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Plasma-surface interactions: diagnostics

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Plasmas with Complex Interactions

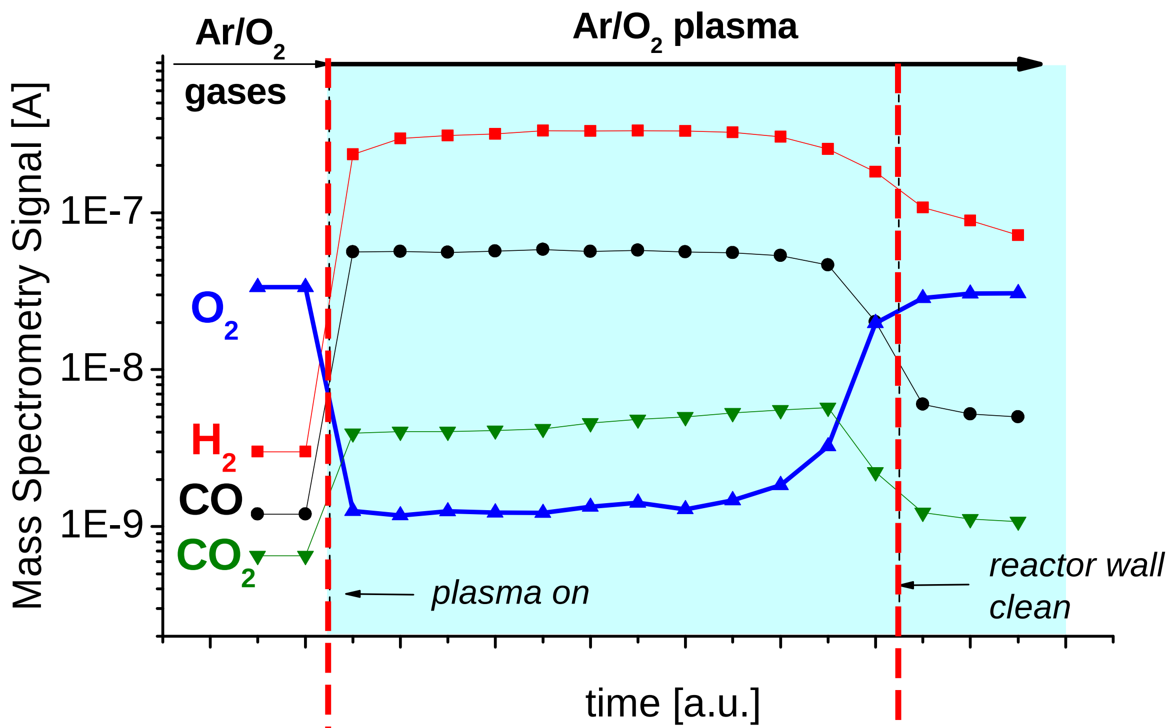
FACULTY FOR PHYSICS AND ASTRONOMY
Group Coupled Plasma-Solid-State Systems

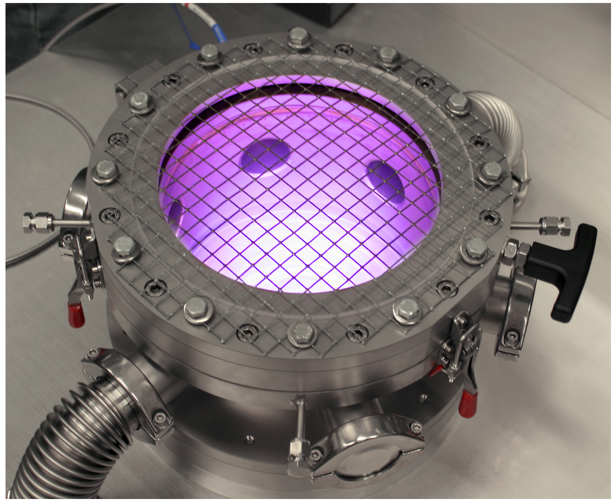
Surface processes and reactive plasmas

Plasma controls surface processes: *deposition, etching, surface modification*

Surface processes influence plasma properties:

Ar/O_2 plasma cleaning of stainless steel reactor with hydrocarbon film on the wall:





Plasma composition is determined by surface reactions!

Reactions in plasma

$O_2 + e^- \rightarrow 2O + e^-$

Surface (with film)

O + a-C:H film → **CO** (**CO_2**)
H and **H_2** is also released

Surface (clean)

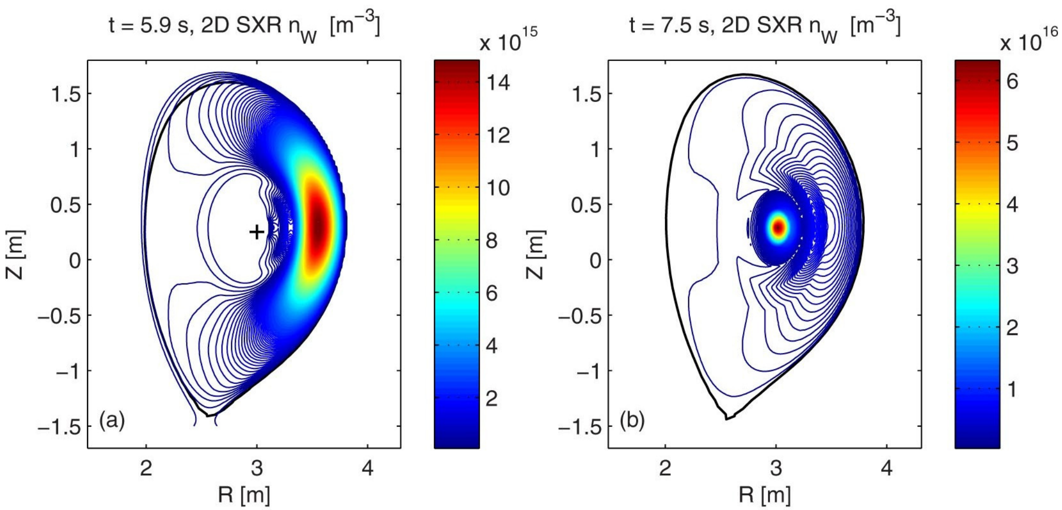
O(gas) + O(wall) → **O_2**(gas)
O(wall) + O(wall) → **O_2**(gas)

Surface processes and hydrogen plasmas

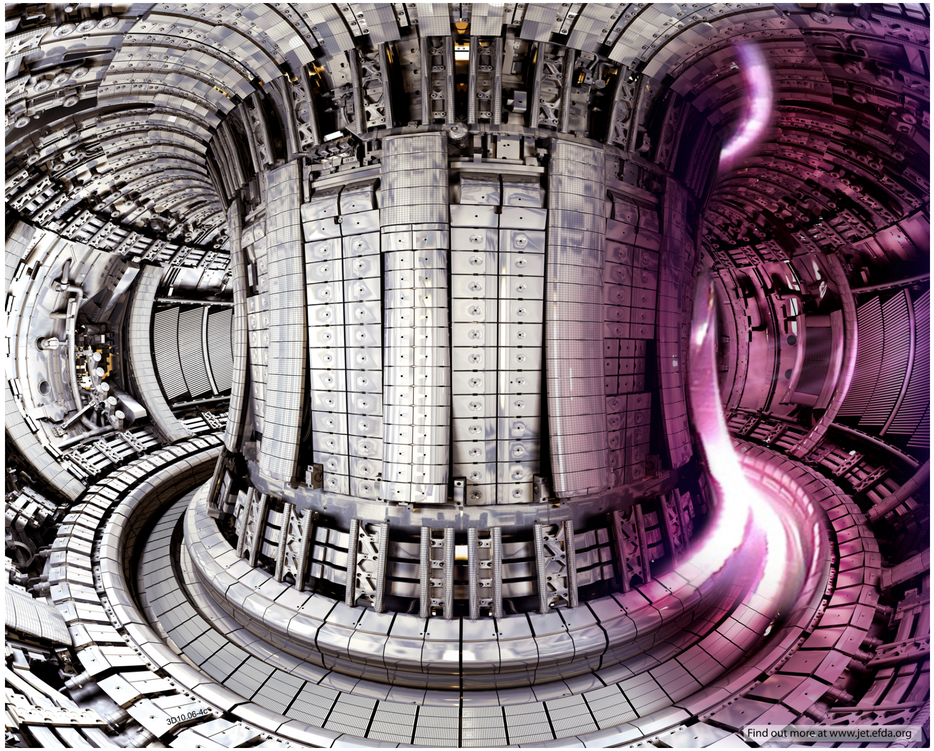
Plasma controls surface processes: *deposition, sputtering, surface modification*

Surface processes influence plasma properties:

W impurity accumulation in the JET tokamak, UK



C. Angioni *et al.*,
Nucl. Fusion 54 (2014) 083028



JET tokamak wit the ITER-like wall (CCFE/JET)

Plasma composition is determined by surface reactions
Impurity accumulation plays a detrimental role on the performance

$$P_{br} \propto Z^2 \qquad P_{line} \propto Z^4$$

How to address surface processes relevant to plasma deposition?

Our goal

deposition of thin film

or

etching of wall material

almost always a combination of deposition <u>and</u> etching

Which plasma species arrive at the wall?
Which energy do they have?

How do they react at the wall?
How does the material form?

How do they influence the plasma?

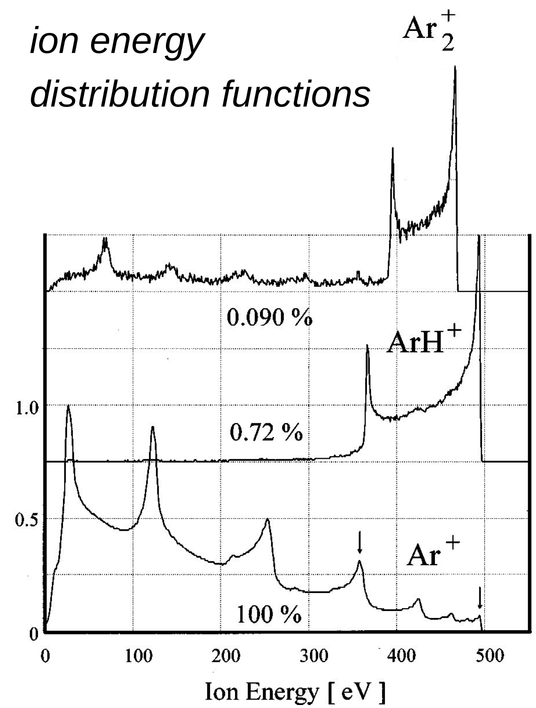
Which species leave the surface?
What is their energy?

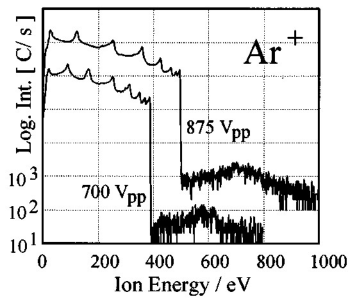
surface

Key challenges

- energy distributions (ions, fast neutrals)
- molecular radicals
- synergistic effects
- not well-defined surfaces
- heterogeneous surface reactions

ion energy distribution functions

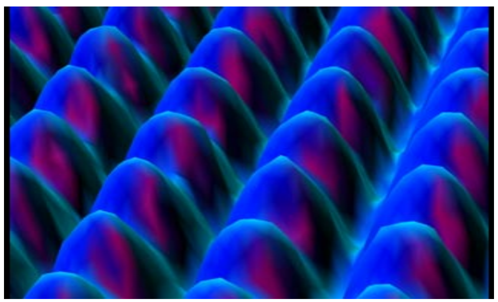




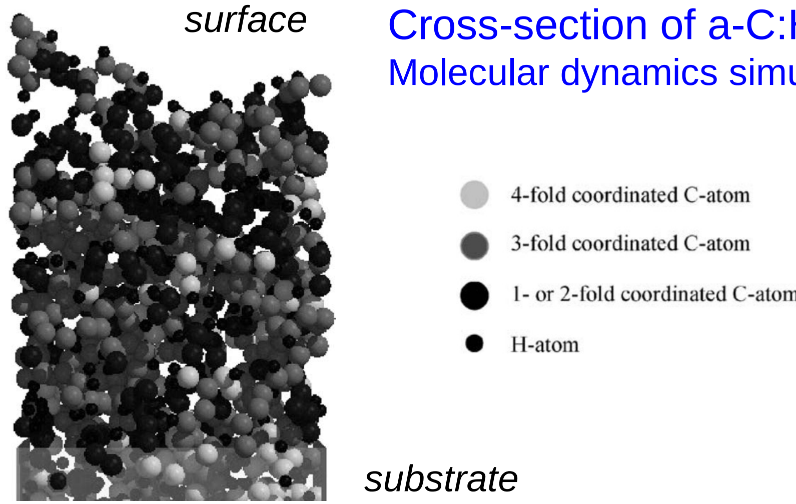
M. Zeuner *et al.*, JAP 81 (1997) 2985

The unreconstructed surface of nickel

Scanning tunneling microscopy image



IBM Research, Almaden Research Center



Cross-section of a-C:H film

Molecular dynamics simulation

E. Neyts *et al.*, Diam. Rel. Mat. 13 (2004) 1873

Outline

Plasma-surface interactions – short summary

Diagnostics of plasma surface processes

- ***ex-situ* and *in-situ* plasma diagnostics**

- **beam experiments and growth models**

Low energy particles at the surface

$r + \gamma + s = 1$

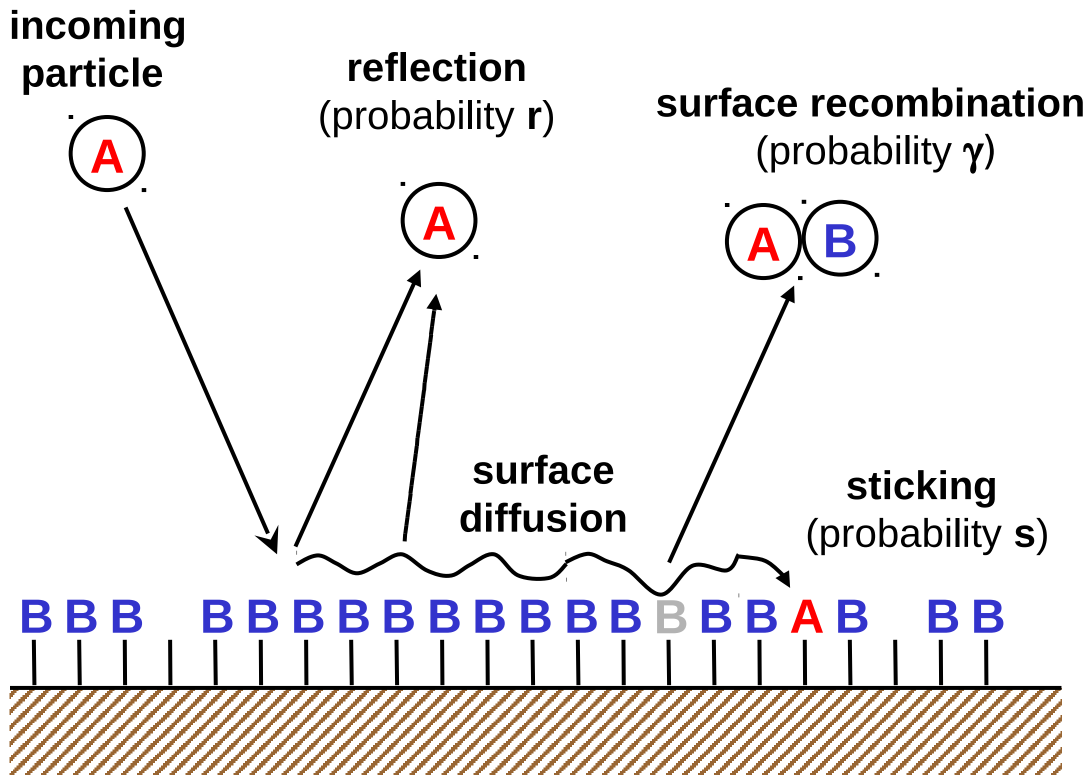
Gas temperature in low pressure plasmas

$T_h \sim 300 - 2000$ K

⇩

$E_k \sim 0.026 - 0.17$ eV

Lower than the binding energy between atoms in the material



Overall surface reaction probability: $\beta = \gamma + s = 1 - r$

Surface reactions often depend on surface coverage

$$\theta = \frac{n_{surface,occupied}}{n_{surface,all}} \in \langle 0,1 \rangle$$

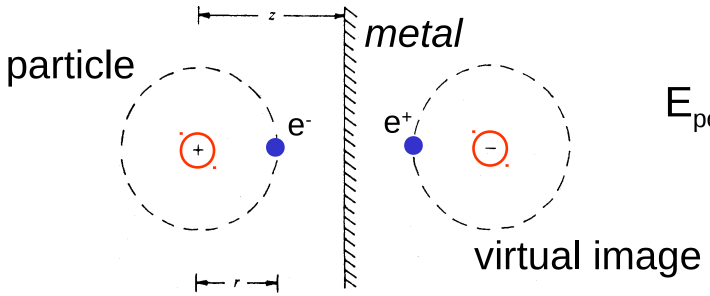
Interaction particle-substrate

Physisorption and **Chemisorption**

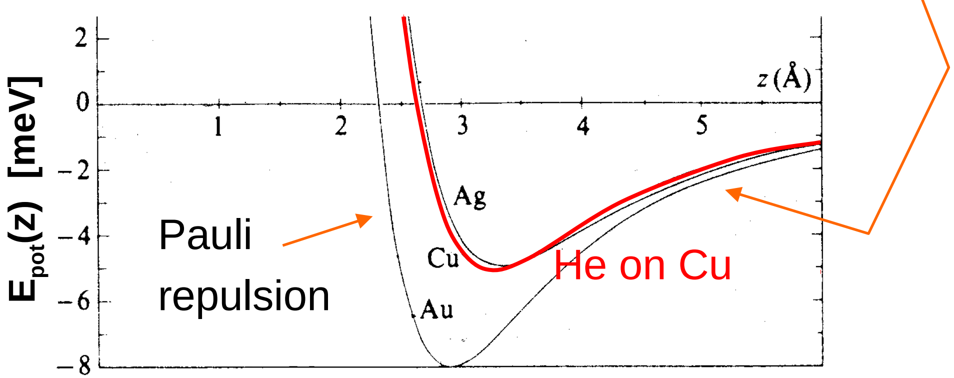
weak van der Waals dipole-dipole interaction

For metals: $E_{pot} \sim \dfrac{1}{r^6}$

interaction between particle and its virtual image



$$E_{pot}(z) \sim \frac{1}{z^3}$$



Binding energy ~ few meV

Electron exchange – chemical bond

By metals:

electron donated from conduction band

By insulators:

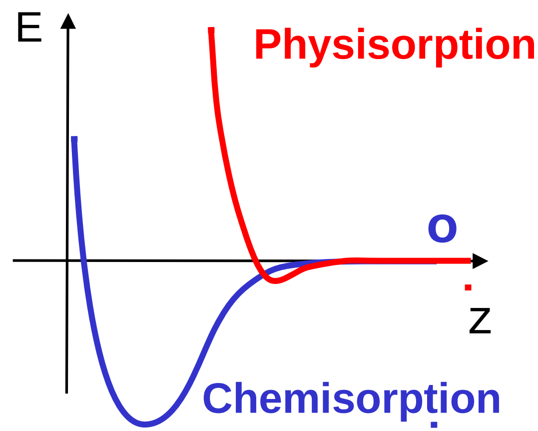
e.g. reaction at unpaired electron

→ radical site/dangling bond

or radical insertion into existing bond

Binding energy > 0.5 eV

Minimum much closer to the surface



E. Zaremba, W. Kohn, Phys. Rev. B15, 1769 (1977)

A. Zangwill, 'Physics at surfaces', Cambridge Univ. Press, Cambridge (1988)

When is a particle reflected and when captured at the surface?

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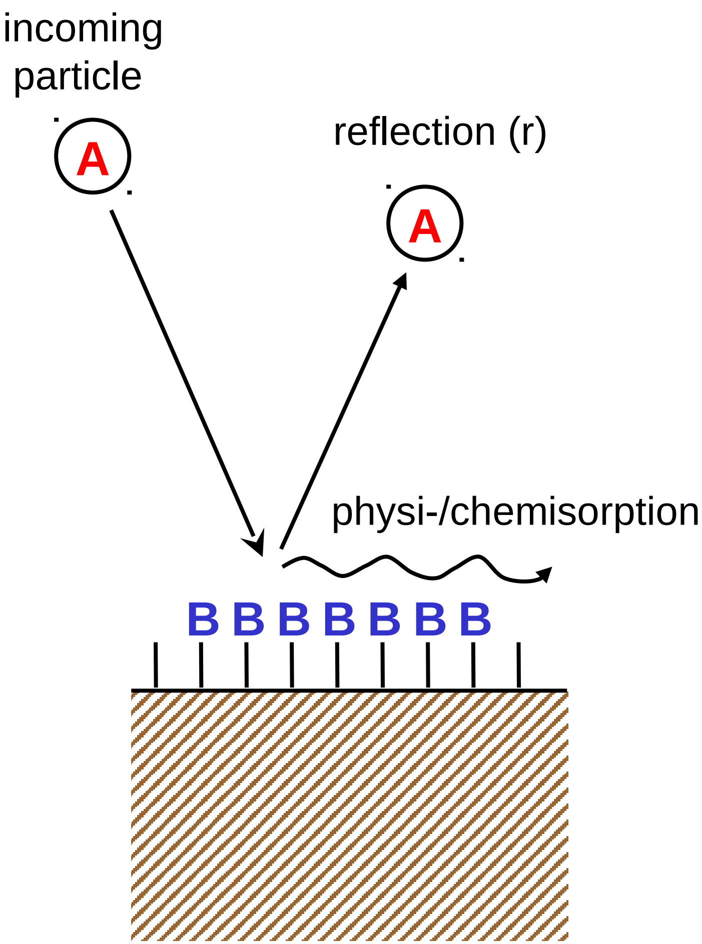


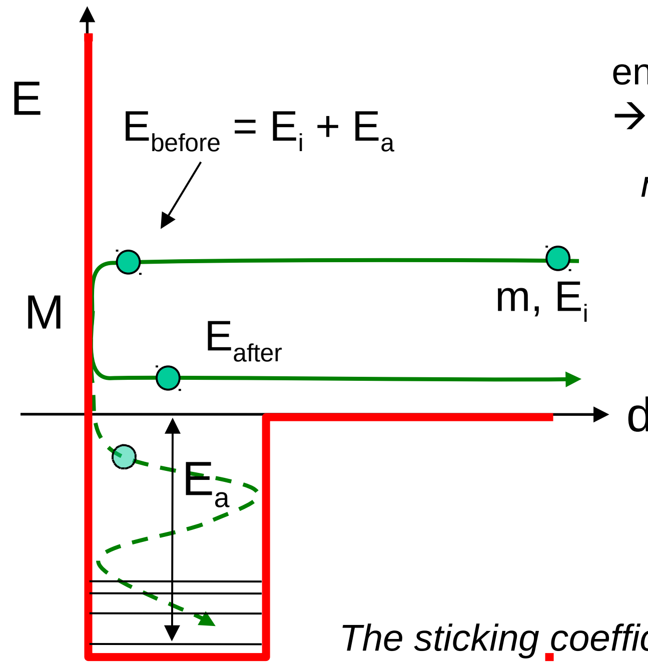
Particle loses part p_{loss} of its kinetic energy in the impact

It is captured when:

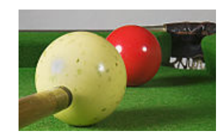
$$E_{after} = (1-p_{loss}) \times E_{before} < E_a$$

energy loss in collision with the surface
→ *m* and *M* dependent

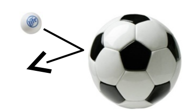
max. energy transfer: $\sim 4 \frac{m \cdot M}{(m+M)^2}$



~ 100% for m=M



~ 4m/M for m<<M



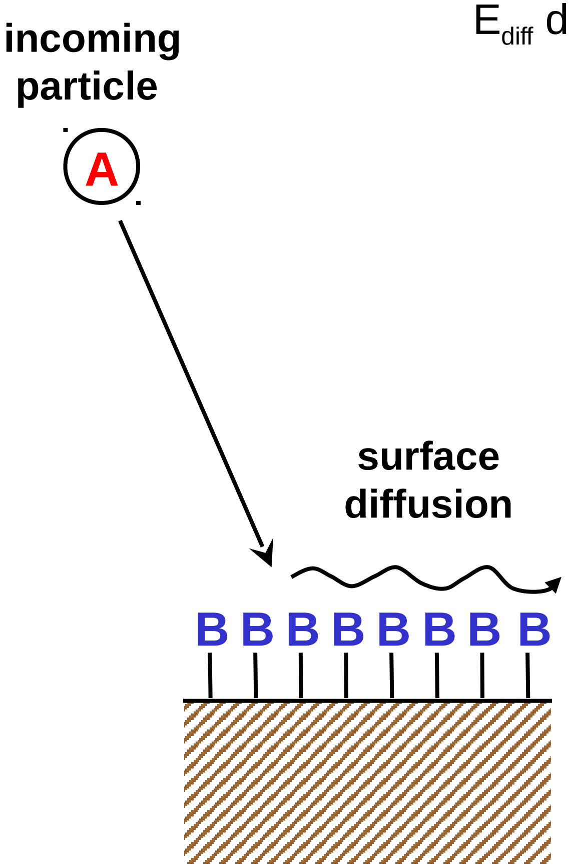
The sticking coefficient is higher if:

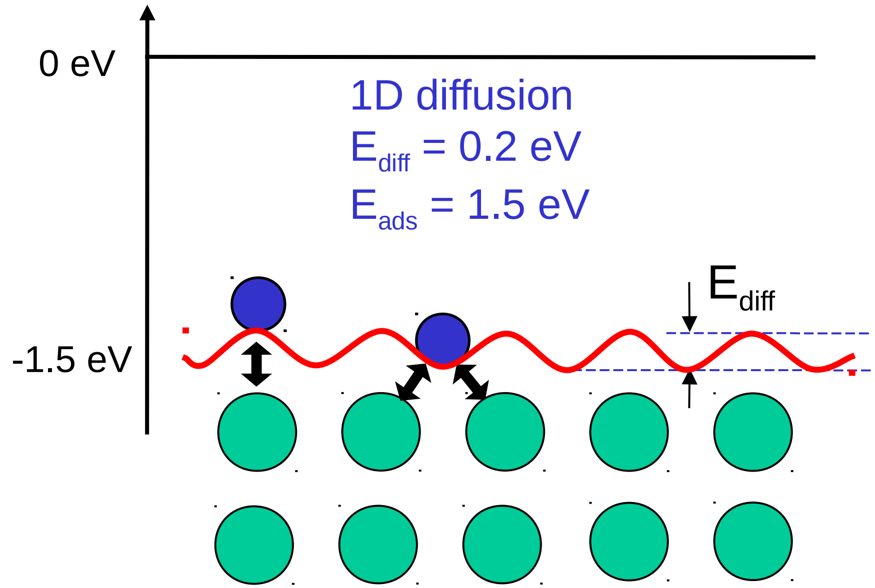
- Kinetic energy (E_i) is small.
- The depth of the potential well (E_a) is large.
- The M and m are similar → effective energy transfer.

Surface diffusion

Surface potential is **corrugated** → particles at the surface do not move freely.

E_{diff} depends on the type of bonding (e.g. larger for chemisorption).





Diffusion:
Temperature activated process: $D = D_0 \exp\left(-\frac{E_{diff}}{RT}\right)$

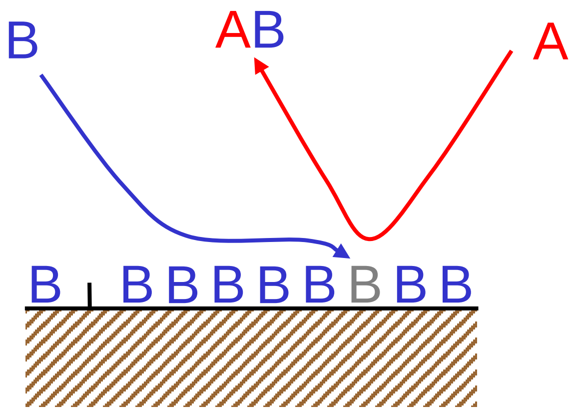
Steps or defect sites have a higher energy barrier.

Surface diffusion can be promoted e.g. by ion bombardment.

Surface reactions

Two basic mechanisms:

1) Eley-Rideal



Direct reaction upon impact

- only barrier-less and exothermic reactions
- usually involves radicals

Reaction rate: $R = k\, p_A\, \Theta_B$

pressure (~flux to the surface)

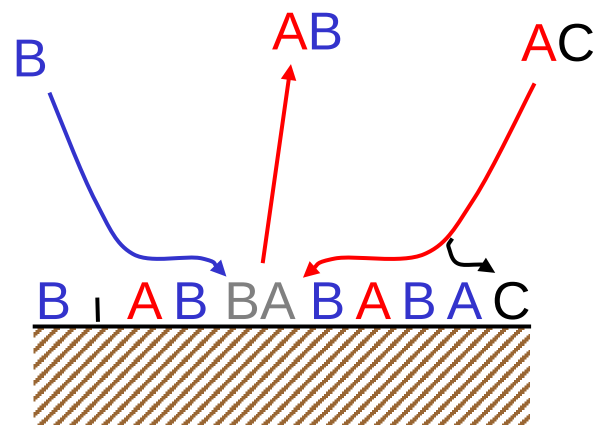
surface coverage

$T_{prod} > T_{substrate}$

Example: $H(g) + H(s) \rightarrow H_2(g)$

hydrogen abstraction

2) Langmuir-Hinshelwood



Reaction of adsorbates at the surface

- most common surface reaction mechanism
- allows reactions between molecules

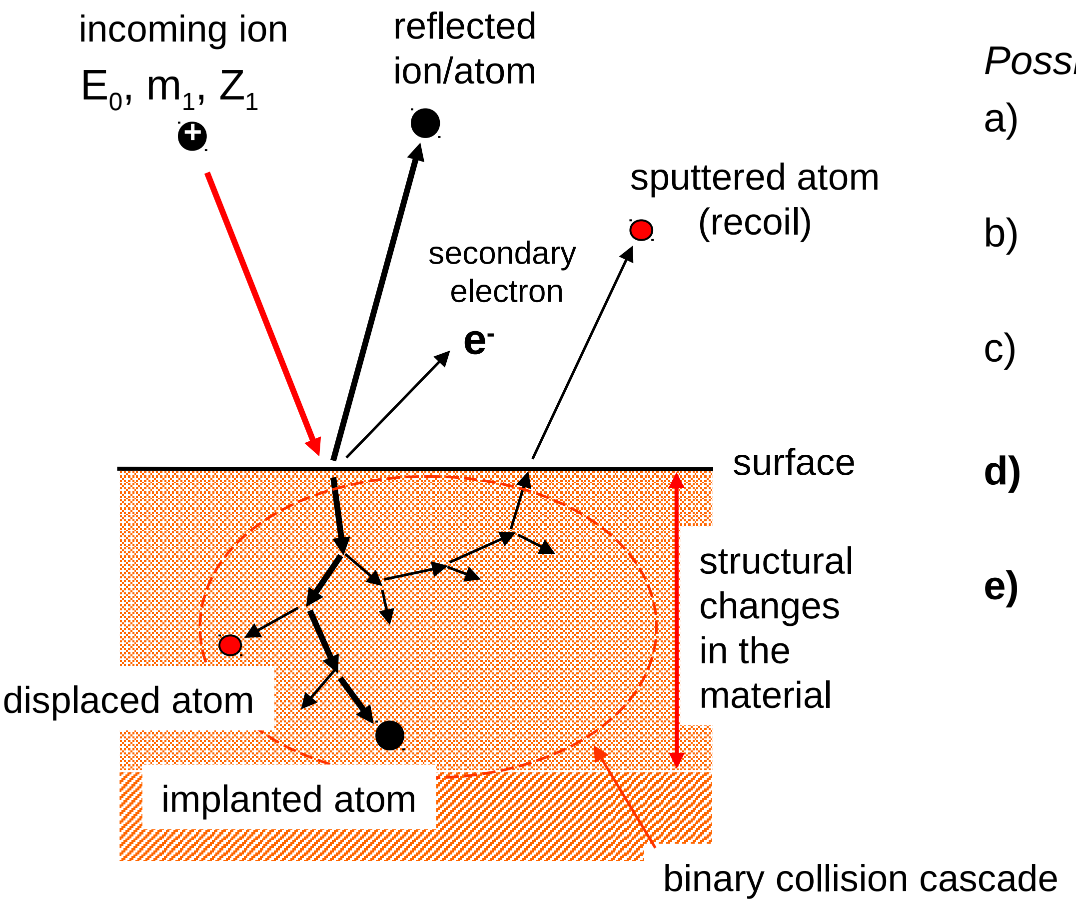
Reaction rate: $R = k\, \Theta_A\, \Theta_B$

$T_{prod} \sim T_{substrate}$

Example: $CO(s) + O(s) \rightarrow CO_2$

Ion-surface interaction

Typical ion energies in low pressure plasmas: eV - keV



Possible interaction at the surface:

a) Reflection: used for surface diagnostic "Ion Scattering Spectroscopy" – ISS

b) Secondary electron emission – important for a plasma ignition and operation: γ–coefficient

c) Ion implantation: e.g. Plasma Immersion Ion Implantation (PIII); E_{ion} > 10 keV

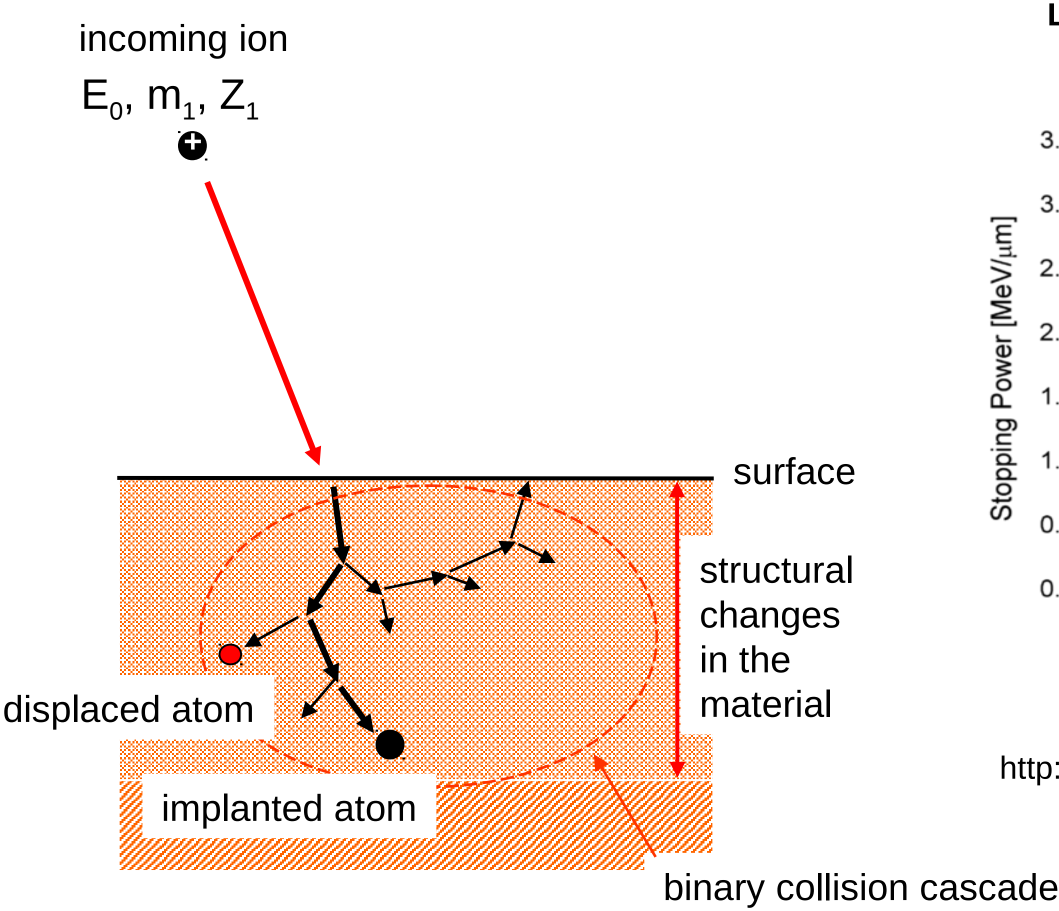
d) Structural changes in the material: enhanced cross-linking → ion assisted growth

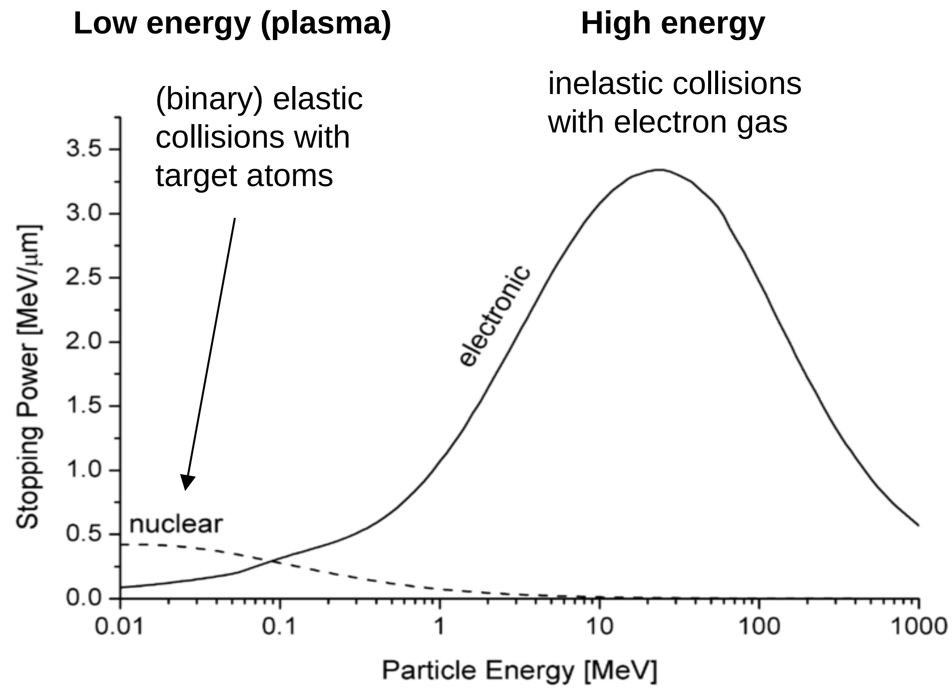
e) Sputtering of material

Dependent on ion energy

Ion-surface interaction: stopping power

Ion interaction in the material:

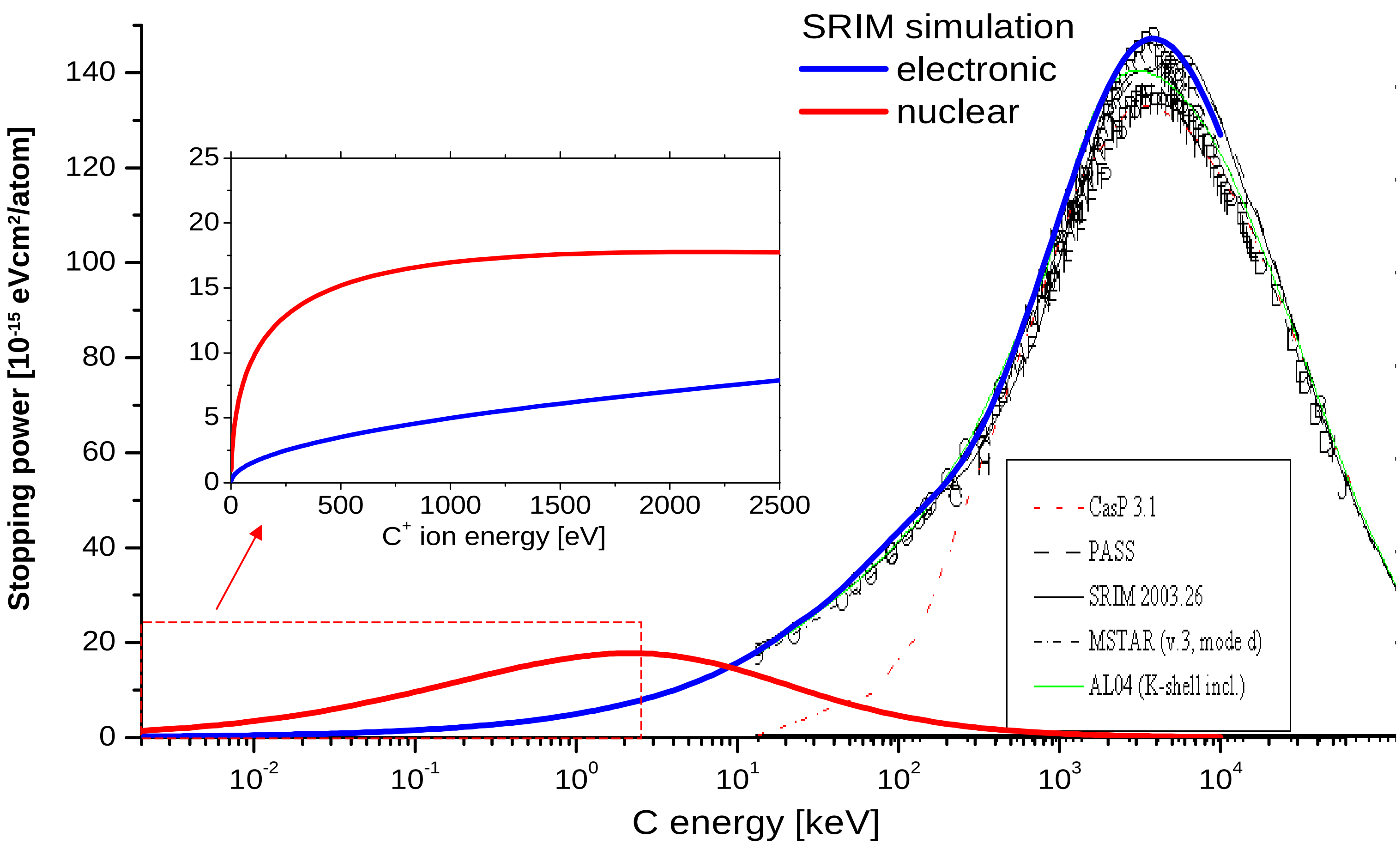




http://en.wikipedia.org/wiki/Stopping_power_(particle_radiation)

Ion-surface interaction: stopping power, example

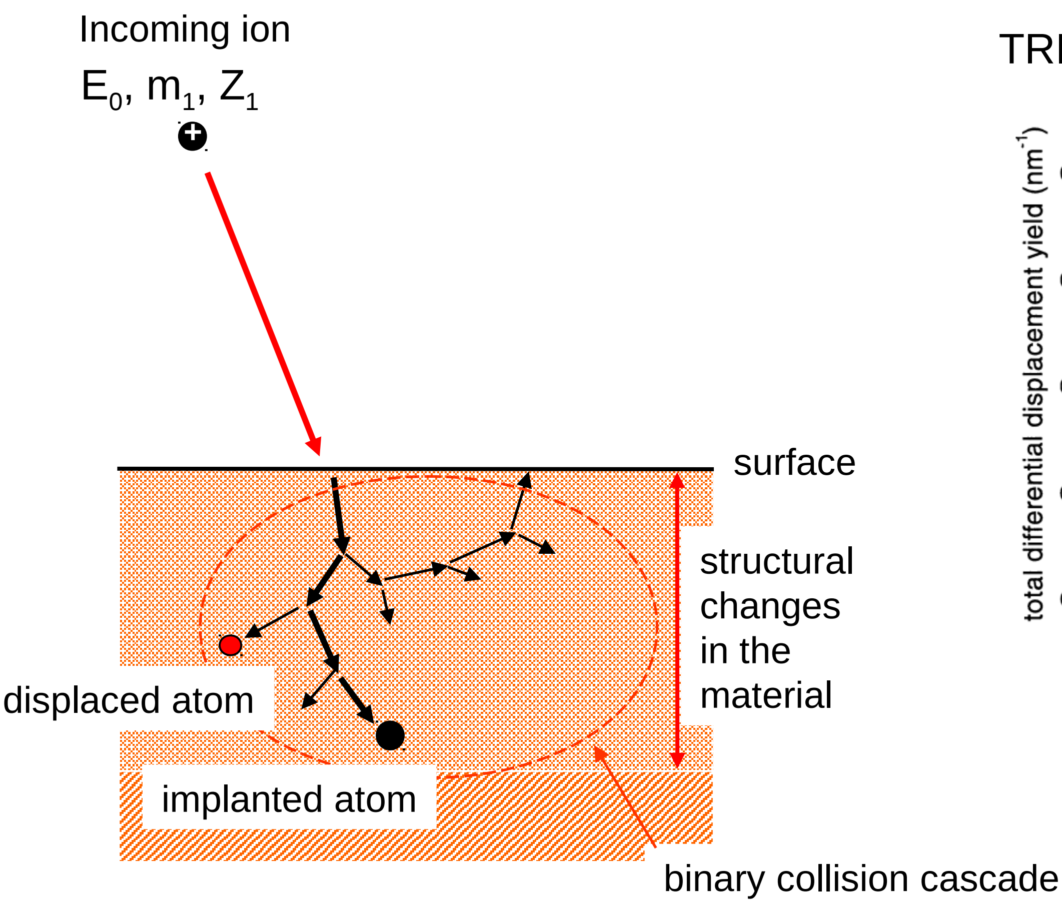
Stopping power: carbon on carbon



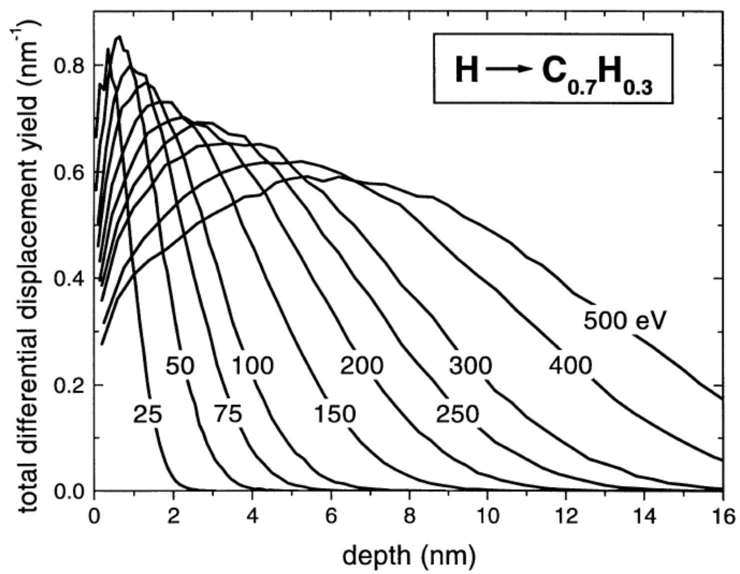
Data from: http://www.exphys.uni-linz.ac.at/stopping/

Ion-surface interaction: binary collision cascade

At the ion energy range of few eV to few keV:
Binary Collision Approximation (BCA) can be used



TRIM code (TRansport of Ions in Matter)

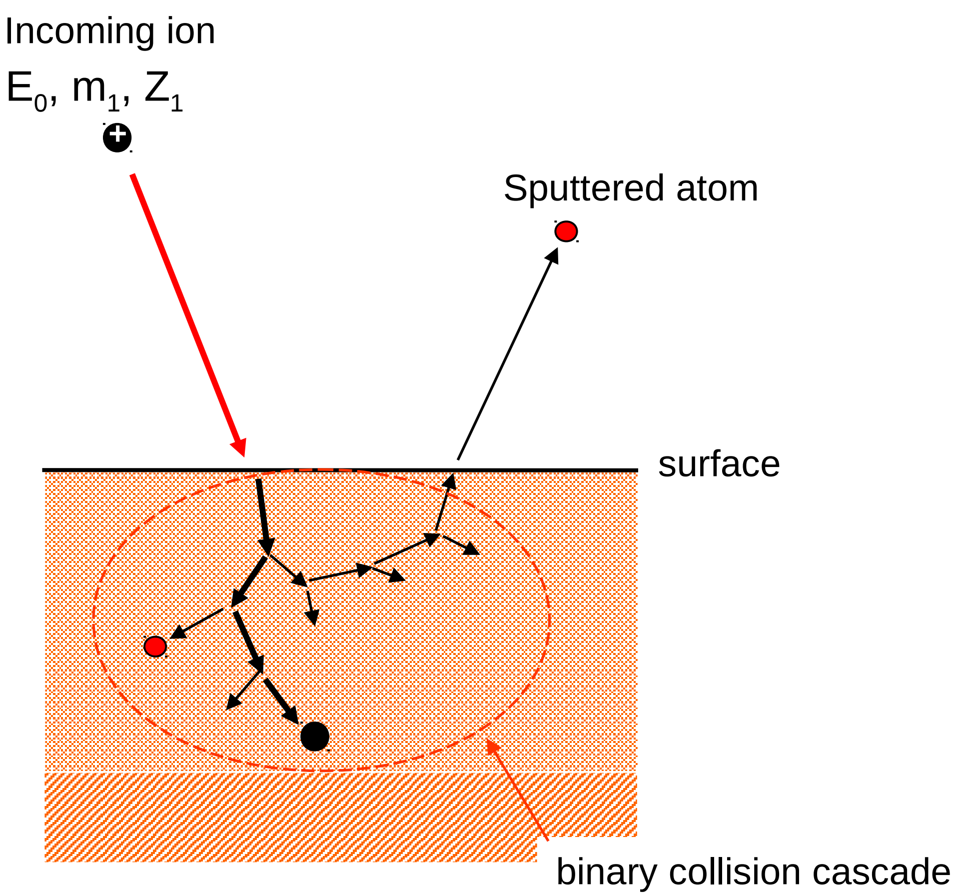


W. Jacob, Thin Solid Films 326 (1998) 1

ion assisted growth

Physical sputtering of target atoms

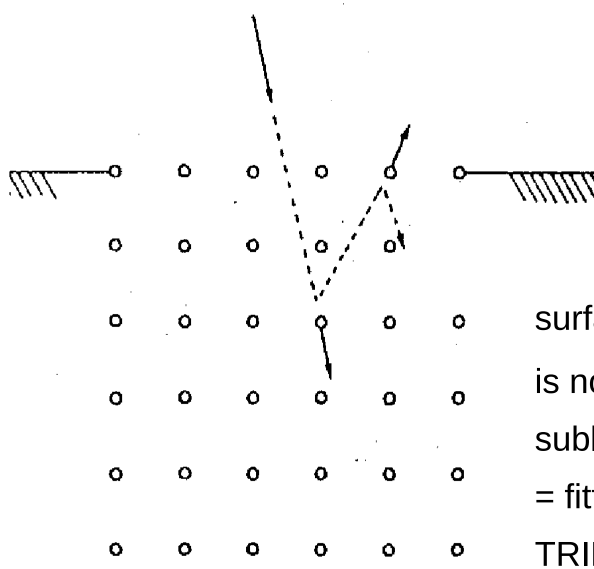
Sputtering yield: $Y = \frac{\Gamma_{sputtered}}{\Gamma_{ions}}$



Threshold for physical sputtering

$$E_{threshold} = E_{SB} \frac{1}{\gamma(1-\gamma)}$$

$$\frac{E_1}{E_0} = 4\frac{m_1 m_2}{\left(m_1 + m_2\right)^2} = \gamma$$



surface binding energy E_{SB}

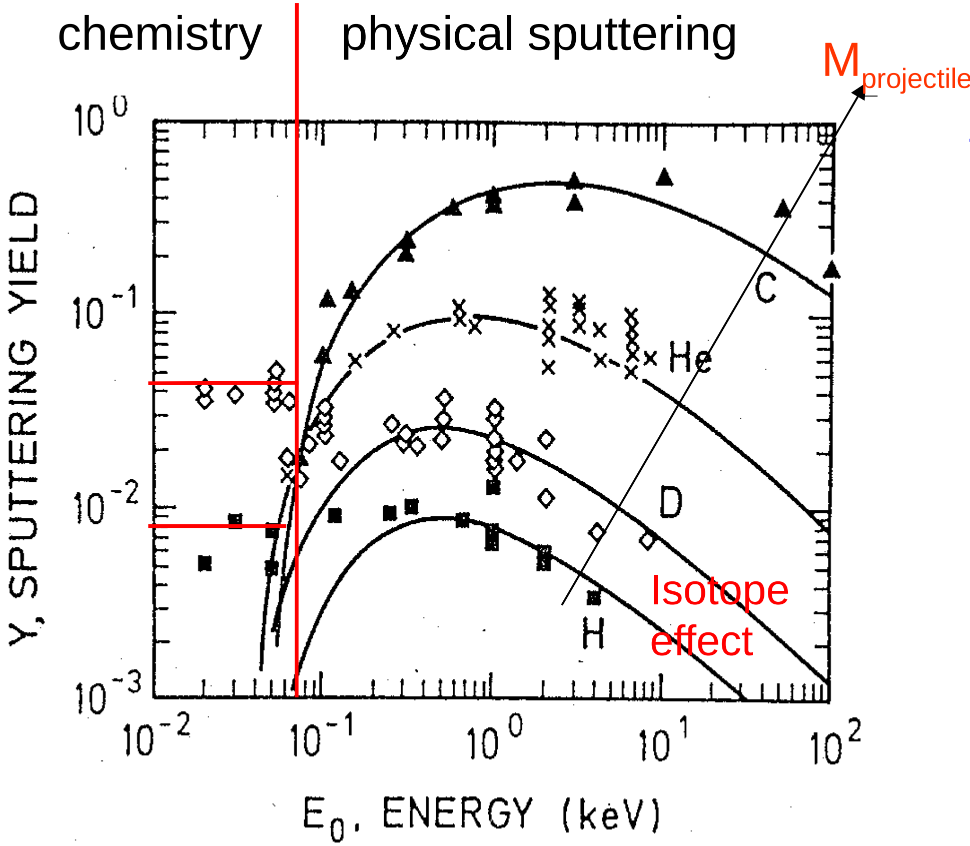
is not identical with

sublimation energy

= fitting parameter for the

TRIM calculation

Sputtering of graphite



K. Krieger in 'lectures on plasma physics'
Summer university for plasma physics (1993)

TRIM is also valid for low energies (~E_{SB})
but chemical effects can dominate the results.

Sputtering yield is dependent on $M_{projectile}$
- more effective E transfer at higher M

Drops at high energies
- energy deposited more into the volume

Chemical reactions can enhance it
- chemical sputtering → see later

E_{ion} ~ 100–1000 eV: sputter yield can be estimated by Sigmund-formula (1969):

$$Y=\frac{\Gamma_{sputtered}}{\Gamma_{ions}}\sim\frac{E_{ion}}{E_{SB}}\frac{4m_i m_t}{(m_i+m_t)^2}\frac{3\alpha}{4\pi^2}$$

$$\alpha=\alpha\left(\frac{m_t}{m_i}\right)\in(0.1\div 2)$$ empirical factor

Outline

Plasma-surface interactions – short summary

Diagnostics of plasma surface processes

- ***ex-situ*** **and** ***in-situ*** **plasma diagnostic**
- **beam experiments and growth models**

Surface reactivity β: imaging of radicals interacting with surfaces (IRIS)

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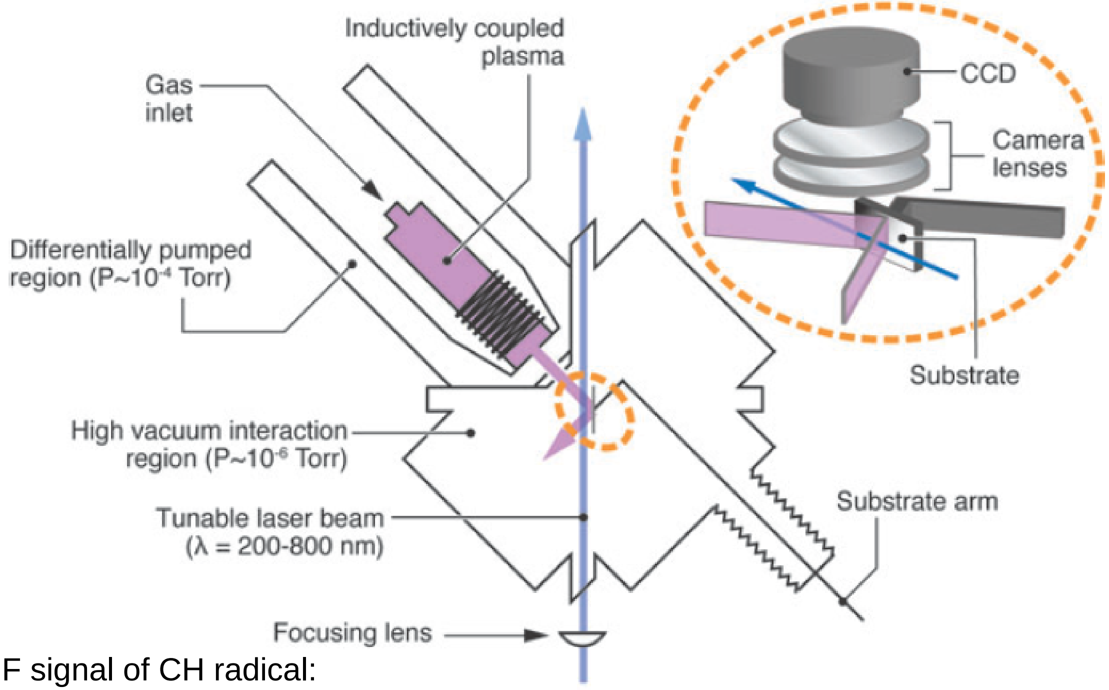
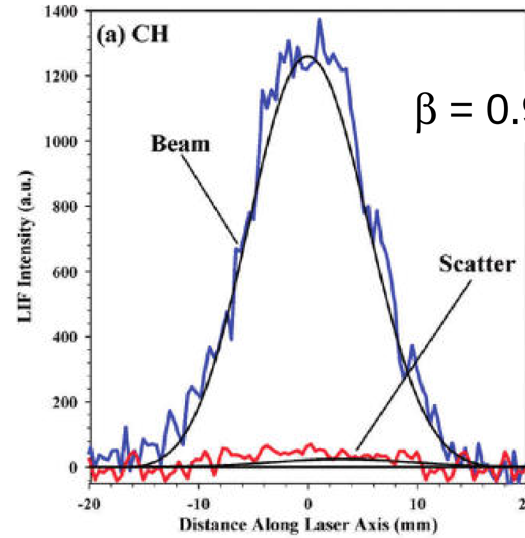
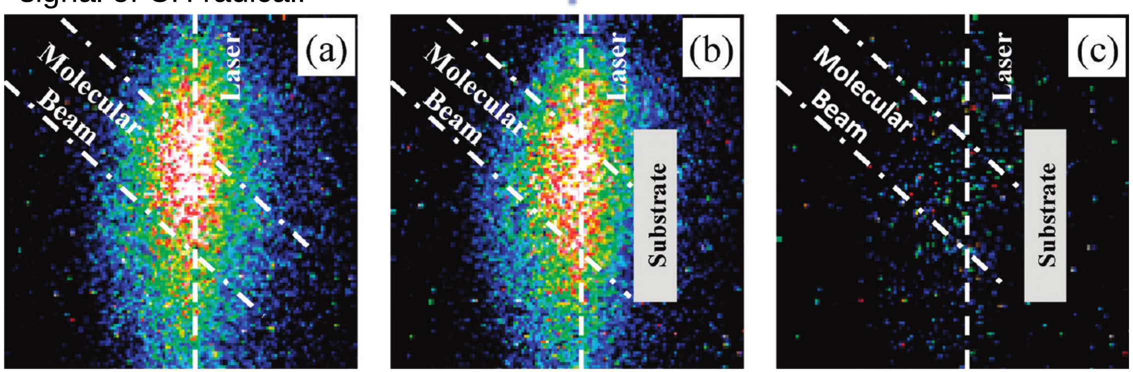


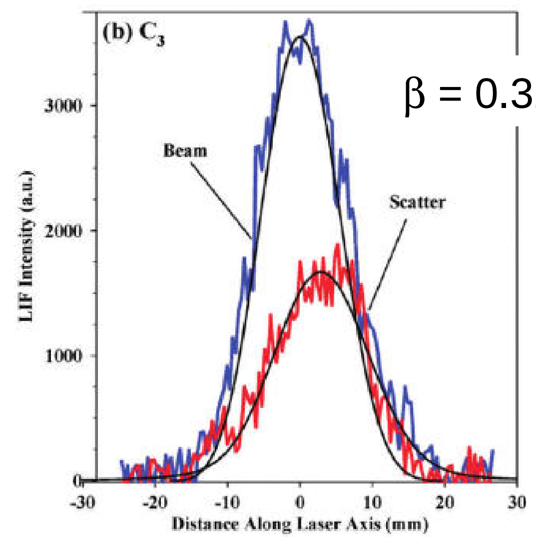


β = 0.95±0.07

LIF signal of CH radical:



Beam | Beam + scatter | Scatter



β = 0.32±0.09

J. M. Stillahn *et al.*, Annu. Rev. Anal. Chem. 2008. 1:261–91

D. Liu *et al.*, Appl. Mater. Interfaces, 2009, 1 (4), pp 934–943

Surface reactivity β: imaging of radicals interacting with surfaces (IRIS)

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Species	Plasma sources	Excited transition	λ(nm)[a]	Radiative lifetime (ns)	Dipole moment (D)	Relative surface reactivity[b]	Reference(s)
C_2	C_xH_y	$A^1\Pi \leftarrow X^1\Sigma^+$	691	1.85×10^4	—	—	143
C_3	C_xH_y	$A^1\Pi \leftarrow X^1\Sigma^+$	410	200	0.44	low/moderate	126, 139
CH	C_xH_y, CH_3OH	$A^2\Delta \leftarrow X^2\Pi$	430	537	0.55	high	117, 139
CHF	CH_xF_{4-x}	$A^1A'' \leftarrow X^1A'$	571	2.45×10^3	1.30	low/moderate	144
CF	C_xF_y	$A^2\Sigma^+ \leftarrow X^2\Pi$	224	26.7	0.64	low/moderate	65
CF_2	C_xF_y	$A^1B_1 \leftarrow X^1A_1$	226	61	0.44	low	65, 84
CCl	CCl_4, CH_4/Cl_2	$A^2\Delta \leftarrow X^2\Pi$	279	105	—	—	145
CN	CH_3CN, CH_4/N_2	$B^2\Sigma^+ \leftarrow X^2\Sigma^+$	387	65	0.50	high	140, 146
NH	NH_3, N_2/H_2	$A^3\Pi \leftarrow X^3\Sigma^-$	336	440	1.39	low/moderate	130
NH_2	NH_3, N_2/H_2	$A^2A_1 \leftarrow X^2B_1$	598	10×10^3	1.82	moderate	130
NO	NO, N_2/O_2	$A^2\Delta \leftarrow X^2\Pi$	226	205	0.16	—	147, 148
OH	H_2O, H_2/O_2	$A^2\Delta \leftarrow X^2\Pi$	308	686	1.80	moderate	28, 149
SiCl	$SiCl_4$, Cl_2[c]	$B^2\Sigma^+ \leftarrow X^2\Pi$	297	10	—	—	150
$SiCl_2$	$SiCl_4$, Cl_2[c]	$A^1B_1 \leftarrow X^1A_1$	320	4.5×10^3	1.46	low	135
SiF	SiF_4, CF_4[c], SF_6[c]	$A^2\Sigma \leftarrow X^2\Pi$	437	230	1.07	moderate	24, 101
SiF_2	SiF_4, CF_4[c], SF_6[c]	$A^1B_1 \leftarrow X^1A_1$	225	6.2	1.23	low	24, 98
SiH	SiH_4, Si_2H_6	$A^2\Delta \leftarrow X^2\Pi$	413	534	0.14	high	20, 107
SiH_2	SiH_4, Si_2H_6	$A^1B_1 \leftarrow X^1A_1$	580	111	0.16	moderate	109
SO	SO_2, SF_6/O_2	$B^3\Sigma \leftarrow X^3\Sigma$	235	16.2	1.55	—	151
SO_2	SO_2, SF_6/O_2	$A^1B_1 \leftarrow X^1A_1$	300	10×10^3	1.63	—	151

[a]Excitation wavelength for listed transition.
[b]Relative reactivity scale: low = < 0.1; low/moderate = ~0.1–0.3; moderate = ~0.3–0.7; high = ~0.7–1.0.
[c]Species of interest is produced during Si processing.

J.M. Stillahn *et al*., Annu. Rev. Anal. Chem. 2008. 1:261–91

Surface reactivity β: well / cavity Experiments

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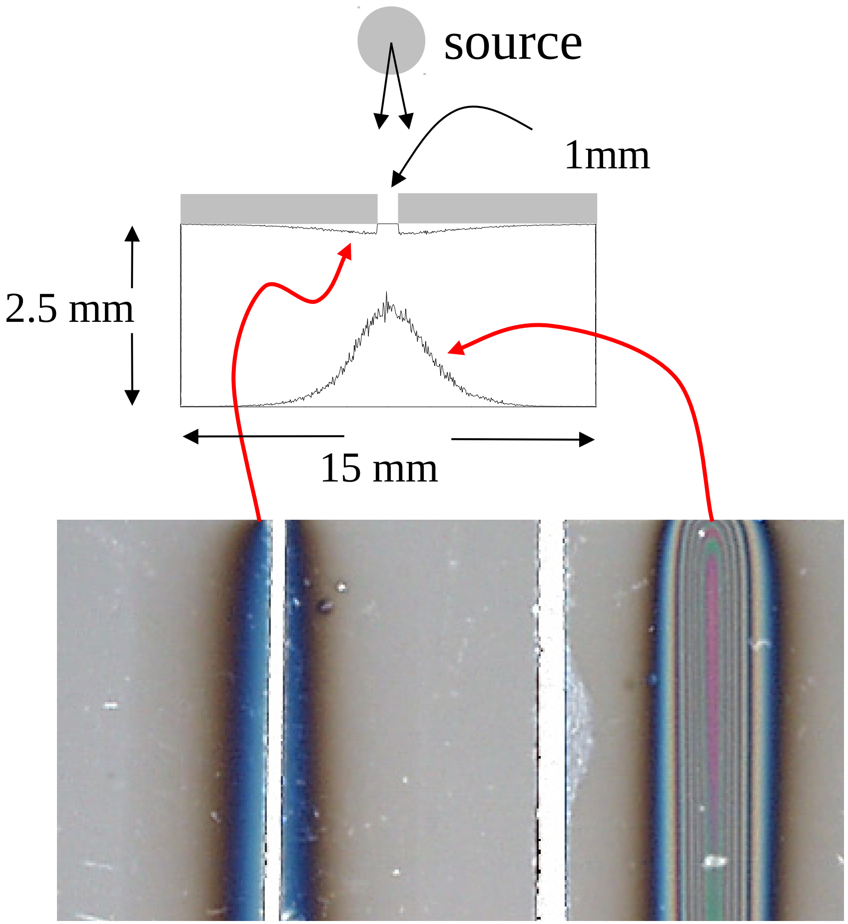
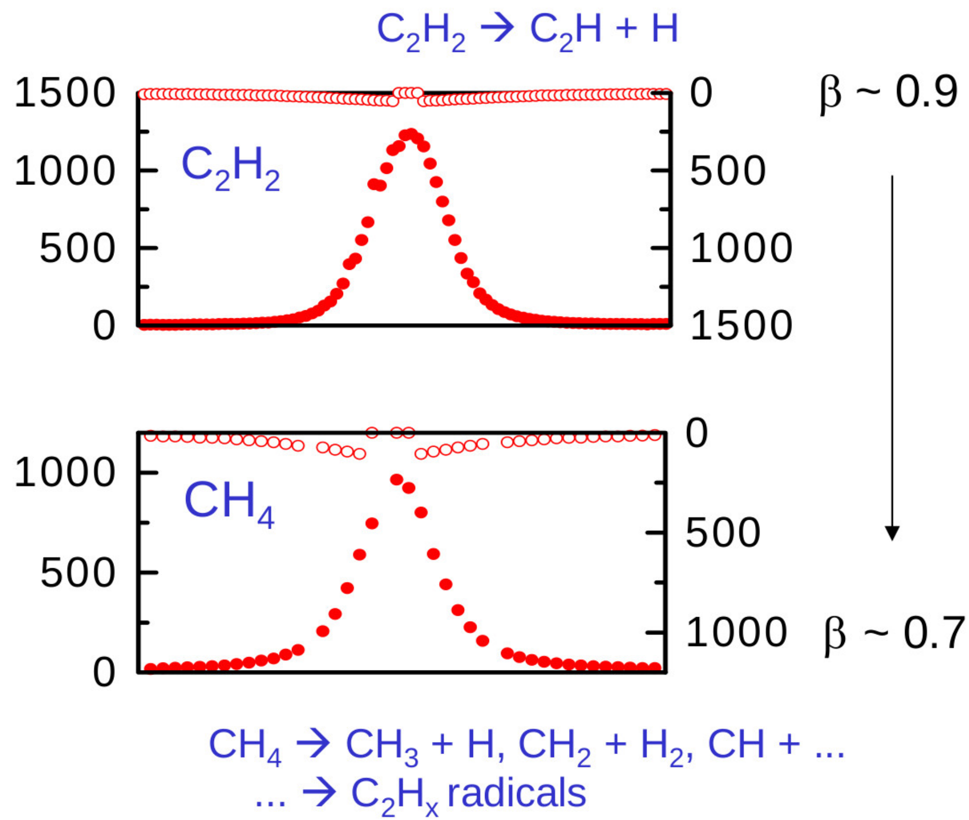




C. Hopf, T. Schwarz-Selinger, W. Jacob, A. von Keudell, JAP 87, 2719 (2000)

Measurement of β in plasmas

Density of reactive species in front of a reactor wall

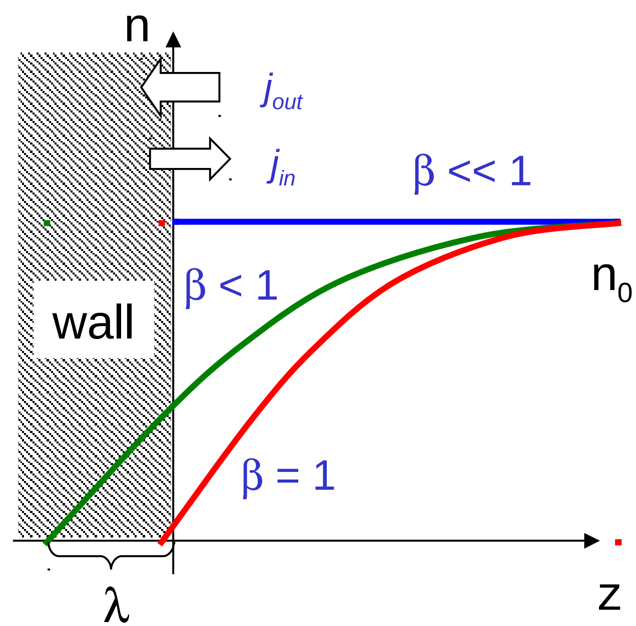
Confinement time of a given species in the reactor

$$\frac{1}{\tau_{confinement}} = \frac{1}{\tau_{gas}} + \frac{1}{\tau_{surface}} + \frac{1}{\tau_{pump}} =$$

$$= \sum_x k_r n_x + \frac{D}{\Lambda^2} + \frac{Speed_{pumping}}{V_{reactor}}$$

loss in gas-phase reactions — diffusion to the wall and surface loss — loss due to gas pumping

→density gradient at the wall!



Flux lost at the surface

$$j_{lost} = \frac{1}{4} n_{wall} v \frac{\beta}{1-\beta/2}$$

Special case (e.g. CH_3 radical)

$$for \quad \beta \rightarrow 0, k_r = 0$$

$$\frac{1}{\tau_{diff}} = \frac{v}{4\frac{volume}{Surface\ area}}\beta$$

Effective diffusion length (empirical)

$$\Lambda^2 = \Lambda_0^2 + \lambda \frac{volume}{surface\,area}$$

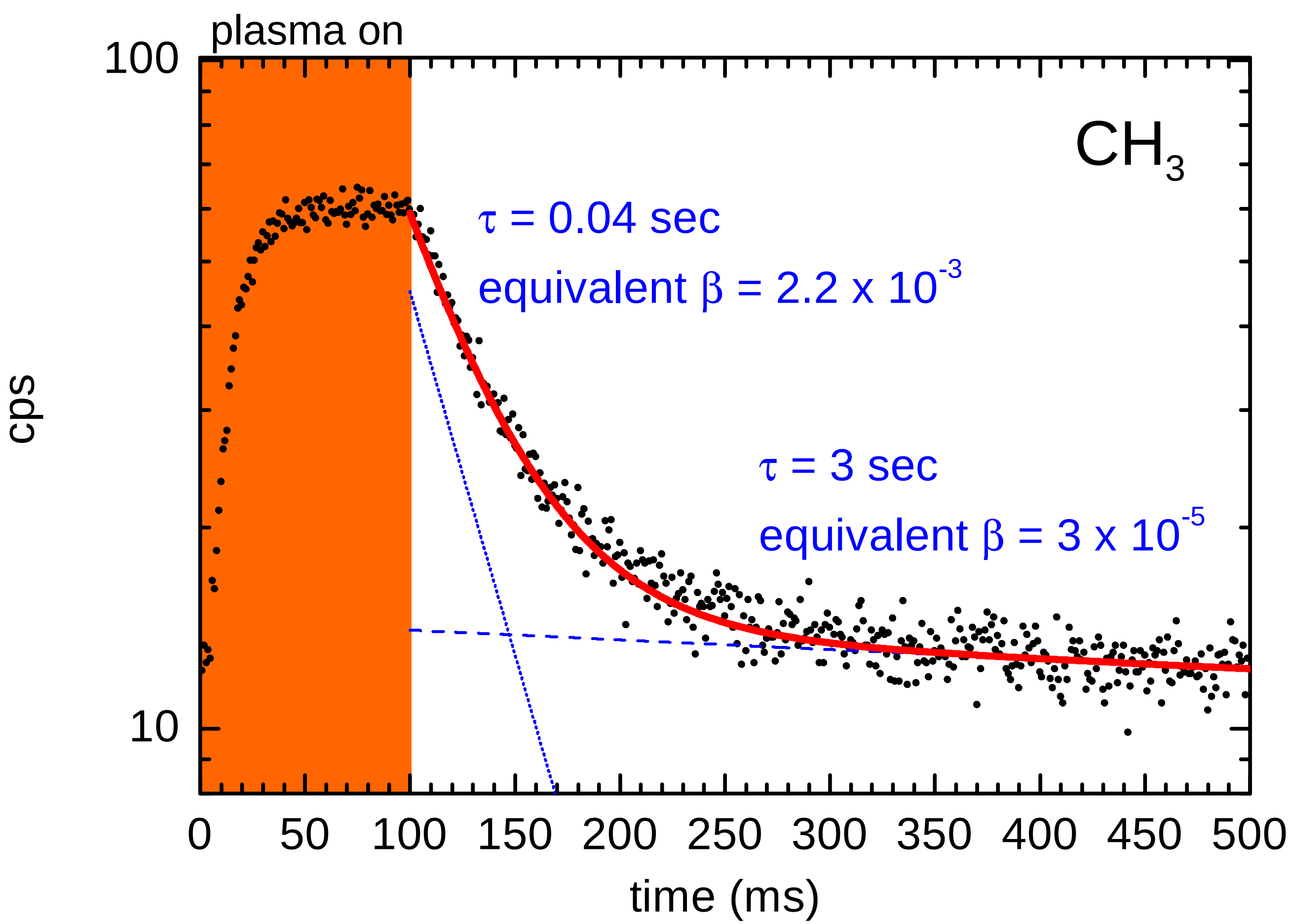
geometry

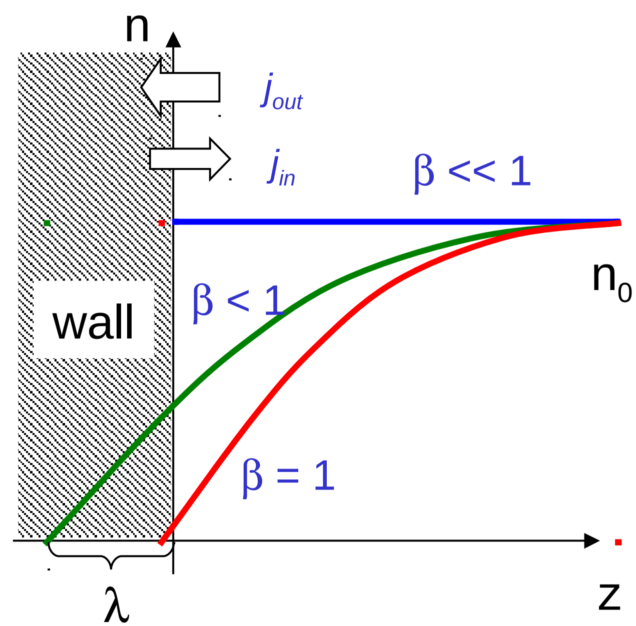
$$\lambda = \frac{4}{3}\lambda_m \frac{(1-\beta/2)}{(\beta)}$$

linear extrapolation length

mean-free-path

Determination of surface reactivity β: decay in plasma afterglow



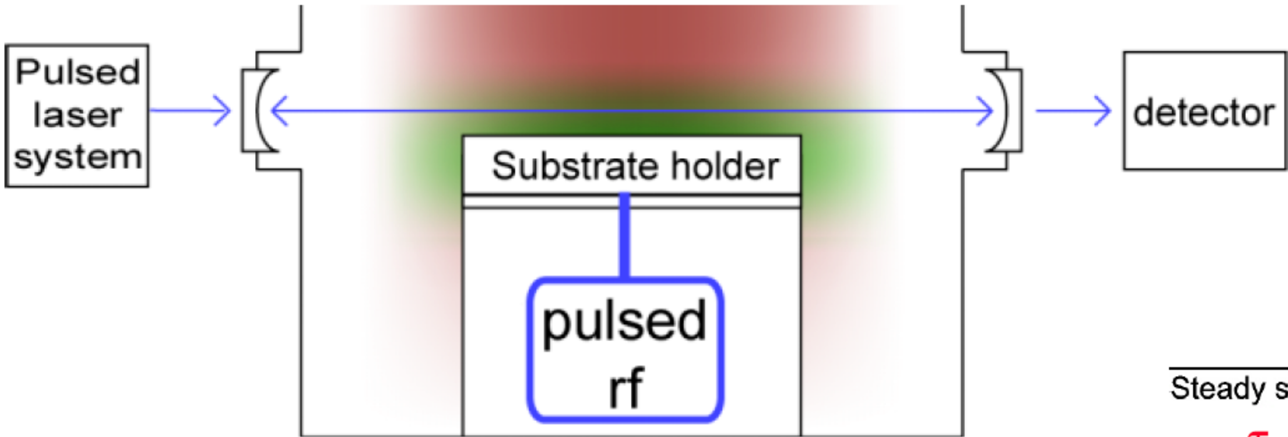


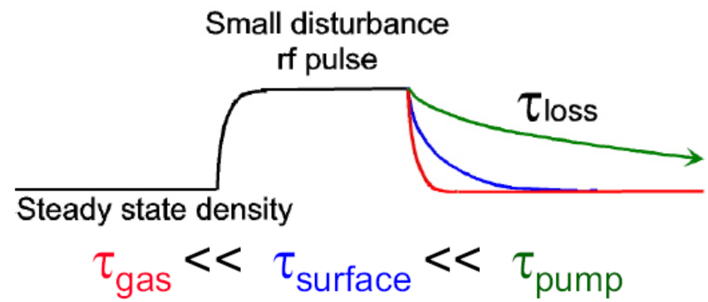
A. von Keudell *et al. unpublished*

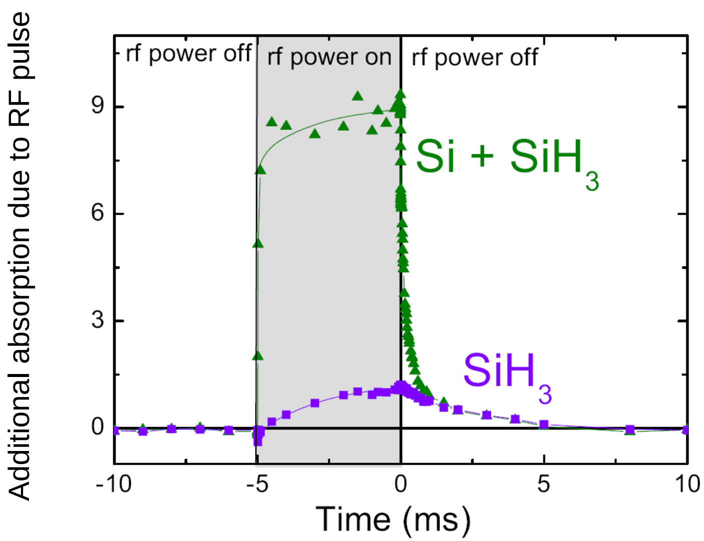
Surface changes after switching off the plasma!

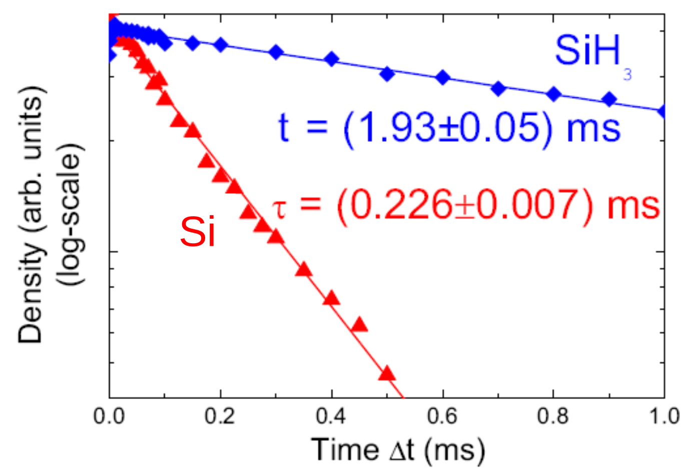
Determination of surface reactivity β: decay in modulated plasmas

→ surface does not change significantly





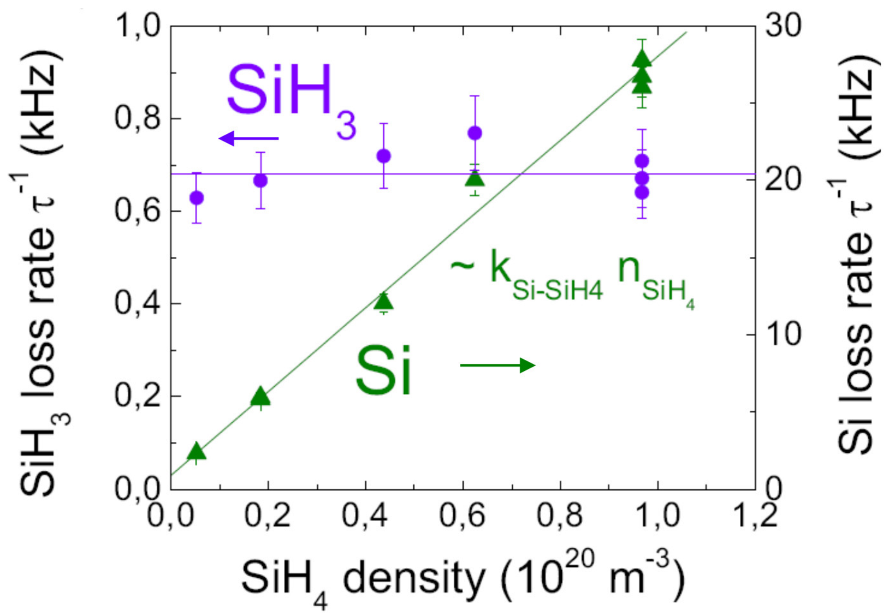




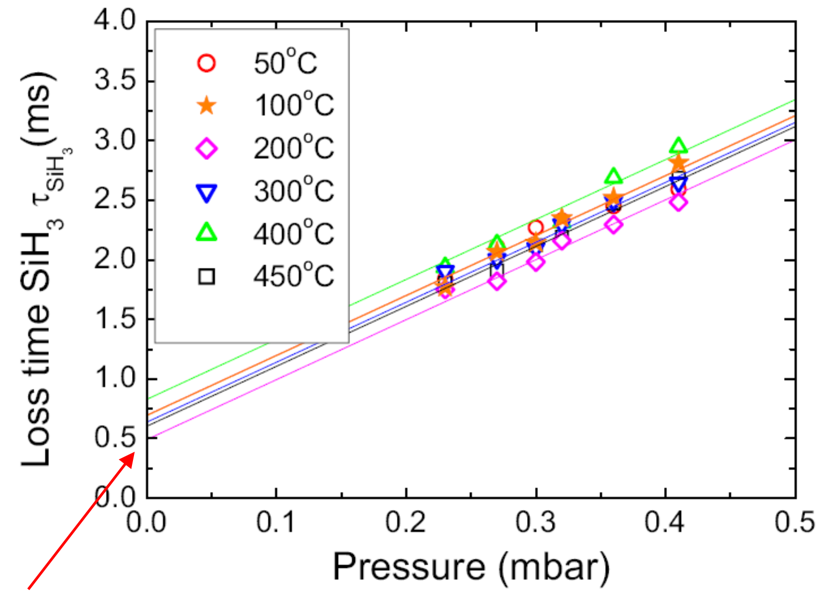
Hoefnagels *et al.*, CPL **36**0 (2002) 189

Determination of surface reactivity β: decay in modulated plasmas

SiH_4 partial pressure varied, total pressure constant



SiH_4 partial pressure constant, total pressure varied



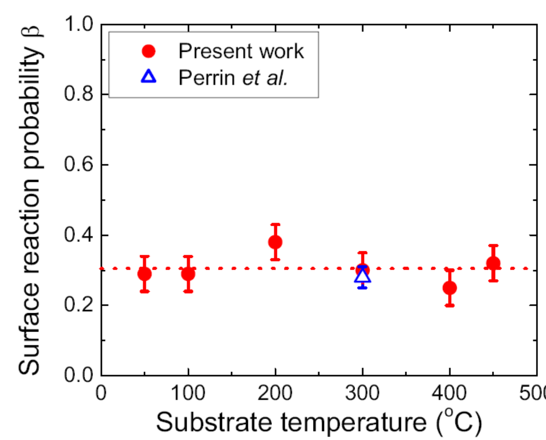
free fall limit → β = 0.3±0.05

- Si lost in gas phase reactions with SiH_4

$k_{Si\text{-}SiH4} = 2.6 \pm 1.0 \times 10^{-10}\ cm^3 s^{-1}$

- SiH_3 does not react in the gas phase!

Hoefnagels *et al.*, CPL **36**0 (2002) 189

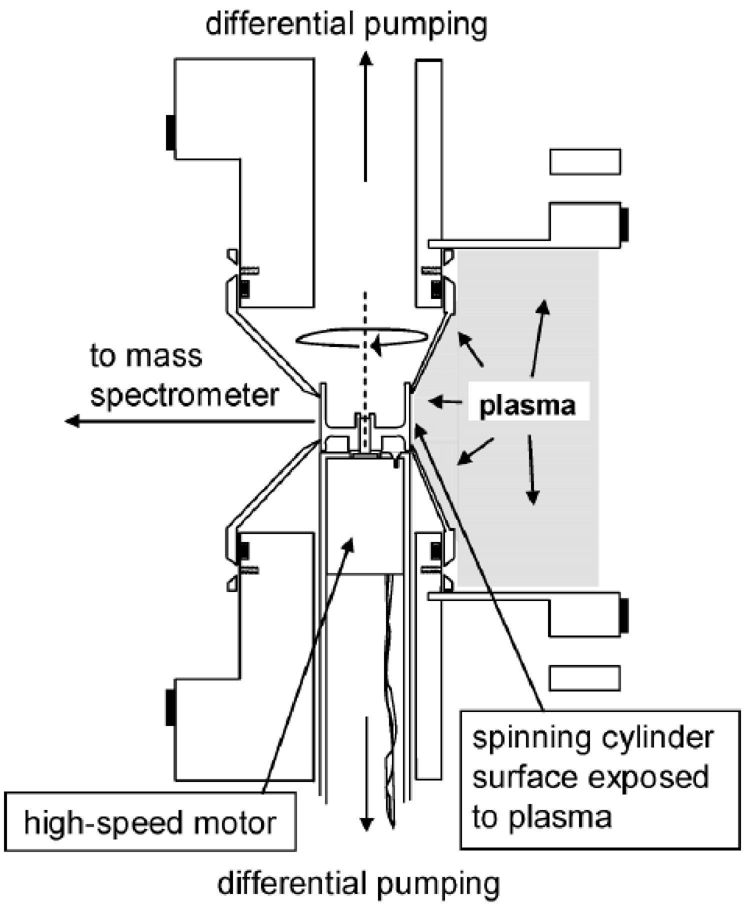


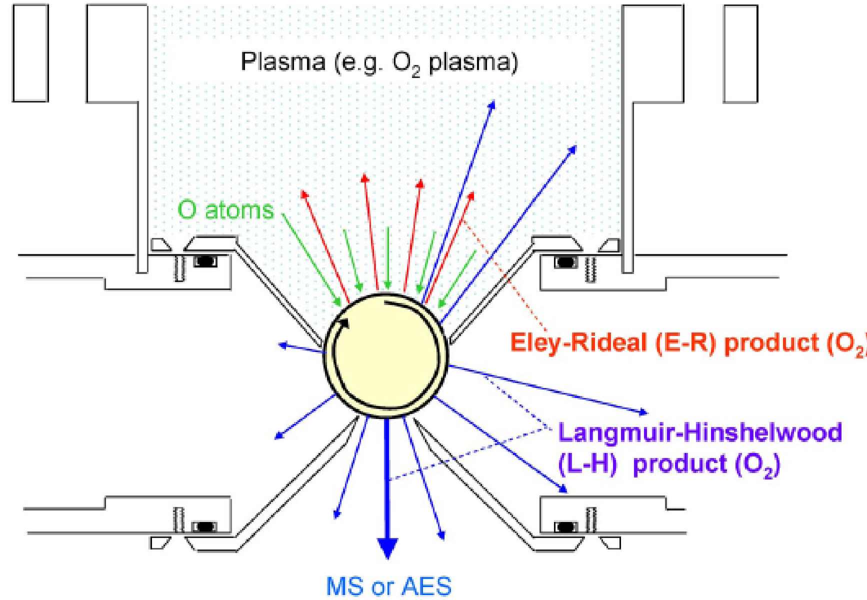
SiH_3 reacts at the wall.

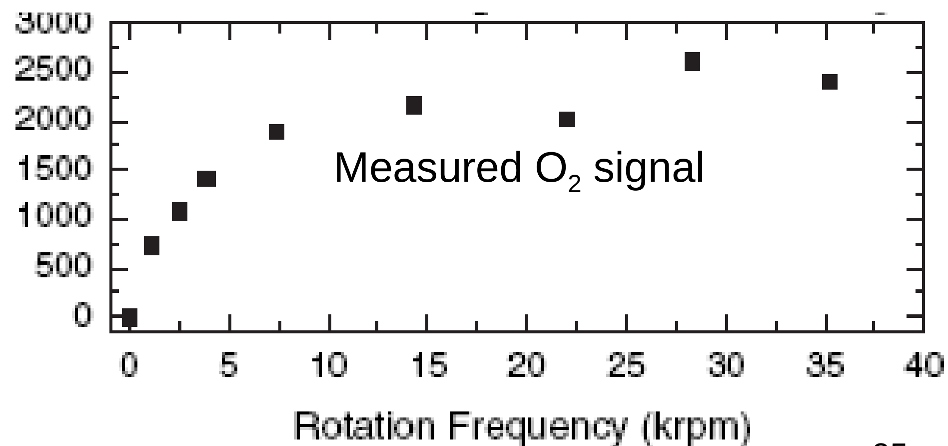
β independent of surface temperature.

Measurement of surface reactions: spinning wall experiment

O recombination at spinning surface







Donnelly *et al.*, e.g.:

P. F. Kurunczi *et al.*, Phys. Rev. Lett. **96,** 018306 (2006)

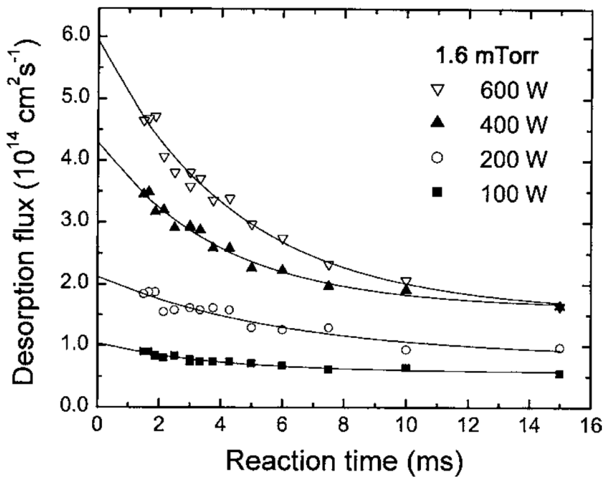
L. Stafford *et al.*, Pure Appl. Chem. **82**, 1301 (2010)

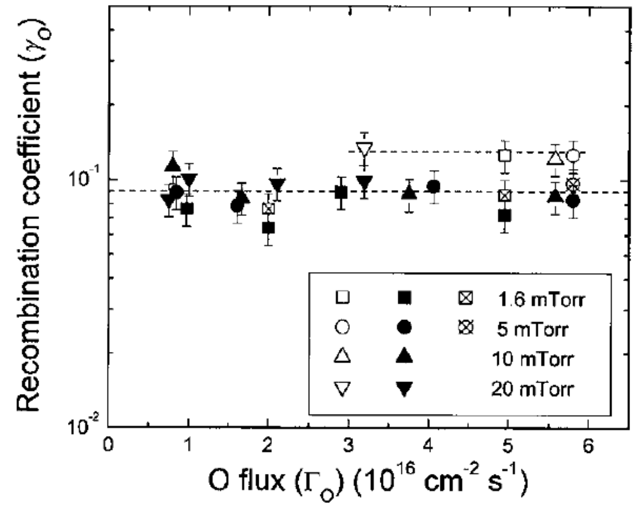
Measurement of surface reactions: spinning wall experiment

RUB

Recombination of atomic oxygen:

L. Stafford *et al.*, J. Vac. Sci. Technol. A 26 (2008) 455

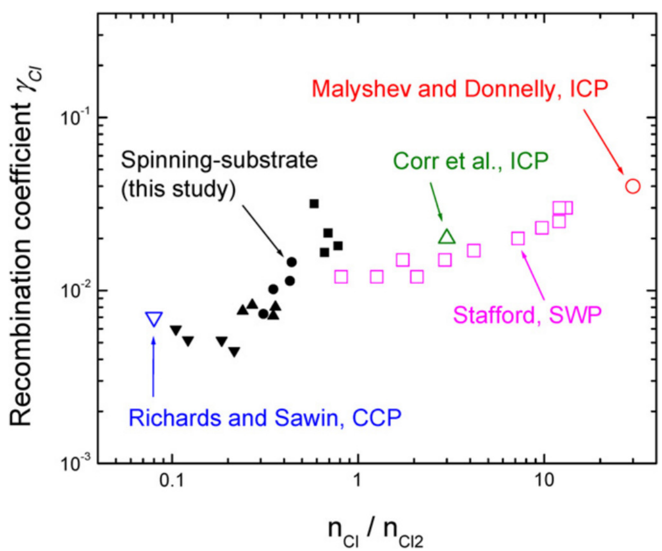




independent of O or O_2 flux

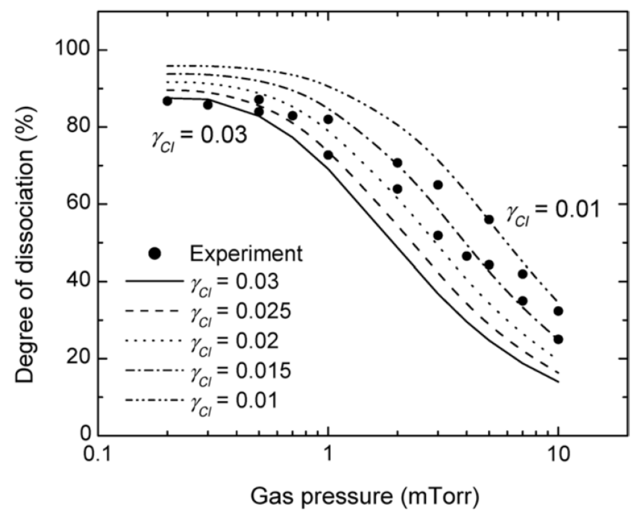
Recombination of atomic chlorine:

L. Stafford *et al.*, J. Phys. D: Appl. Phys. 42 (2009) 055206



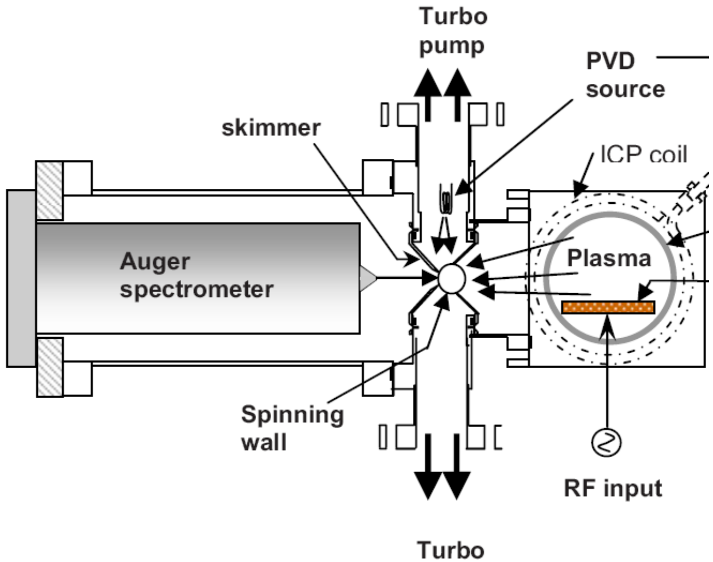
Cl recombination depends on Cl_2 surface coverage

→ has to be considered in e.g plasma models

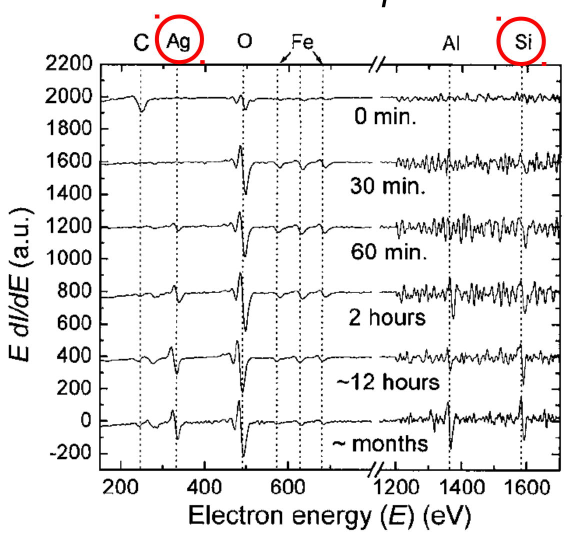


Measurement of surface reactions: spinning wall–effect of impurities

Spinning wall combined with Auger electron spectroscopy and evaporation sources.



AES detectable composition of the wall:



Redeposition of wall material in the chamber on stainless steal spinning wall

	Atomic concentration (%)	
Species	60 min	2 h
C	0.0	0.0
Ag	5.1	8.6
O	73.1	68.5
Fe	13.5	8.4
Al	0.0	3.7
Si	8.2	10.9

L. Stafford *et al.*, J. Vac. Sci. Technol. A 26 (2008) 455

Effect of controlled "contamination" on the surface on O atom recombination coefficient:

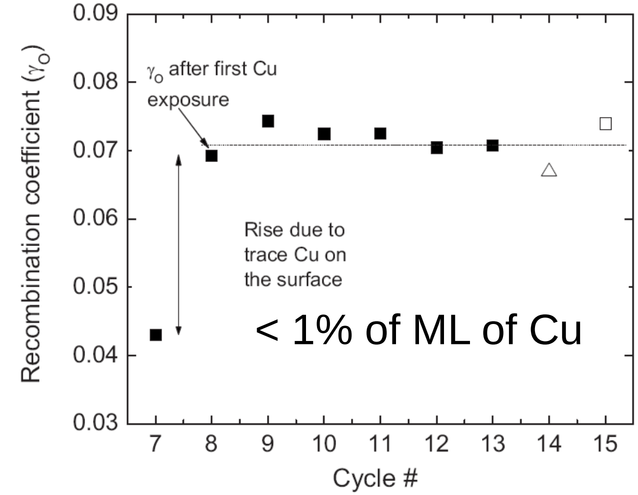


FIG. 6. Recombination coefficients, γ_O, of O-atoms on oxidized Si, measured before (cycle 7) and after (cycles 7–13) successive Cu doses of 1.4×10^{13}, 2.8×10^{13}, 5.6×10^{13}, 1.4×10^{14}, 8.4×10^{14}, and 3.4×10^{15} cm^{-2}, respectively, and after the surface was recoated with sputtered Si for 2 h (cycle 14, open triangle) and 4 h (cycle 15, open square).

J. Guha *et al.*, J. Appl. Phys. 105, 113309 (2009)

Small contamination can have large effect!

The surface is not as clean as you think!

Outline

Plasma-surface interactions – short summary

Diagnostics of plasma surface processes

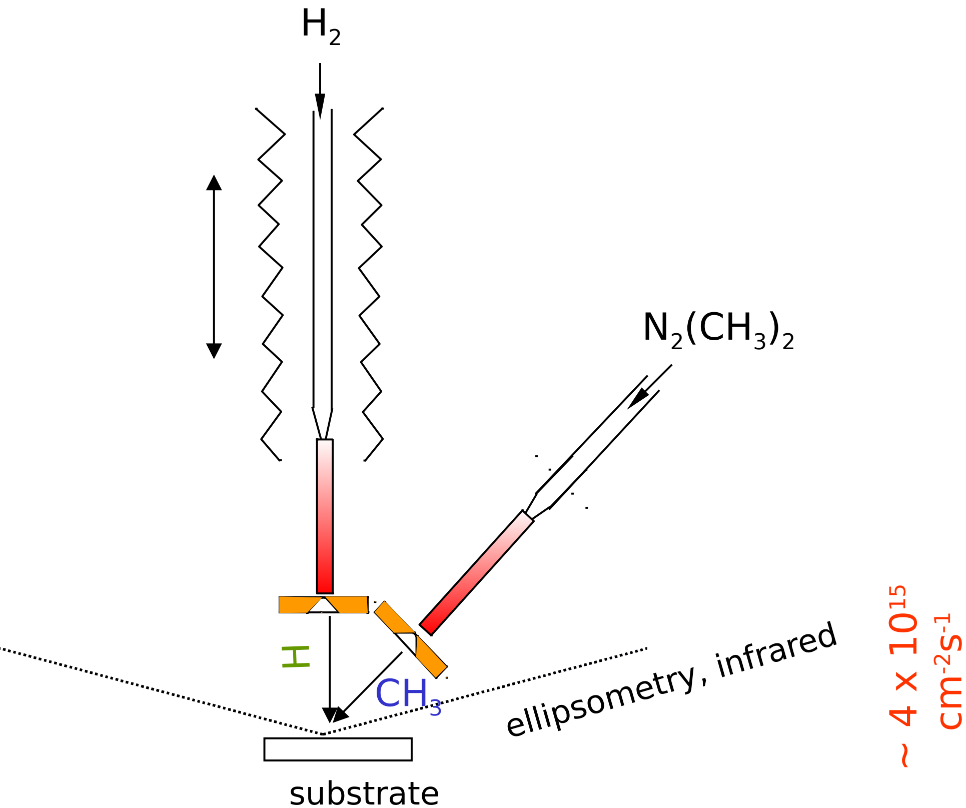
- ***ex-situ*** **and** ***in-situ*** **plasma diagnostic**
- **beam experiments and growth models**

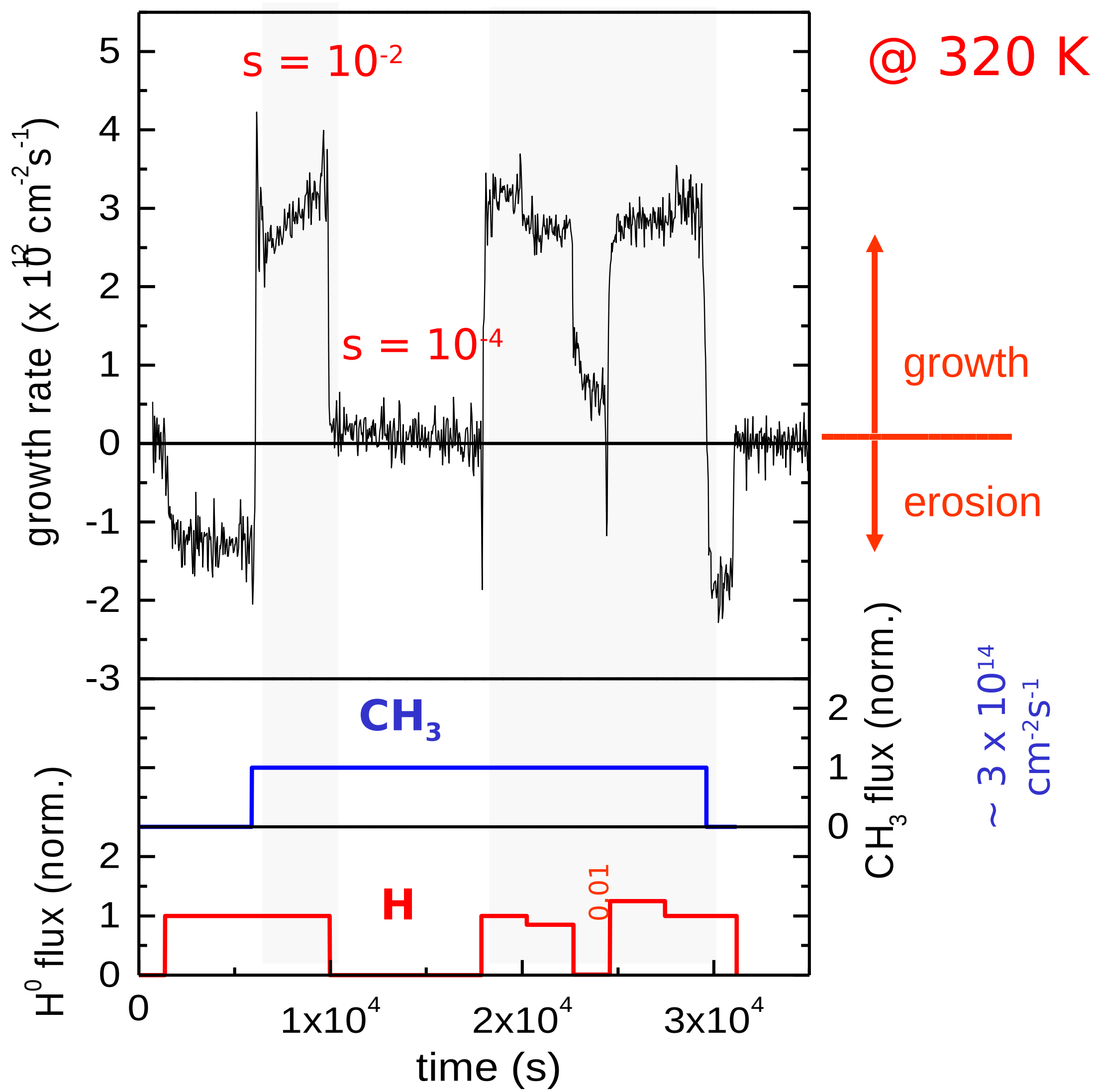
Beam experiment to study surface reactions of "plasma" particles

RUB

Beam sources of radicals or ions are used to simulate in low pressure chamber the conditions in a plasma experiment

→ with well-defined particle fluxes



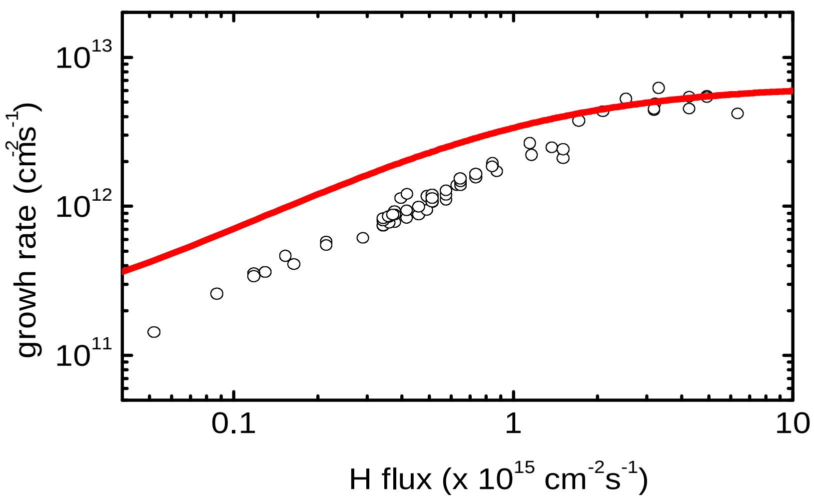


A. von Keudell, Thin Solid Films 402 (2002) 1

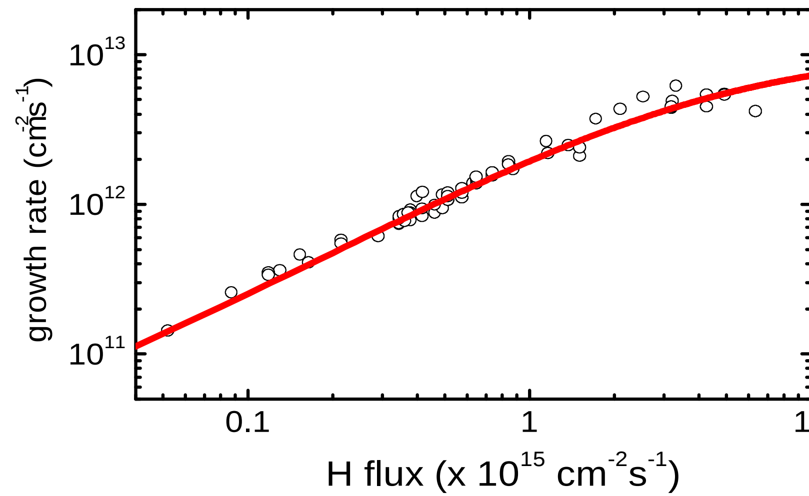
Sticking of CH_3 varies with H flux to the surface

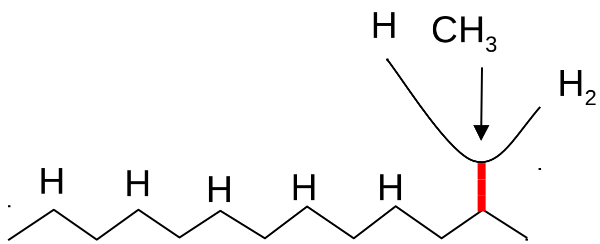
Beam experiments: CH_3|H synergism, simple vs. extended model

simple model



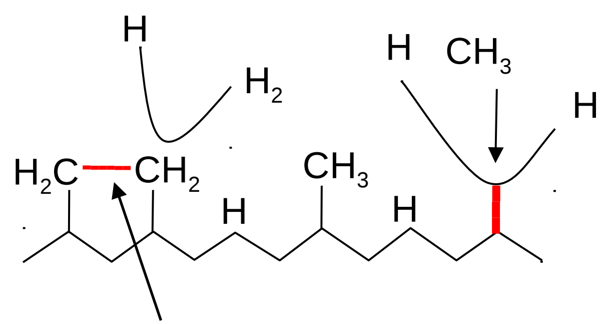
extended model including cross linking





$$\frac{d\Theta_{\mathrm{db}}}{dt}=(j_{\mathrm{H}}\sigma_{\mathrm{abstraction,H}}+j_{\mathrm{CH_3}}\sigma_{\mathrm{abstraction,CH_3}})(1-\Theta_{\mathrm{db}})$$
$$-(j_{\mathrm{H}}\sigma_{\mathrm{addition,H}}+j_{\mathrm{CH_3}}\sigma_{\mathrm{addition,CH_3}}$$
$$+k_{\mathrm{release,CH_3}}(T))\Theta_{\mathrm{db}}.$$

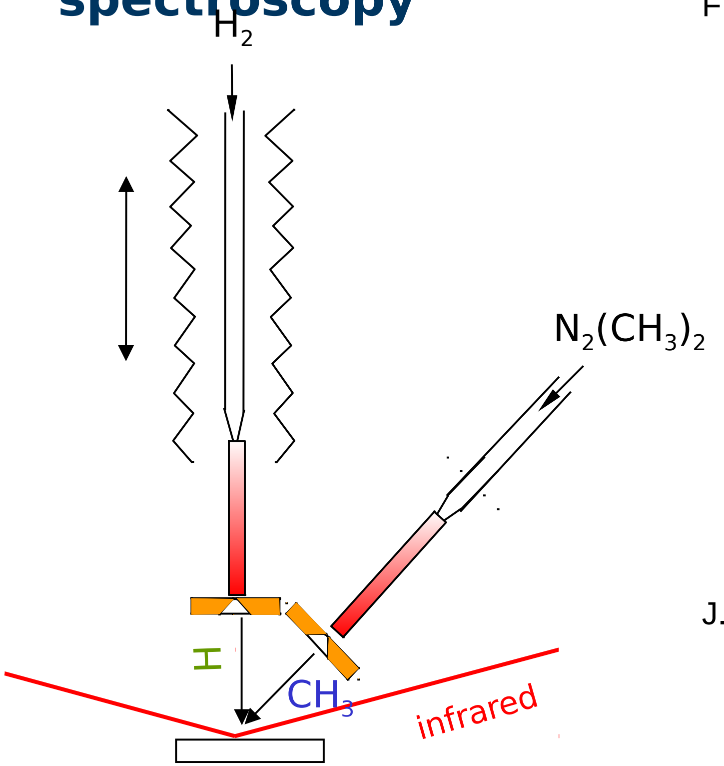
$$\Gamma=j_{\mathrm{CH_3}}\sigma_{\mathrm{addition,CH_3}}n_0\Theta_{\mathrm{db}}-k_{\mathrm{release,CH_3}}n_0\Theta_{\mathrm{db}}$$



cross linking of two neighboring dangling bonds

M. Meier, A. von Keudell JAP 90, 3585 (2001)

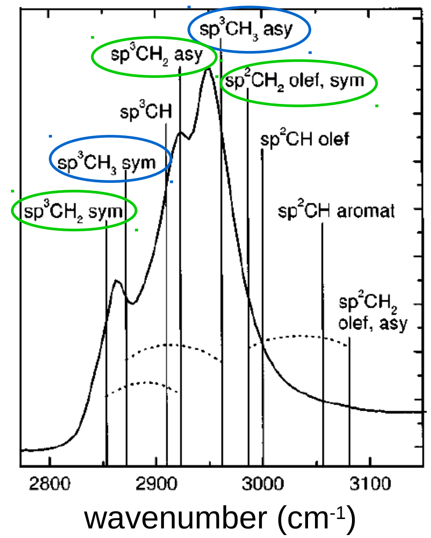
Measurement of surface reactions: infrared absorption spectroscopy



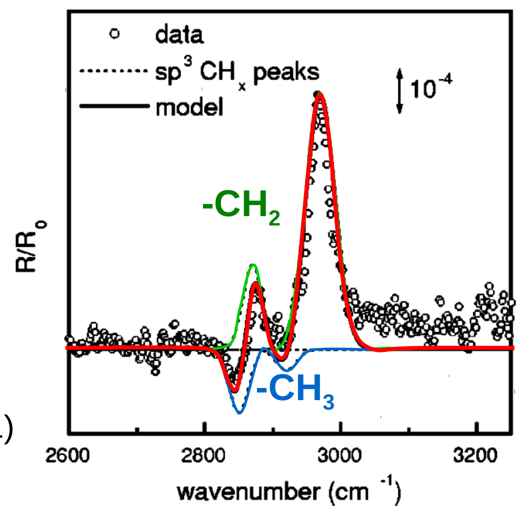
substrate, a-C:H film

M. Meier, A. von Keudell JAP 90, 3585 (2001)

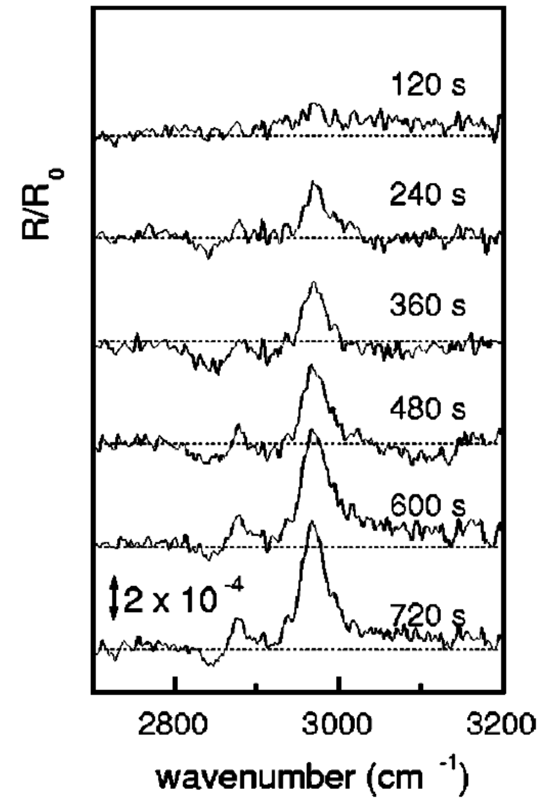
FTIR absorption spectra of an a-C:H film



J. Ristein *et al.*, JAP 84, 3836 (1998)



Evolution of an FTIR spectrum after turning off the CH_3 radical source



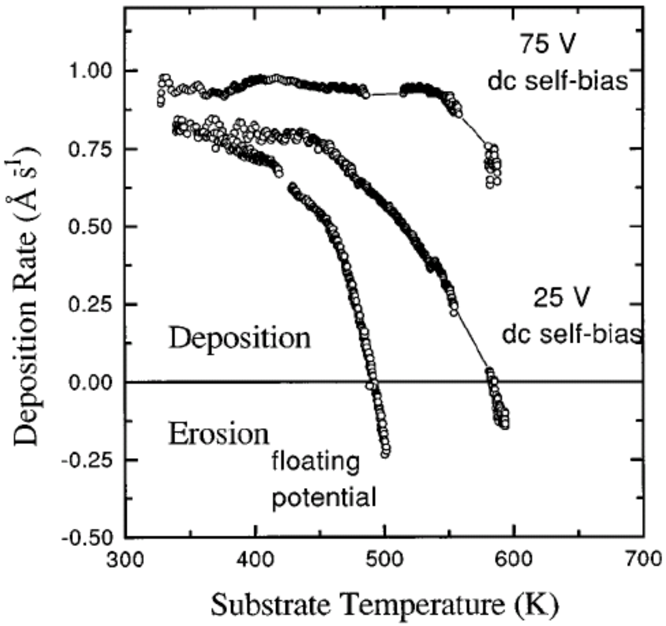
FTIR can also be used in combination with isotopes (e.g. flux of D or D_2)

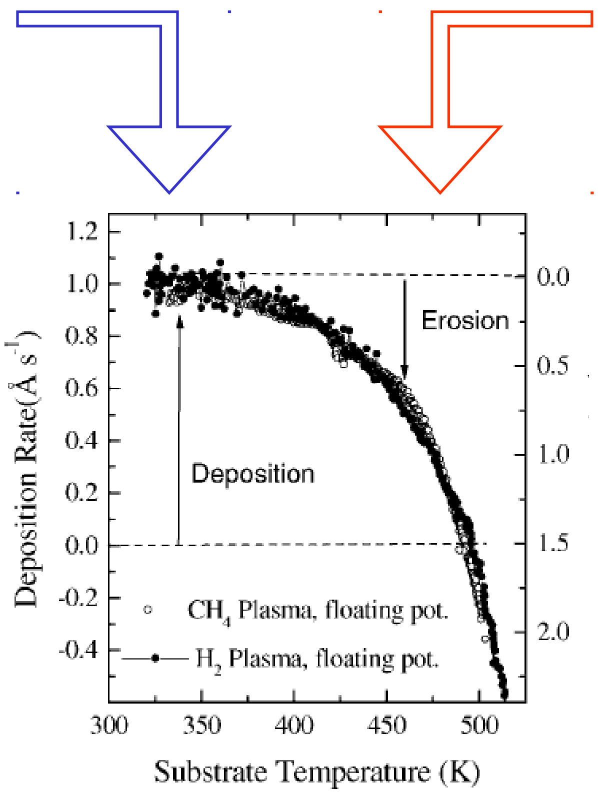
"Simple" test of a growth mechanism

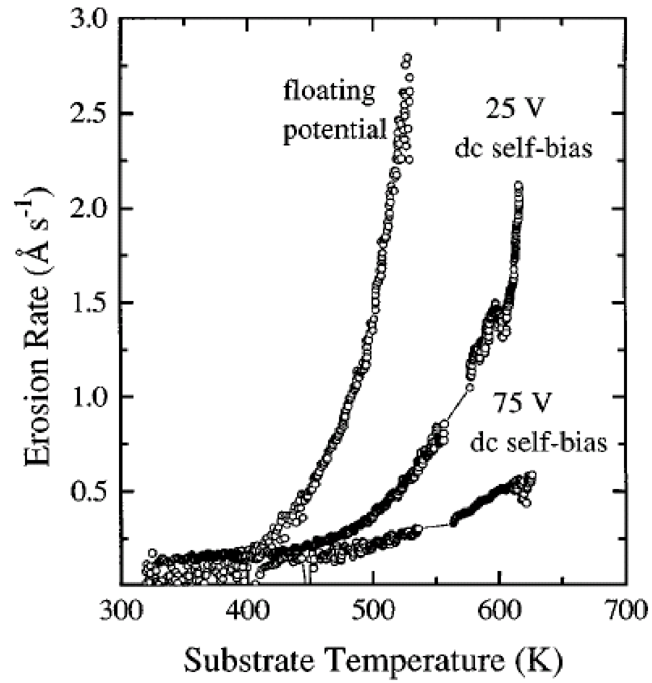
Analysis of a T-dependent growth of a-C:H films from electron cyclotron resonance CH_4 discharge

T-dependent film growth/erosion rate in CH_4 plasma

T-dependent film erosion rate in H_2 plasma





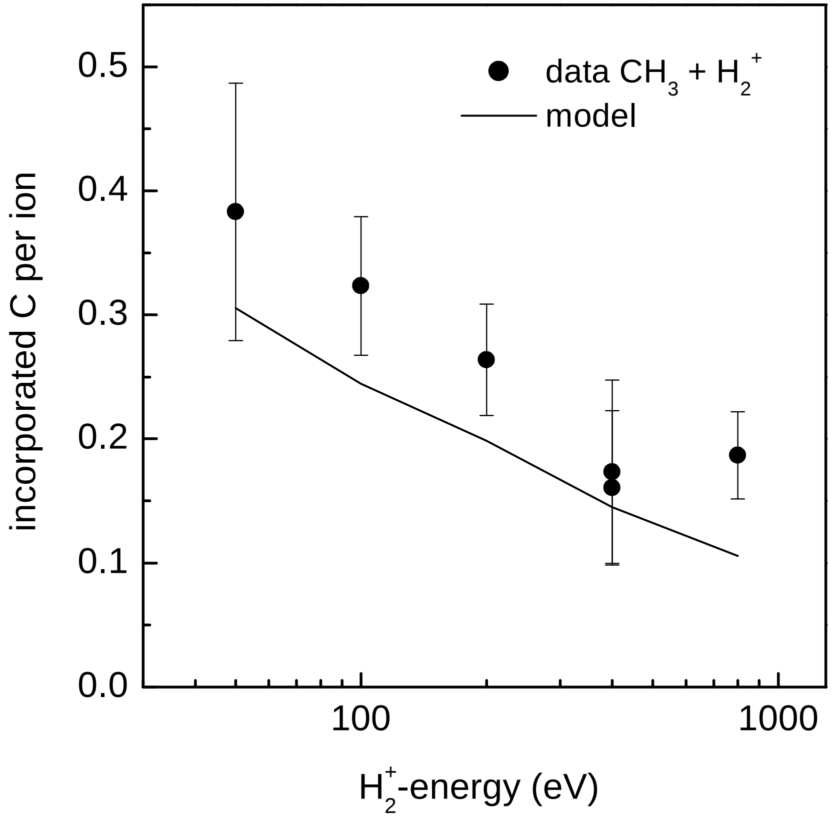


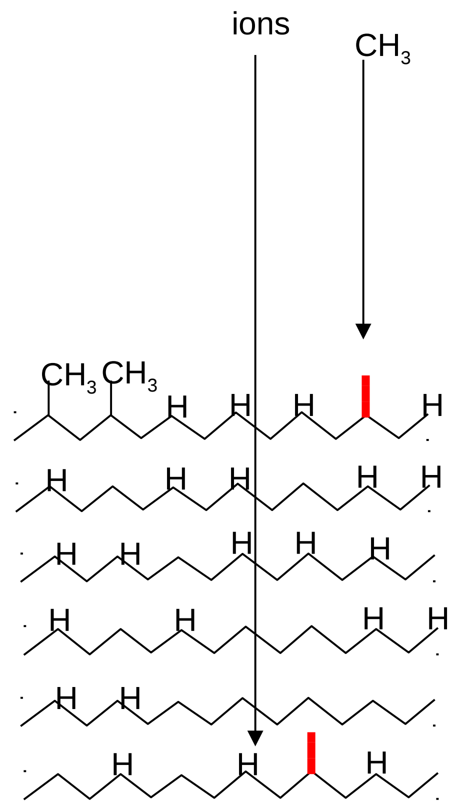
growth rate measured by in-situ single wavelength ellipsometry

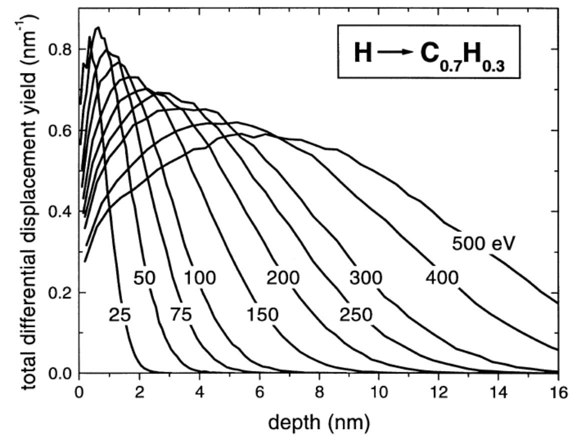
A. von Keudell, Plasma Sources Sci. Technol. 9 (2000) 455–467

→ combination of constant deposition rate with T-dependent film erosion by hydrogen

Beam experiments:
ion-assisted film growth: energy dependence of $s(CH_3|\, H_2^+)$





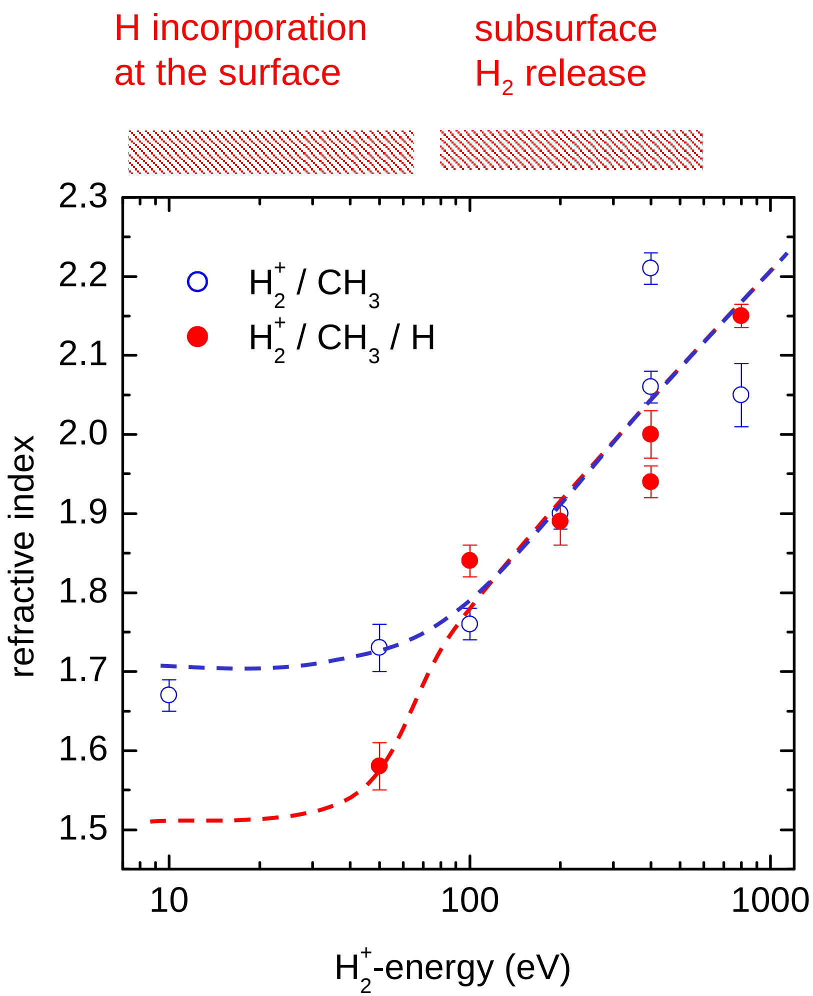


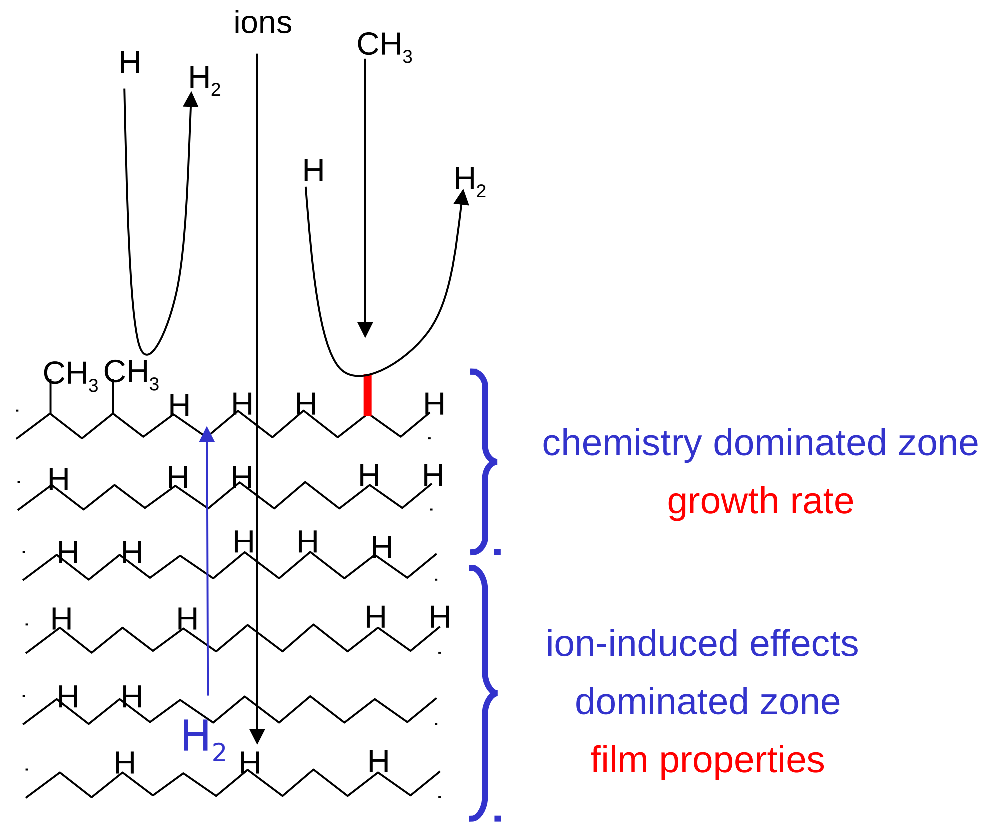
model TRIM.SP displaced H in the first ML

$c_H = 0.3$, $E_{dp}^{H} = 2.5$ eV

A. von Keudell, M. Meier, C. Hopf, Diamond and Related Materials 11, 969 (2002)

Beam experiments: ion-assisted film growth: film properties



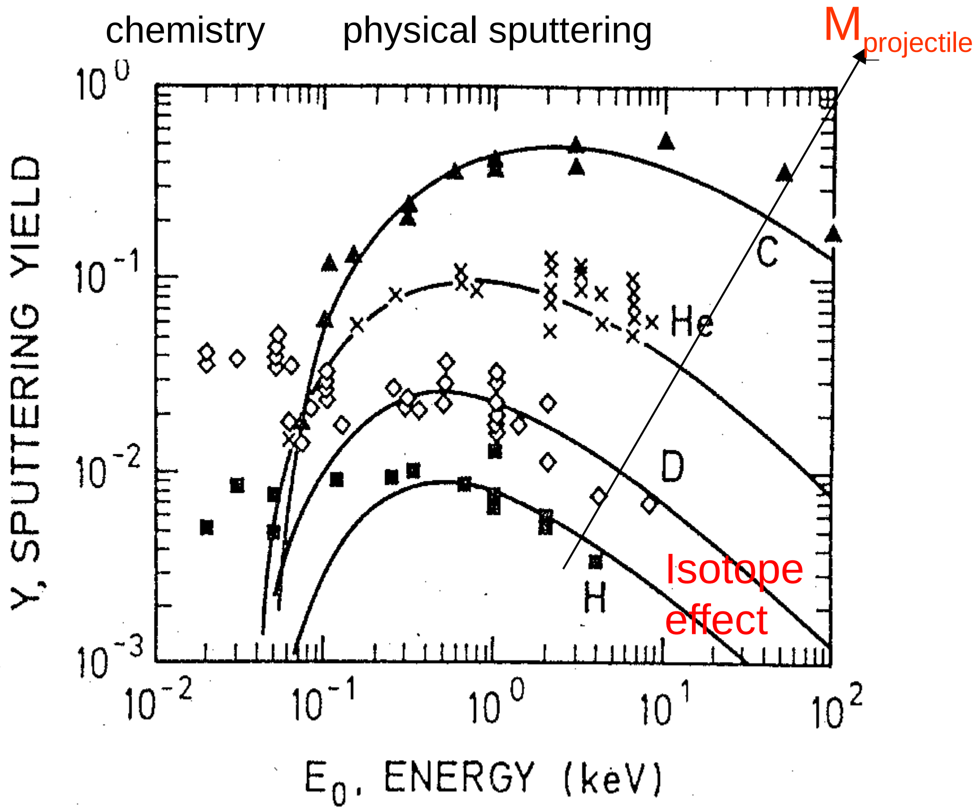


A. von Keudell, M. Meier, C. Hopf, Diamond and Related Materials 11, 969 (2002)

Beam experiments in study of physical and chemical sputtering

RUB

Sputtering of graphite

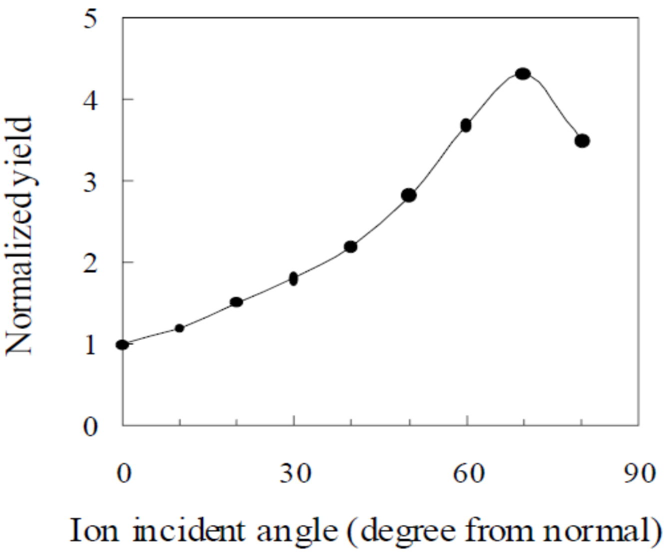


Beam experiments allow:

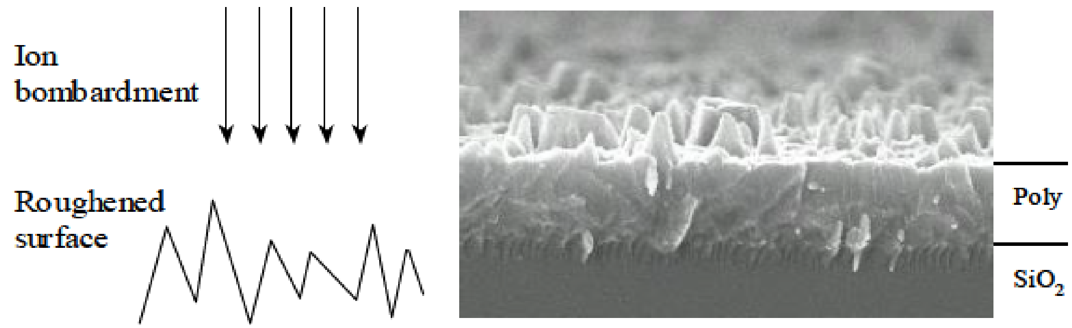
- measurements of absolute sputtering yields
- determination of angular dependence
- study of different chemistries

K. Krieger in 'lectures on plasma physics'
Summer university for plasma physics
MPI für Plasmaphysik (1993)

Angular dependence of sputtering yield: physical sputtering



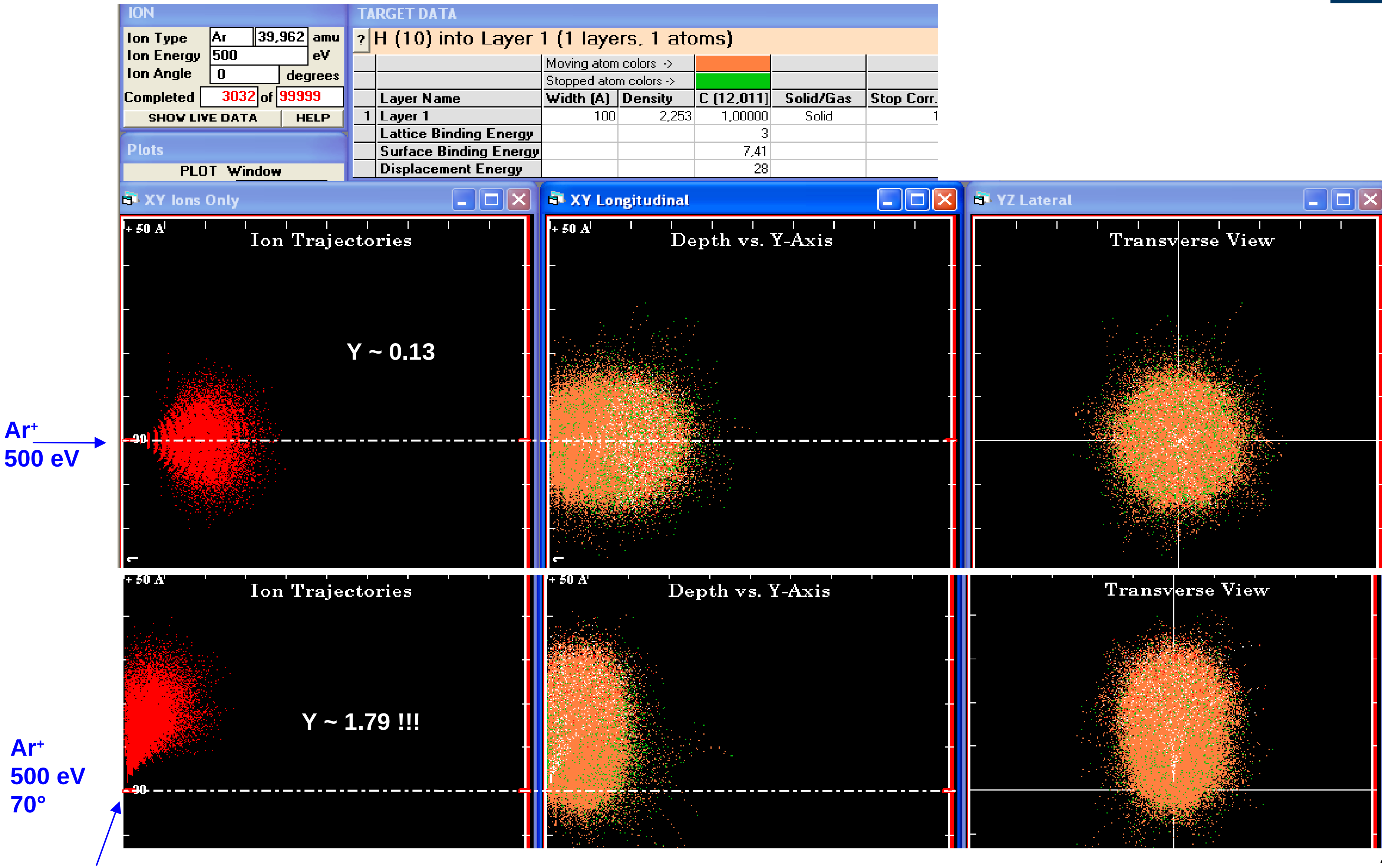
Dependence of etching yield
on ion incident angles



Formation of „grass“ due to micromasking

Lecture Notes on Principles of Plasma Processing
F.F. Chen, J.P. Chang
http://www.ee.ucla.edu/~ffchen/Publs/Chen208i.pdf

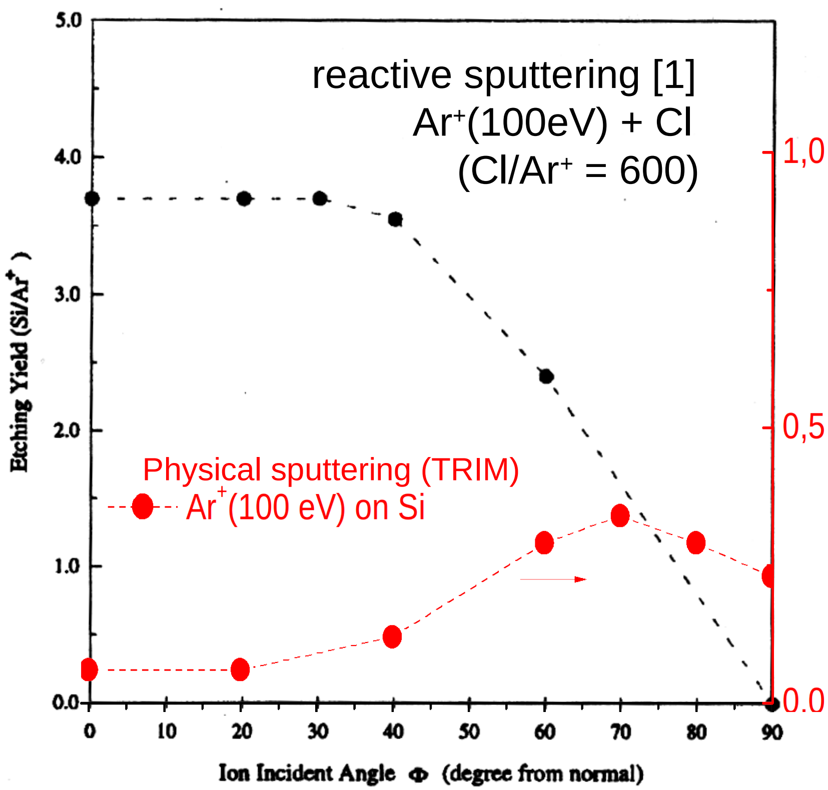
Angular dependence of physical sputtering yield: TRIM calculation

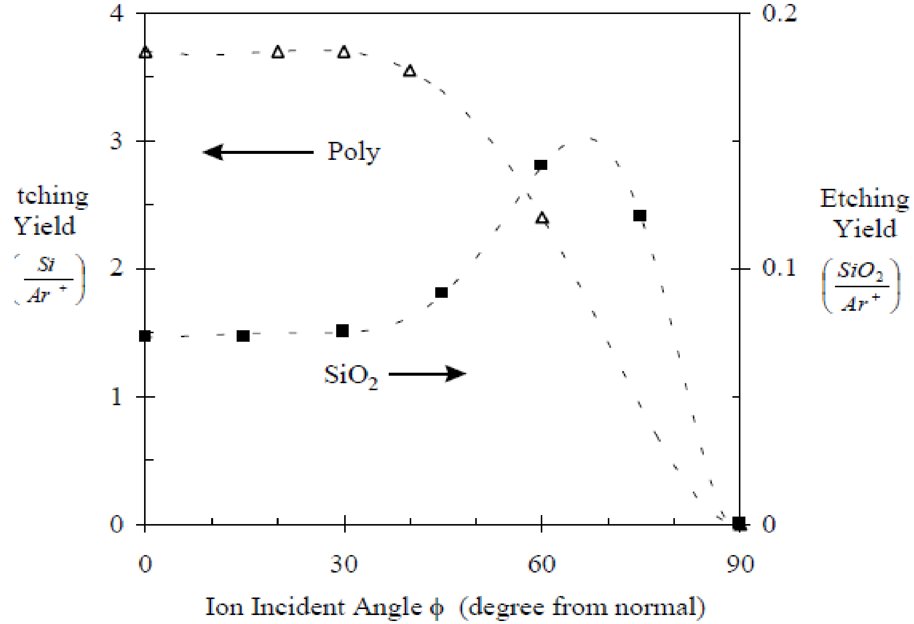


Angular dependence of sputtering yield: chemical sputtering

RUB

Si (polysilicon) etching with
100 eV Ar^+ ions and Cl atoms





Lecture Notes on Principles of Plasma Processing
F.F. Chen, J.P. Chang

Depends on material:
Cl can be easily implanted into poly-Si →chem. sput.
but not into SiO_2 → physical sputtering

[1] J.P. Chang *et al.*, JVSTA15, 1853 (1997)

Proper angular dependence for each material has to be incorporated into profile simulators

Reactive sputtering: molecular dynamic simulation

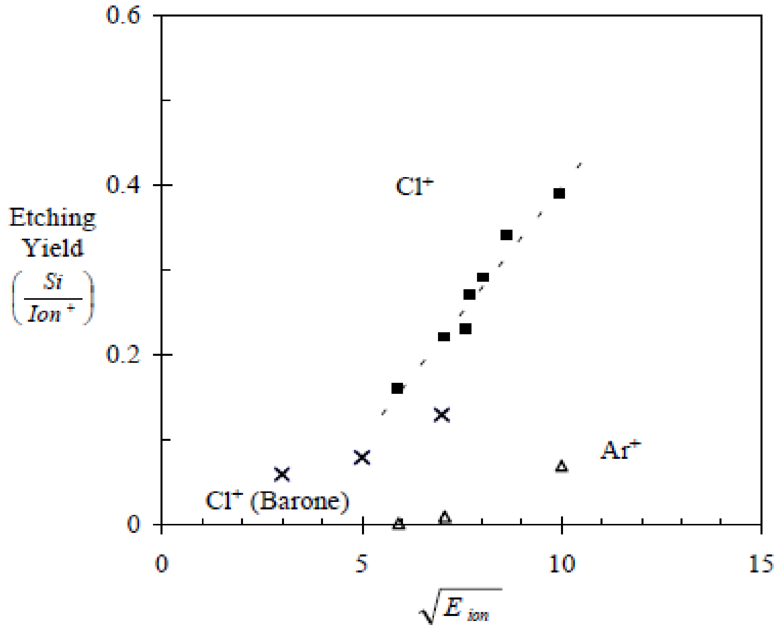


Fig. 11. Sputtering yield of polysilicon by Cl^+ in the low energy regime, in comparison to molecular dynamic simulation results and low energy sputtering yield by Ar^+.

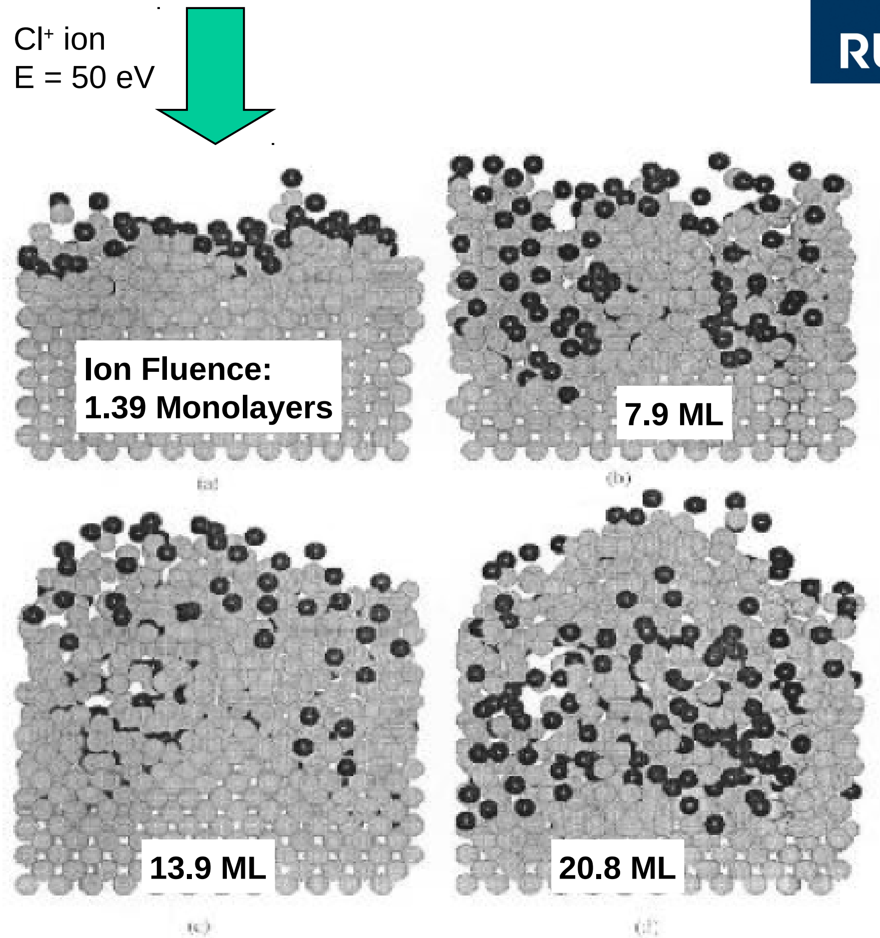
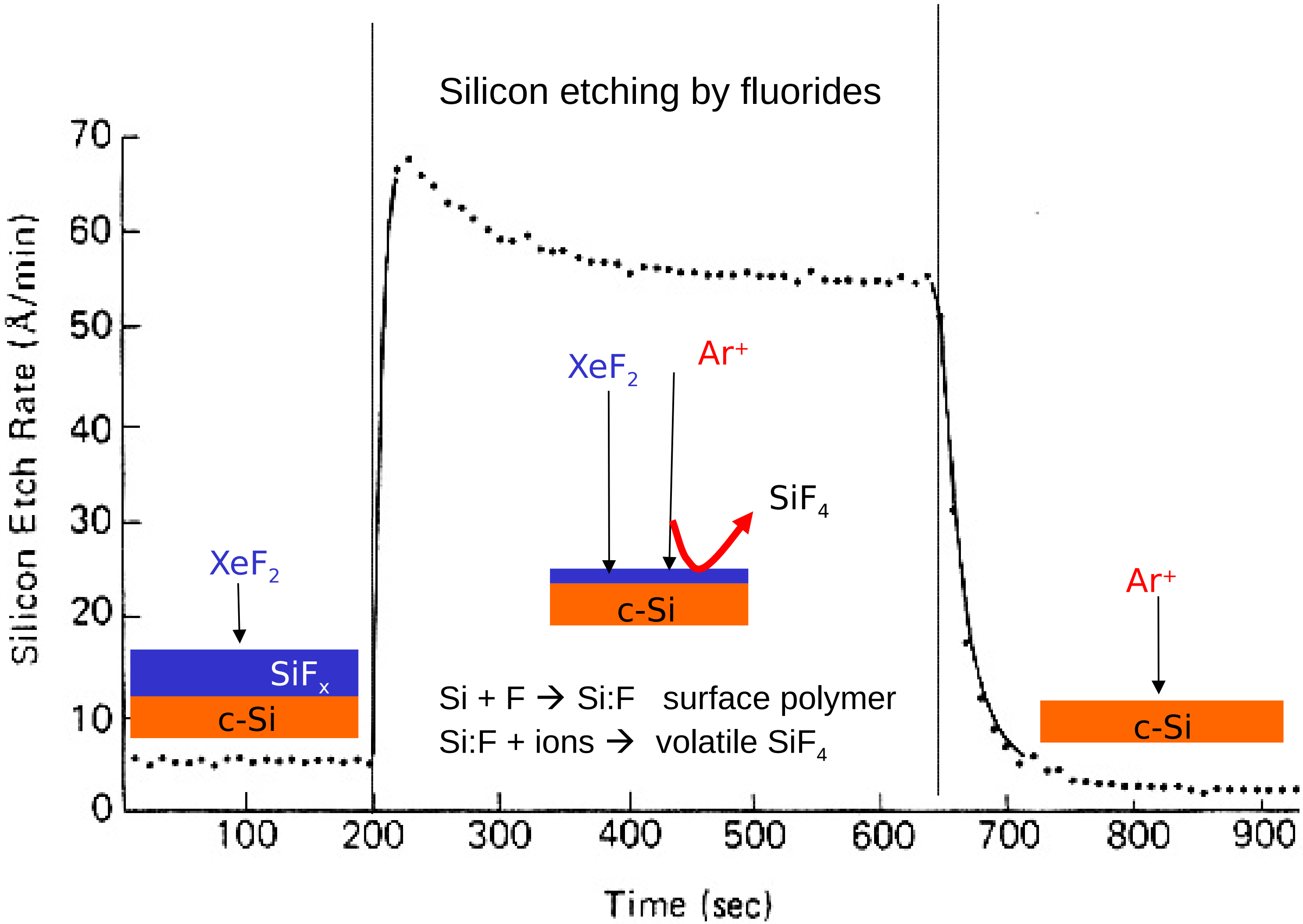


Fig. 13. Molecular dynamic simulation of Cl^+ interacting with Si [Barone and Graves]. JAP 78 (1995) 6604

Cl-rich surface layer – reduces the surface binding energy – lower threshold, higher yield…

Beam experiments: chemical sputtering

The famous plasma surface interaction experiment by Coburn and Winters JAP 50, 3189 (1979)

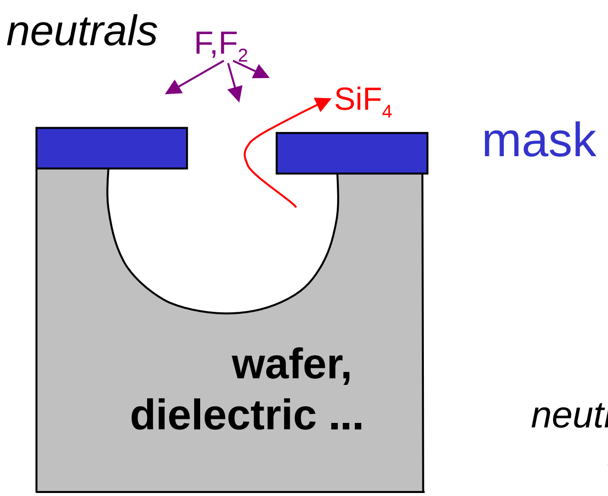


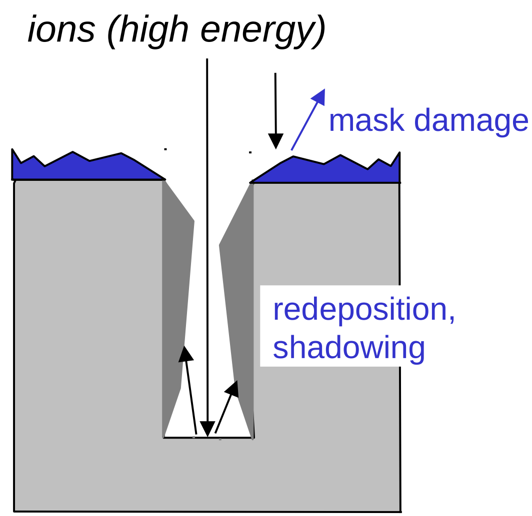
Key features in the success of chemical sputtering

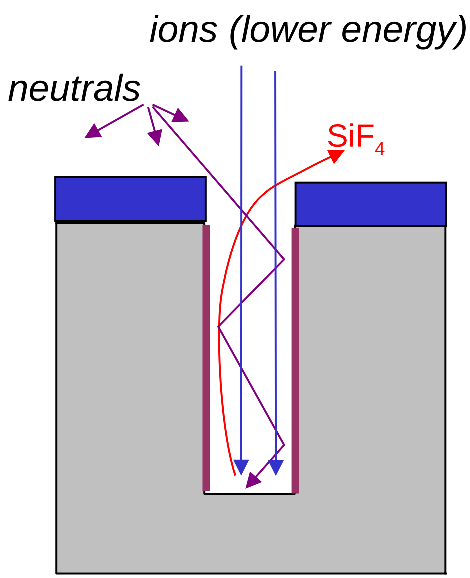
Anisotropy, selectivity, removal of etch products

Chemical etching:
selective, fast, good removal of etch products, but no anisotropy

Physical sputtering:
anisotropic, but not very selective, slow and problems with removal of etch products







Chemical sputtering (ideal case):
Selective (mask not etched)
Fast (neutral chemistry + ion damage)
Good removal of etch products (volatile)
Anisotropy (directed ions):
effect only at the bottom of the trench,
side walls passivated → (almost) no etching

Conclusions

RUB

Plasma is a unique tool for surface modification

- provides reactive radical species with high reactivity at the surface
- provides energetic ions → essential for selective and anisotropic etching
- allows film growth at low substrate temperatures

Surface processes are determined by

- the fluxes of incoming species (including their energy and angular distribution)
- the state of the surface (temperature, composition roughness, passivation…)
- synergistic mechanisms between different species at the surface

Surface processes can be analyzed in

- particle beam experiments
- time resolved experiments (modulation of plasma, afterglow decay)
- time resolved measurement of surface properties (IR absorption, isotopic studies)
- spinning wall experiments, rotating substrate experiments
- well/cavity experiments
- molecular dynamic simulations, TRIM simulations
- …

Further reading

K. W. Kolasinski, *Surface Science*, John Wiley & Sons Ltd., 2002

A. Zangwill, ‘Physics at surfaces’, Cambridge Univ. Press, 1988

M. Nastasi, J.W. Mayer, J.K. Hirvonen, *Ion-solid interactions: Fundamental and applications*. Cambridge University Press,1996

F.F. Chen, J.P. Chang, *Lecture Notes on Principles of Plasma Processing* http://www.ee.ucla.edu/~ffchen/Publs/Chen208i.pdfc

W. Eckstein, *Computer Simulation of Ion Solid Interactions*. Springer Series in Materials Science, Berlin and Heidelberg, 1st edition, 1991.

P. Sigmund. Sputtering by ion bombardment: Theoretical concepts. In R. Behrisch, editor, *Sputtering by Particle Bombardment I*, pages 9-71. Springer, Berlin, 1981.

J.W. Coburn, H. Winters, JVSTA16, 391 (1979)