ASTRON :
A Toroidal Plasma Source and its Applications

Technology for Productivity

ASTeX®
Baratron®
D.I.P.™
HPS®
Mass-Flo®
Spectra

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MKS/ASTeX Products

Wilmington, MA

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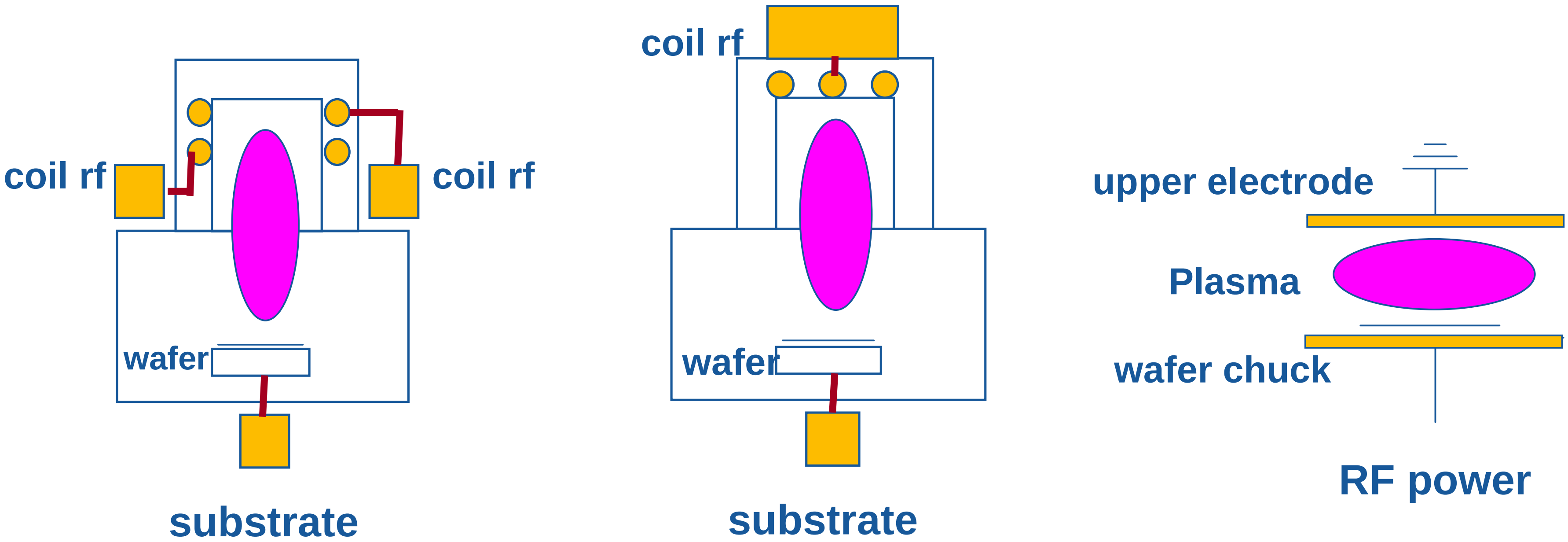
Outline

- I. Background on remote plasma processes
- II. ASTRON plasma devices
- III. Applications
  - CVD chamber clean
  - Photoresist removal
  - Plasma abatement

Some Background on Plasma Sources

- In semiconductor processing, plasmas are used to create activated species to enable or accelerate chemical and physical reactions.
- For ion driven processes, plasma is generated in process chamber and exposed to substrate.
- For processes driven by neutral reactive gases, plasma is generated outside process chamber. Activated gas is flowed to the process chamber to eliminate charged particles.

Conventional Plasma Processing Chambers



Ion Bombardment + Reactive Neutrals

Why the Interest in Remote Plasma Sources ?

- Chemical reactions of neutral species have certain advantages
  - avoids damage from charging or sputtering
  - higher selectivity than plasma processes

- Highly reactive species can be produced and transported
  - F, O, H, N, O_3

- The use of a separate generator of reactive species allows their production to be optimized, outside of the process chamber

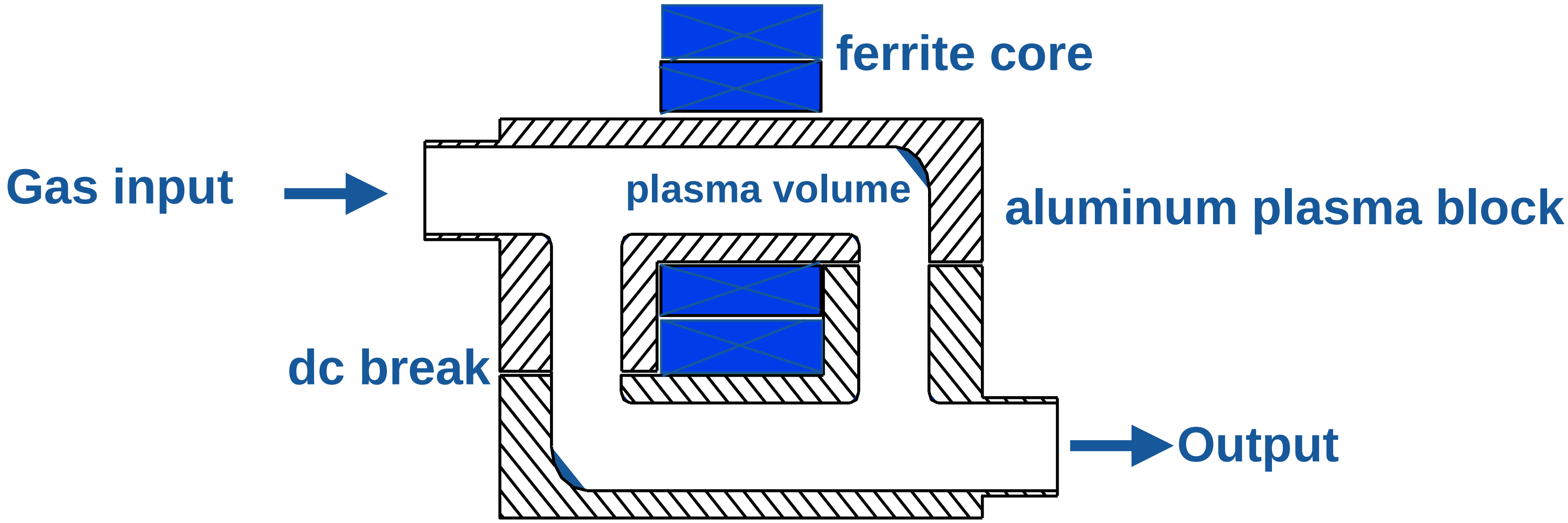
Examples of Reactive Gas Generators Manufactured by MKS

- Ozone
  - dielectric barrier discharge
  - used in SiO_2 deposition, wafer cleaning and wet bench
- Microwave
  - microwave discharge in dielectric tubes
  - stripping, wafer cleaning, annealing, chamber clean
- ASTRON
  - RF toroidal plasma

ASTRON (TM) LOW-FIELD TOROIDAL PLASMA SOURCE

- Delivers high flows of reactive gases:
  - atomic **F, O, N, H**
- Uses a plasma to activate gases
  - **ne = 10^{13} cm^{-3}**
  - **Te = 2-3 eV**
- Three functions in a single package
  - **Control**
  - **Power generation**
  - **Plasma generation**

ASTRON PRINCIPLES OF OPERATION



- Current in primary coil induces a current in the plasma (secondary) in opposite direction (Faraday's induction law)
- Ferrite core confines the electromagnetic field to improve magnetic coupling
- DC break required to couple electromagnetic fields through conductor

ASTRON Principles Of Operation *(Cont'd)*

- The primary of the transformer is powered by an on-board 400 kHz switching RF power supply.
- The electric fields within the plasma are kept low so that sputtering of walls is avoided. Electric fields range from 4-8 v/cm.
- Energy efficiency from wall power to plasma is 85-90%.
- The aluminum plasma channel is water-cooled and allows very high power density.

ASTRON Product Line

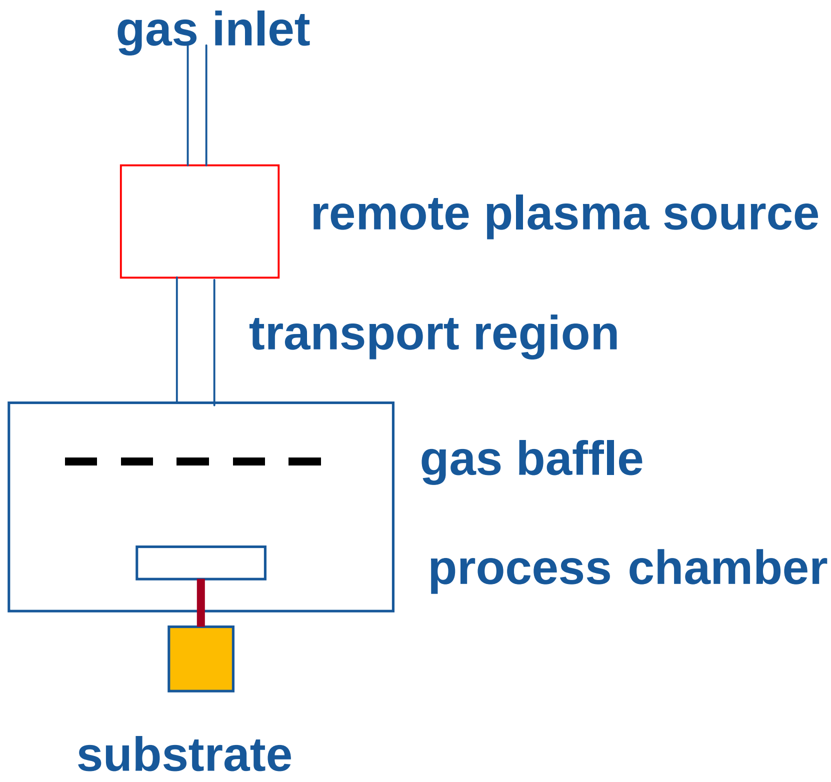
	Primary Applications	Flow Capabilities	Power Capability
ASTRON 2L	CVD chamber clean	2 slm NF3 @10 Torr	5 kW
ASTRONi	CVD chamber clean	2.5-3 slm NF3 @10 Torr	6.5-7 kW
ASTRONe	CVD chamber clean	4-8 slm NF3 @10 Torr	8-10 kW
Abatement ASTRON	PFC removal	0.1-1 slm CF4	5-10 kW

Typical Setup of Remote Plasma Device

1-5 slm gas flow

1-10 Torr pressure

0.5-5 Torr pressure



Typical transport time for reactive species 1-10 millisec

Key issues in remote plasma applications

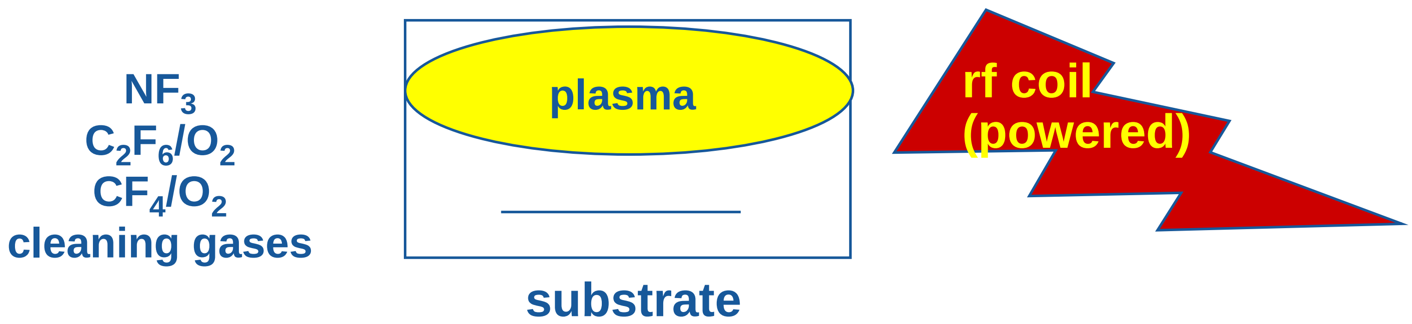
- **Activation** - activating or dissociating gases in a plasma
  - appropriate wall materials in the plasma source
  - enough power to do the job
- **Transport** - distributing reactant to process chamber
  - The reactant species are relatively unstable (lifetimes of msec's). Short residence time is key.
  - Great attention must be paid to materials of construction.
- **Reaction** - typically driven by thermal mechanisms.
  - Reaction rates follow an exponential dependence on substrate temperature
  - Reaction rate are proportional to the partial pressure of reactive gases

Application: CVD Chamber Clean

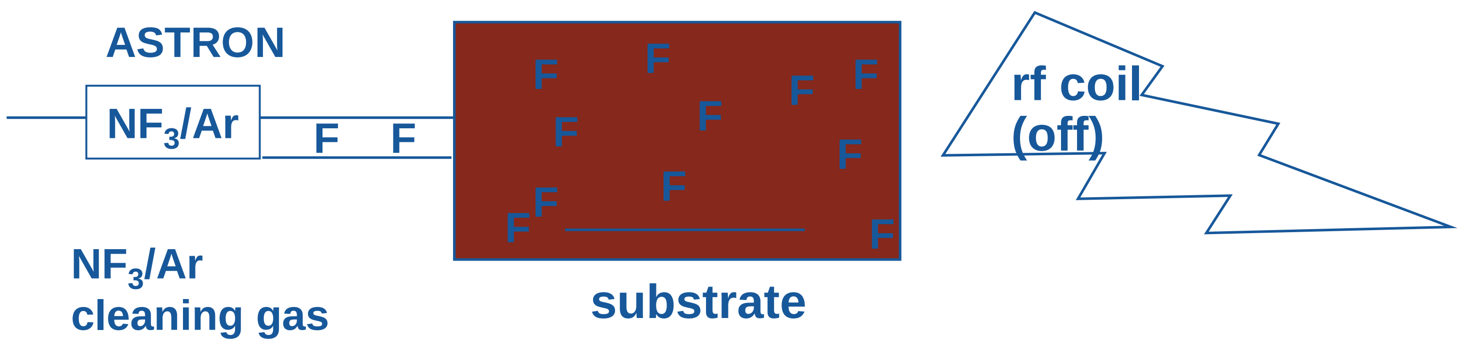
- CVD chambers need to be cleaned periodically to prevent chamber deposits from flaking and generating particles
- Clean time is a significant part of tool time, sometimes longer than deposition time
- Due to use of aggressive chemistry, in situ clean causes significant damage to chamber internal surfaces
- Remote plasma clean is preferred because
  - reduced damage to chamber internals
  - higher clean rates
  - higher uniformity
  - separates optimization processes for deposition and clean

CVD Chamber Clean Techniques

In-Situ RF



Atomic Fluorine



Materials etched at our labs with F

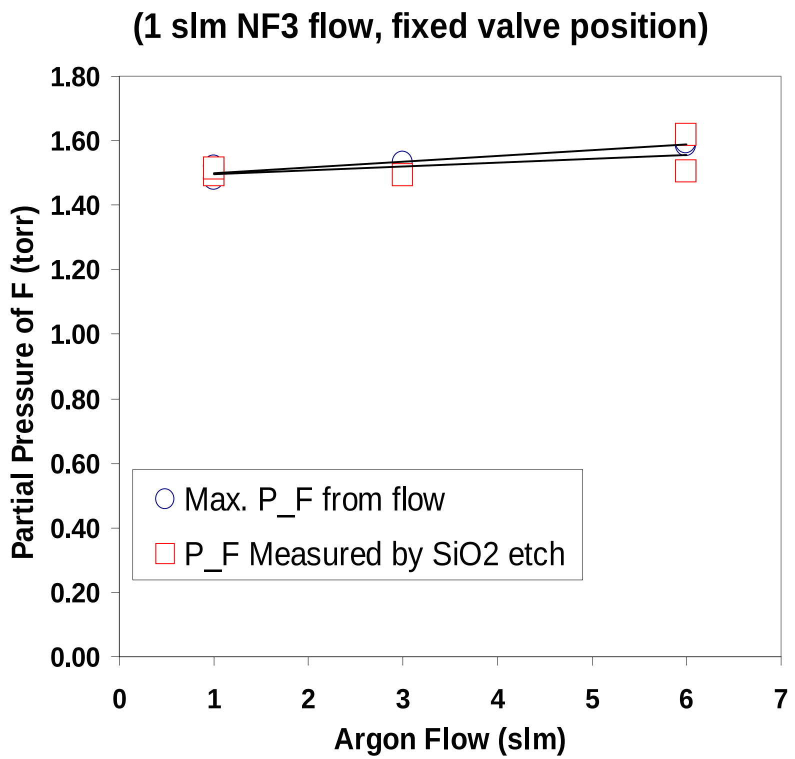
- SiO_2
- Si_3N_4
- Si
- W
- WN
- TiN
- SiC
- Ta
- Ru

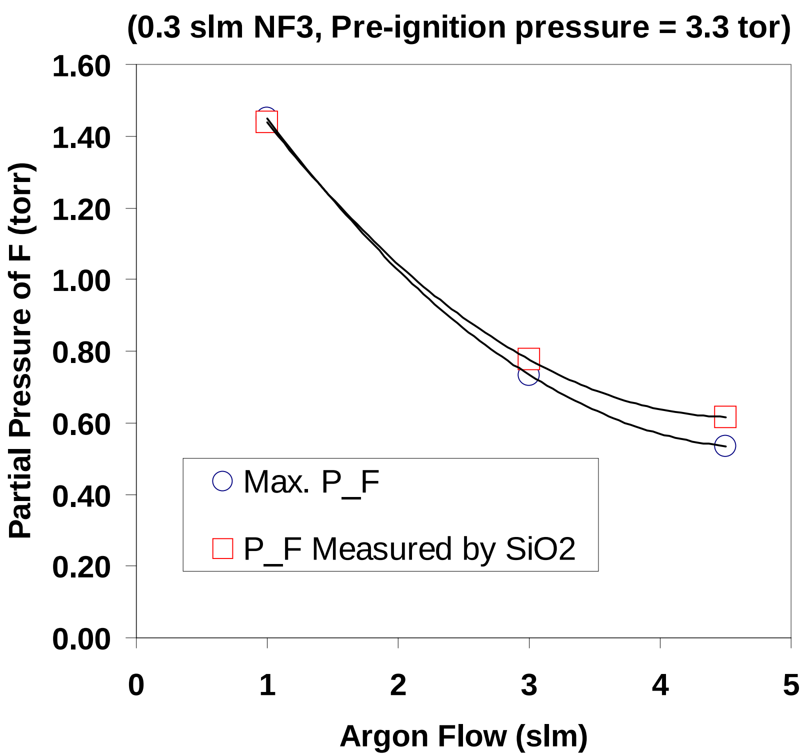
Production Of Atomic Fluorine

- NF_3, CF_4, C_2F_6, C_3F_8 are common sources of atomic fluorine
  - **When fluorocarbon is used, oxygen is added to form CO, CO2 and F**
- Production efficiency of atomic fluorine can be measured by FTIR or by comparing SiO_2 etch rate with the calculated maximum etch rate for given source gas flow rate and pressure.
- Partial pressure of F is calculated using (Ref. Flamm, D.L. et. al., J. Appl. Phys., 1981)

Reaction Probability:	$P = 1.12 \times 10^{-2} \times e^{-1892/T(k)}$
Etch Rate (um/min):	$R = 6.14 \times 10^{-17} \times N_F\,(cm^{-3}) \times T^{1/2}(k) \times e^{-1892/T(k)}$

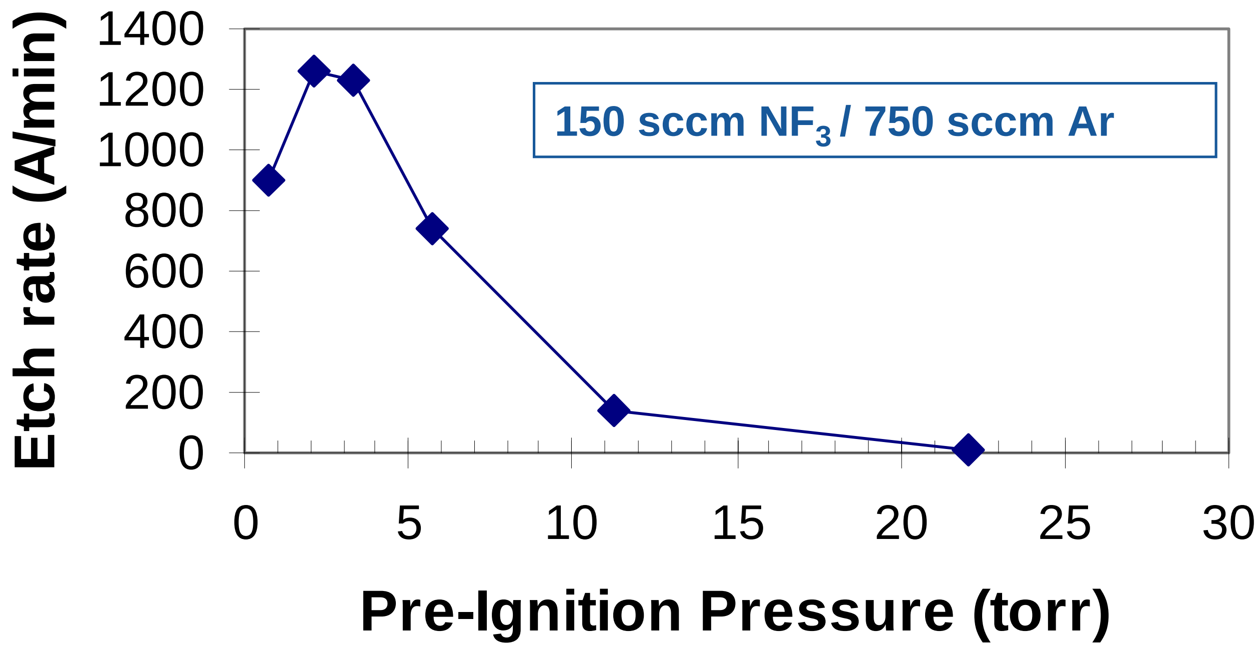
Production Efficiency Of Atomic Fluorine Is Near Unity





- Atomic fluorine production efficiency is nearly independent of flow rates of argon and pressure.

SiO_2 etch rate vs. chamber pressure

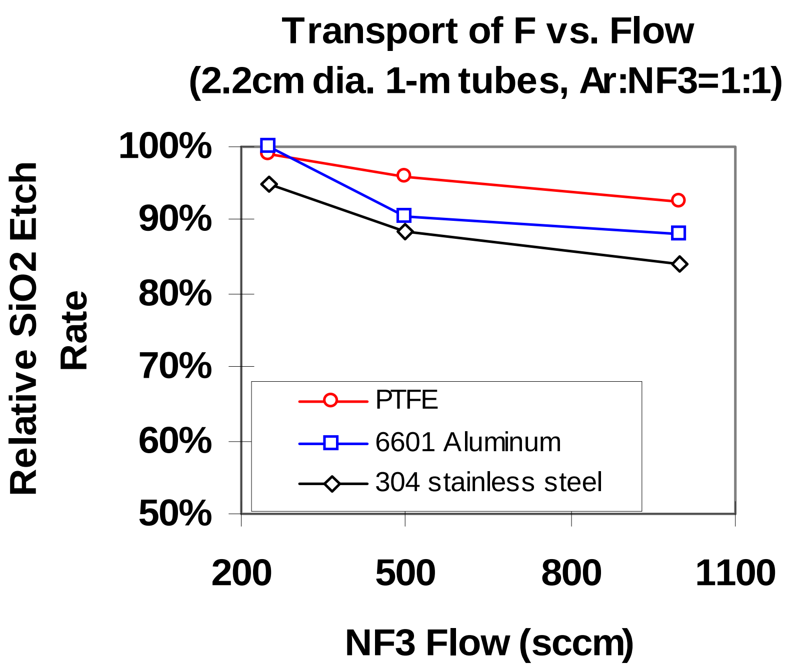


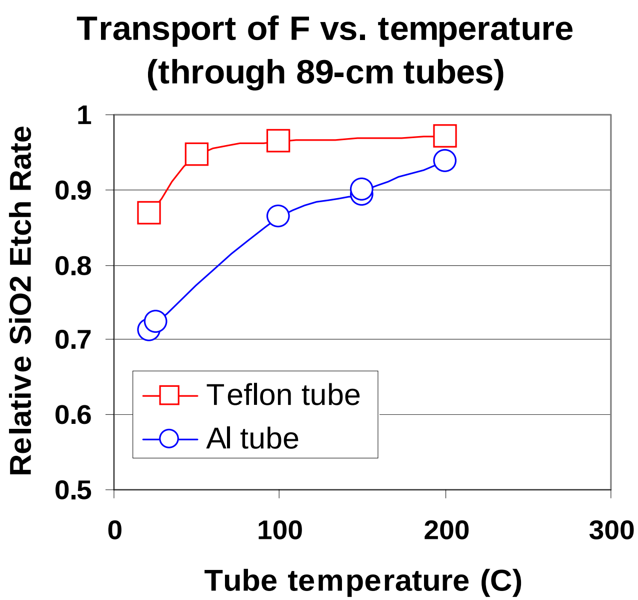
T=150 C

- **There is an optimal pressure that corresponds to peak etch rate**
  - At low pressures atomic fluorine is lost due to vacuum pump
  - At high pressures atomic fluorine is lost during transport due to recombination

Transport of Atomic Fluorine vs. Flow Tube Materials and Temperature

- **Transport efficiency of atomic fluorine is measured from SiO_2 etch rate with and without transport tubes**





- **Over 90% of F can be transported through a 1-m long tube**
- **Higher temperature improves transport efficiency**

Etching W with Atomic Fluorine

Unlike the case for SiO_2, the published rate constants for W-etching show that there can be contributions from both F and F_2

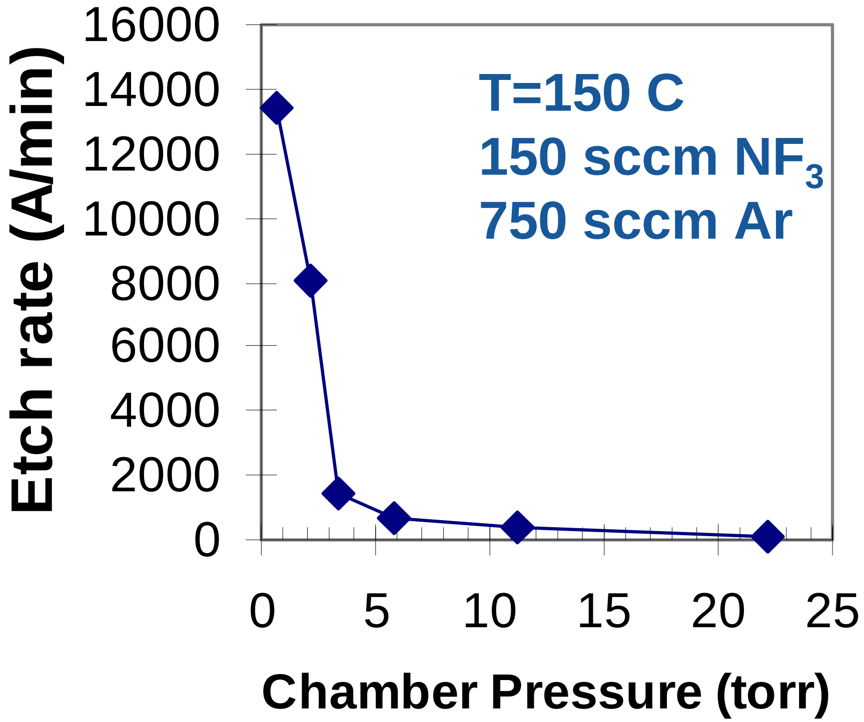
(D.E. Rosner & H.D. Allendorf, 1971)

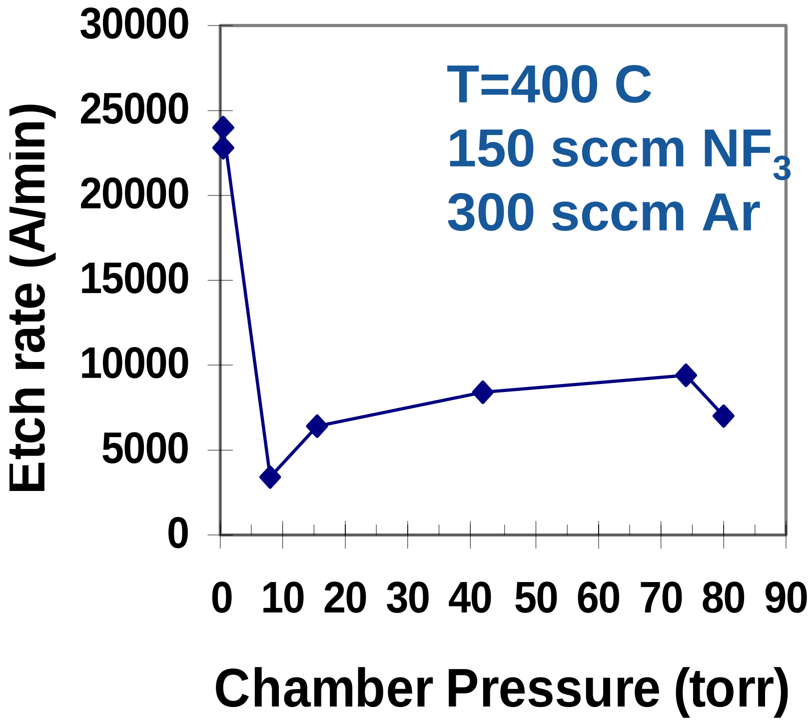
For F: rate = 2.92e-14*sqrt(Tg(k))*n(F)*exp(-3900/T(k)) (um/min)

For $F_{2:}$ rate = 6.6e-15*sqrt(Tg(k))*n(F2)*exp(-6432/T(k)) (um/min)

Note that the etching for F_2 has a much higher activation energy than for F

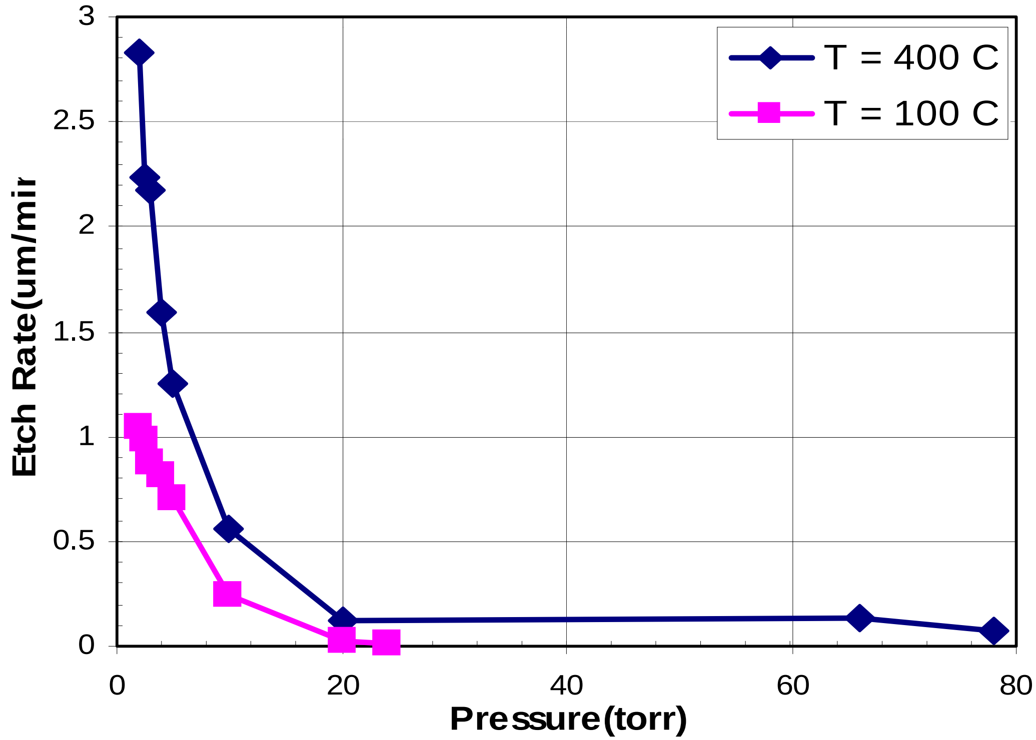
Etching W With Atomic and Molecular Fluorine





- F etch dominates at low pressure
- F_2 etch becomes significant at high temperature and pressure

ETCHING Si_3N_4 WITH ATOMIC FLUORINE



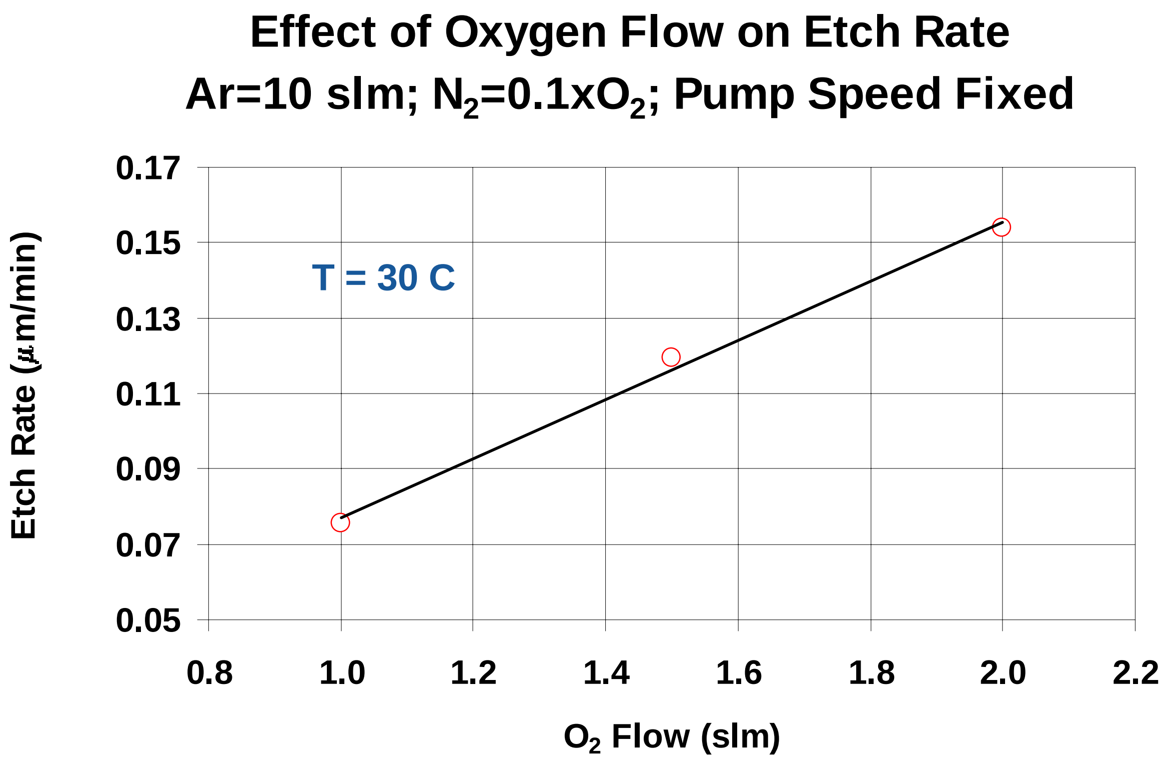
- **Data taken in ASTeX test chamber with ASTRON;**
- **0.3 slm NF_3 / 1.5 slm Ar**

Application: Photoresist Etching

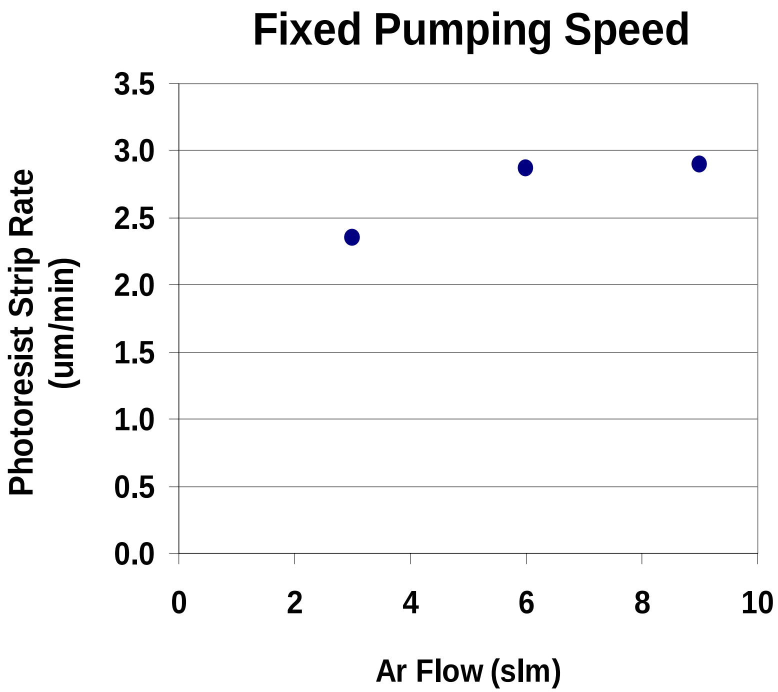
- Photoresist is used to create patterns on wafers
- Once patterns are created, photoresist must be removed and the surface be cleaned.
- Atomic gases are preferred due to reduction of damage and higher selectivity
- Typical process uses atomic oxygen
  - Dopant gases are added to improve process
    - **add N_2 to increase dissociation**
    - **add CF_4, H_2O etc. to increase rates and enhance chemistry**
- Typical etch rate a few μm per minute at temperature of 200-250 C.

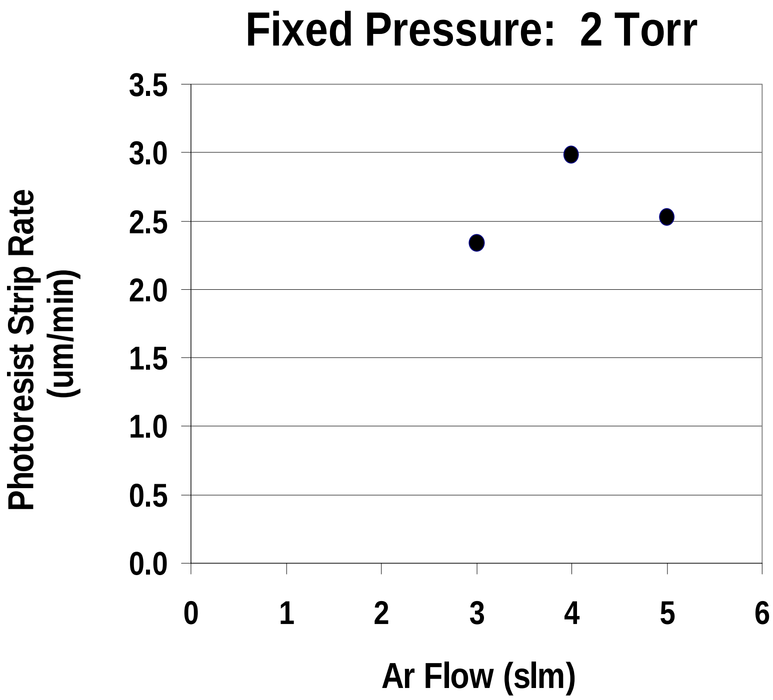
GENERATION OF ATOMIC OXYGEN

- Production of atomic oxygen is monitored by photoresist etch
- Higher flow rate of argon increases delivery of atomic oxygen



Photoresist Removal Data from a Strip Chamber





800 sccm O_2 / 70 sccm N_2
Argon flow rate as shown

Application: PFC Abatement

- PFCs are used in semiconductor manufacturing for plasma etch and CVD chamber clean
  - SiO_2 Etch: CHF_3, CF_4, C_2F_6
  - Chamber Clean: CF_4, C_2F_6, C_3F_8 , NF_3
- PFCs are greenhouse gases with long- term impact on global climate
  - Strong absorbers of infrared radiation (1000x higher than CO_2)
  - Long atmosphere life results in accumulation in atmosphere

Plasma Abatement of PFCs

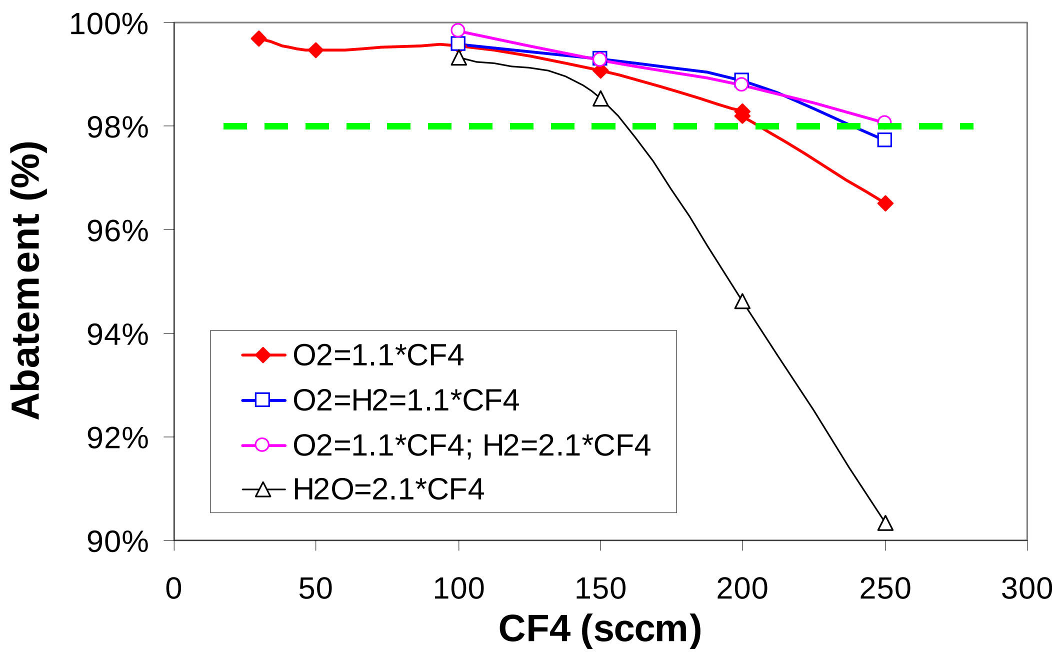
- **Concept - Chemically destruct undesirable species in a plasma reactor**
  - **Add reactive gases, such as O_2, H_2 and H_2O, to the chamber exhaust so that the plasma converts the PFCs to harmless or manageable ones.**

e.g.

$$\text{PFC} + O_2 \xrightarrow{\text{Plasma}} CO_2 + F_2$$

  - **Oxygen is needed to reduce free carbon to CO_2. Chemical balance dictates the ratio of O_2 to C to be 1 or greater.**

ABATEMENT OF CF_4



- Destruction efficiency of > 98% at CF_4 flow of 250 sccm obtained with ASTRON.