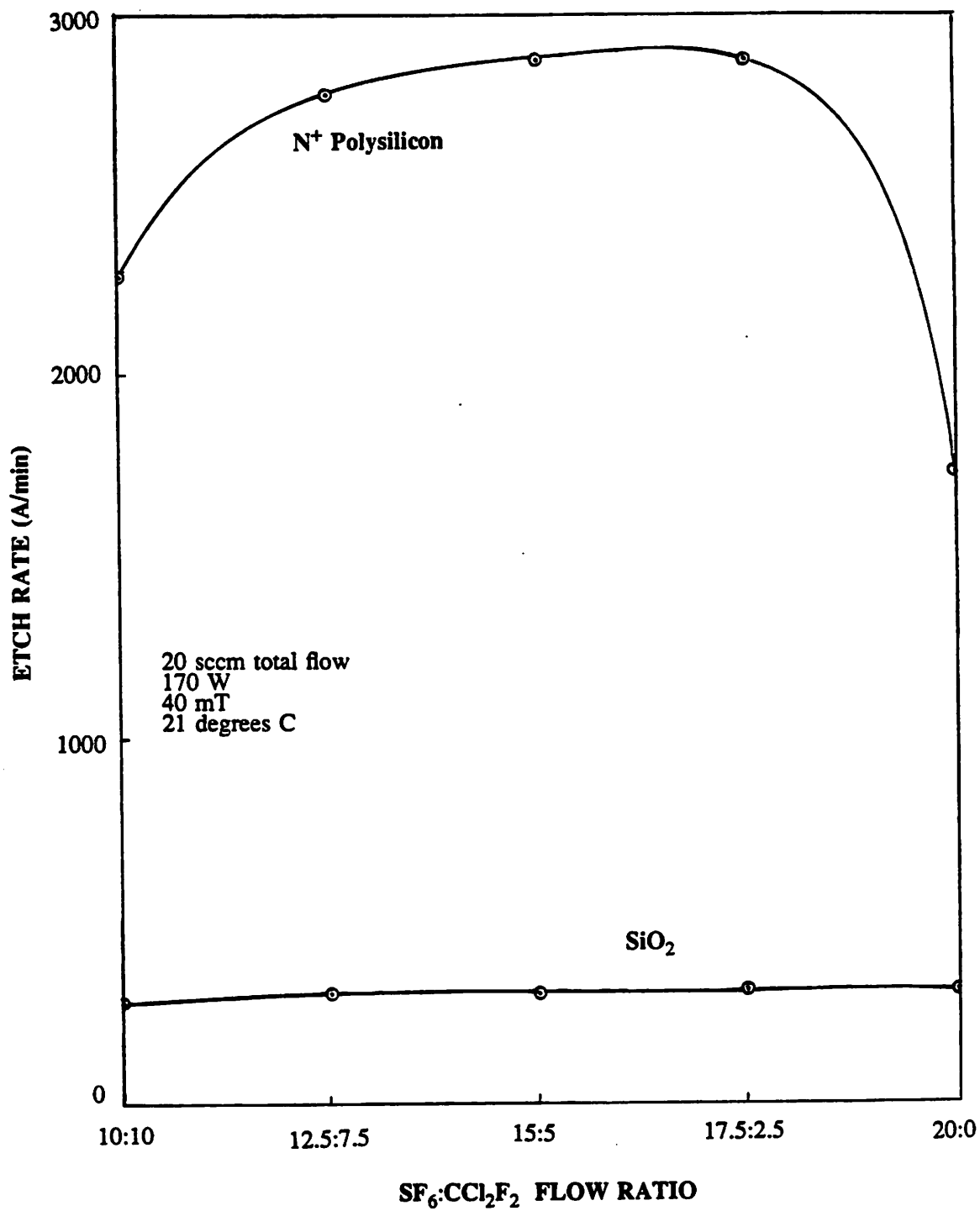**Figure 2.** *Polysilicon and SiO$_2$ etch rates as a function of forward rf power in SF$_6$/CCl$_2$F$_2$ discharges. The plasma power density can be determined by dividing the power level by the electrode area, 457.3 cm$^2$.*
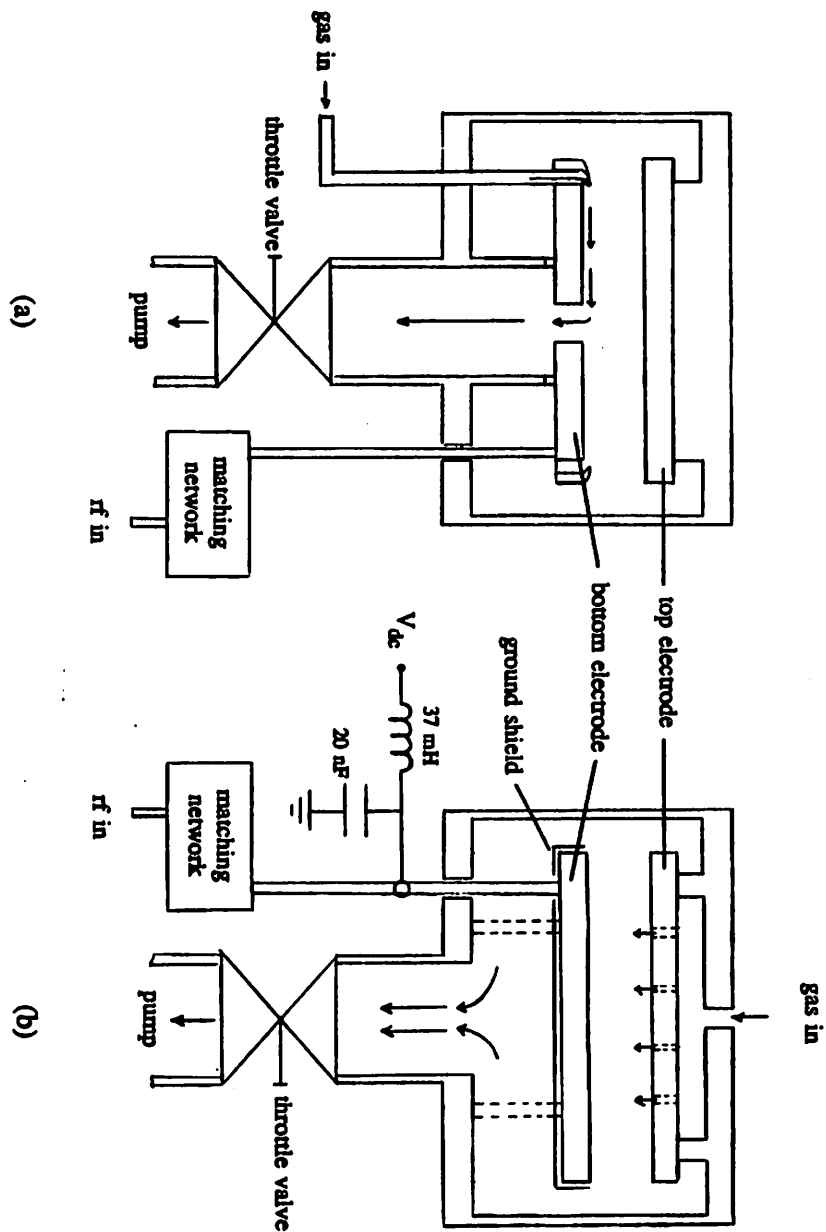
**Figure 3.** *Polysilicon and SiO$_2$ etch rates as a function of SF$_6$:CCl$_2$F$_2$ flow rate ratio. Other etch parameters were held constant at values printed on the graph.*
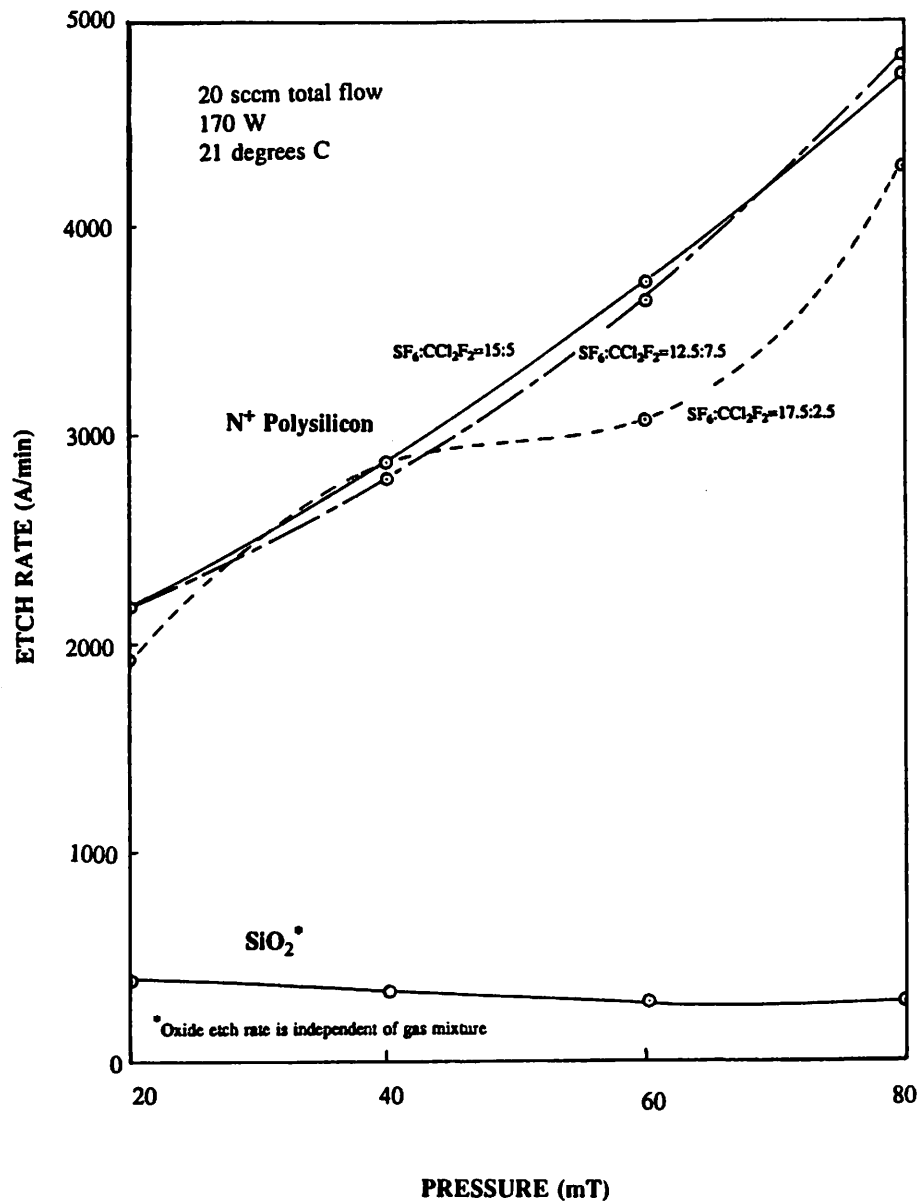
**Figure 4.** *Polysilicon and SiO₂ etch rates vs. reactor pressure for SF₆/CCl₂F₂ discharges.*
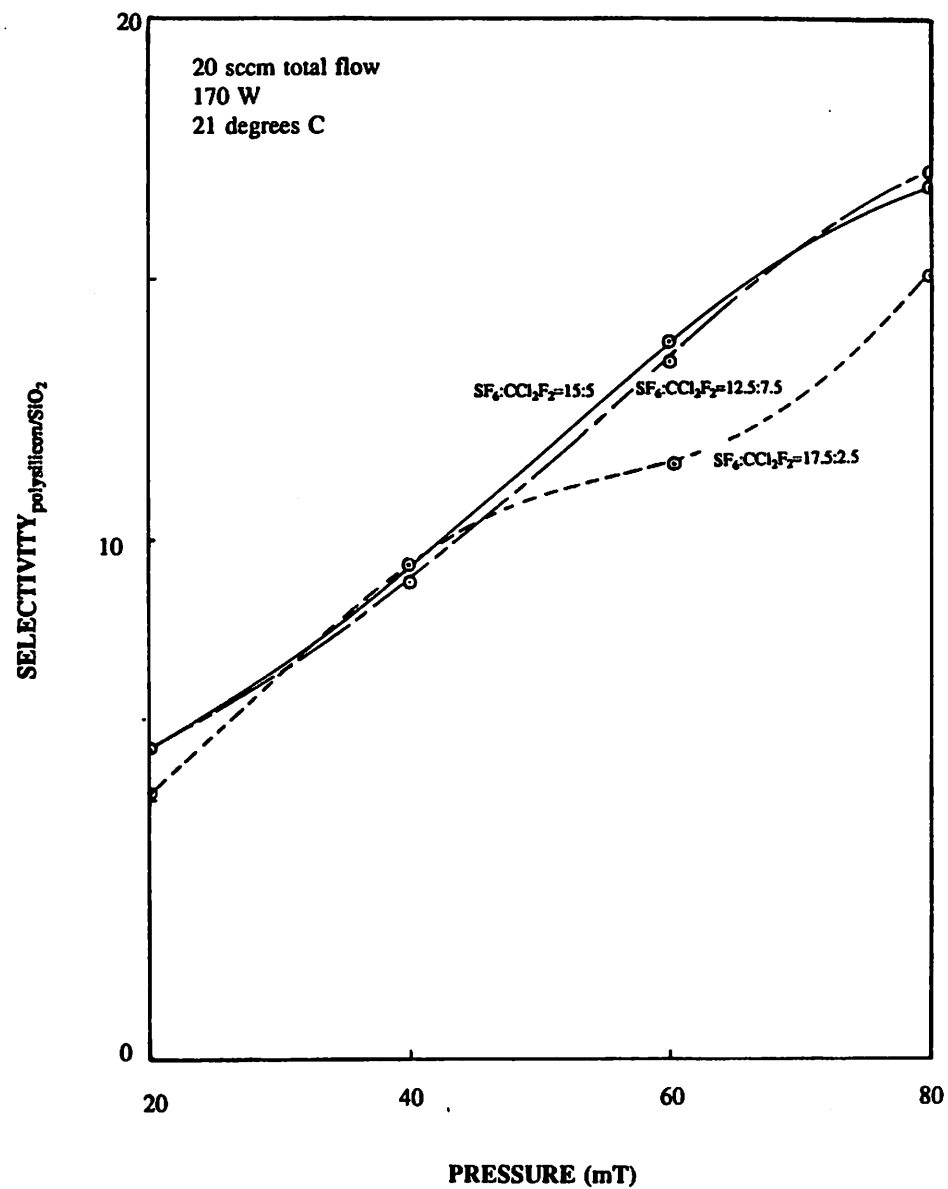
**Figure 5.** *Polysilicon-to-SiO₂ etch selectivity as a function of reactor pressure for SF₆/CCl₂F₂ discharges.*
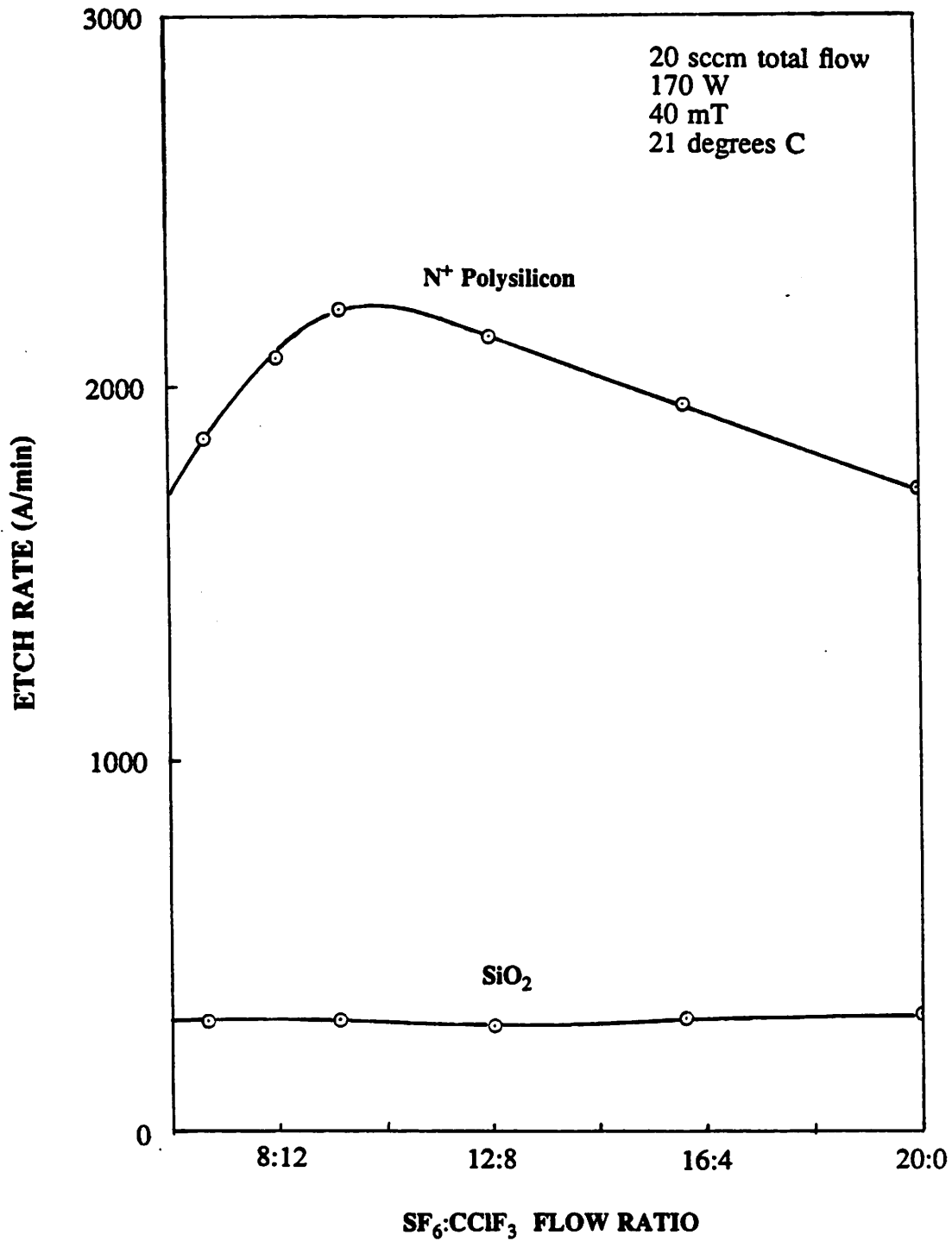
**Figure 6.** *Polysilicon and $SiO_2$ etch rates vs. $SF_6$:$CClF_3$ flow rate ratio. Other etch parameters were held constant at values printed on the graph.*
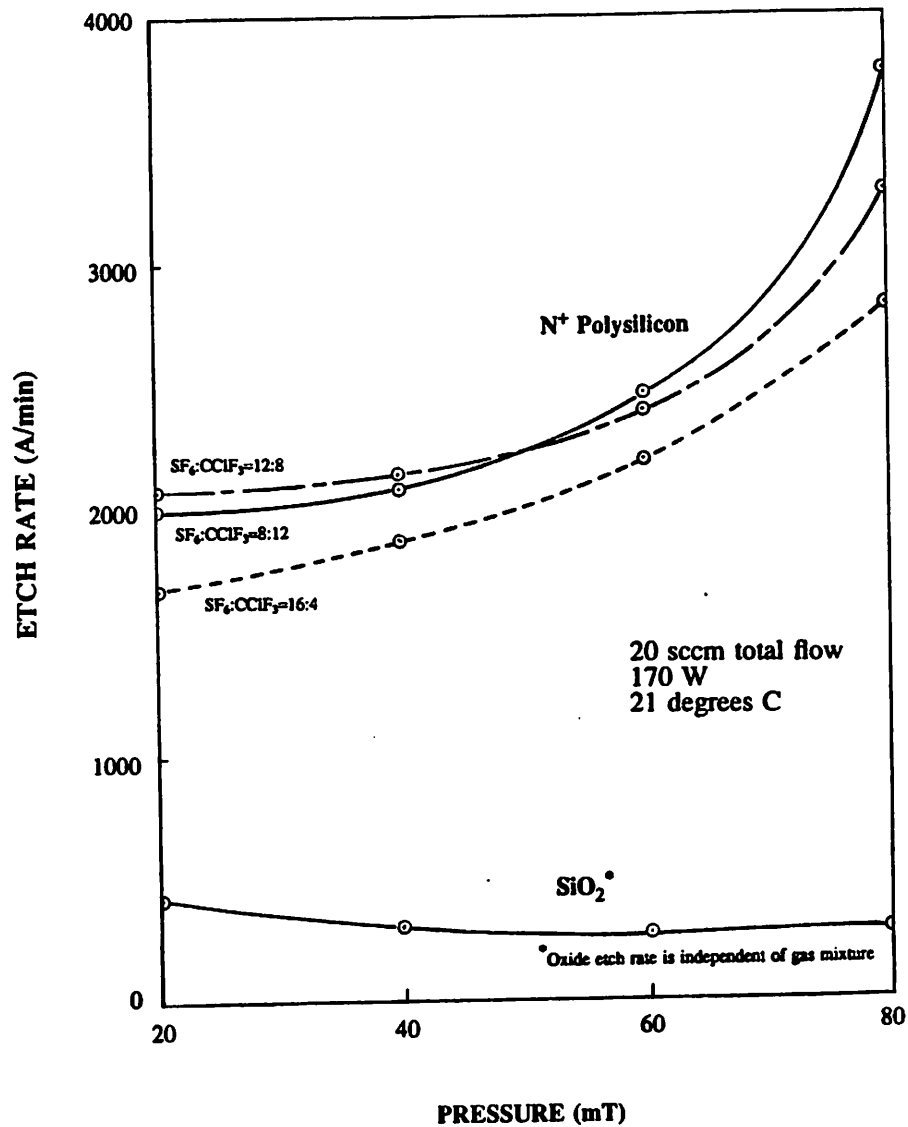
**Figure 7.** *Polysilicon and SiO$_2$ etch rates vs. reactor pressure for SF$_6$/CClF$_3$ discharges.*
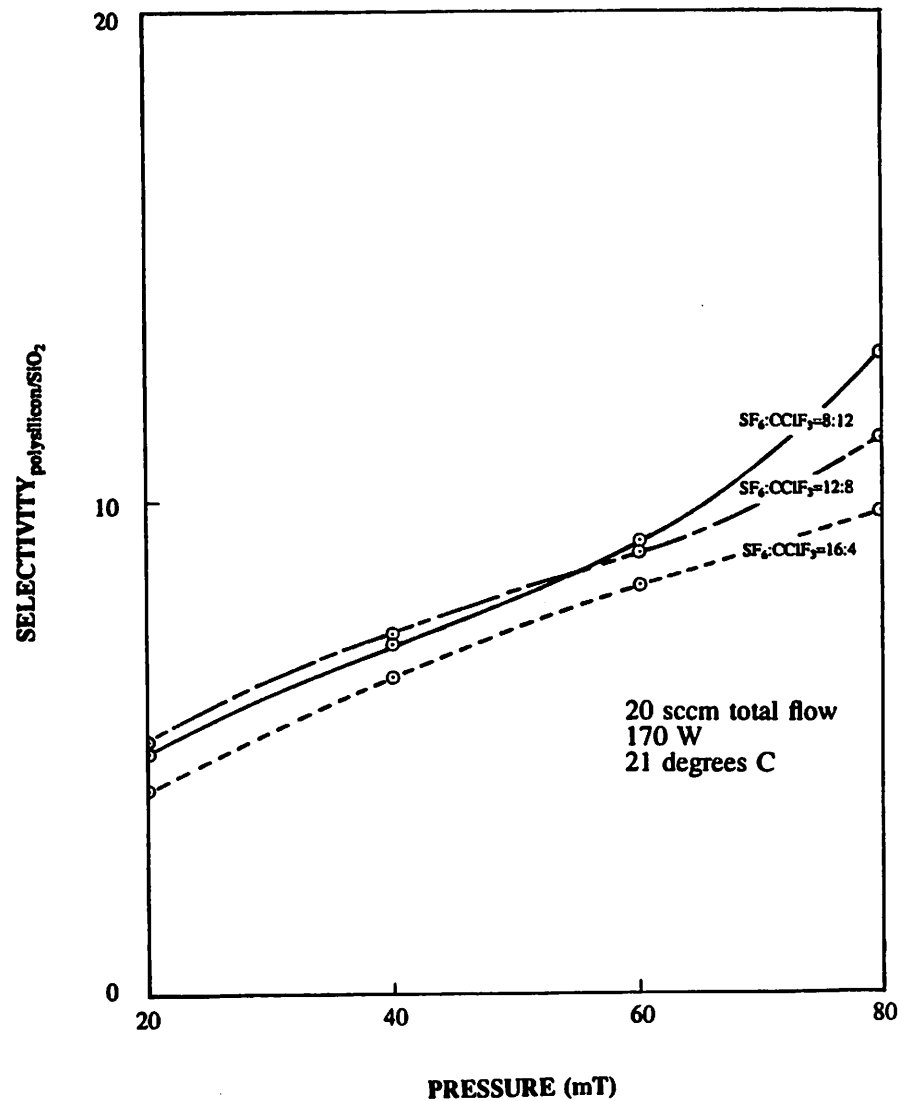
**Figure 8.** *Polysilicon-to-SiO$_2$ selectivity as a function of reactor pressure for SF$_6$/CClF$_3$ discharges.*

resist
Ta-silicide
polysilicon
SiO$_2$
Si-substrate

(a)
SF$_6$:Cl$_2$ = 20:0

(b)
SF$_6$:Cl$_2$ = 15:5

(c)
SF$_6$:Cl$_2$ = 12.5:7.5

(d)
SF$_6$:Cl$_2$ = 10:10

(e)
SF$_6$:Cl$_2$ = 5:15
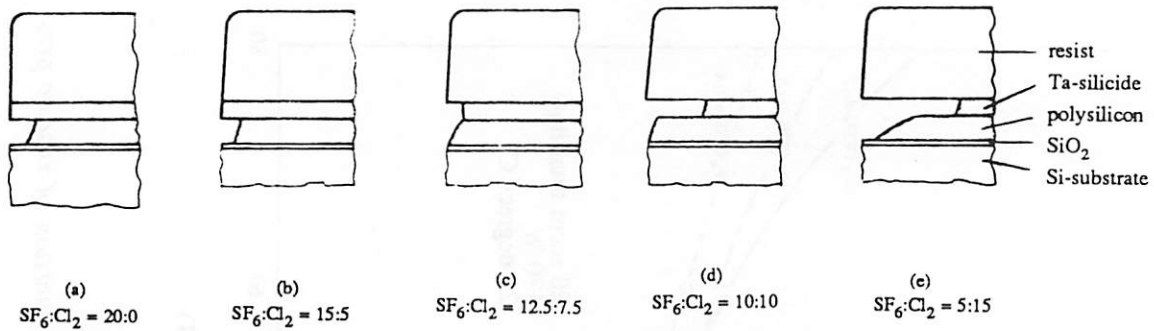
**Figure 9.** *The influence of the SF$_6$:Cl$_2$ flow ratio on the edge profile of the polysilicon/Ta-silicide double-layer (as reported in Reference 3). The chamber pressure was 40 mT and the rf power level was 350 W.*
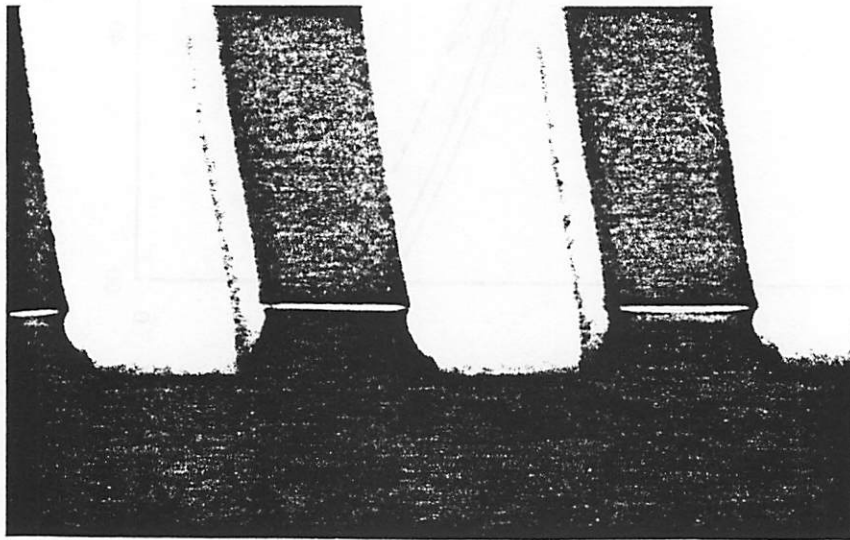


(a)
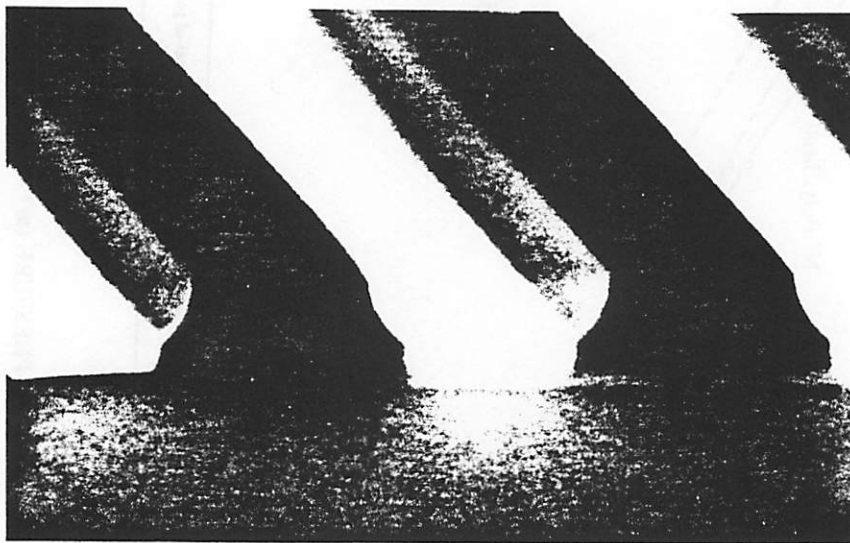


(b)

**Figure 10.** *SEM micrographs showing photoresist profiles... (a) prior to etch, and (b) after a typical etch (Sample #UCB06). Linewidth measurements indicated no significant erosion of the resist material during the etch process.*
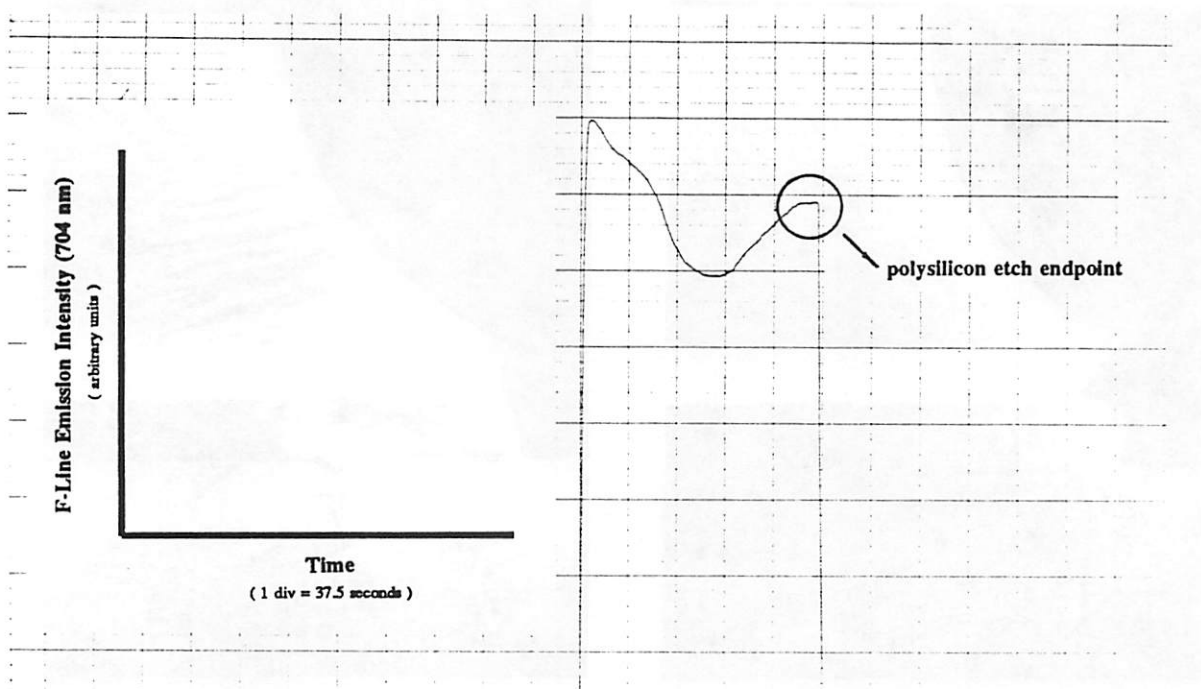
**Figure 11.** *Endpoint trace for Wafer #UCB17. The atomic fluorine emission intensity remains constant following removal of the polysilicon layer.*



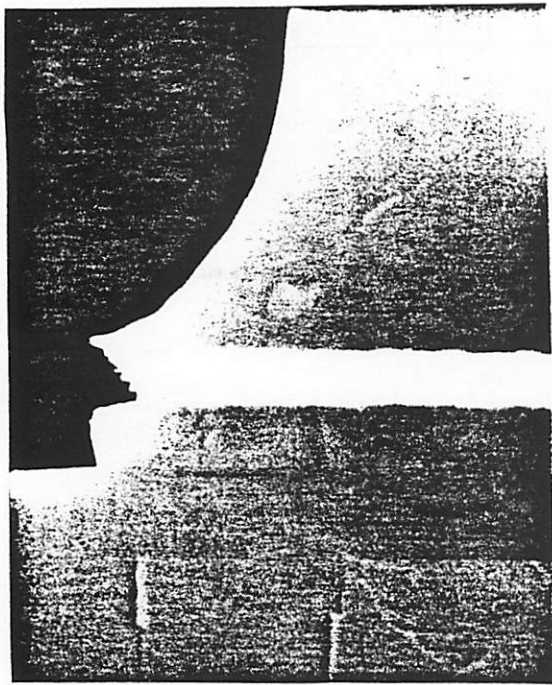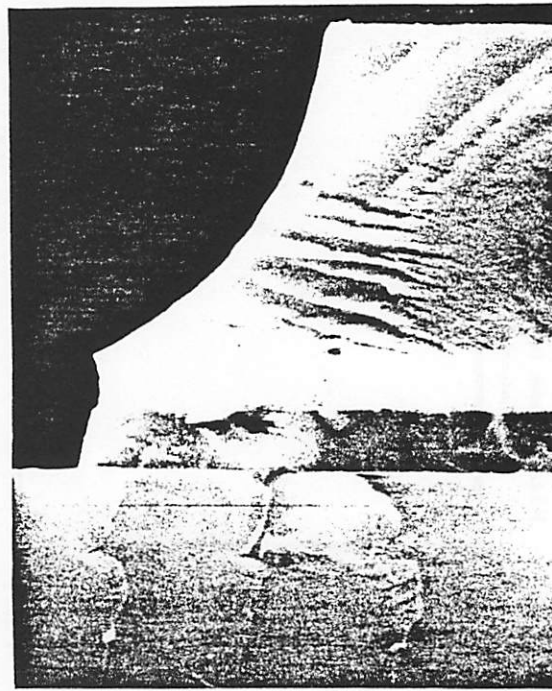(a)                                                        (b)
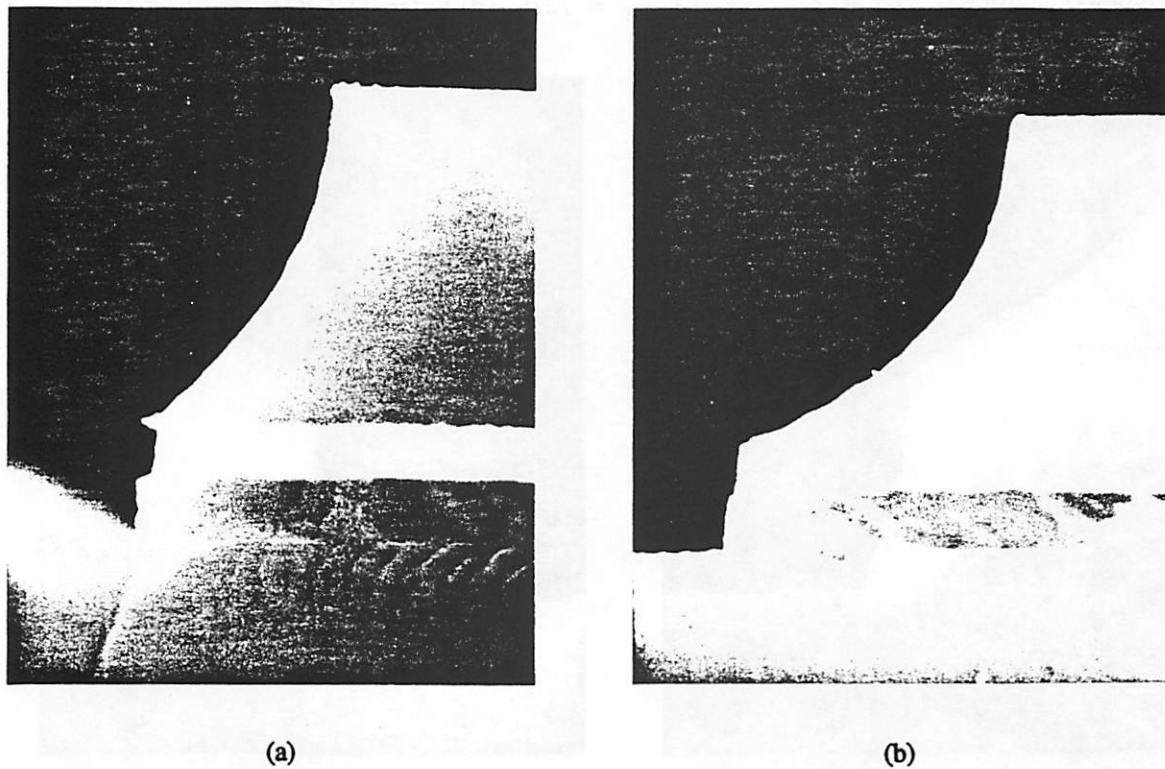
**Figure 12.** *SEM photographs showing the effect of the $SF_6$:$CCl_2F_2$ flow ratio on edge profile (magnification is 30,000x). Less overcut of the $TaSi_2$ layer occurs for gas mixtures higher in $SF_6$ content...(a)Wafer #UCB06 — $SF_6$:$CCl_2F_2$ = 12.5:7.5, (b)Wafer #UCB11 — $SF_6$:$CCl_2F_2$ = 17.5:2.5.*
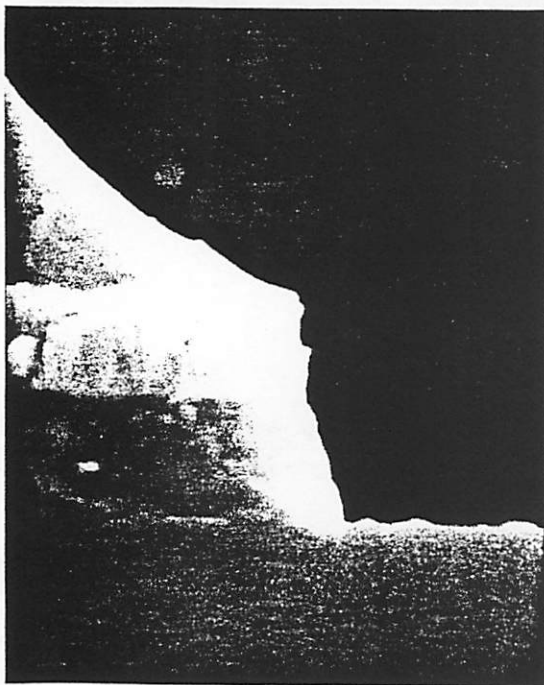
(a)　　　　　　　　　　　　　　　　　(b)

**Figure 13.** *SEM photographs showing the effect of the $SF_6$:$CClF_3$ flow ratio on edge profile (magnification is 30,000x). Less overcut of the $TaSi_2$ layer occurs for gas mixtures higher in $SF_6$ content...(a)Wafer #UCB17 — $SF_6$:$CClF_3$ = 12:8, (b)Wafer #UCB18 — $SF_6$:$CClF_3$ = 16:4.*



(a)　　　　　　　　　　　　　　　　　(b)

**Figure 14.** *Edge profiles resulting from processing at "optimum" set points (magnification is 60,000x)... (a) Wafer #UCB07 — 25 sccm $SF_6$, 15 sccm $CCl_2F_2$; 170 W; 100 mT; 21° C; (b) Wafer #UCB16 — 12 sccm $SF_6$, 8 sccm $CClF_3$; 170 W; 80 mT; 21° C.*

## Acknowledgements

# References / Notes

[1] B.L. Crowder and S. Zirinsky, "1 $\mu$m MOSFET VLSI Technology: Part VII—Metal Silicide Interconnection Technology—A Future Perspective," *IEEE Trans. Electron Devices*, vol. ED-26, no. 4 pp. 369-371, April 1979.

[2] S.P. Murarka, "Refractory Silicides for Integrated Circuits," *J. Vac. Sci. Technol.*, vol. 17, no. 4, pp. 775-792, Jul./Aug. 1980.

[3] H.J. Mattausch, B. Hasler, and W. Beinvogl, "Reactive Ion Etching of Ta-silicide/Polysilicon Double Layers for the Fabrication of Integrated Circuits," *J. Vac. Sci. Technol. B 1 (1)*, pp. 15-22, Jan.-Mar. 1983.

[4] S.E. Clark, J.-K. Tsang, and J.W. Marolf, "Deposition and Patterning of Tungsten and Tantalum Polycides," *Solid State Technology*, pp. 235-242, April 1984.

[5] J. Herrmann, P. Martins, and W. Rust, "A Multistep Etch Process for TaSi$_2$/Polysilicon Composite Films," *Proceedings of the Sixth Symposium on Plasma Processing*, The Electrochemical Society, vol. 87-6, pp. 494-506.

[6] The showerhead hole pattern was borrowed with permission by *The SEMI Group*, a manufacturer of commercial Reactive Ion Etching systems.

[7] A. M. Voshchenkov, "Plasma Etching and Etching Systems", U.C. Berkeley report.

[8] S.P. Murarka, D.B. Fraser, A.K. Sinha, and H.J. Levinstein, "Refractory Silicides of Titanium and Tantalum for Low-Resistivity Gates and Interconnects," *IEEE Trans. Electron Devices*, vol. ED-27, no. 8, pp. 1409-1417, Aug. 1980.

[9] M. Zhang, J.Z. Li, I. Adesida, and E.D. Wolf, "Reactive Ion Etching for Submicron Structures of Refractory Metal Silicides and Polycides," *J. Vac. Sci. Technol. B 1 (4)*, pp. 1037-1042, Oct.-Dec. 1983.

[10] W.R. Bell II, "Determination of Process Simulation Parameters from Experiment : Plasma Etching and Photoresist Dissolution," U.C. Berkeley M.S. Thesis, Memorandum No. UCB/ERL M87/47, June 1987.

[11] R.C. Weast, ed., "Bond Strengths In Diatomic Molecules," p. F-224, and "Bond Strengths in Polyatomic Molecules," p. F-236, *Handbook of Chemistry and Physics*, 61st ed., 1980.

[12] Actually, in some cases, higher pressures were desired and the total flow rate was doubled to 40 sccm. In these instances, samples processed at 20 sccm and 40 sccm (at a fixed pressure of 80 mT) were compared, and no appreciable difference in their etch rates was found.

[13] D.L. Flamm, V.M. Donnelly, and J.A. Mucha, "The Reaction of Fluorine Atoms with Silicon," *J. Appl. Phys.*, vol. 52, no. 5, pp. 3633-3639, May 1981.

[14] T. Enomoto, "Loading Effect and Temperature Dependence of Etch Rate of Silicon Materials in CF$_4$ Plasma," *Solid State Technology*, pp. 117-121, Apr. 1980.

[15] Ron Light, personal communication, July 1987.

[16] C.J. Mogab and T.A. Shankoff, "Plasma Etching of Titanium for Application to the Patterning of Ti-Pd-Au Metallization," *J. Electrochem. Soc. : Solid-State Science and Technology*, vol. 124, no. 11, pp. 1766-1771, Nov. 1977.