Process Development and Control for Silicon Trench Etching using Plasma Parameters

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Outline

- Motivation
- Experimental Procedure
- System Description
- SEERS Description
- Electron Heating
- Process Characterization Results
- Summary

Silicon Trench Etching and Plasma Parameters

- **Motivation:** The development and characterization of a sloped trench process was needed for a new power trench device. The development process in a high density reactor involved the investigation of several different chemistries and a number of different process conditions including pressure, inductive and bias powers and gas flows.

- The use of SEERS (Self-Excited Electron Resonance Spectroscopy) was adopted to aid in the development to get a better understanding of some of the mechanisms taking place in the plasma. This was useful in determining baselines and setting up system controls to insure a stable repeatable process.

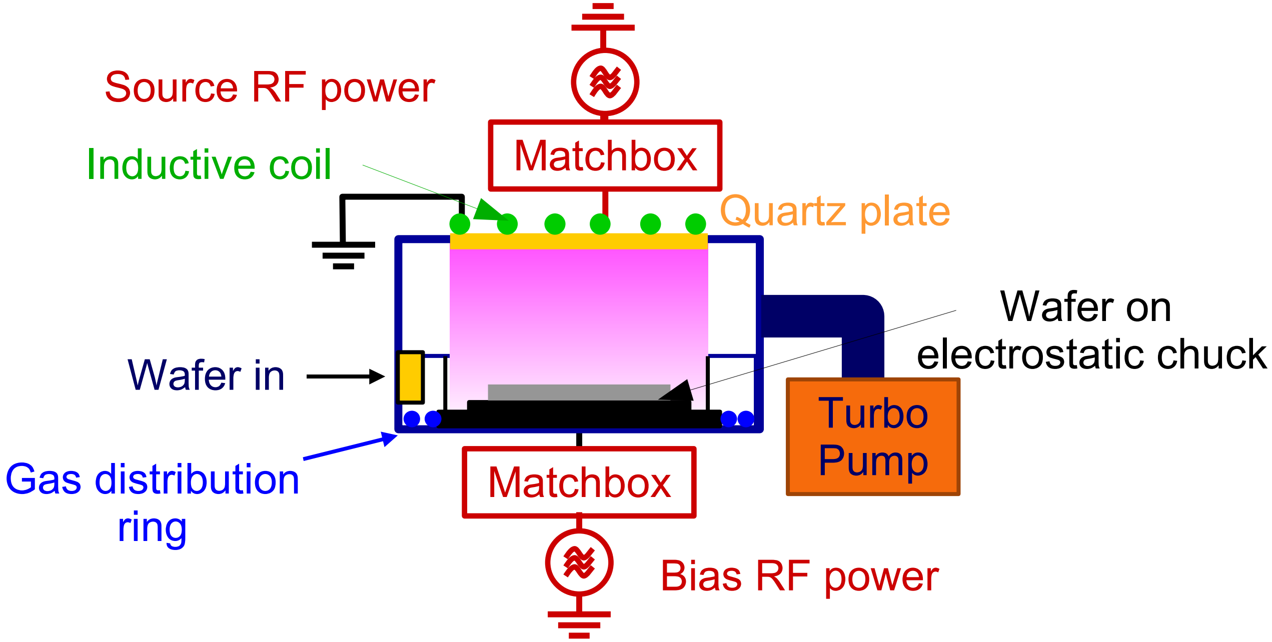
Experimental Procedure

- Wafers patterned with a thermal oxide hard mask were etched using different etch conditions and chemistries to determine the initial starting point.
- HBr/ SF_6/ O_2 was chosen due to its flexibility in terms of profile control.
- Wafers were etched under different conditions of inductive power, bias power, pressure and gas ratios (SF_6:O_2) to evaluate their effects on etch rate and profile.
- SEERS data was collected during each run. SEERS data consisted of electron collision rate, electron density, sheath width and peak voltage.
- Auto clean was run between each wafer to control chamber conditions.
- Wafers were cross sectioned using a scanning electron microscope (SEM) equipped with a Focused Ion Beam to evaluate trench depth and profile.

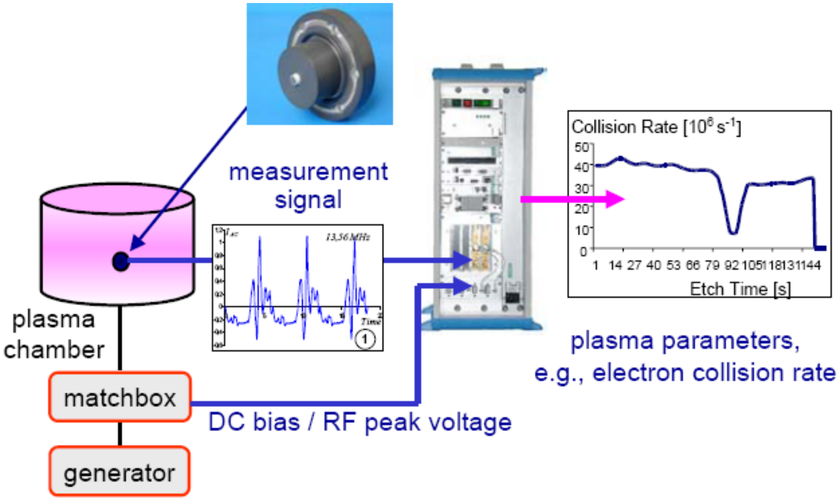
System Description

Commercial inductive coupled plasma (ICP) Reactor with separate inductive and bias power sources for separate control of the ion density and ion energy.

Bottom gas feed and bipolar electrostatic chuck.



SEERS Description


measurement signal

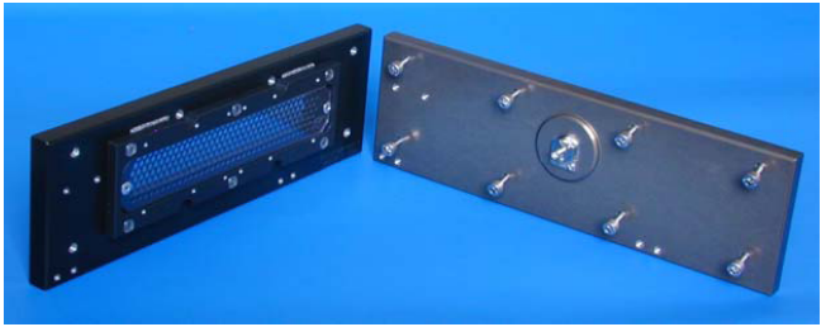
plasma chamber

matchbox

generator

DC bias / RF peak voltage

plasma parameters, e.g., electron collision rate


SEERS Sensor Configuration

- The sensor head is mounted at the chamber wall and is grounded so it doesn’t influence the plasma conditions and behaves like a virtual part of the chamber wall.
- System measures radio frequency (RF) current only so there is no impact on the measured signal due to polymer build up.
- The sensor is connected through a 50Ω coaxial cable which interfaces with the main controller.
- DC bias and peak voltage are pulled from the lower matching network via the RF sense box.

SEERS Theory

- SEERS is based on the nonlinearity of the space charge sheath at the RF electrode. This provides harmonics with the modulated sheath width and high frequency oscillations in the plasma bulk.

- Using this model allows the determination of the volume averaged electron density, collision rate and bulk power dissipated in the plasma.

- The collision rate is based on the elastic collisions between electrons and neutrals where they acquire thermal energy.

M.Klick, W. Rehak and M. Kammeyer, *Jpn. J. Appl. Phys*. **36**, 4625 (1997)

Electron Heating

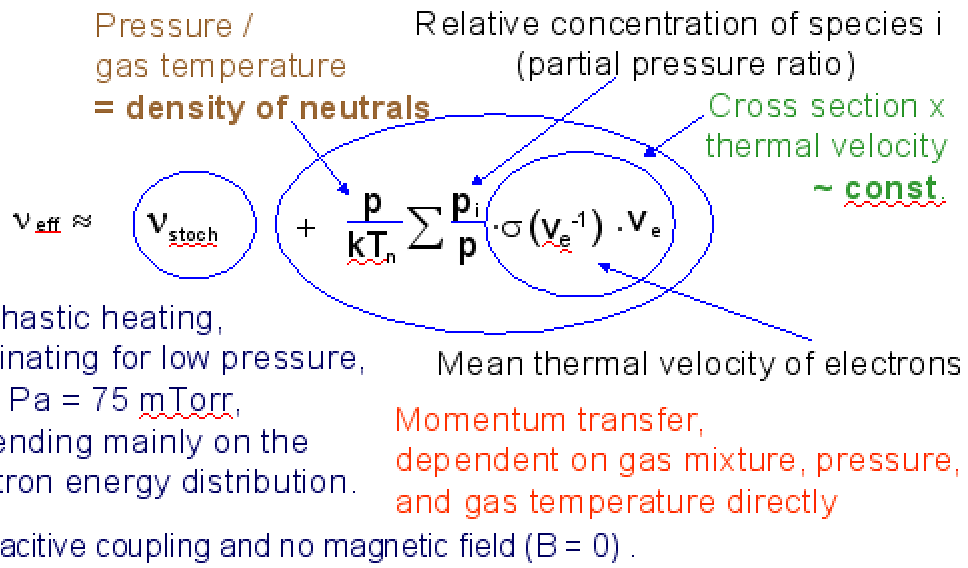
- **Stochastic Heating:** Collisions of electrons with the oscillating boundary of the space charge sheath of the plasma. Oscillation amplitude of the boundary increases with falling pressure. Main heating mechanism at low pressures (especially at electropositive gases).

- **Ohmic Heating:** Electrons accumulate energy from the E-field made possible by collisions with gas molecules. Directed movement of electrons transformed into random walk, collision rate proportional to the gas density. Main mechanism at high pressures.

- Transition pressure between both modes depends on power input, gases used,etc.(2)

G. Franz, M. Klick: *J. Vac. Sci. Technol* A23(4), Jul/Aug 2005.

Effect of Process Parameters on Collision Rate



Pressure / gas temperature **= density of neutrals**

Relative concentration of species i (partial pressure ratio)

Cross section x thermal velocity ~ const.

$$\nu_{eff} \approx \nu_{stoch} + \frac{p}{kT_n}\sum \frac{p_i}{p} \cdot \sigma(v_e^{-1}) \cdot v_e$$

Stochastic heating, dominating for low pressure, < 10 Pa = 75 mTorr, depending mainly on the electron energy distribution.

Mean thermal velocity of electrons

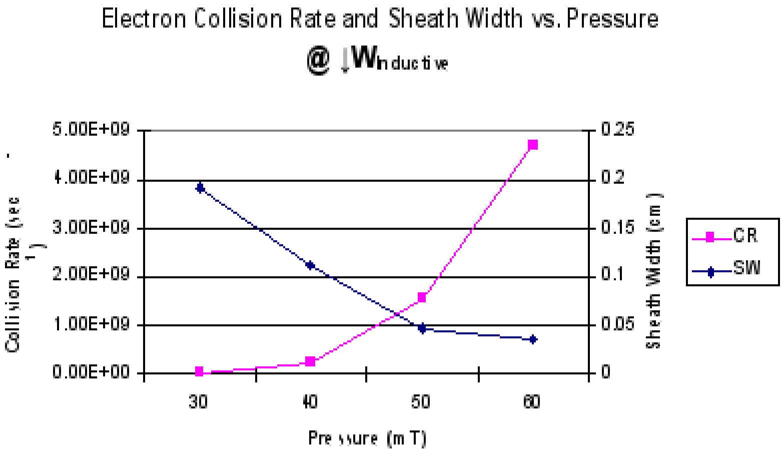
Momentum transfer, dependent on gas mixture, pressure, and gas temperature directly

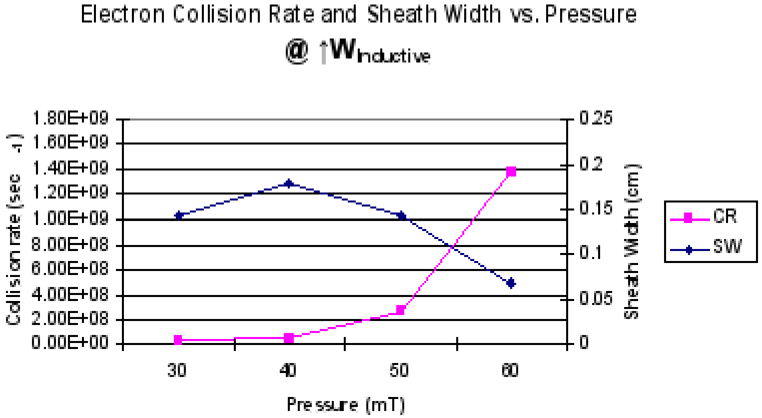
Capacitive coupling and no magnetic field (B = 0) .

- Collision rate (ν_{eff}) is a combination of the stochastic and ohmic contributions.
- Ohmic heating is a function of pressure (p), gas temperature (T_n), gas mixture ($\frac{p_i}{p}$) and indirectly on power
- The inductive power influences the electron velocities and neutral densities by increasing the gas temperature (T_n).

V. A. Godyak, “Soviet Radio Frequency Discharge Research,” Technical Report, Delphic Associates Inc., Falls Chruch, VA, 1986.

Collision Rate and Sheath Width vs. Pressure



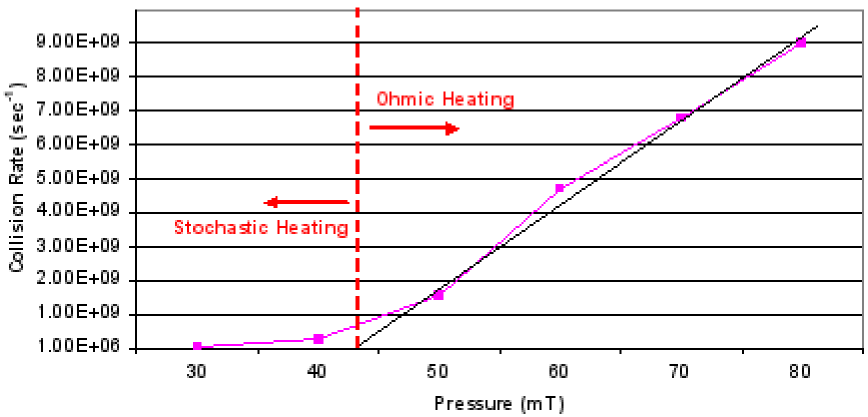


- The sharp increase in the collision rate with pressure is due to the transition from stochastic to Ohmic heating.
- There appears to be a relationship between pressure at which the transition occurs and the inductive power.
- The higher inductive power appears to lead to a higher transition pressure.
- Higher inductive powers lead to higher gas temperatures and reduced neutral densities creating a virtual pressure decrease. This leads to a decreased measured collision rates.
- There is also a relationship between the sheath width and the transition point. A larger sheath width oscillates stronger leading to more stochastic heating.

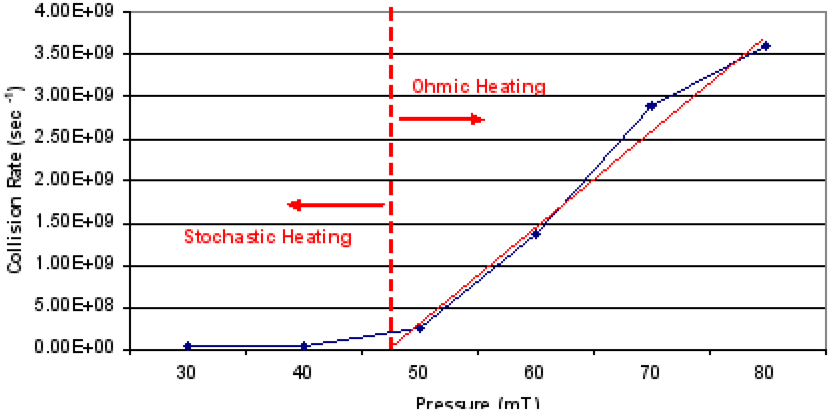
Stochastic to Ohmic Heating Transition Pressure

Collision Rate vs. Pressure

@ ↓W inductive

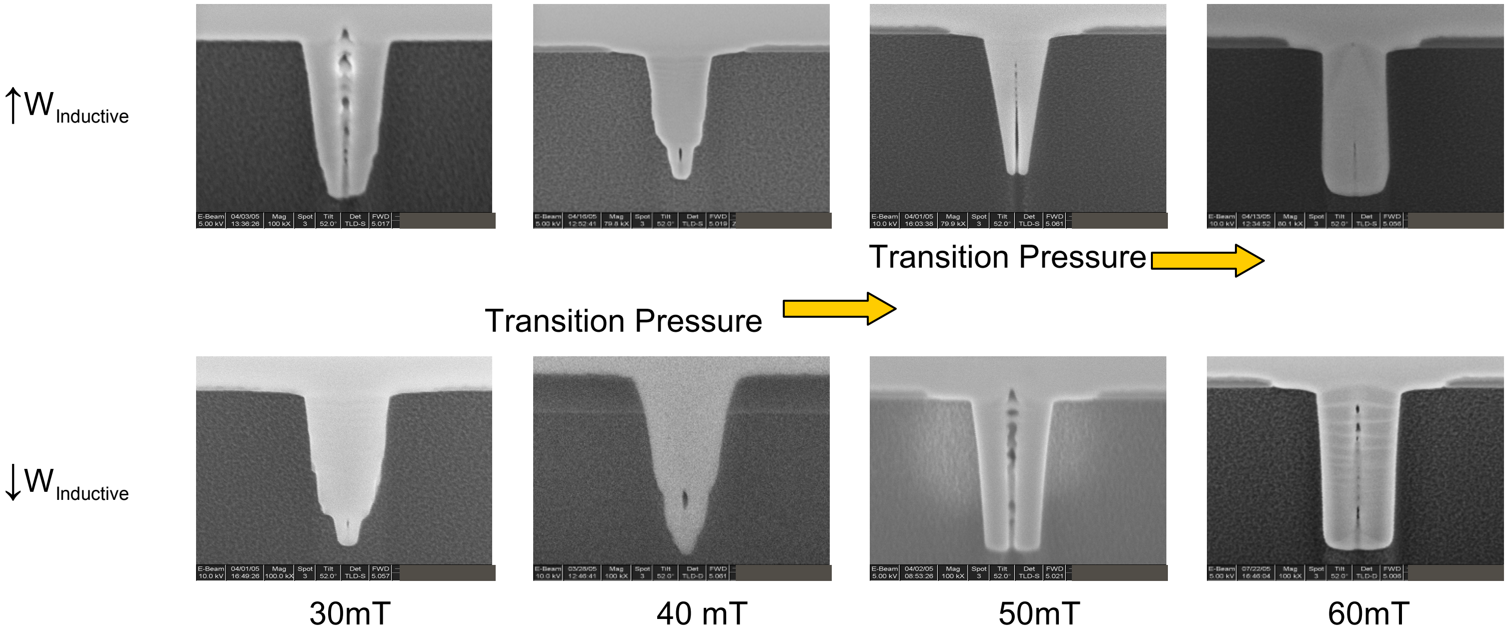


@ ↑W inductive



- It can be shown that the transition from stochastic to Ohmic heating is continuous and a linear fit can be made through the Ohmic portion of the data to help approximate the transition pressure.
- In this case the transition pressures appears to be at 43mT and 48mT for the low and high inductive power processes respectively.

Effect of Pressure and Inductive Power on Trench Profile



- Tests run at a fixed bias power and gas ratio shows a large transition in the profile at around 40mt for low inductive powers and 50mT for high inductive powers.
- This corresponds well with the transition pressure approximations from stochastic to ohmic heating.
- This transition is more pronounced at higher inductive powers where the profile goes from tapered to re-entrant (>90°).
- This is due to an increase in the free fluorine which consumes the sidewall passivation.

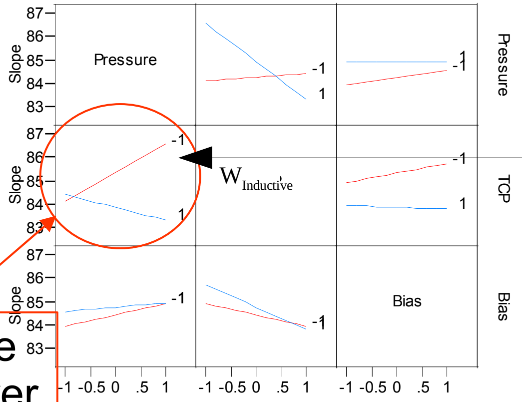
Process Characterization

Initial Screening experiments: Look at pressure and power effects on trench profile and electron collision rate

Control Variables:
- Pressure
- Inductive power
- Bias Power

Response Variables:
- Etch rate
- Trench Profile
- Collision Rate

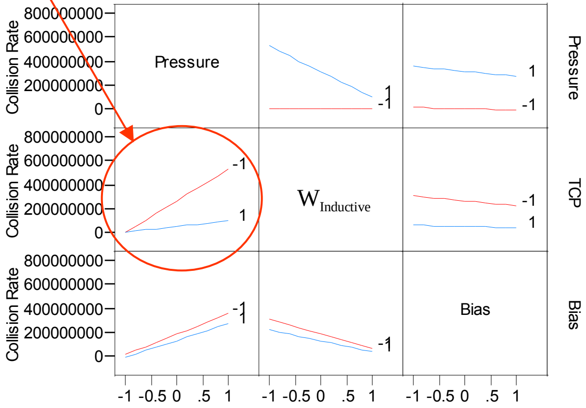
Process Characterization Results for Trench Profile and Collision Rate



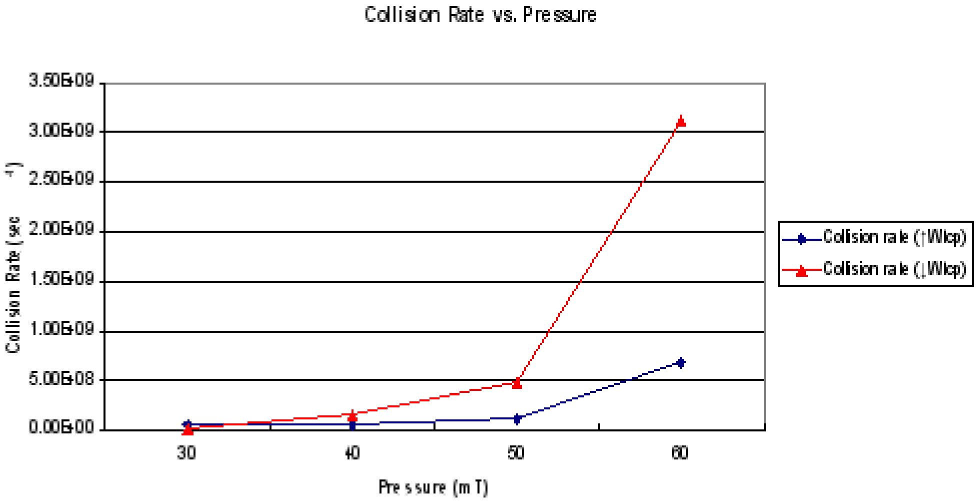
Strong Pressure - Inductive Power Interaction

Interactions Plot for Trench Profile (slope)

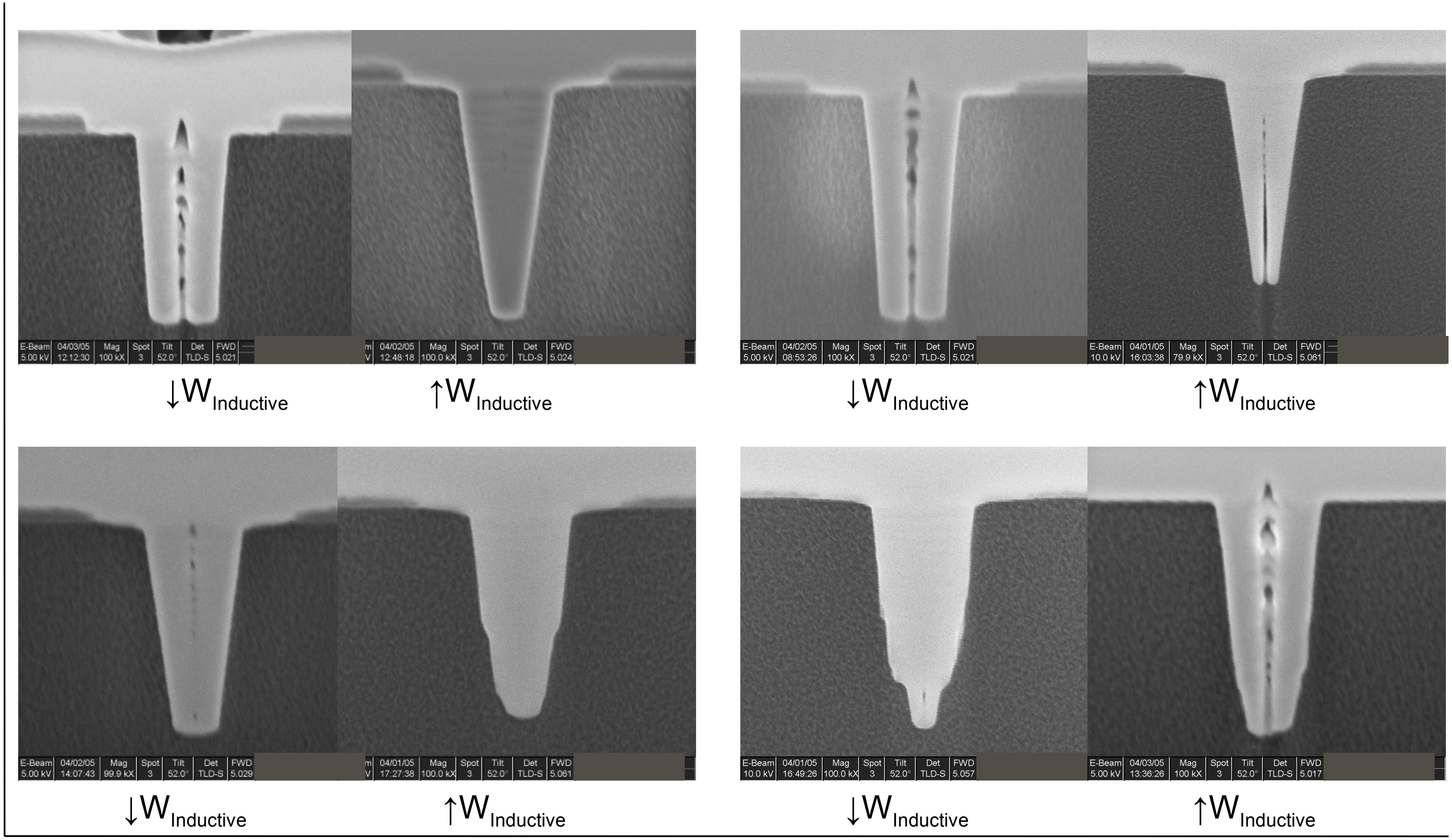
Explanation example: independent variable = pressure, parameter TCP-power (red = low, blue = high)



Interactions Plot for Collision Rate



Process Characterization Results: Slope as a Function of Pressure, Bias and TCP Power



High

Press (mT)

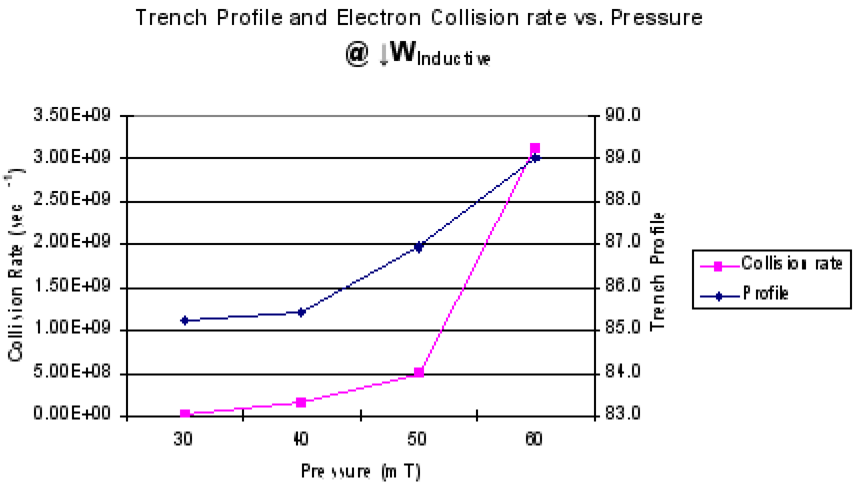
Low

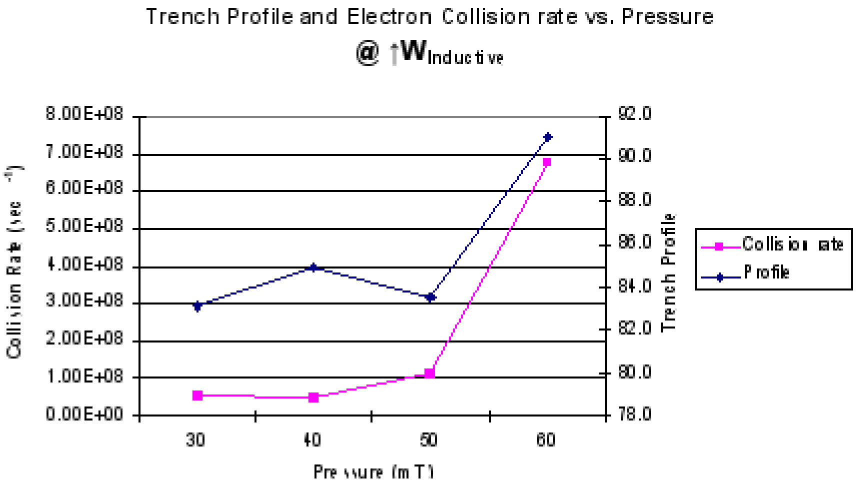
$\downarrow W_{\text{Inductive}}$ $\uparrow W_{\text{Inductive}}$ $\downarrow W_{\text{Inductive}}$ $\uparrow W_{\text{Inductive}}$

$\downarrow W_{\text{Inductive}}$ $\uparrow W_{\text{Inductive}}$ $\downarrow W_{\text{Inductive}}$ $\uparrow W_{\text{Inductive}}$

Low Bias (W) High

Profile vs. Electron Collision Rate





- The correlation between the collision rate and the profile is most probably due to the effect of the heating mode change on the electron energy distribution and the resulting effects on the chemistry.

- The higher inductive powers lead to higher gas temperatures and thus to lower electron collision rates and the transition occurs at a higher pressure.

- Higher inductive power leads to higher transition pressure for mode change and trench shape.

Process Characterization (cont.)

Second Screening experiments: Look at the effects of pressure and gas flows on trench profile and electron collision rate.

Control Variables:

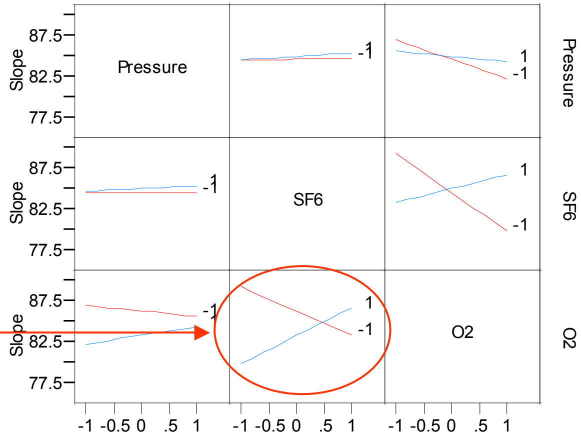
- Pressure
- SF_6 flow
- O_2 flow

→

Response Variables:

- Etch rate
- Trench Profile
- Collision Rate

Process Characterization Results for Trench Profile and Collision Rate



Interaction Plot
for Trench Profile

Strong SF_6 / O_2 interaction for trench profile

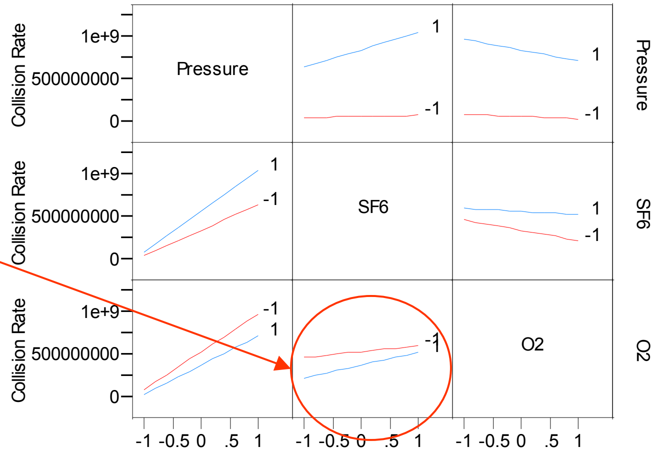
- Potential Mechanism:

$Si + Br \longrightarrow SiBr$ main etch by-product

$Si + Br + O \longrightarrow SiO_xBr_y$ sidewall passivation

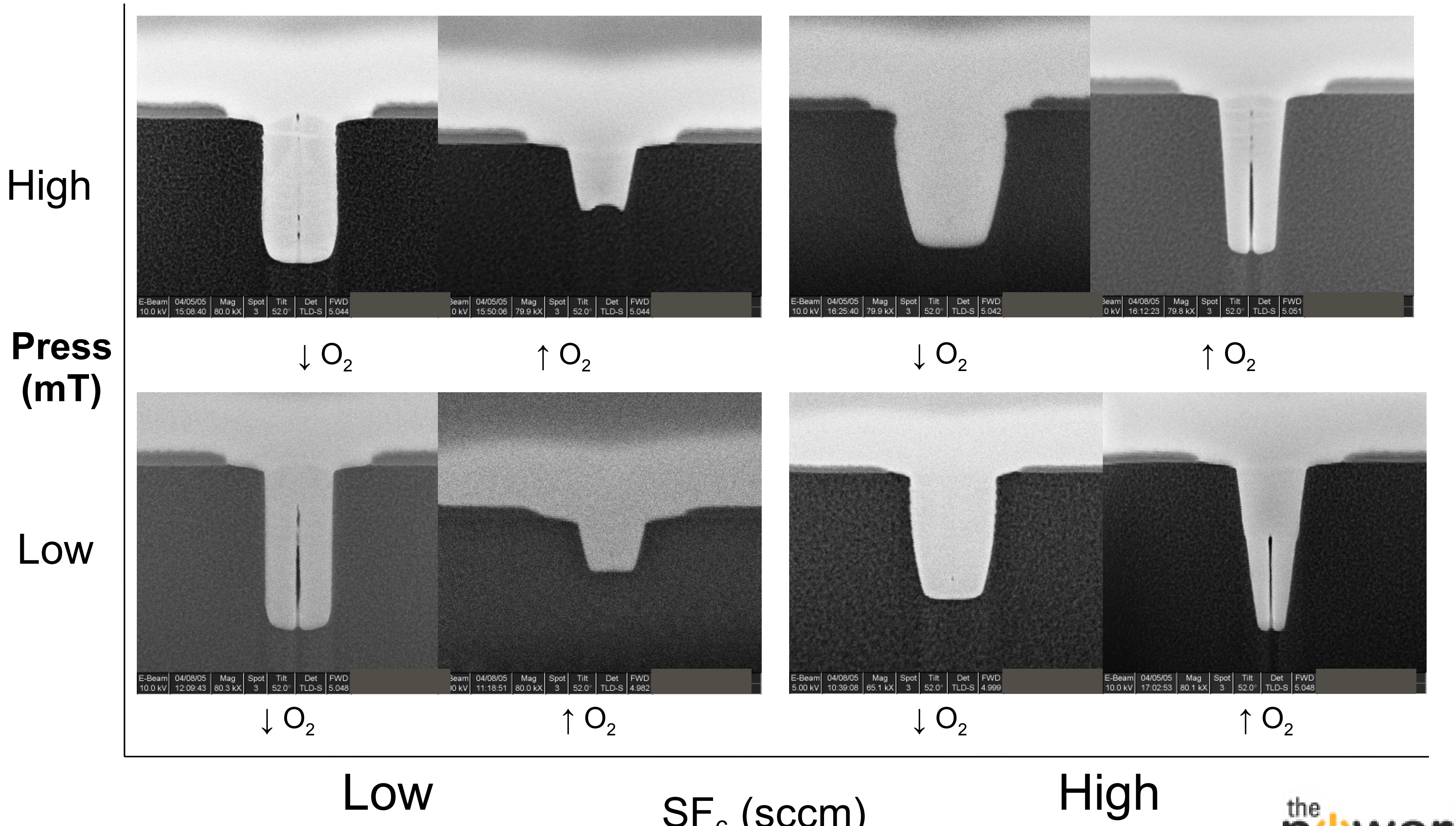
$SiBr_xO_y + F \longrightarrow SiBr_xF_y$

The interaction is less pronounced for collision rate.



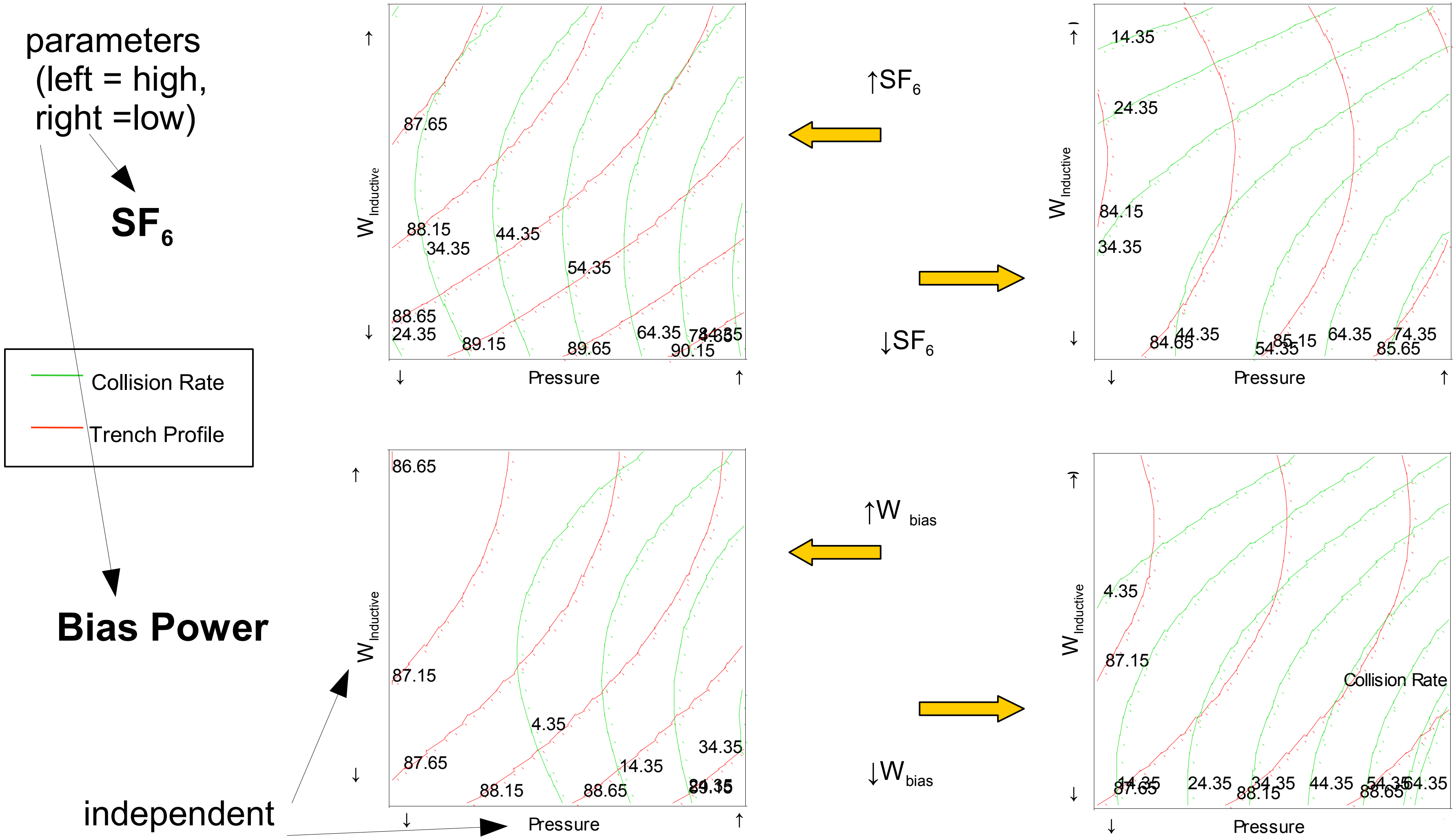
Interaction Plot
for collision Rate

Slope as a Function of Pressure, SF_6 and O_2



Trench Profile Process Window Study

(± 20% Pressure, Inductive and Bias Power, SF_6, O_2)



parameters (left = high, right =low)

SF_6

Bias Power

independent variables

Collision Rate

Trench Profile

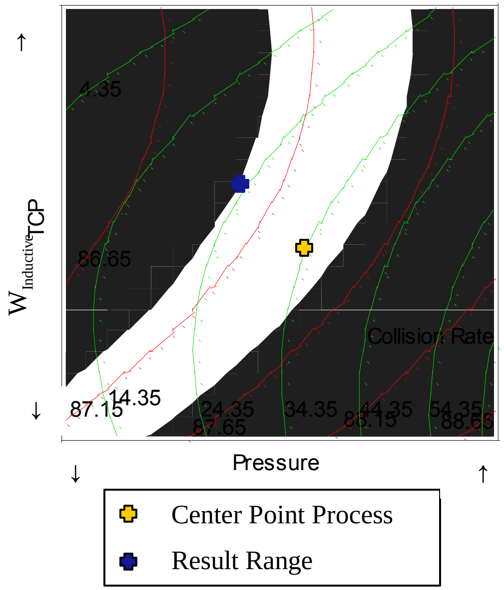
↑SF_6

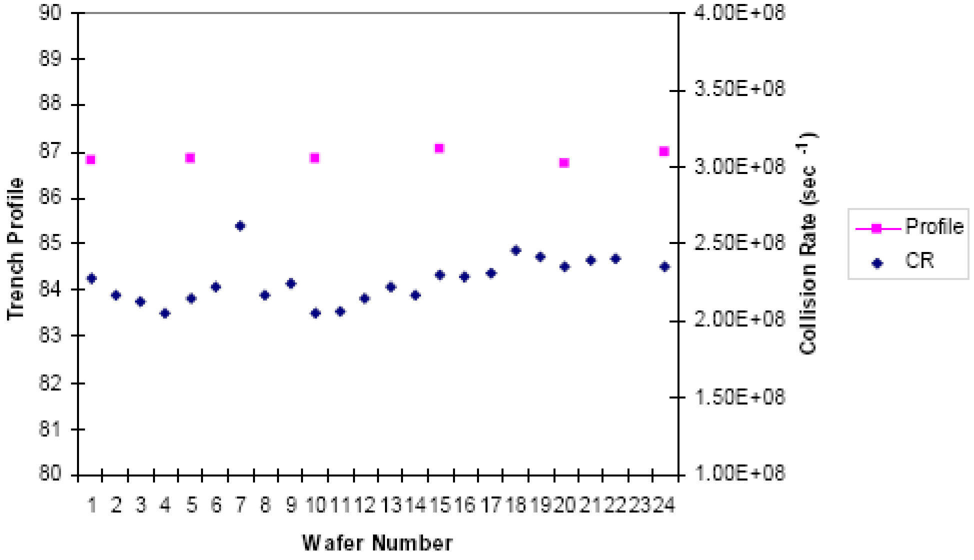
↓SF_6

↑W_{bias}

↓W_{bias}

Process Repeatability





- Based on the process model, a collision rate of between 2.4*10^8 s^{-1} and 3.3*10^8 s^{-1} should be controlled to maintain a trench profile of 87 to 87.5° in this particular process regime.
- A repeatability test was run which monitored the collision rate and trench profile across a 24 wafer run. SEERS data was collected for each wafer and wafers 1,5,10,15, 20 and 24 were cross sectioned to measure trench profile and depth.
- The average collision rate was 2.25*10^8 s^{-1} and the average profile was 86.9°.

Summary

- A new sloped trench etch process was developed with the aid of Self-Excited Electron Resonance Spectroscopy.
- Good correlation was found between the trench profile and the electron collision rate.
- An abrupt change in trench profile was found to occur at or near the transition point between the stochastic and ohmic electron heating regime.
- Process models run around the base process identified a region where the collision rate could be used to monitor process stability in terms of profile control.