Control of Process Plasmas for Next-Generation ULSI Devices

2008.12.17

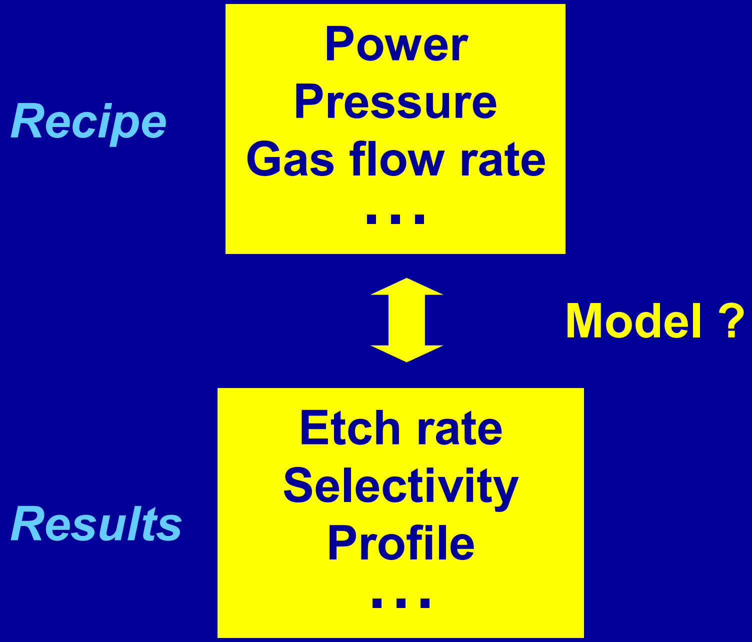
Tetsuya Tatsumi
Sony corporation

Outline

1. Introduction
2. Plasma & Surface reaction models (Yesterday)
3. Current issues for CMOS fabrication (Today)
4. Requirement for “data base” (Tomorrow)
5. Summary

Requirement (Yesterday)

Plasma control
for high aspect ratio
contact hole etching



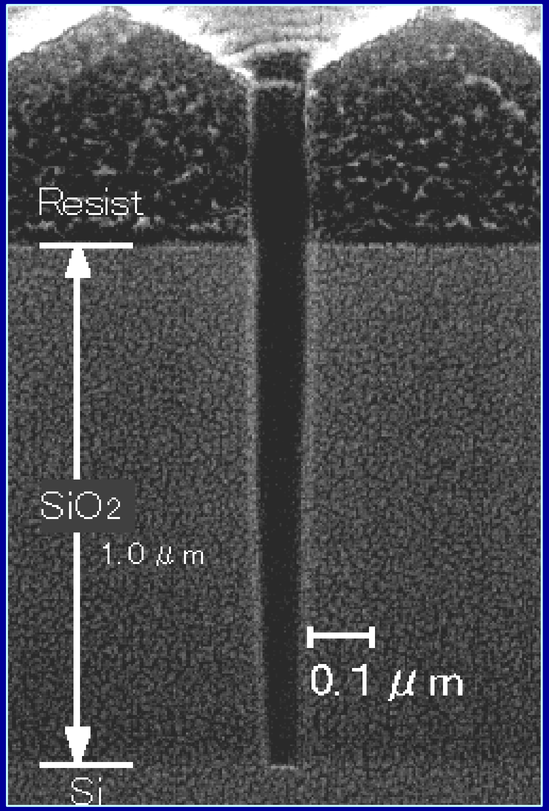
Recipe

Power
Pressure
Gas flow rate
…

Model ?

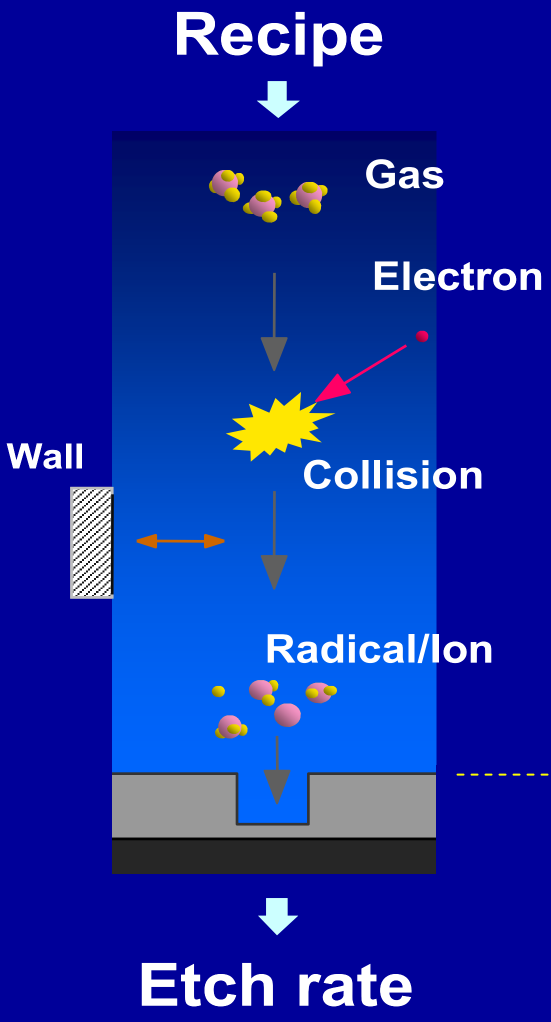
Results

Etch rate
Selectivity
Profile
…



T. Tatsumi, JJAP 37 (1998) 2394

Reactions



Electron heating

Dissociation

Plasma-wall interaction

Incident flux (radical/ion)

Plasma control

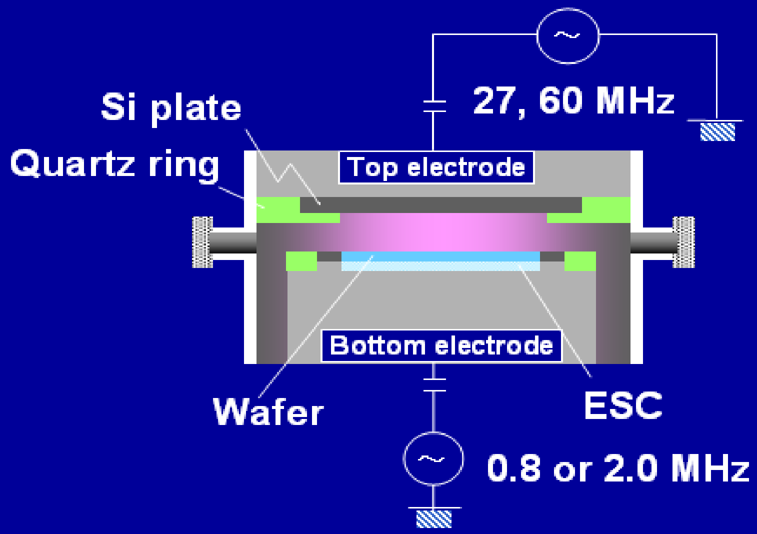
Surface control

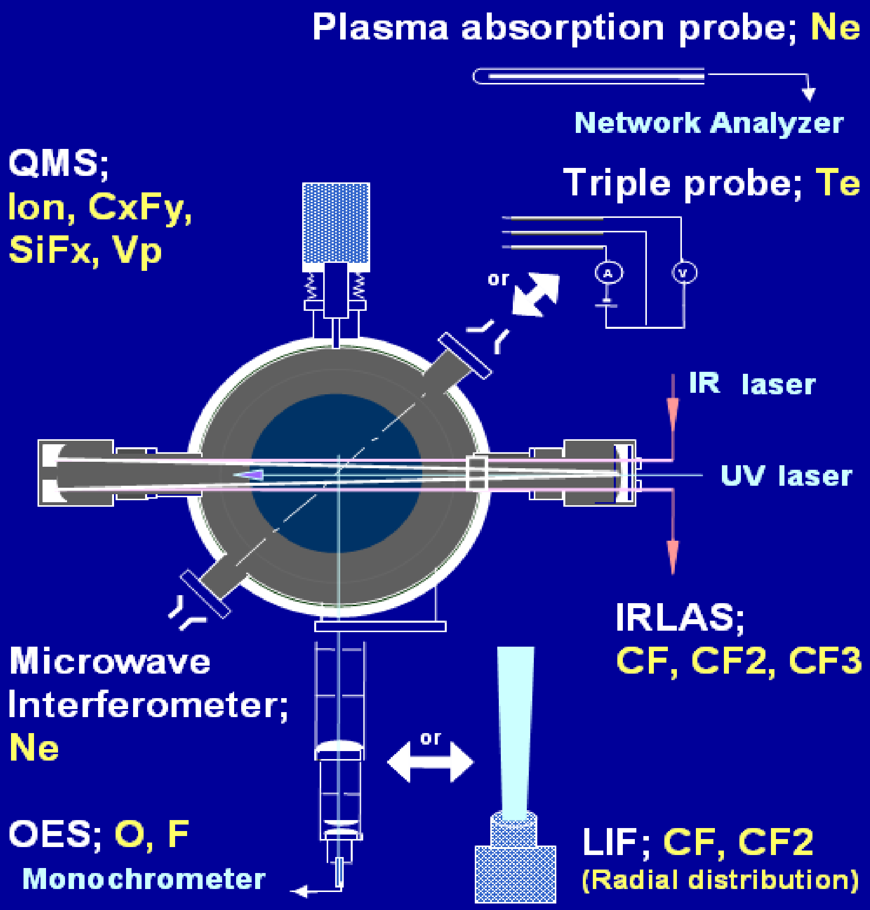
Transportation

Surface reaction

In-situ monitoring of C-F plasma

Dual Frequency CCP
C4F8/Ar/O2(N2)

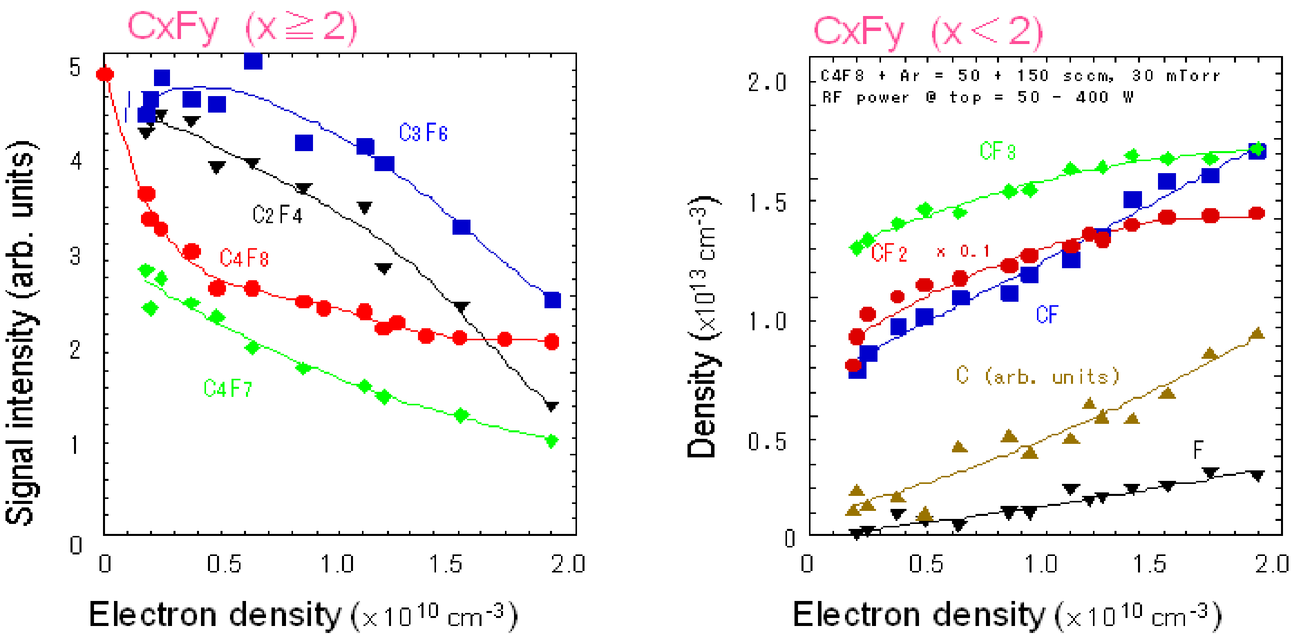




In-situ monitoring of Ne, Te, ions and radicals

Control of radical composition

H. Hayashi, JVST A 17 (5) (1999) 2557

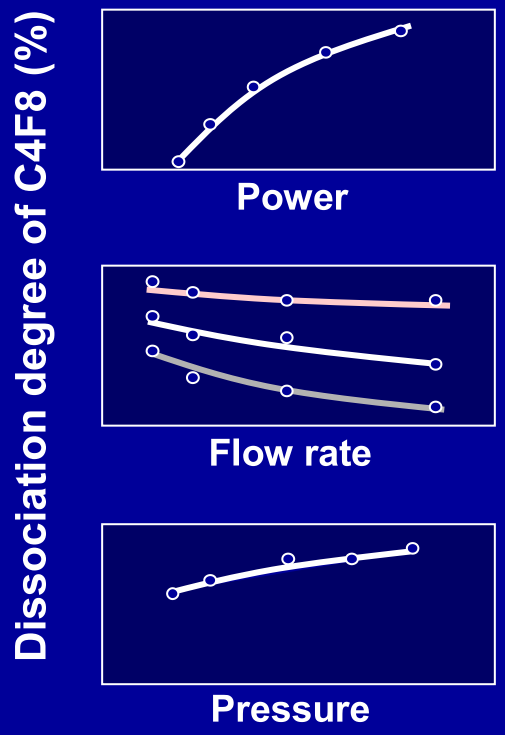


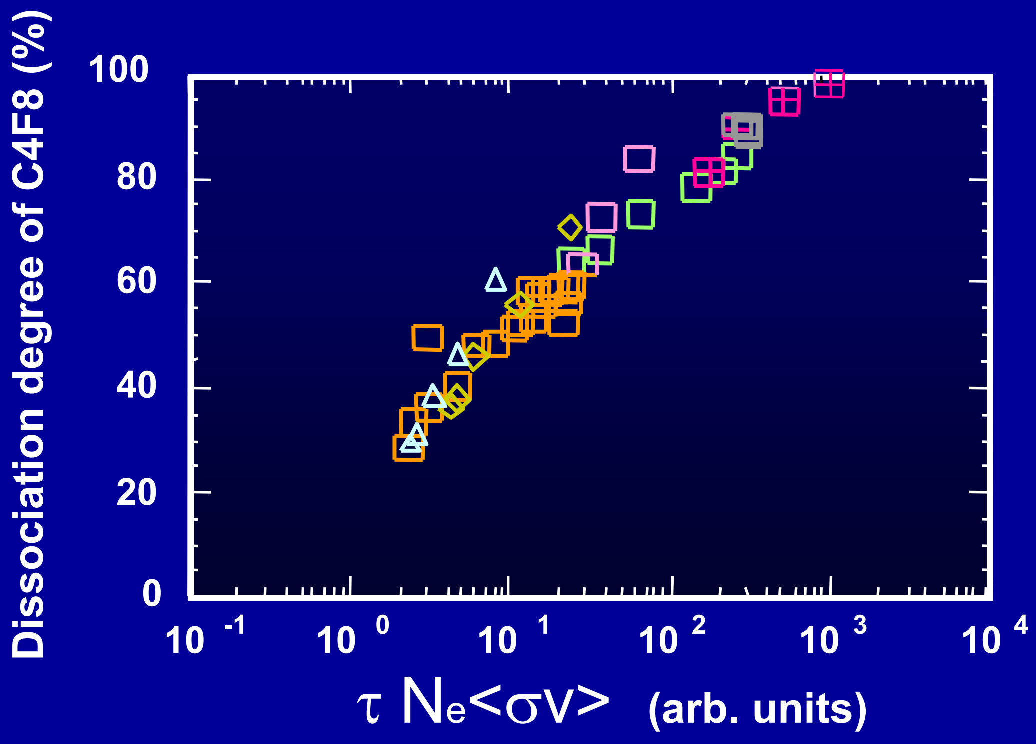
H. Hayashi et al., '98 SPP, 3A3-1

C_4F_8 → C_xF_y (?) → ··· → CF_2 → F

Dissociation of fluorocarbon molecule

Dissociation of CF gases





External parameters

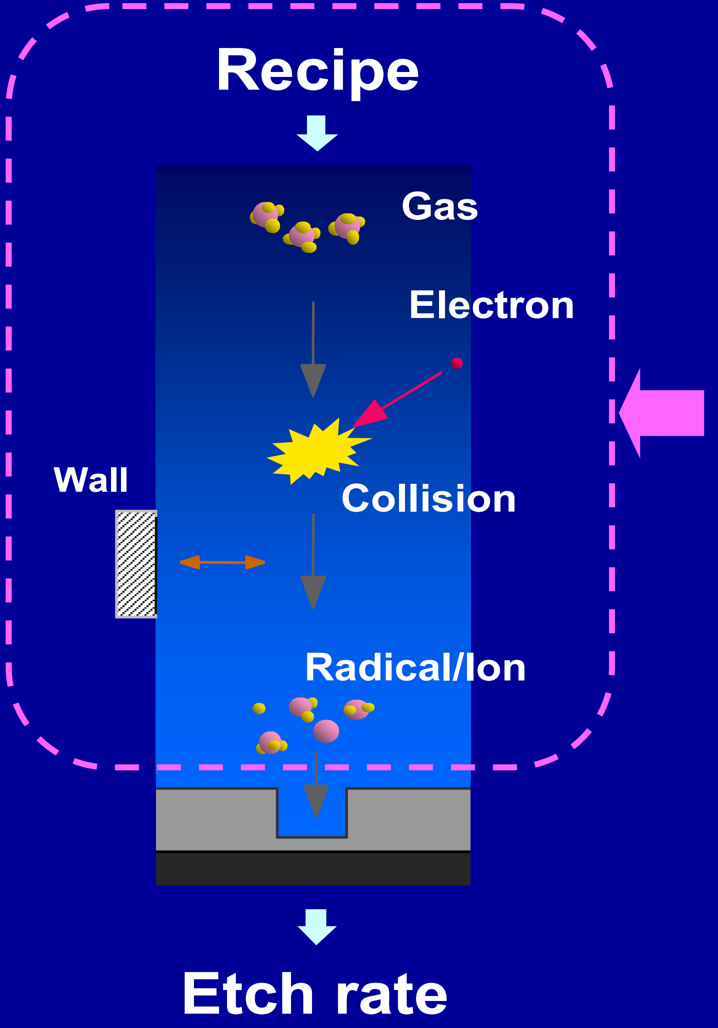
Power: 100-2000W
Pressure: 20-100mTorr
Total flow: 100-600sccm
Gap: 17-27mm

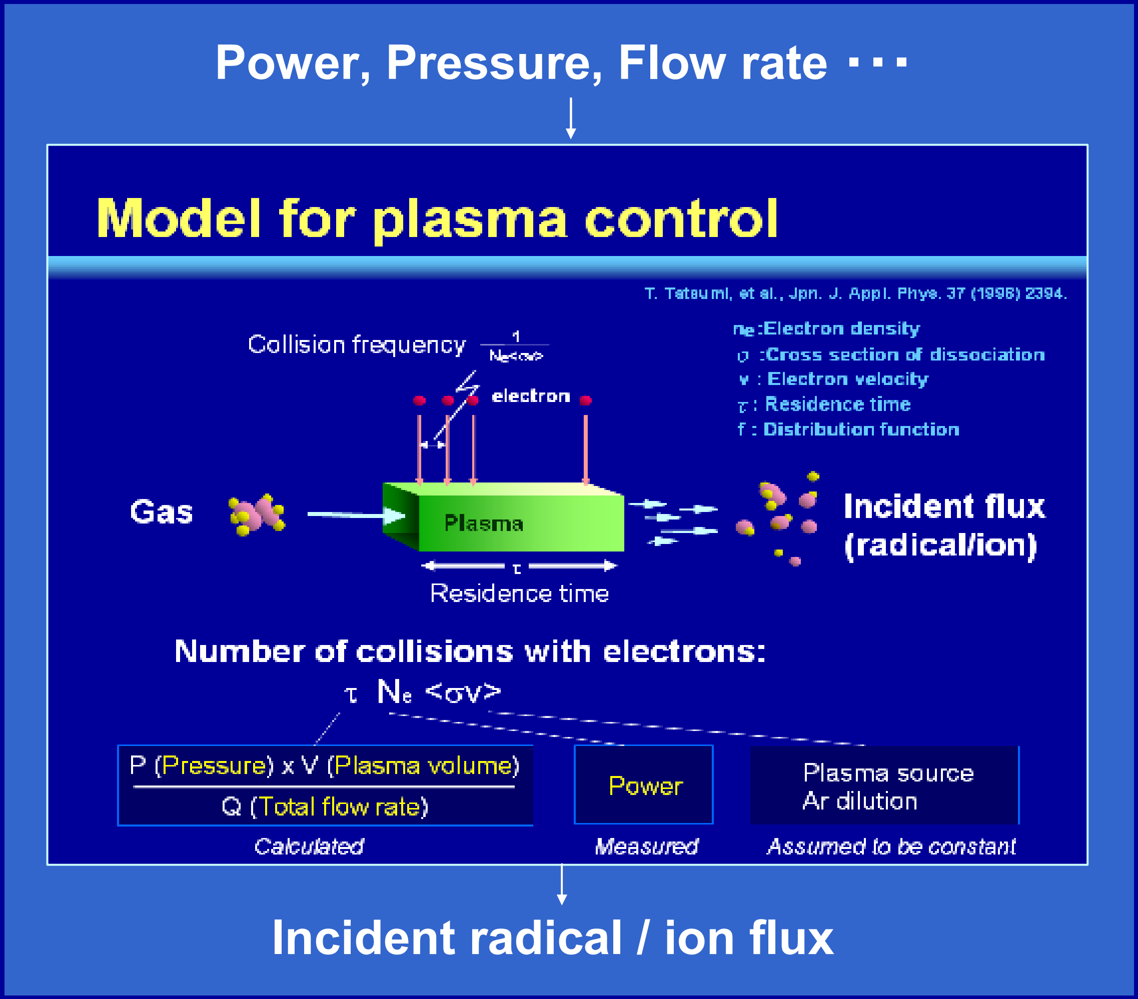
➔

Number of collisions

τ ➔ residence time (4-24ms)
Ne ➔ electron density (2e9-11cm-3)
<σv> ➔ electron energy (3-5eV)

External parameters → Incident fluxes





Model for plasma control

T. Tatsumi, et al., Jpn. J. Appl. Phys. 37 (1998) 2394.

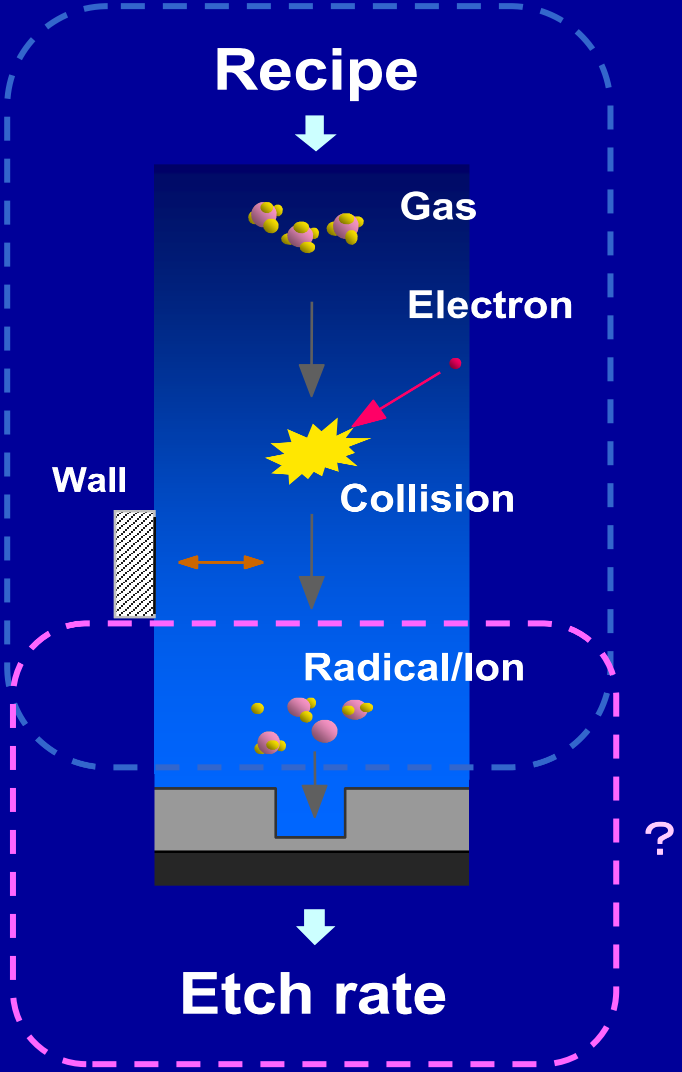
n_e :Electron density
σ :Cross section of dissociation
v : Electron velocity
τ : Residence time
f : Distribution function

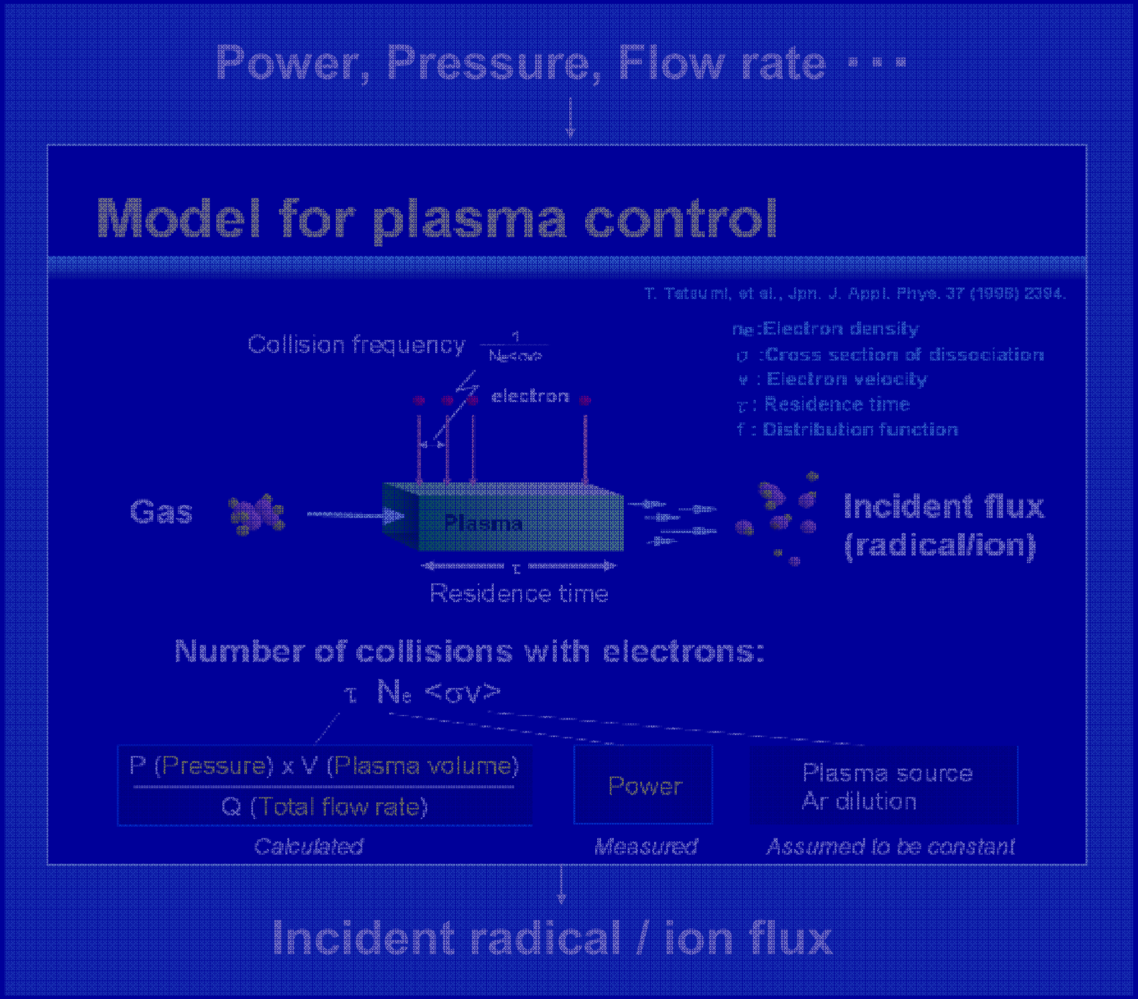
Number of collisions with electrons:

$\tau \; N_e <\sigma v>$

$\frac{P\text{ (Pressure)} \times V\text{ (Plasma volume)}}{Q\text{ (Total flow rate)}}$	Power	Plasma source Ar dilution
Calculated	*Measured*	*Assumed to be constant*

Incident fluxes → Etch rate





Power, Pressure, Flow rate ・・・

Model for plasma control

T. Tatsumi, et al., Jpn. J. Appl. Phys. 37 (1998) 2394.

Collision frequency $\frac{1}{N_e<\sigma v>}$

n_e :Electron density
σ :Cross section of dissociation
v : Electron velocity
τ : Residence time
f : Distribution function

Gas

Plasma

electron

τ

Residence time

Incident flux (radical/ion)

Number of collisions with electrons:

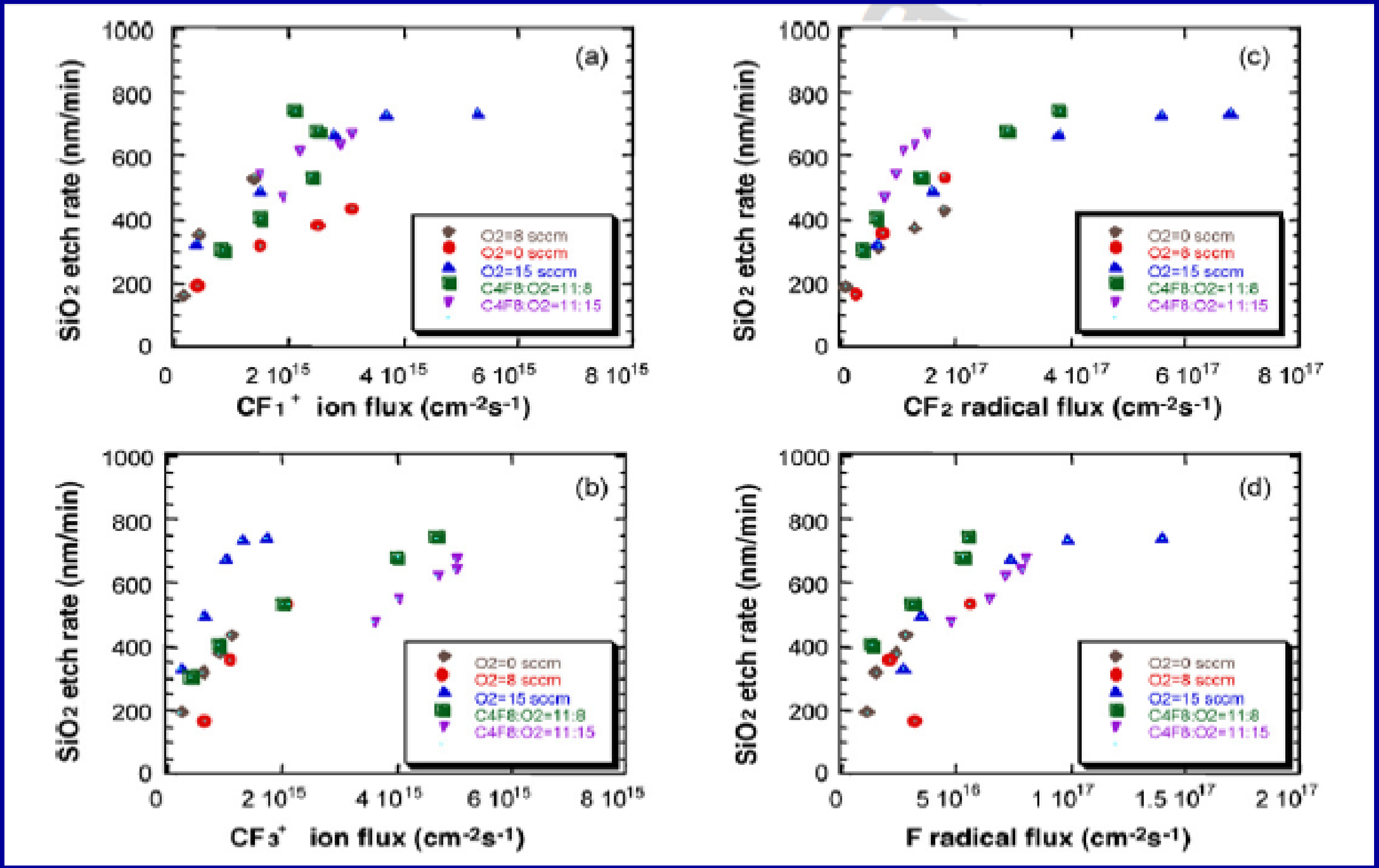
$\tau \; N_e <\sigma v>$

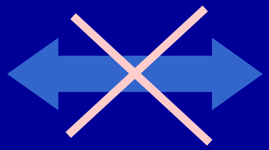
$\frac{\text{P (Pressure) x V (Plasma volume)}}{\text{Q (Total flow rate)}}$	Power	Plasma source Ar dilution
Calculated	*Measured*	*Assumed to be constant*

Incident radical / ion flux

Incident fluxes → Etch rate

T.Tatsumi, Applied Surface Science 253(2007) 6716

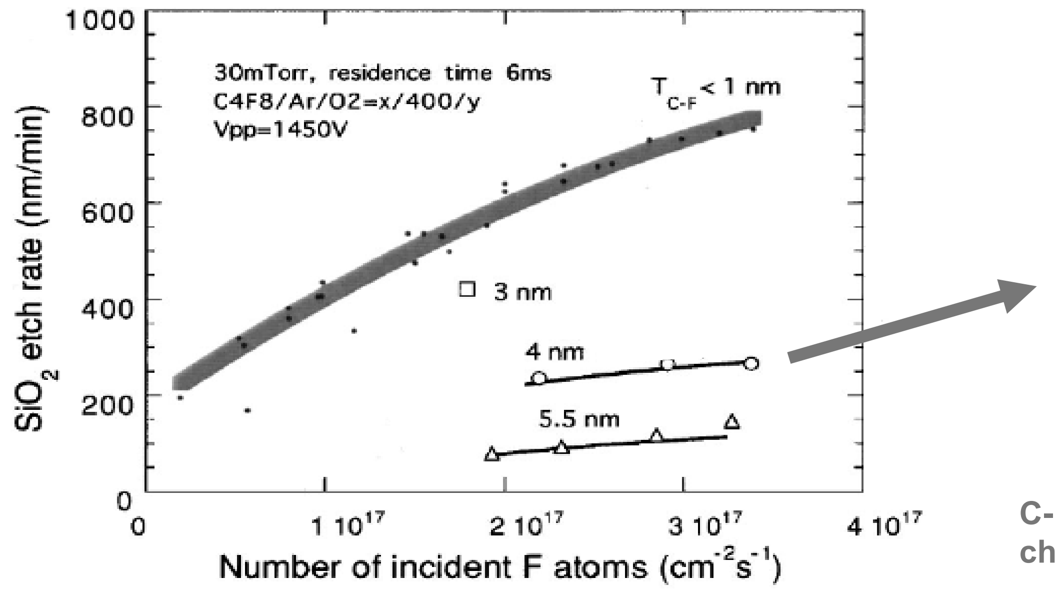


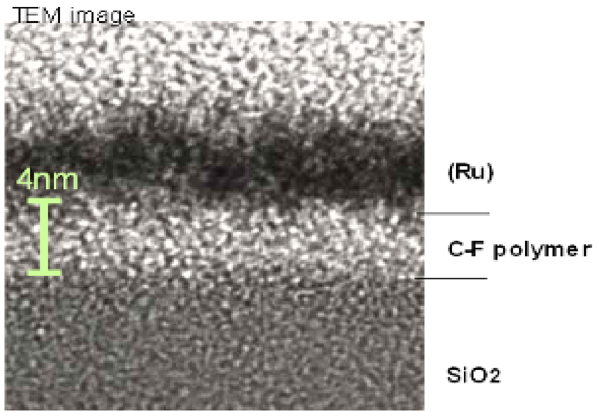


CF^+, CF_3^+, CF_2, F, ･･･ SiO$_2$ etch rate

Incident fluxes → Etch rate

T. Tatsumi et al., JVST B, Vol. 18 (2000) 1897





C-F polymer on etched surface changes the reaction probability of F

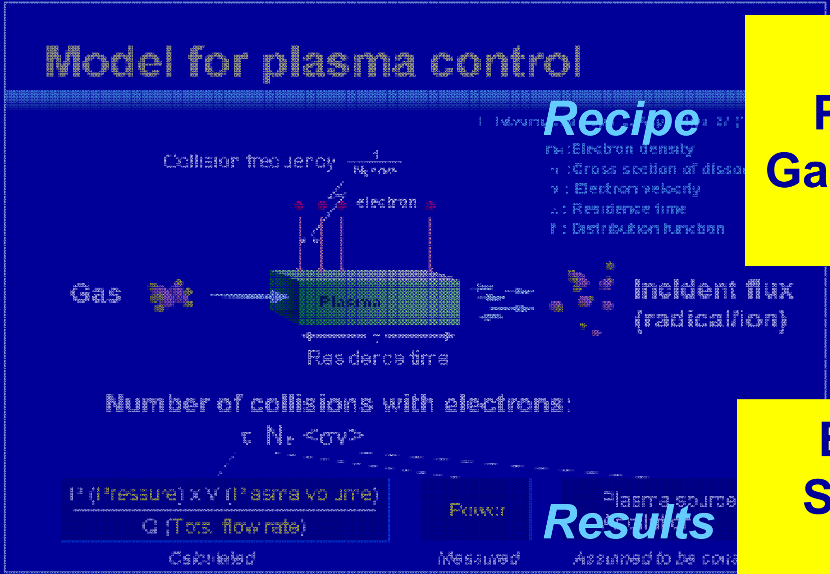
Total F in all incident CF_x radical and/or ion fluxes

x

Reaction probability
(ion energy and polymer thickness)

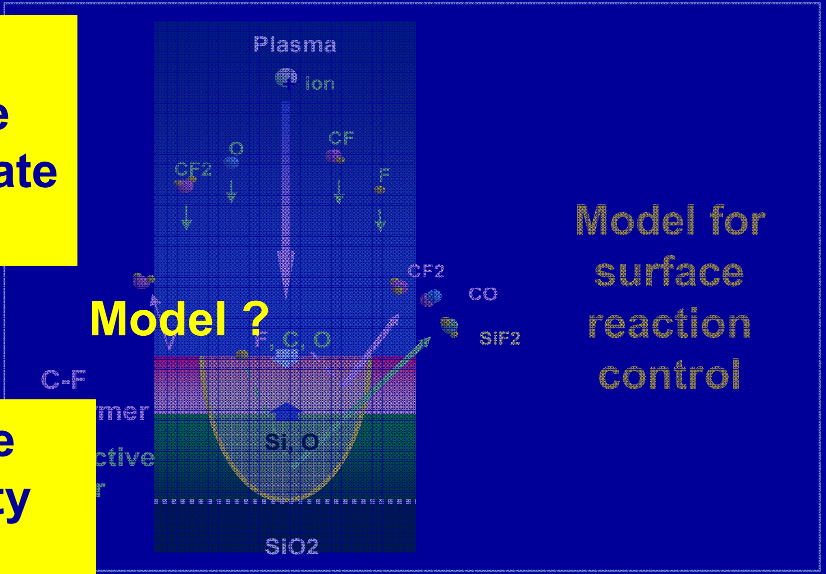
↔ **SiO_2 etch rate**

Etch rate prediction



Power
Pressure
Gas flow rate
…

Etch rate
Selectivity
Profile
…



Dissociation of C_4F_8

Bias power & C_4F_8/O_2 ratio

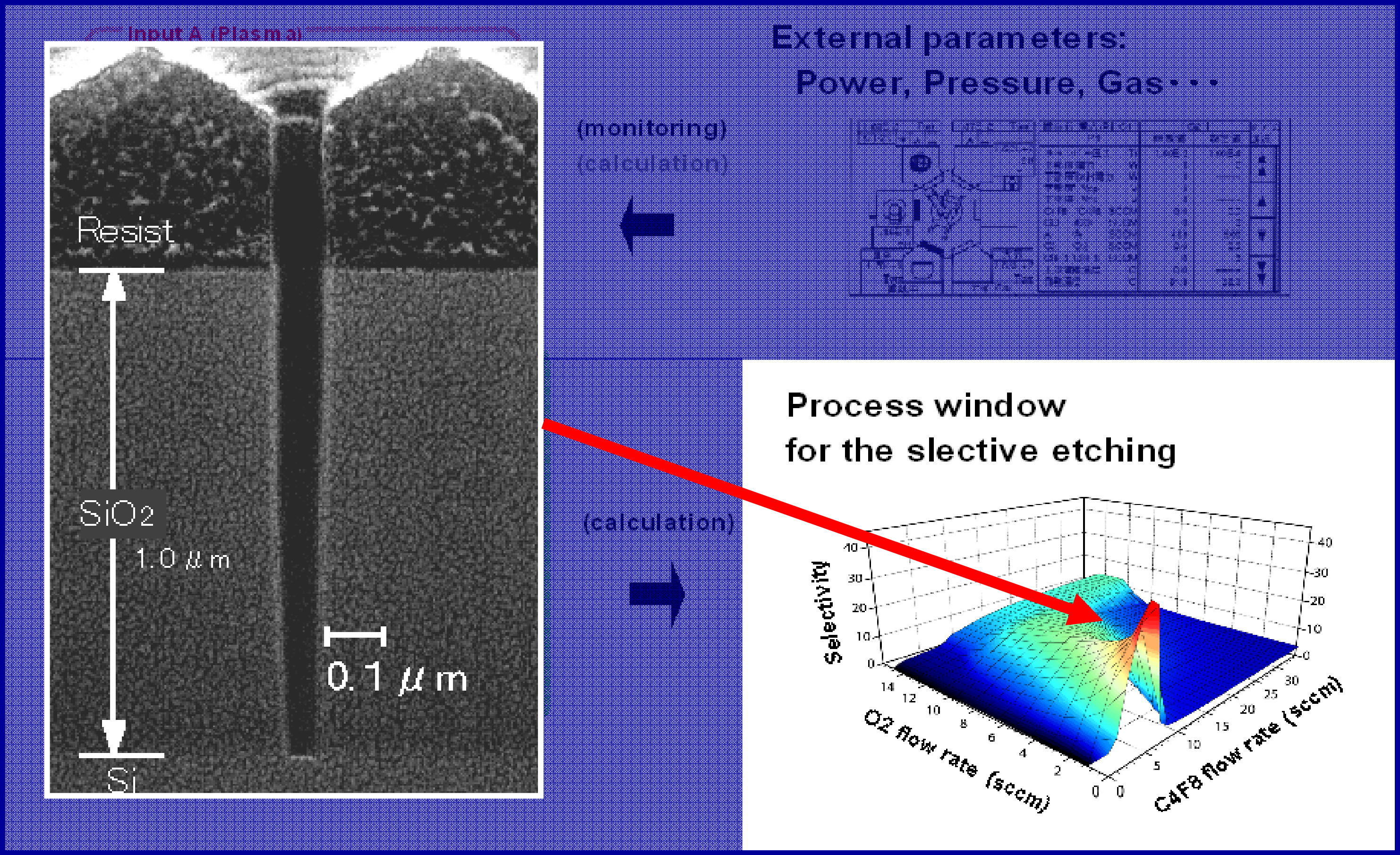
Total F in all incident CF_x radical and/or ion fluxes

x

Reaction probability
(ion energy and polymer thickness)

⟷ **SiO_2 etch rate**

Etch rate prediction



External parameters:
Power, Pressure, Gas・・・

(monitoring)

(calculation)

(calculation)

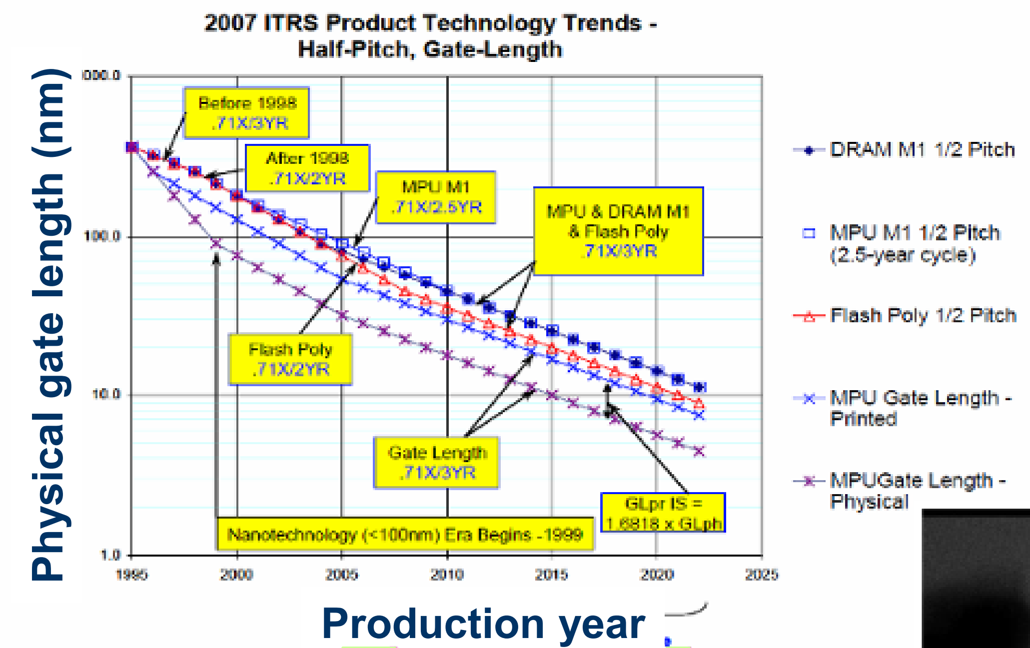
Process window
for the slective etching

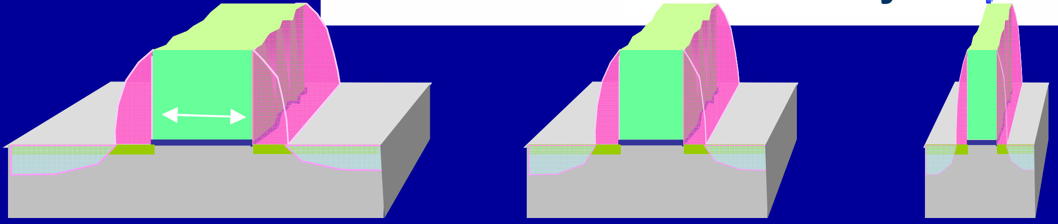
Plasma + Surface reactions → Process performance

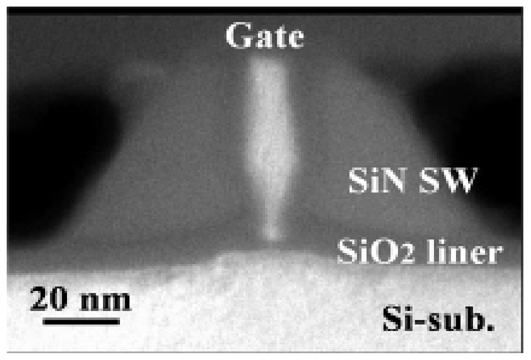
Outline

1. Introduction
2. Plasma & Surface reaction models (Yesterday)
3. Current issues for CMOS fabrication (Today)
4. Advanced process control (Tomorrow)
5. Summary

ITRS roadmap 2007



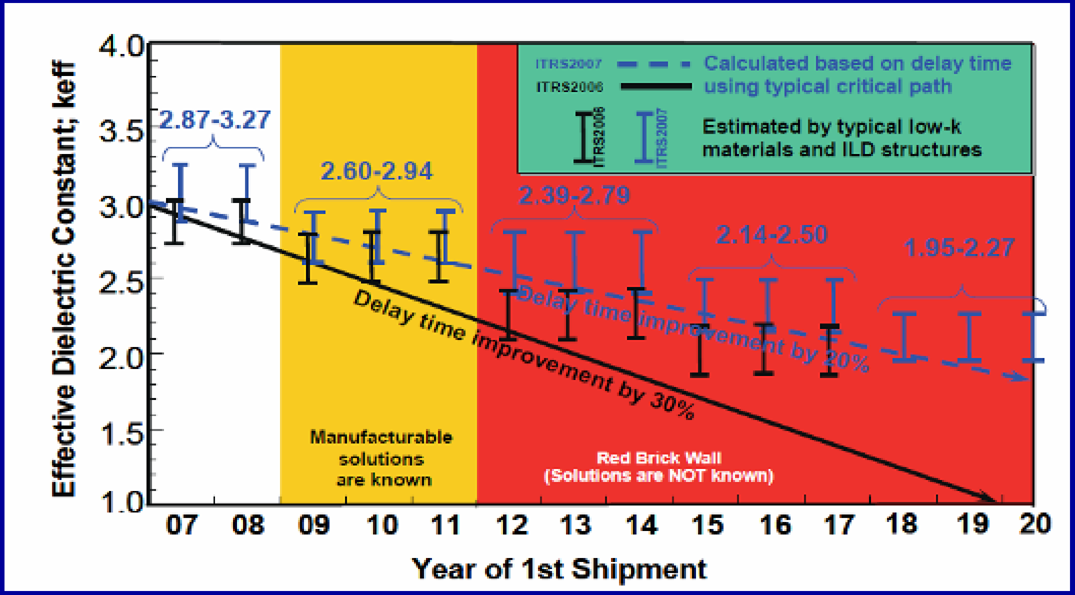


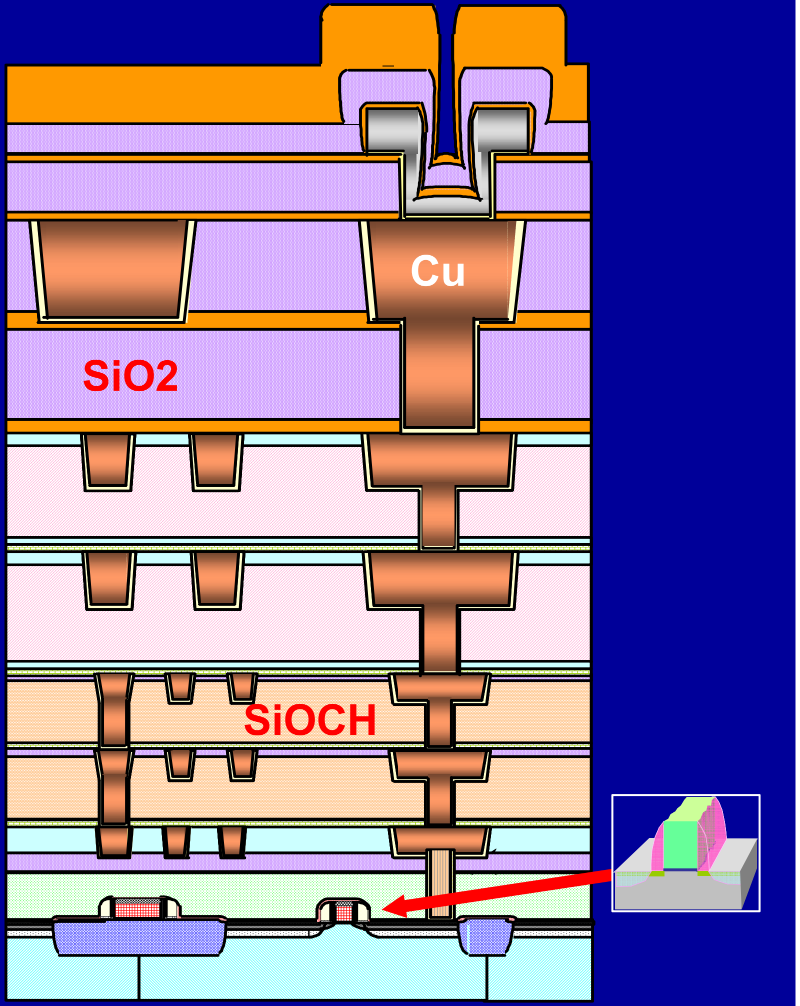


Wakabayashi, 2004 IEDM

Gate length ➔ 10nm±1nm @2015

ITRS roadmap 2007





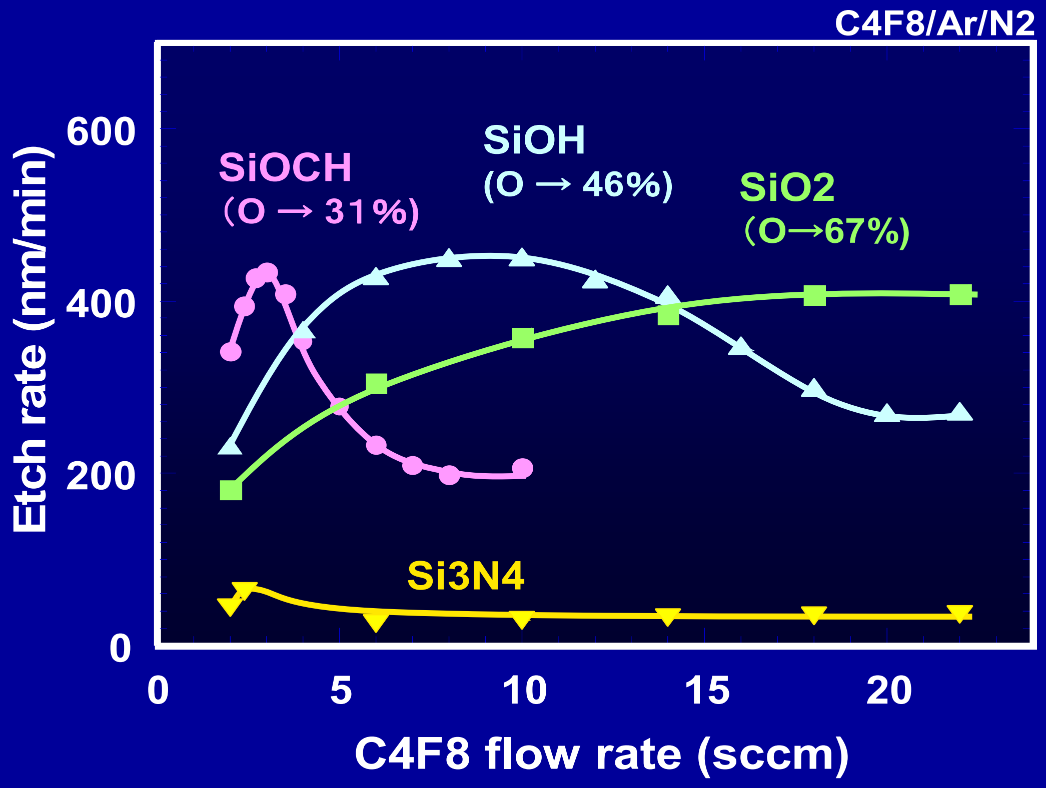
SiOCH (low-k materials)

➔ Reduction of capacitance between Cu wiring

Small process window

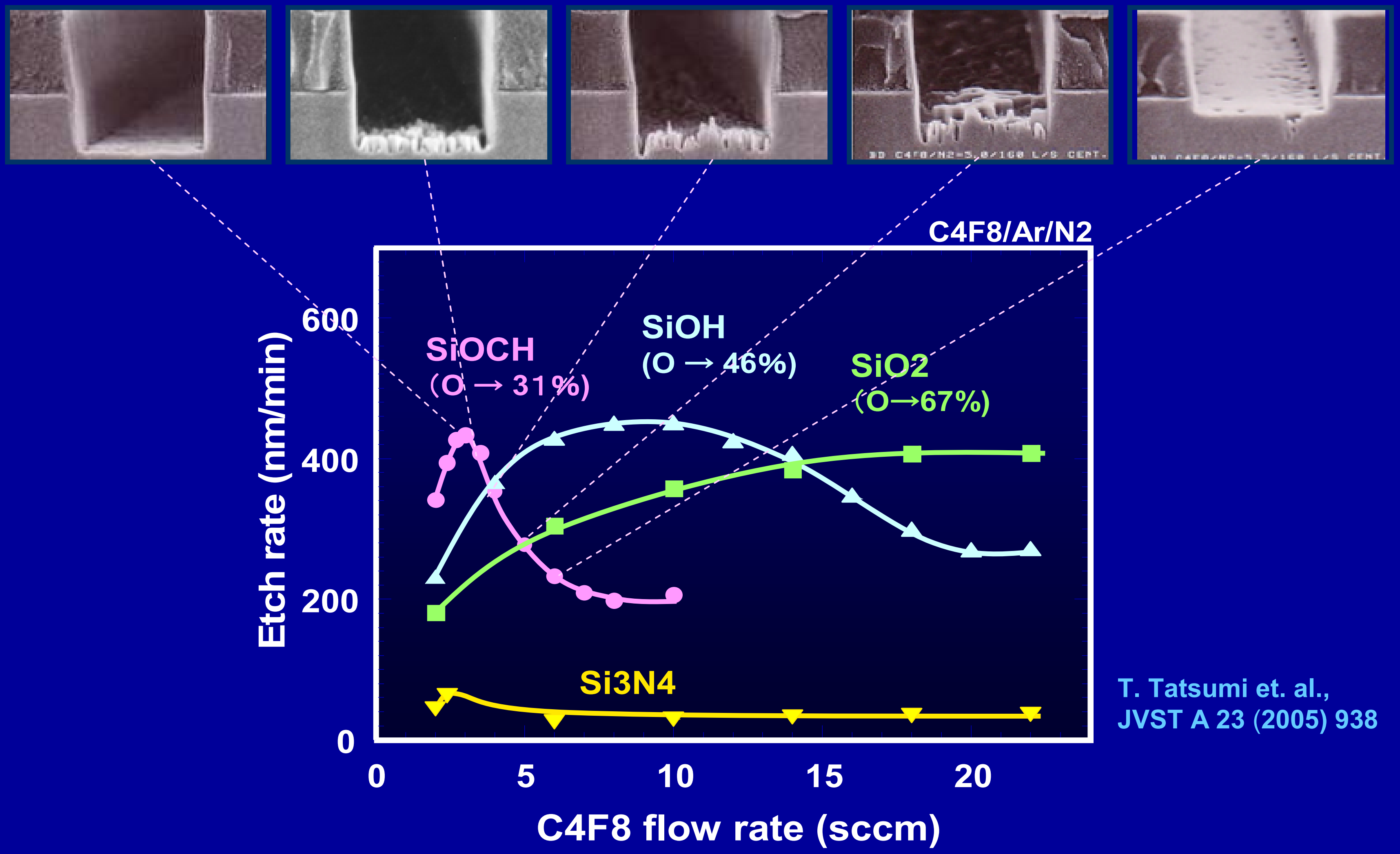
Decrease in O concentration in SiOCH film

➔ Etch rate is sensitive to change in CFx densities.



T. Tatsumi et. al., JVST A 23 (2005) 938

Small process window



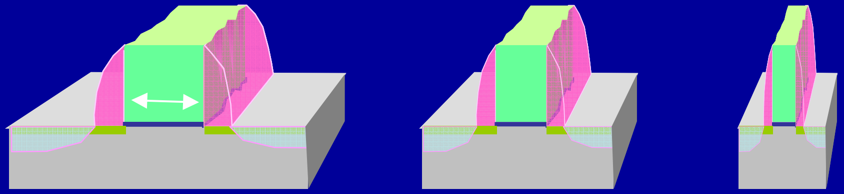
T. Tatsumi et. al.,
JVST A 23 (2005) 938

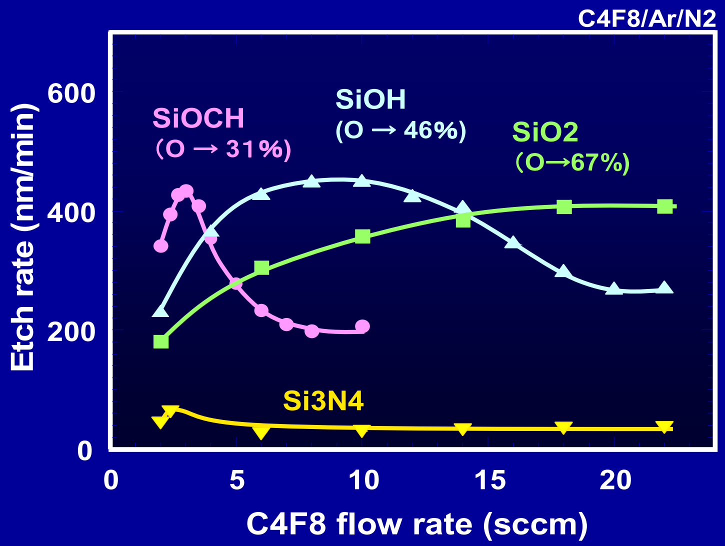
Requirements (Today)

Small size

➔ Atomic layer control

ΔCD < 1nm ?





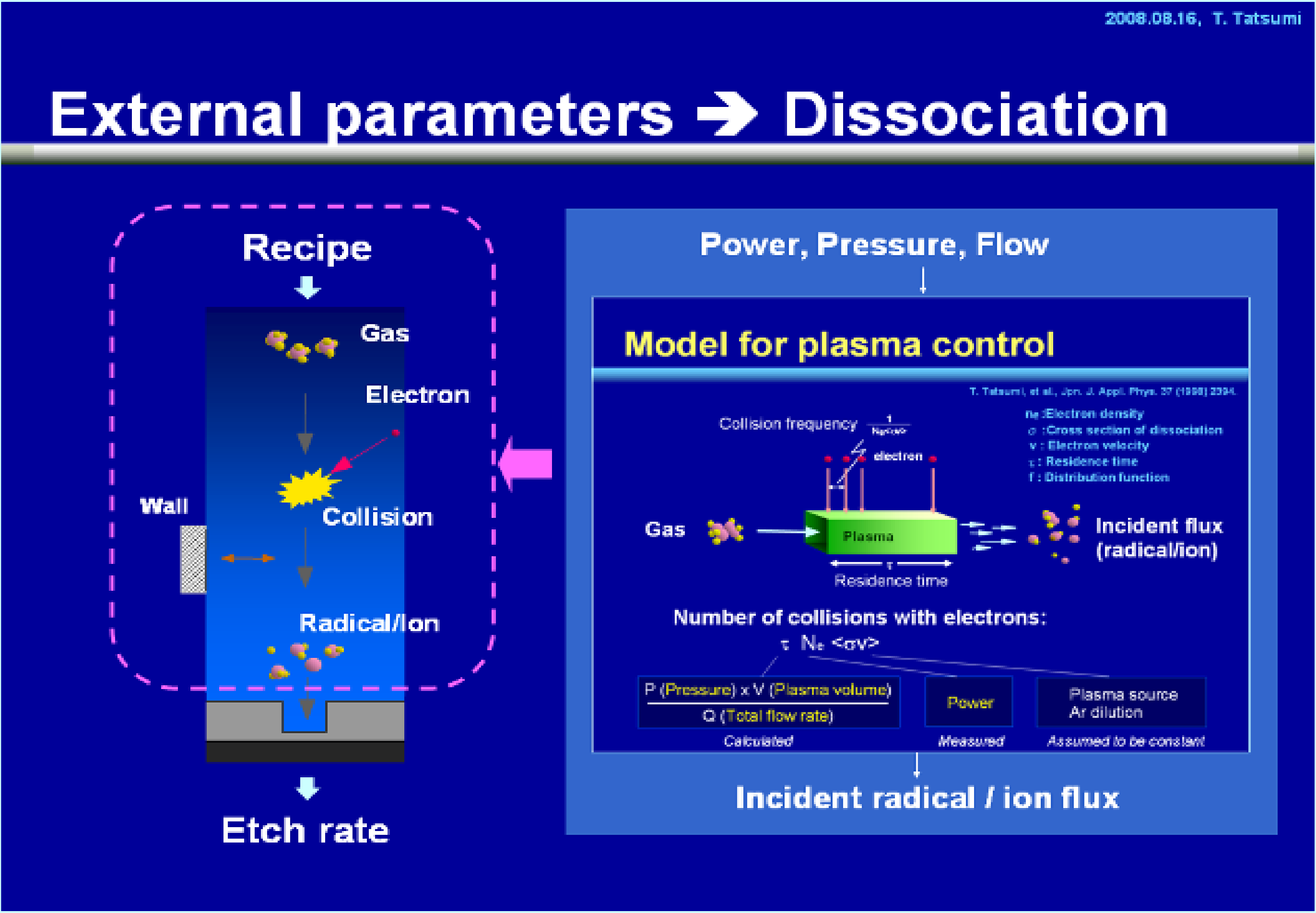
New materials (Low-k, High-k)

➔ Narrow process window

Complete suppression of fluctuation

2008.12.17, T. Tatsumi

Plasma wall interaction



2008.08.16, T. Tatsumi

External parameters → Dissociation

Power, Pressure, Flow

Model for plasma control

T. Tatsumi, et al., Jpn. J. Appl. Phys. 37 (1998) 2394.

n_e :Electron density
σ :Cross section of dissociation
v : Electron velocity
τ : Residence time
f : Distribution function

Number of collisions with electrons:

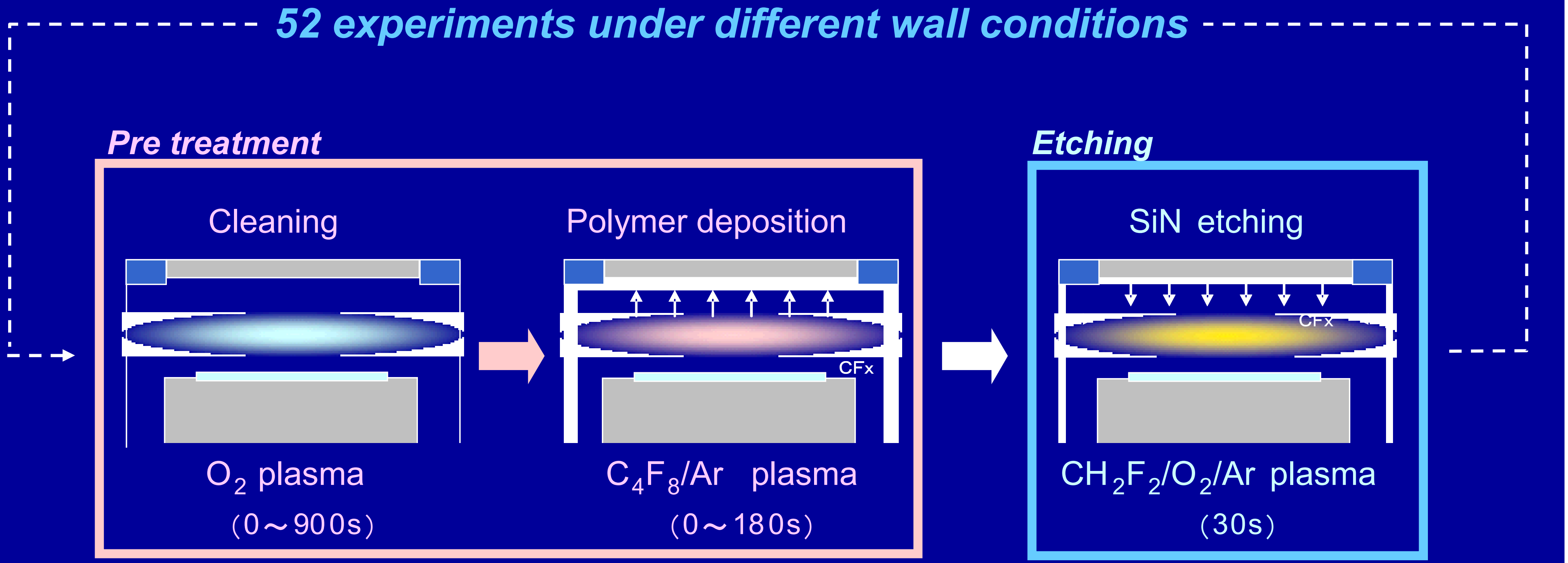
$\tau\ N_e \langle\sigma v\rangle$

$\dfrac{\text{P (Pressure) x V (Plasma volume)}}{\text{Q (Total flow rate)}}$	Power	Plasma source Ar dilution
Calculated	*Measured*	*Assumed to be constant*

Incident radical / ion flux

Effect of wall conditions on etch rate ?

Experiment



52 experiments under different wall conditions

Pre treatment

Cleaning

O_2 plasma

(0～900s)

Polymer deposition

C_4F_8/Ar plasma

(0～180s)

Etching

SiN etching

$CH_2F_2/O_2/Ar$ plasma

(30s)

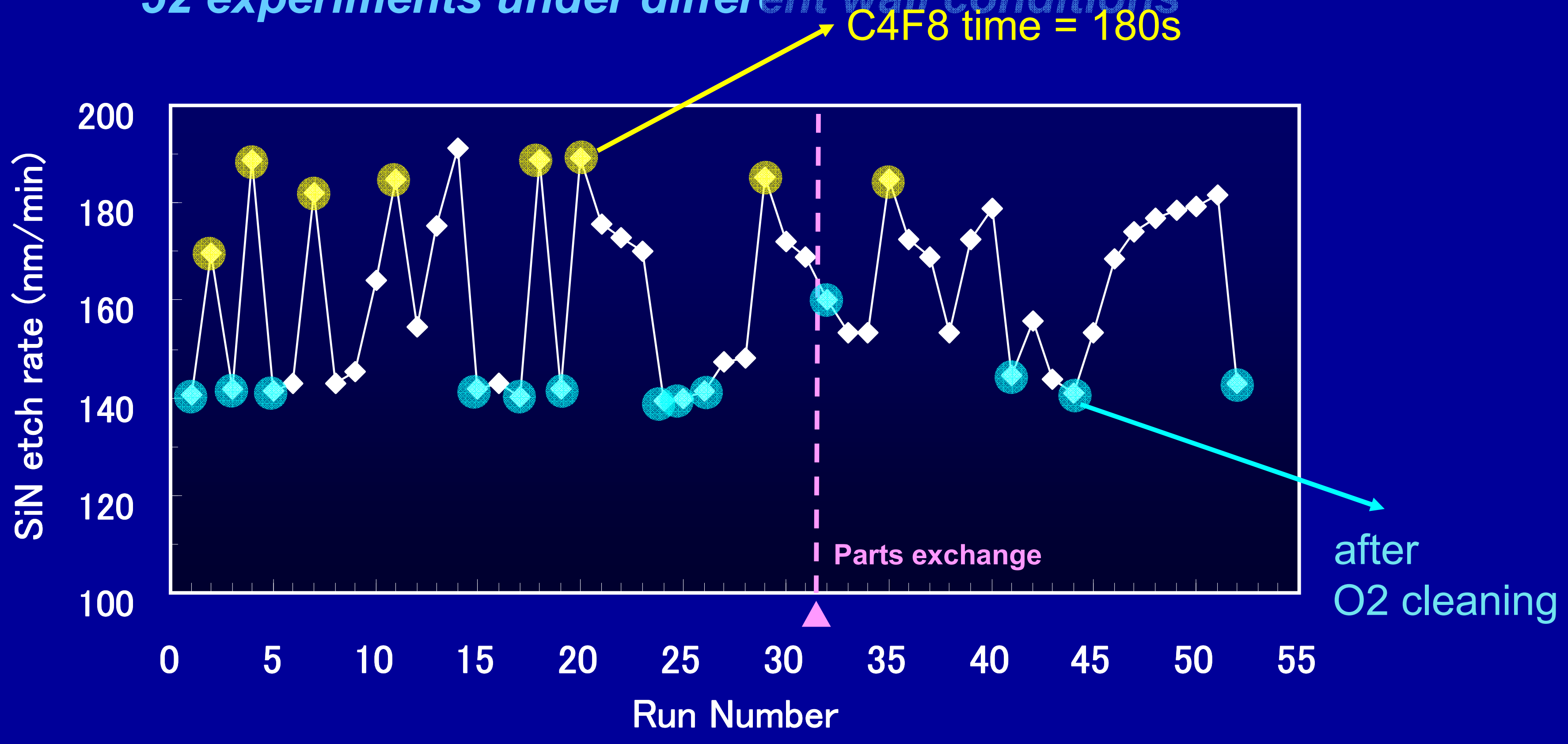
Polymer formation

Etch rate evaluation

Effect of wall conditions on etch rate ?

Fluctuation of SiN etch rate

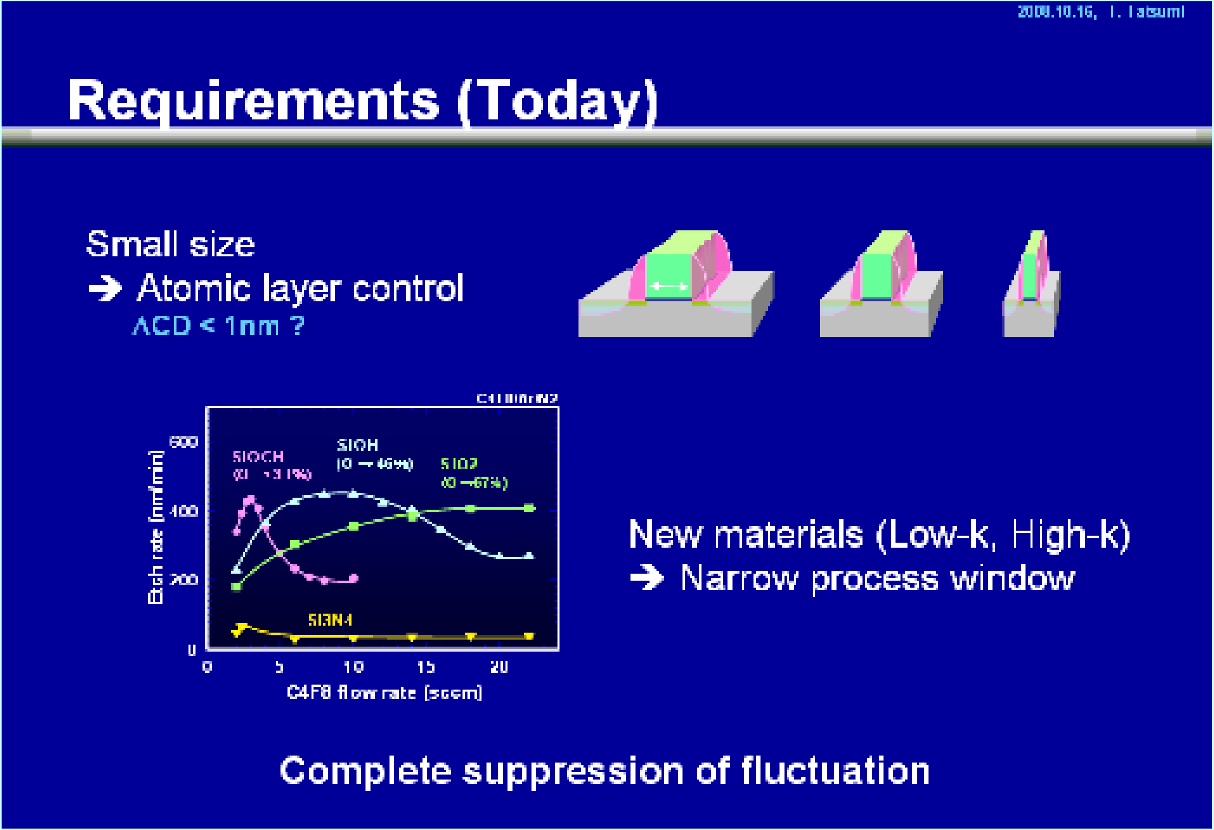
52 experiments under different wall conditions



The same external parameters, but different etch rate.

Polymer, oxidation of electrode, parts erosions, wafer･･･

“Noise factor”



2008.10.16, T. Tatsumi

Requirements (Today)

Small size
➔ Atomic layer control
ACD < 1nm ?

New materials (Low-k, High-k)
➔ Narrow process window

Complete suppression of fluctuation

Requirement for stable plasma

(control factor)

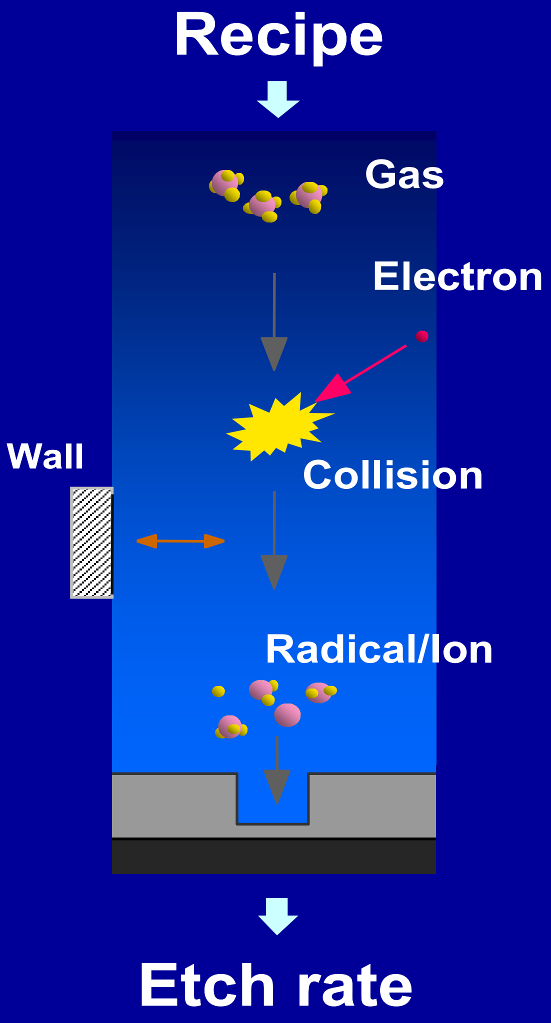
Dissociation ⇔ external parameters

Wall reaction ⇔ history of plasma treatment **(noise factor)**

Outline

1. Introduction
2. Plasma & Surface reaction models (Yesterday)
3. Current issues for CMOS fabrication (Today)
4. Requirement for “data base” (Tomorrow)
5. Summary

Data base for quantitative simulation



A: Plasma

Collision cross sections
for actual process plasma
(dissociation, ionization)

B: Wall

Sticking probabilities
on various materials

C: Wafer surface

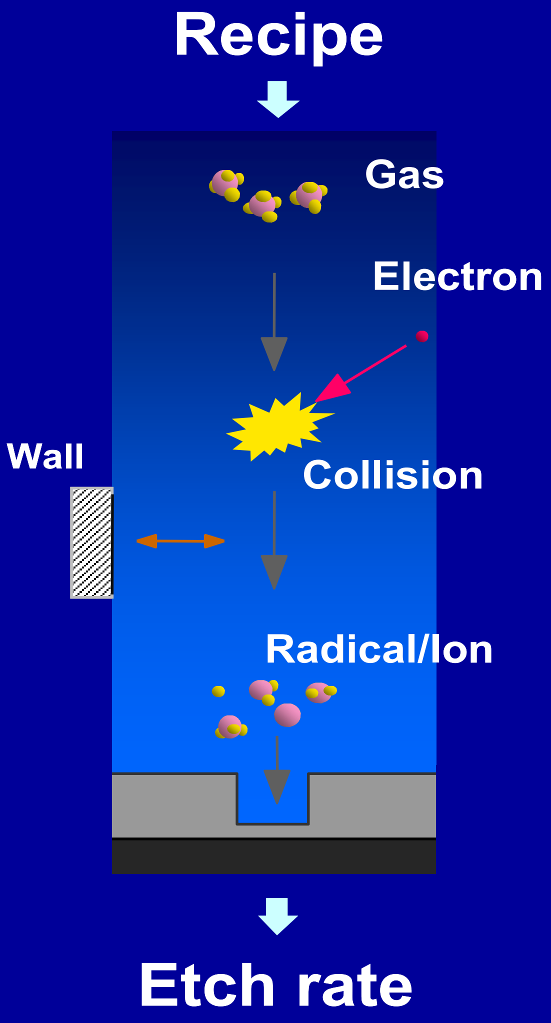
Reaction probabilities
Etch yields

Collision cross section

Materials	Gas
Si	SF6, Cl2, HBr, O2, Ar, He, N2, NF3, SiF4
SiO2	CF4, CHF3, CH2F2, CH3F, C4F6 C4F8, C5F8, CO, O2, N2, Ar
Al	Cl2, BCl3, HCl, Ar
Organic polymer	O2, H2, N2, CO, NH3, Ar, He, H2O

σ for Ionization, dissociation and optical emission.

Data base for quantitative simulation



A: Plasma

Collision cross sections
for actual process plasma
(dissociation, ionization)

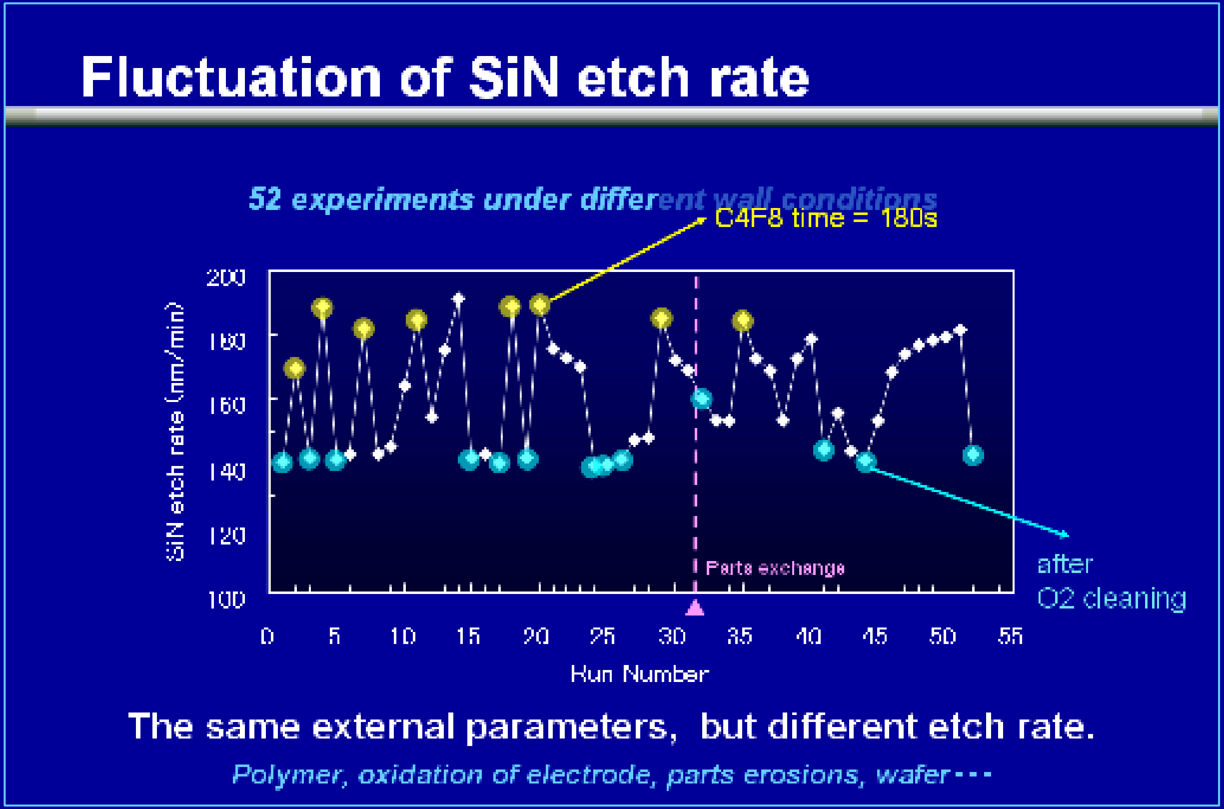
B: Wall

Sticking probabilities
on various materials

C: Wafer surface

Reaction probabilities
Etch yields

Sticking coefficient

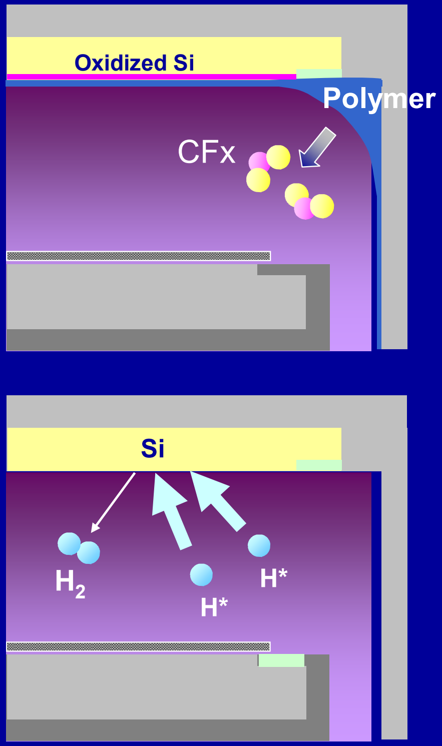


Fluctuation of SiN etch rate

52 experiments under different wall conditions

The same external parameters, but different etch rate.

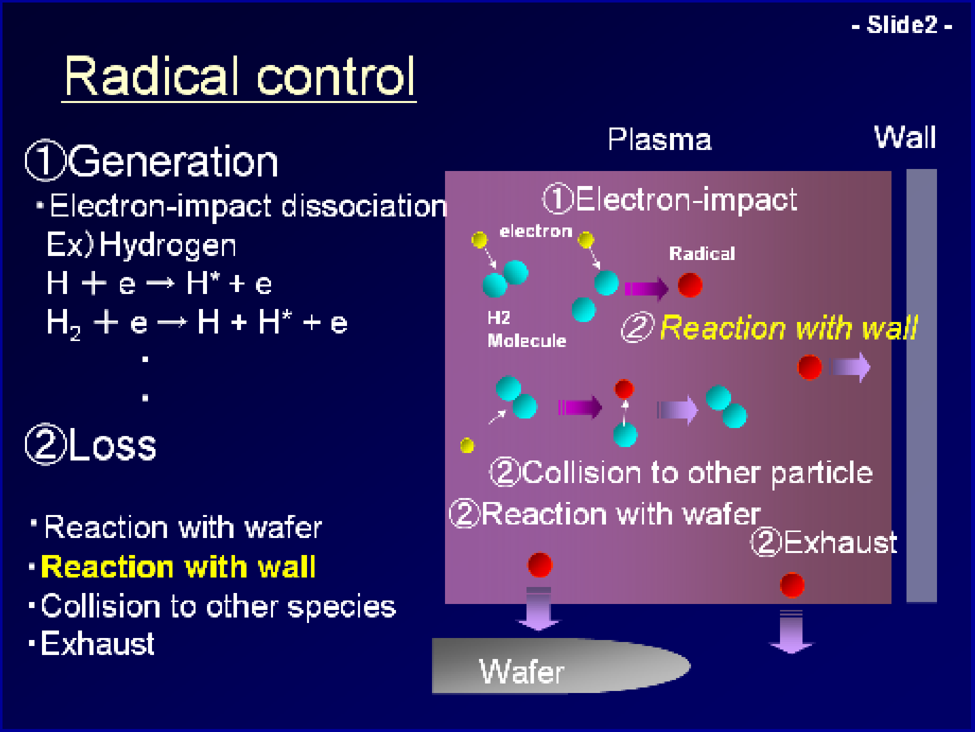
Polymer, oxidation of electrode, parts erosions, wafer･･･



Etch rate sensitively depends on wall conditions

Sticking coefficient

T.Tatsumi, Applied Surface Science 253(2007) 6716



- Slide2 -

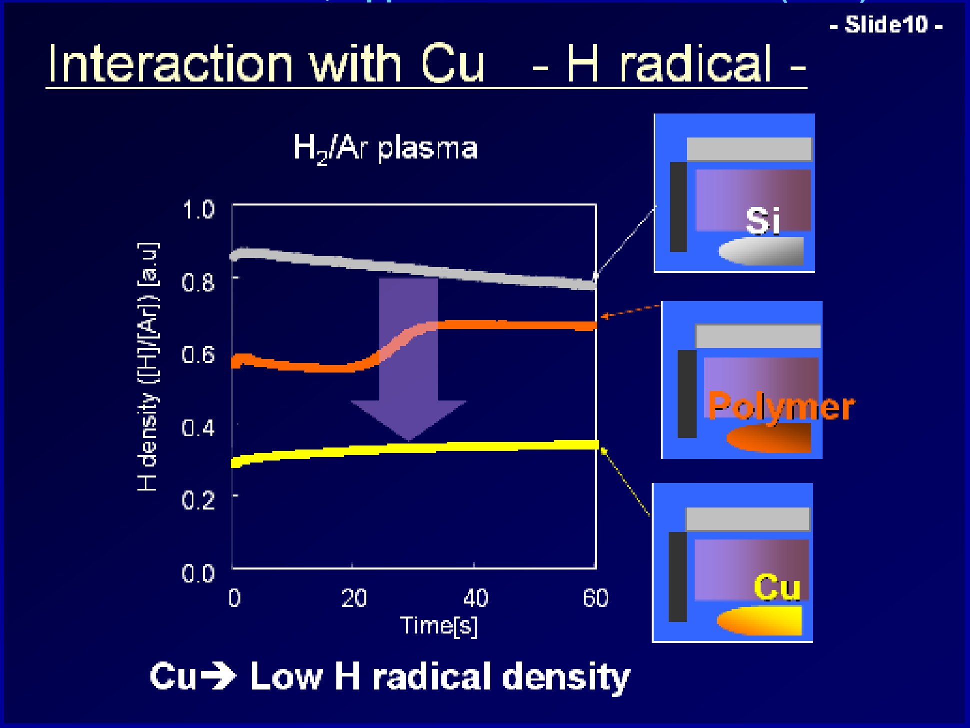
Radical control

①Generation

・Electron-impact dissociation
Ex) Hydrogen
$H + e \rightarrow H^* + e$
$H_2 + e \rightarrow H + H^* + e$
・
・

②Loss

- Reaction with wafer
- **Reaction with wall**
- Collision to other species
- Exhaust



- Slide10 -

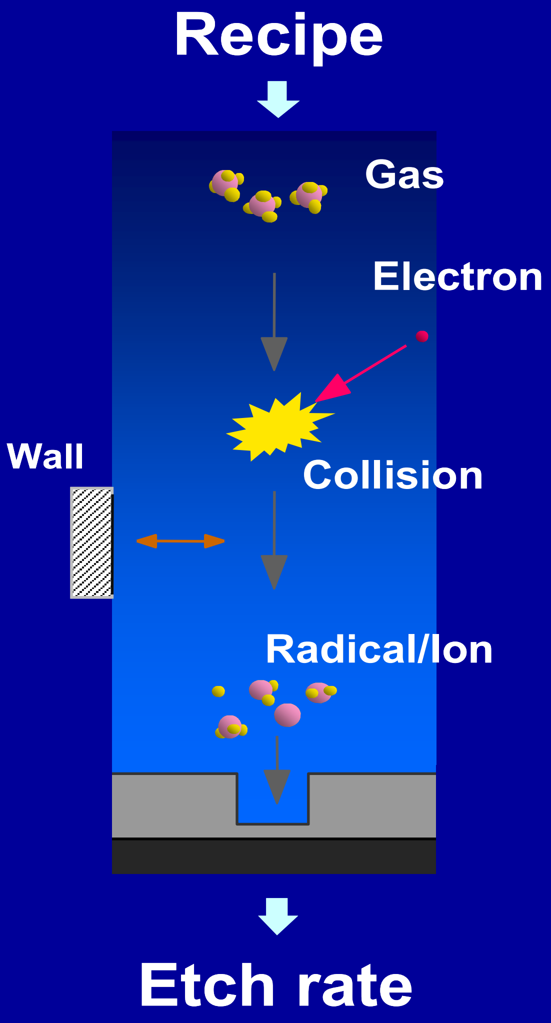
Interaction with Cu - H radical -

Cu➔ Low H radical density

Generation and loss on chamber walls

Materials: Si, SiO2(Quartz), Y2O3, Al2O3, C-F polymer, SiBrxOy・・・
Conditions: Temperature, Ion energy, conductivity, roughness, UV・・・

Data base for quantitative simulation



A: Plasma

Collision cross sections
for actual process plasma
(dissociation, ionization)

B: Wall

Sticking probabilities
on various materials

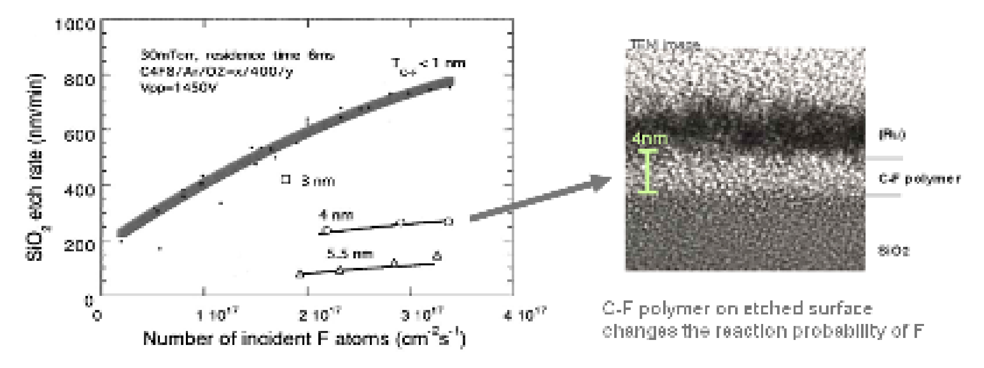
C: Wafer surface

Reaction probabilities
Etch yields

Reaction probability

Incident fluxes → Etch rate

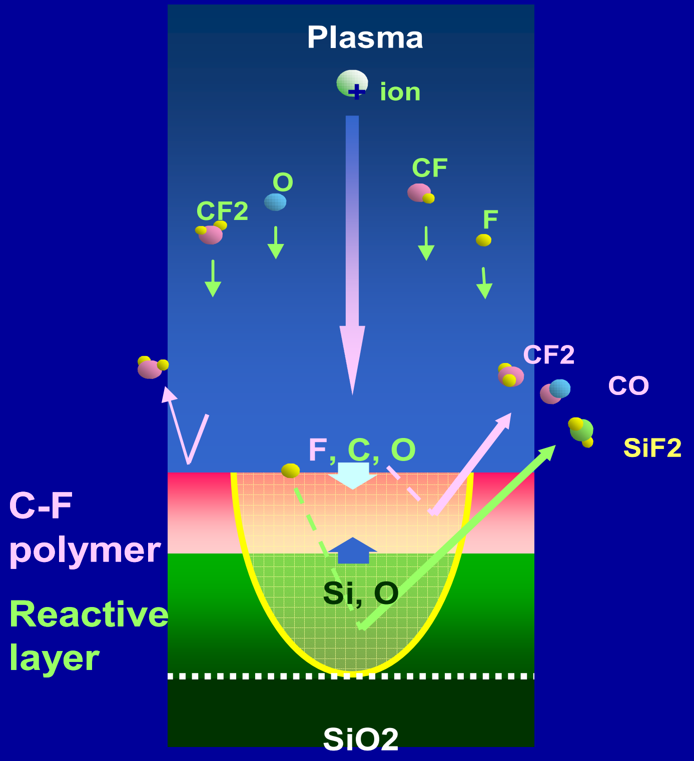
T. Tatsumi et al., JVST B, Vol. 18 (2000) 1897



C-F polymer on etched surface changes the reaction probability of F

Total F in all incident CF_x radical and/or ion fluxes x **Reaction probability (ion energy and polymer thickness)**

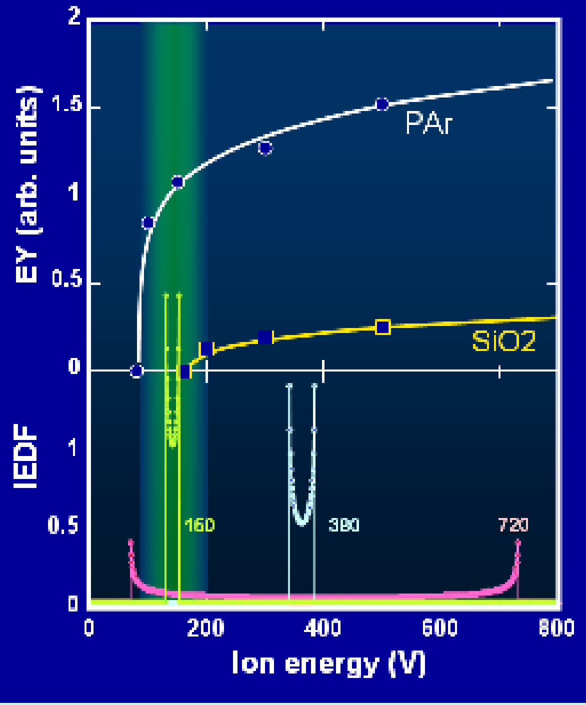
⟷ SiO_2 etch rate

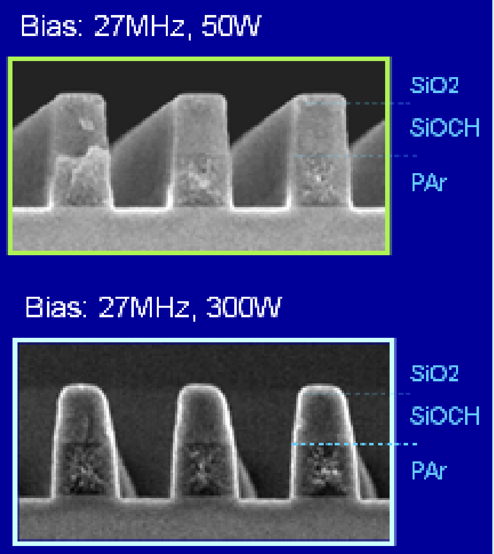


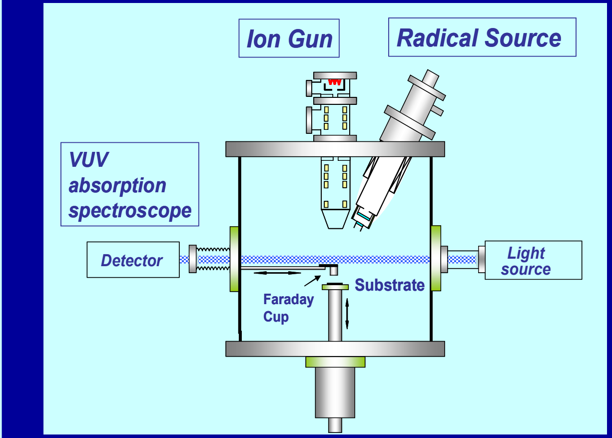
Etch rate depends on “incident flux” and “reaction probability”

Reaction probability

IEDF







Etching yield depends on temperature, ion energy, …..

Summary

In fabrication of “near future” Si-CMOS devices,

1. Fluctuation of pattern width and damage must be suppressed within several atomic layers.

2. Quantitative reaction models, monitoring technologies, simulation technologies and feed back control systems are required.

3. Date base of collision cross sections, sticking coefficient on chamber walls, and reaction probabilities on wafers.