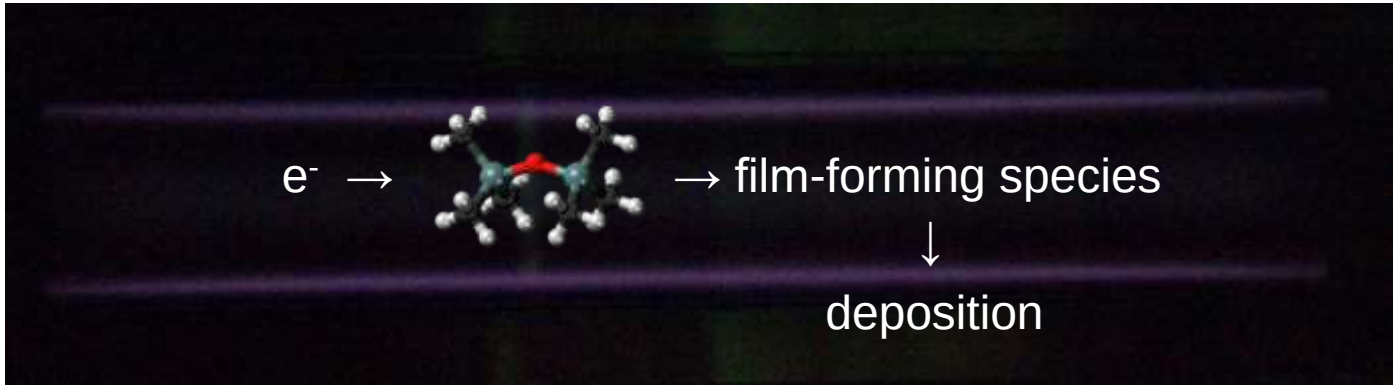
*International Online Plasma Seminar (IOPS) 1/2021*
*Tutorial/Review*
*Virtual, May 6, 2021*

Empa
Materials Science and Technology

# Plasma Polymerization in Industrial Applications

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# Empa

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Materials Science and Technology

## Swiss Federal Laboratories for Materials Science and Technology

Research institute
of ETH domain
3 sites
1000 employees

**St.Gallen**
Functional Materials
Life Sciences

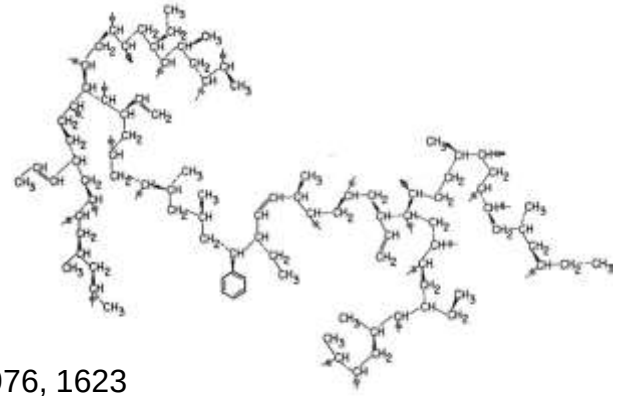
# Motivation

## Plasma polymerization

Conversion of ‘monomer’ gas molecules into film-forming species ***via gas phase processes*** yielding plasma polymer films (PPFs) involving ***surface processes***

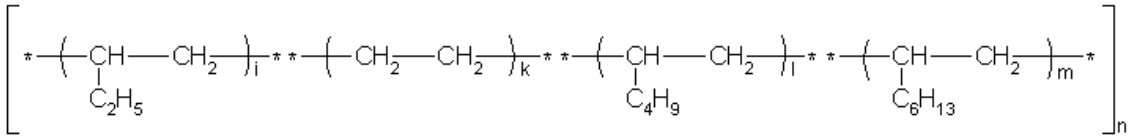
$C_2H_4$ plasma
at 250 Pa
($n_{max}$ ≈ 6 - 10)

→ highly branched PPF

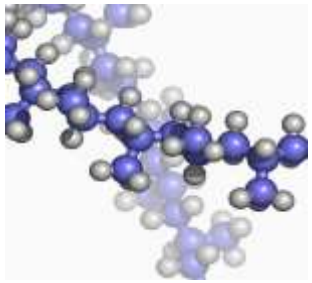


J.M. Tibbitt et al.,
*J. Macromol. Sci. Chem. A* 10, 1976, 1623

Succeeds in polymerizing monomer units also at ***low pressure***, including organic molecules characterized by ***saturated bonds*** – unlike conventional (chain-growth) polymerization

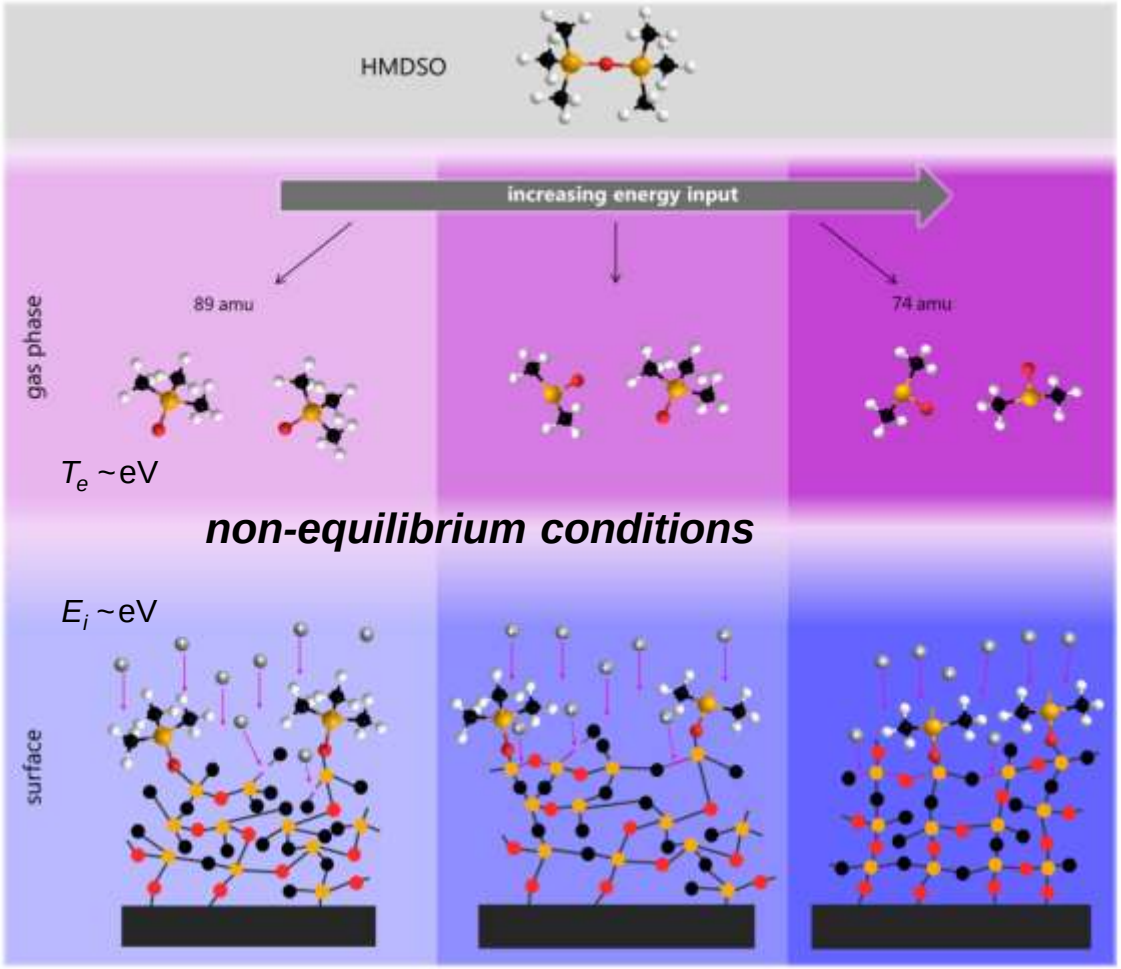



linear low density polyethylene (n ≈ 10‘000 - 100‘000)



# Motivation

## Plasma polymerization – gas phase + surface processes




‘monomer’
e.g. hexamethyldisiloxane
+ inert and reactive gases

**film-forming species**
*energy per monomer molecule*
excitation, dissociation

**sticking probability**
*energy per condensed species*
ablation/densification

gas phase + surface processes

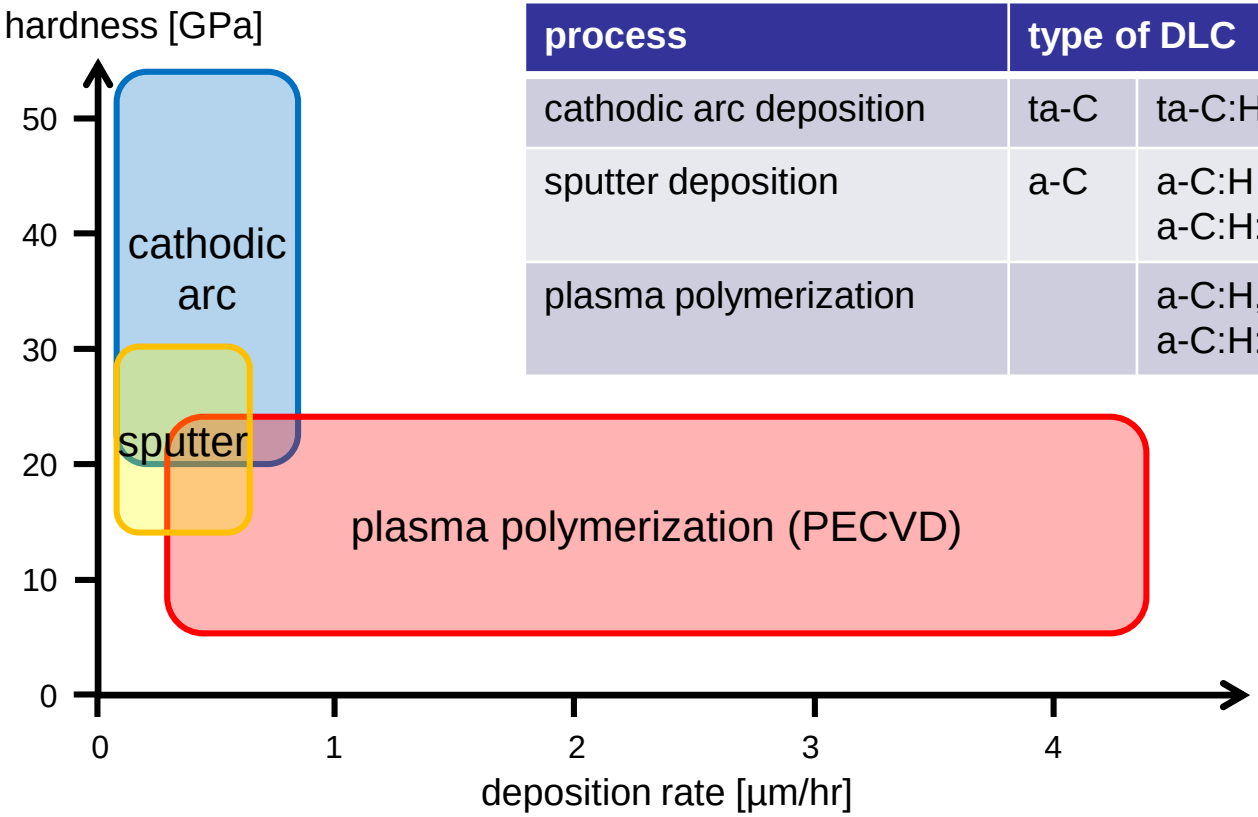
**PPF properties**

N.E. Blanchard, D. Hegemann et al. *Plasma Process. Polym.* 12 (2015) 32

# Motivation

## Field of industrial applications for plasma coatings

### Diamond-like carbon (DLC) coatings




| process | type of DLC | | hardness | surface |
|---|---|---|---|---|
| cathodic arc deposition | ta-C | ta-C:H | 20-55 GPa | rough |
| sputter deposition | a-C | a-C:H<br>a-C:H:Me | 15-30 Gpa<br><10 GPa | smooth |
| plasma polymerization | | a-C:H,<br>a-C:H:Si | 5-25 GPa | smooth |

→ **higher deposition rates by plasma polymerization**

H. Tamagaki, PSE2016

# Motivation

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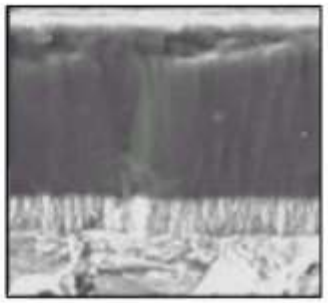
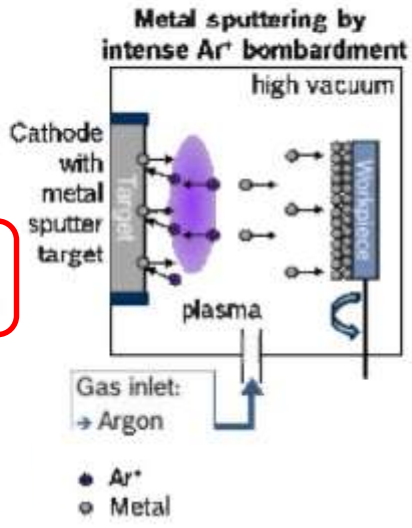
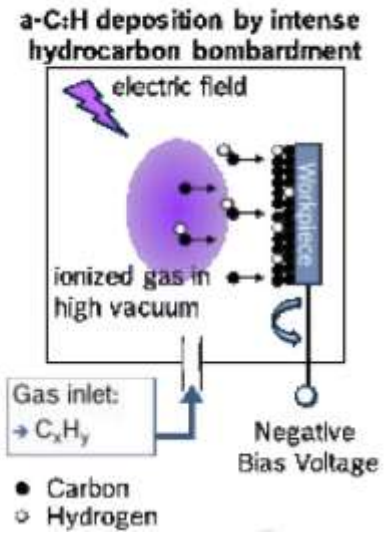
## Field of industrial applications for plasma coatings

### PLASMA APPLICATIONS @ BOSCH
### PROCESS STEPS OF DLC COATING

- Loading the vessel with components and evacuation
- Plasma Etching — Cleaning process by low pressure plasma
- Adhesion Layer — PVD (Physical Vapor Deposition)
- Transition Layer — Combination of PVD and PECVD (Plasma Enhanced Chemical Vapor Deposition)
- Functional Layer (~1-2 µm) — PECVD: Mainly ion bombardment determines the DLC properties
- Venting of vessel and unloading






Matthias Müller, ROBERT BOSCH MANUFACTURING SOLUTIONS GMBH
*PLASMA GERMANY Frühjahrssitzung April 2019, Karlsruhe*

BOSCH

# Motivation

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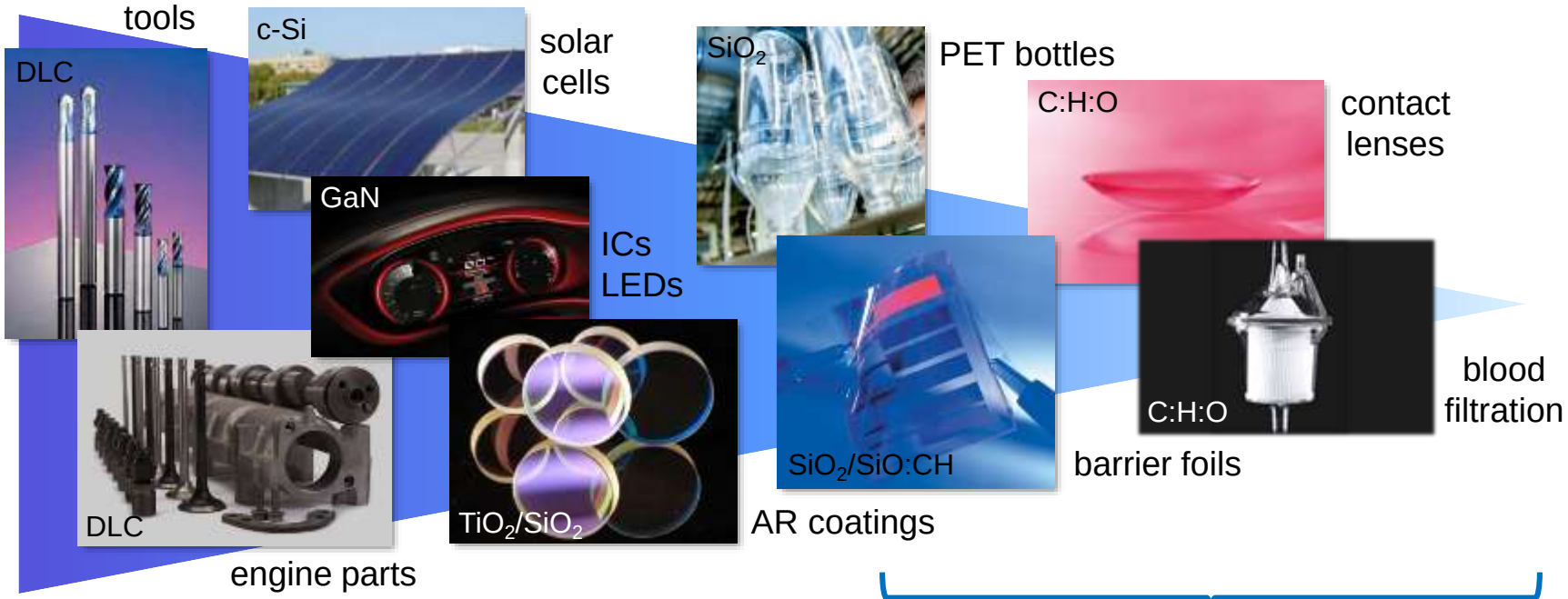
## Field of industrial applications for plasma polymer films (PPFs)

hard coatings / semiconductors / optical coatings / barrier coatings / functional coatings




→ predominantly inorganic coatings
(dominated by conditions at film growth)

’polymer-like’ PPFs

→ **control of gas phase and surface conditions required**

# Outline

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## Plasma Polymerization in Industrial Applications

- Plasma polymerization mechanism
  → coupling of microscopic and macroscopic parameters
  → specific energy input and energy transfer
  → production of film-forming species

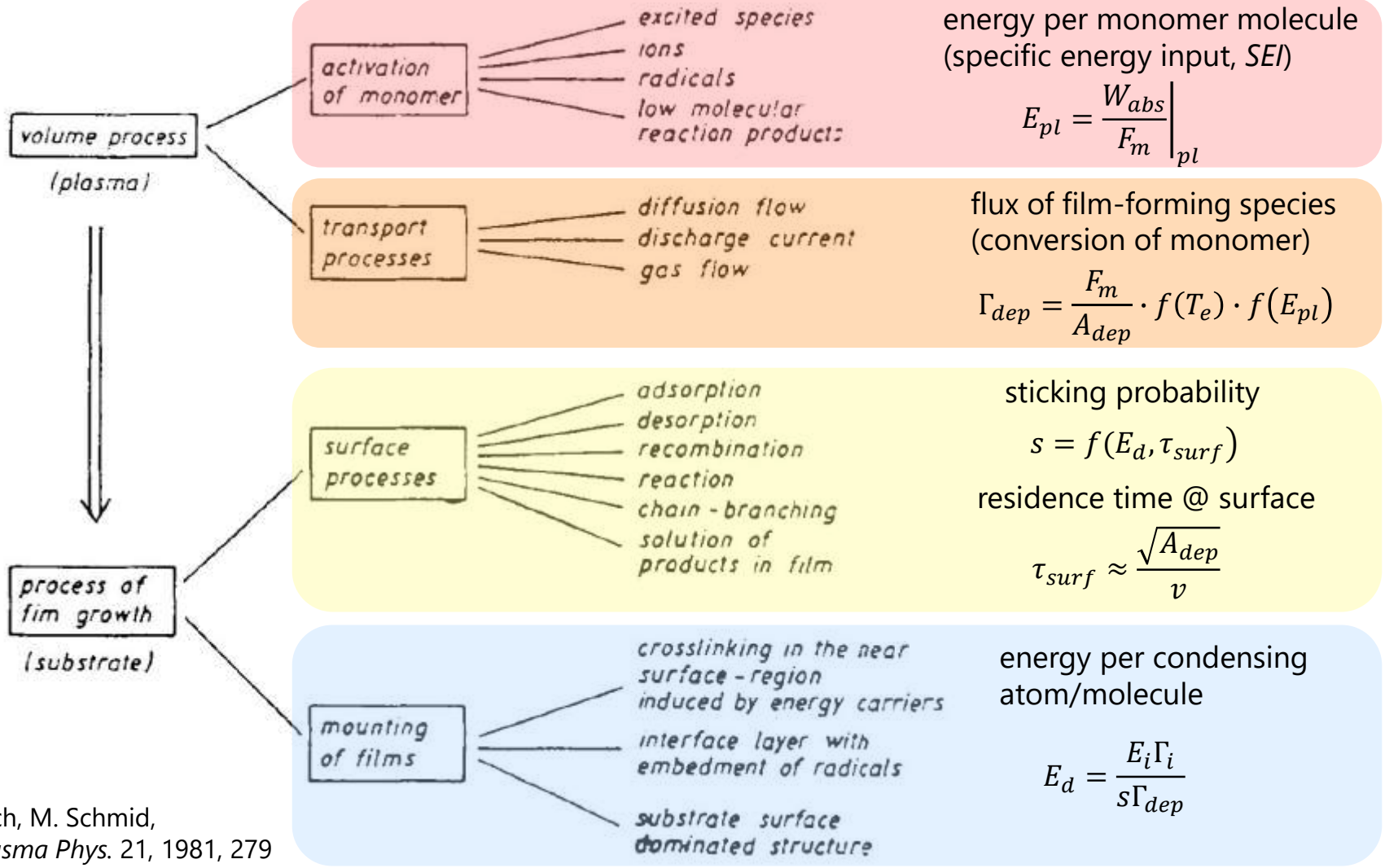
- Gas phase and surface processes
  → control of film properties

- Monomers: HMDSO, hydrocarbons (+ reactive gases)
  → plasma polymer films for industrial applications

- Economic robust processing for diverse industrial applications
  → ’simple’ process optimization and control

# Plasma Polymerization

## Involved steps and some related governing equations




energy per monomer molecule (specific energy input, *SEI*)

$$E_{pl} = \left.\frac{W_{abs}}{F_m}\right|_{pl}$$

flux of film-forming species (conversion of monomer)

$$\Gamma_{dep} = \frac{F_m}{A_{dep}} \cdot f(T_e) \cdot f\left(E_{pl}\right)$$

sticking probability

$$s = f(E_d, \tau_{surf})$$

residence time @ surface

$$\tau_{surf} \approx \frac{\sqrt{A_{dep}}}{v}$$

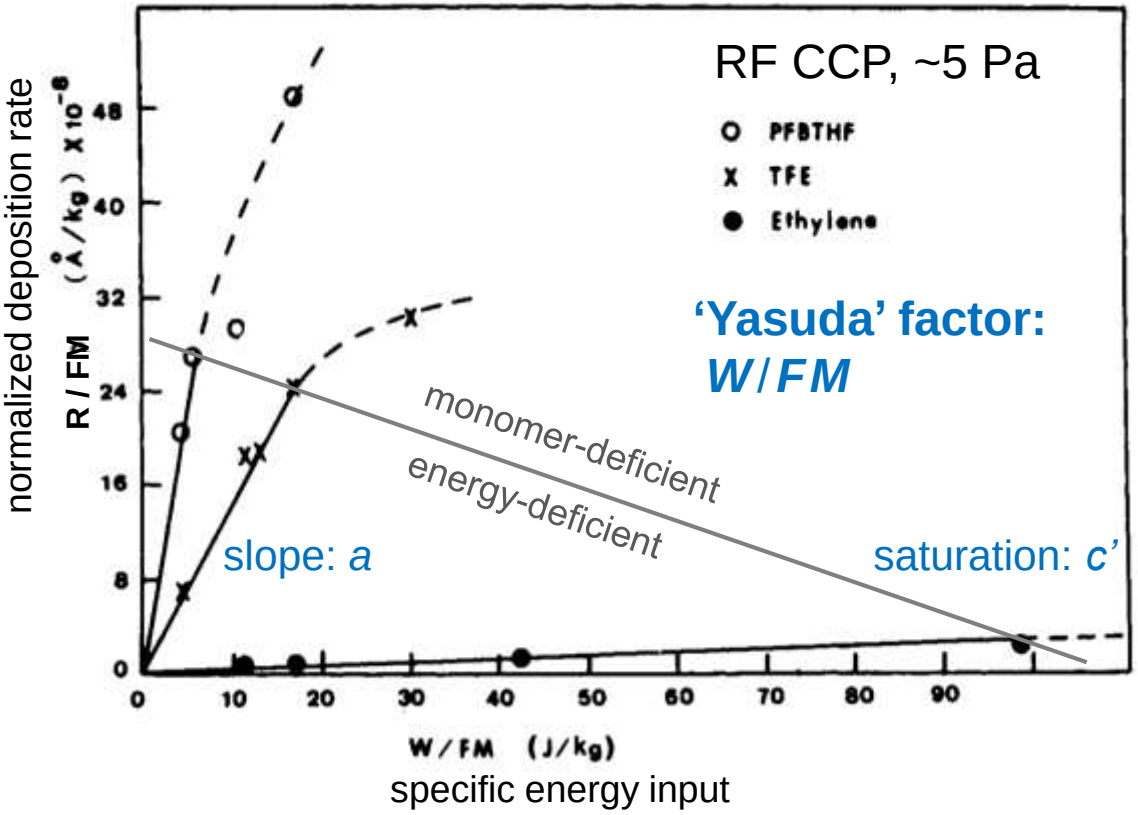
energy per condensing atom/molecule

$$E_d = \frac{E_i \Gamma_i}{s \Gamma_{dep}}$$

H. Deutsch, M. Schmid,
*Contr. Plasma Phys.* 21, 1981, 279

# Plasma Polymerization

## Conversion of monomer in gas phase related to deposition rates



Hirotsugu 'Koge' Yasuda
1930-2018

observed deposition rate, *R*, in *energy-deficient* regime

$$R = a \cdot W$$

in *monomer-deficient* regime at saturation

$$R = c' \cdot FM$$

*W*: power input; *F*: gas flow rate
*M*: molecular mass of monomer


**H. Yasuda**, C.R. Wang, *J. Polym. Sci., Polym Chem. Ed.* 23, 1985, 87
A.K. Sharma, **H. Yasuda**, *Thin Solid Films* 110, 1983, 171
**H. Yasuda**, T. Hirotsu, *J. Polym. Sci., Polym. Chem. Ed.* 16, 1978, 313

# Plasma Polymerization

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## Hydrophilic plasma polymer films on contact lenses – industrial application

**C:H:O plasma polymer** ($CH_4$ + air 1:2, 5 Pa) → ca. 20 nm

on contact lenses made of silicone hydrogel

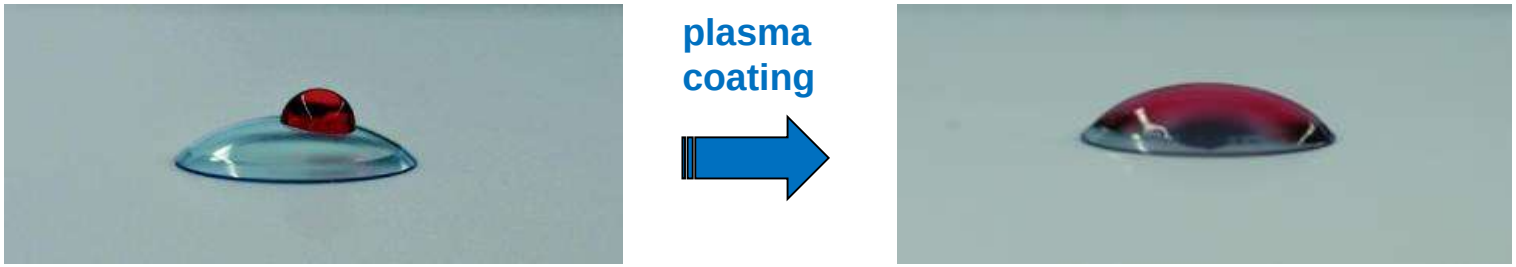



photo: Diener Electronic

→ vertical gradient by interphase formation (ablation vs. deposition)

→ improved wettability and breathability (wearing comfort)

→ cost efficient production (compared to wet-chemical treatment):

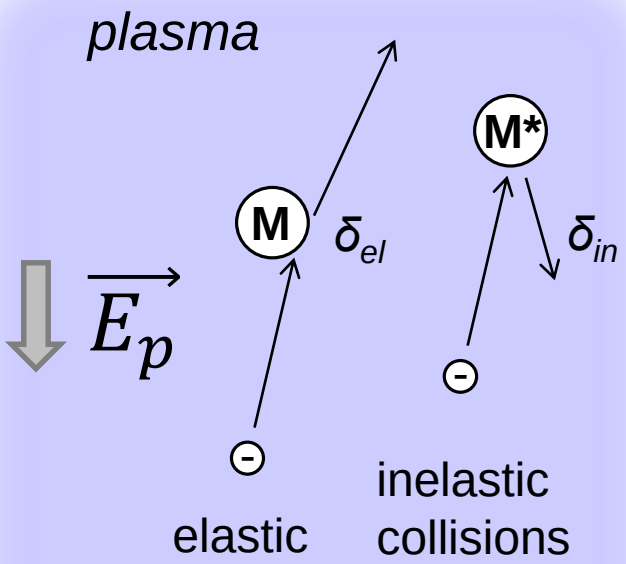
400 contact lenses per run (total processing time of 4 min)

→ 30 Mio CL per year (1 Eurocent per CL vs. 2 Eurocent wet-chemically)

Based on «H. Yasuda, *Plasma Process. Polym.* 2, 2005, 507» by considering some corrections

# Plasma Polymerization

## Energy transfer via electrons in the electric field of the plasma




frequency of field $\omega$

energy transfer coefficient $\delta_{el} << \delta_{in}$

electron temperature $T_e >> T_{gas}$

mass of molecules $M >> m_e$

average power absorbed per electron (in [W])

$$\theta_{abs} = \frac{e^2 {E_p}^2 \nu}{2m_e(\nu^2 + \omega^2)} = \bar{\varepsilon}\,\delta\,\nu$$

$$T_e = \frac{2\bar{\varepsilon}}{3e} \text{ (in [eV])}$$

$\bar{\varepsilon}$ : mean electron energy  $\delta$ : energy transfer coefficient

average electron collision frequency

$$\nu = N \cdot \underbrace{\langle \sigma(v_e) \cdot v_e \rangle}_{\text{rate coefficient, } k}$$

$N$ : particle density
$\sigma$ : cross-section
$v_e$ : electron velocity

total absorbed power of electrons (in [W cm$^{-3}$])

$$P_{abs} = n_e \theta_{abs} = n_e \bar{\varepsilon}\,\delta\,\nu \equiv \frac{W_{abs}}{V_{pl}}$$

*absorbed power per plasma volume*

*coupling of microscopic and macroscopic plasma parameters*

M. Moisan, J. Pelletier, *Physics of Collisional Plasmas*, Springer, Dordrecht, NL, 2012

# Plasma Polymerization

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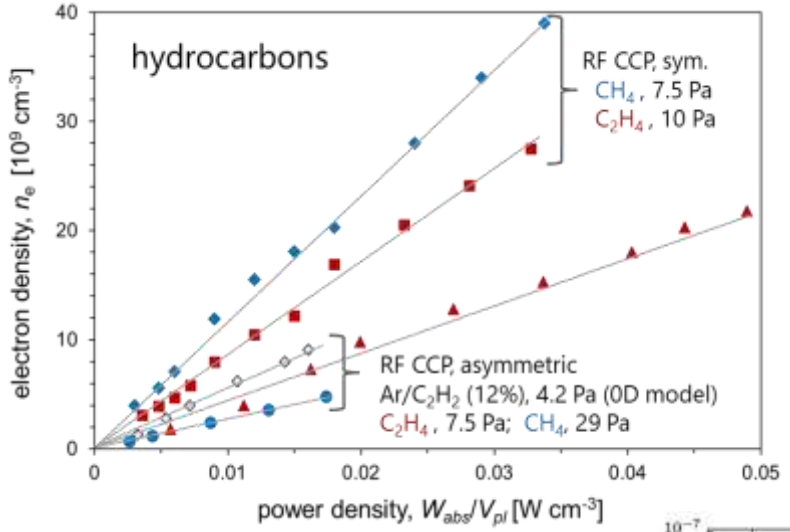
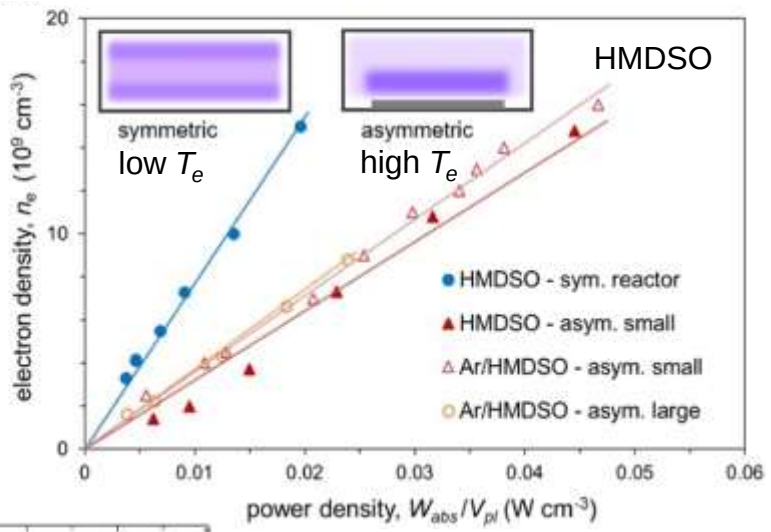
## Coupling of microscopic and macroscopic plasma parameters

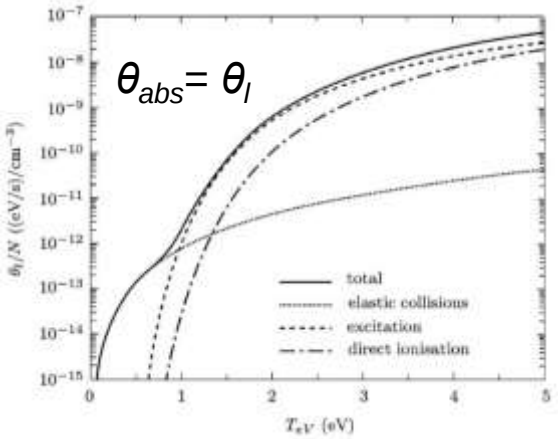
Electron density proportional to absorbed power density for many monomers




$$n_e = (\theta_{abs})^{-1} \frac{W_{abs}}{V_{pl}}$$

$\theta_{abs}$ only depends on $N$ and $T_e$ (i.e. on pressure)



- capacitive coupled discharge
- symmetric configuration
- radio frequency (13.56 MHz)

# Plasma Polymerization

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## Simplified model for the production of film-forming species in the gas phase

One averaged reaction pathway yielding activation reactions: $\nu \rightarrow \bar{\nu}_a$

→ reaction rate:

$$\frac{dn_a}{dt} = n_e \bar{\nu}_a = n_e n_m k_a$$

**Conversion of monomer into film-forming species:**

$$c_a = \frac{\tau_{act}}{n_m}\frac{dn_a}{dt} = \tau_{act}\frac{n_e}{n_m}\bar{\nu}_a = \tau_{act} n_e k_a$$

residence time in plasma:

$$\tau_{act} = \frac{V_{pl}}{F_m} n_m \frac{kT_0}{p_0}$$

$$n_e \theta_{abs} = \frac{W_{abs}}{V_{pl}}$$

$$c_a = \frac{W_{abs}}{F_m}\frac{kT_0}{p_0}\frac{\bar{\nu}_a}{\theta_{abs}} = eE_{pl}\frac{\bar{\nu}_a}{\theta_{abs}}$$

Specific Energy Input (*SEI*):

$$E_{pl} = \frac{kT_0}{ep_0}\frac{W_{abs}}{F_m}$$

available energy * number of molecules converted per energy

fraction of transferred energy to activation channels with threshold energy ($E_{pl} \leq E_{th}$):

$$\theta_{l,a} = \alpha\, \theta_{abs} \approx \alpha \sum_m \nu_m\, eE_m = \bar{\nu}_a\, eE_{th}$$

sum of excitation/dissociation reactions

$$c_a = \alpha \frac{E_{pl}}{E_{th}}$$

$$\alpha(T_e) = \frac{\theta_{l,a}}{\theta_{abs}} < 1$$

(operational parameters)

# Plasma Polymerization

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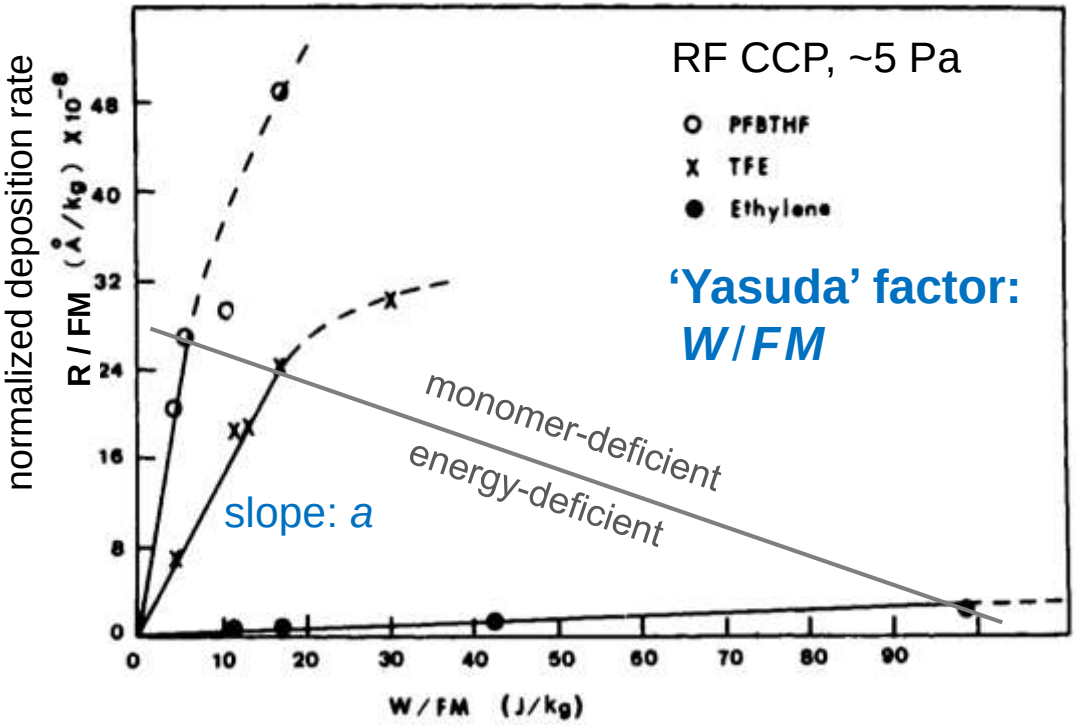
## Conversion of monomer in gas phase related to deposition rates

$$R/\cancel{F_m} = s\frac{M_{dep}}{N_A A_{dep}}\frac{p_0}{kT_0}c_a = s\frac{M_{dep}}{N_A A_{dep}}\frac{\alpha}{eE_{th}}\frac{W_{abs}}{F_m} = a(T_e)\frac{W_{abs}}{\cancel{F_m}} \qquad \text{for } E_{pl} \le E_{th}$$

*s*: sticking probability; $M_{dep}$: mass of deposited species; $A_{dep}$: deposition area




Yasuda (1976-1985)

$$R = a \cdot W$$

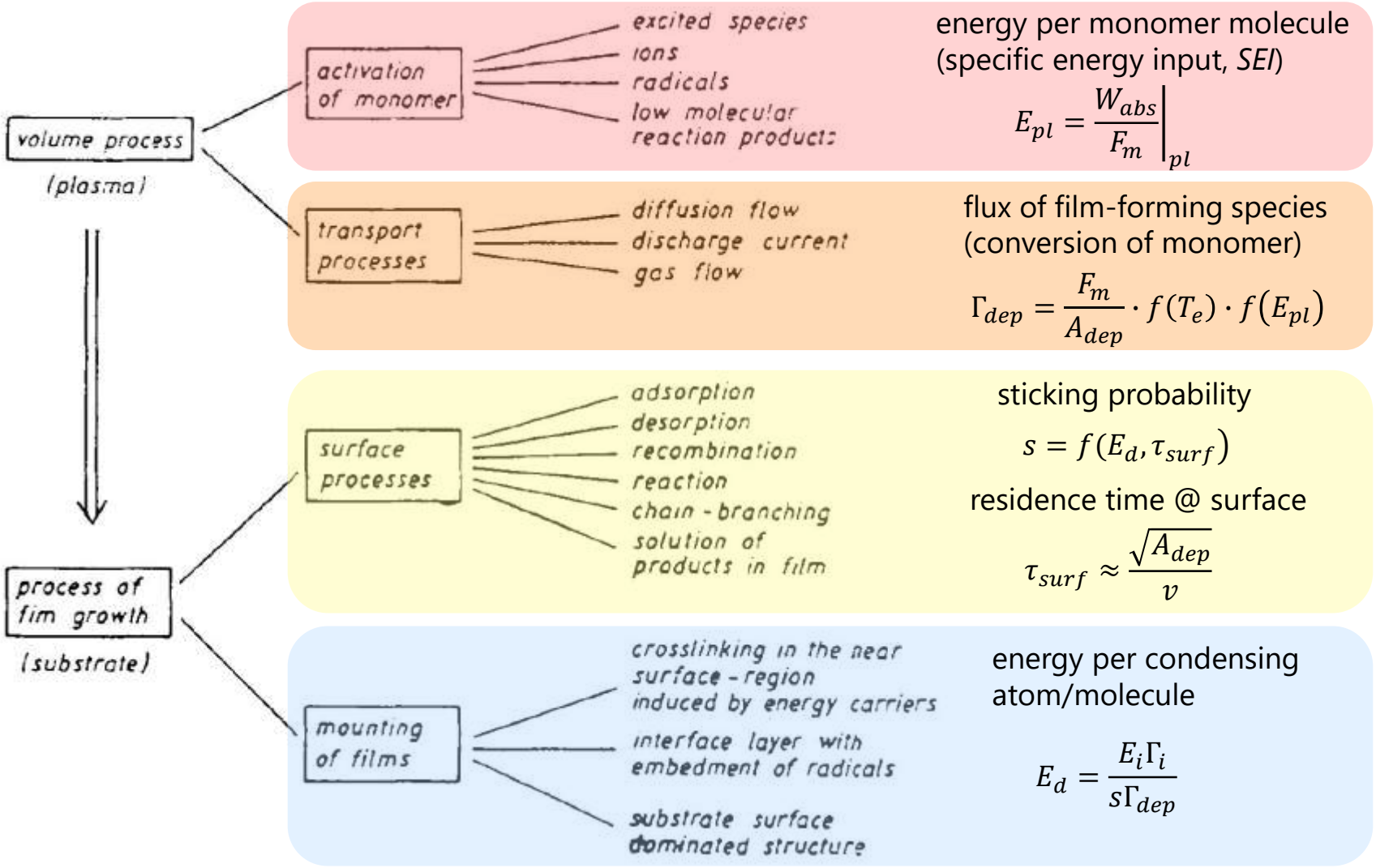
observed deposition rate, *R*, in *energy-deficient* regime

**'plasma-state polymerization'**

activation in the plasma is considered as the essential step (reaction kinetics-limited)

# Plasma Polymerization

## Involved steps and some related governing equations




energy per monomer molecule (specific energy input, *SEI*)

$$E_{pl} = \left.\frac{W_{abs}}{F_m}\right|_{pl}$$

flux of film-forming species (conversion of monomer)

$$\Gamma_{dep} = \frac{F_m}{A_{dep}} \cdot f(T_e) \cdot f\left(E_{pl}\right)$$

sticking probability

$$s = f(E_d, \tau_{surf})$$

residence time @ surface

$$\tau_{surf} \approx \frac{\sqrt{A_{dep}}}{v}$$

energy per condensing atom/molecule

$$E_d = \frac{E_i \Gamma_i}{s \Gamma_{dep}}$$

# Surface Processes

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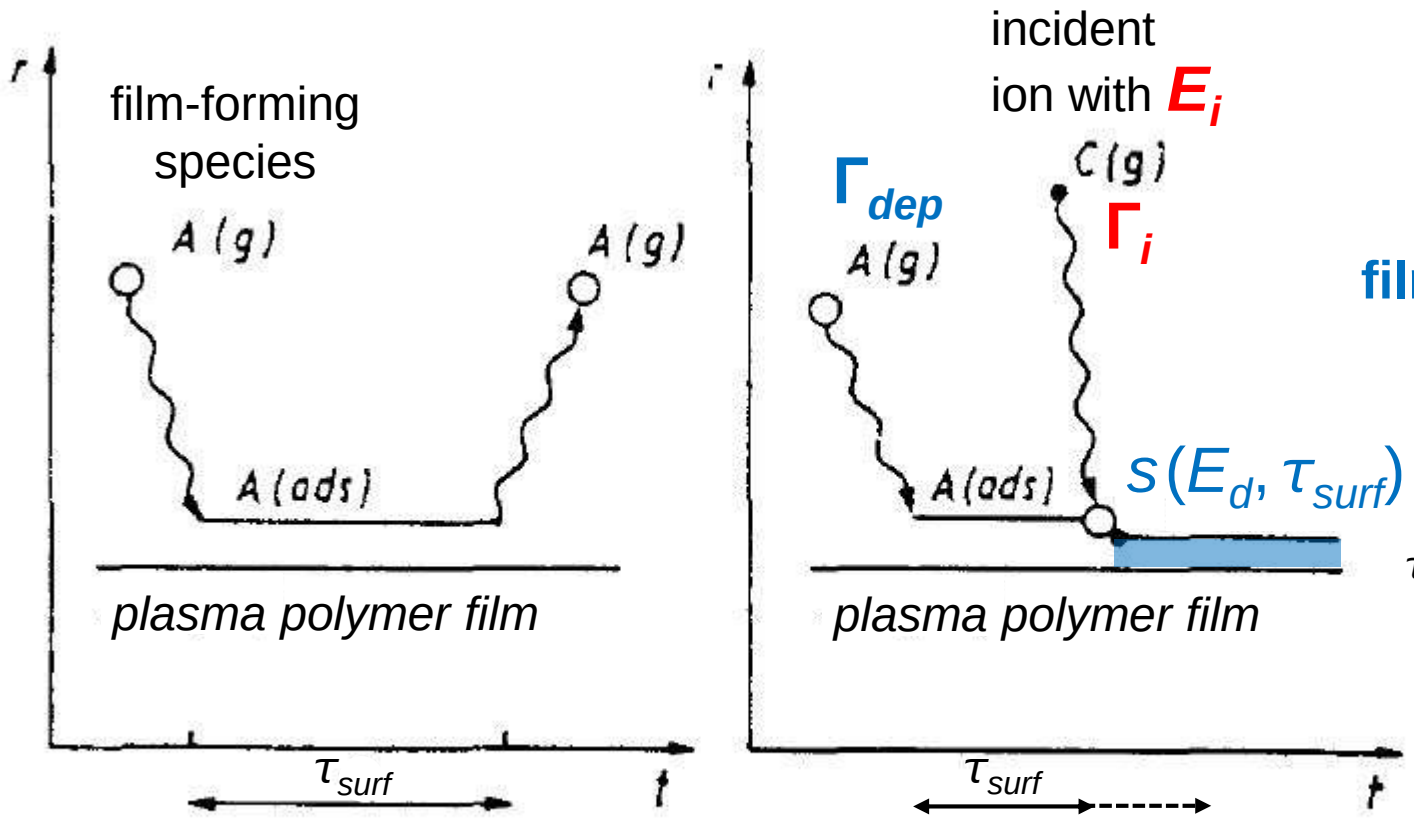
## Sticking probability *s* – depending on residence time and deposited energy




**energy flux**

$E_i \cdot \Gamma_i$

**film growth rate**

$s \cdot \Gamma_{dep}$

$\tau_{surf}$ : residence time (at surface)

$E_d$ : energy per condensing atom/molecule

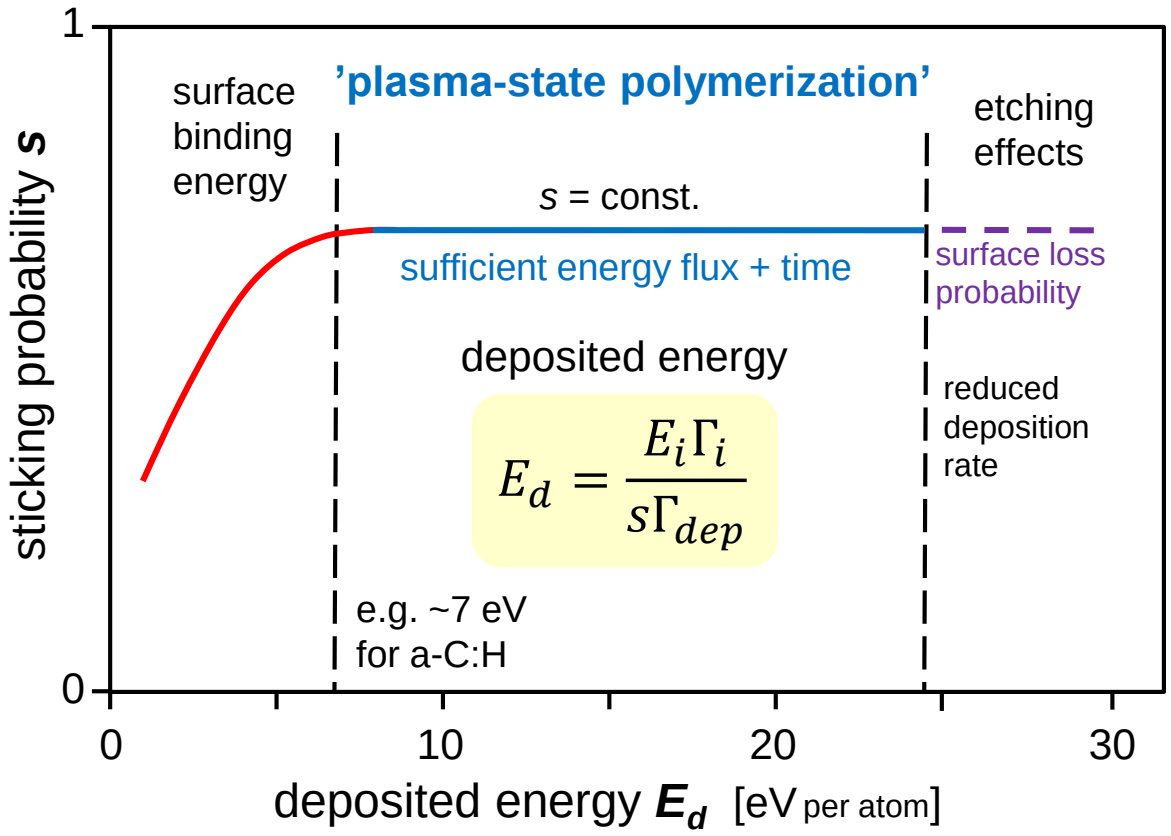
**Fig. 2. Space-time-graph of adsorption/desorption and polymerization**

H. Deutsch, H. Kersten, S. Klagge, A. Rutscher, *Contr. Plasma Phys.* 28, 1988, 149

# Surface Processes

## Sticking probability depending on deposited energy

### AGM *'(ion-) Activated Growth Model'*



Riccardo d'Agostino 1942-2018

Sufficient nucleation sites required that film-forming species get stuck in the growing film

Etching affects film growth (more surface-dominated) → hard coatings (for >25 eV)

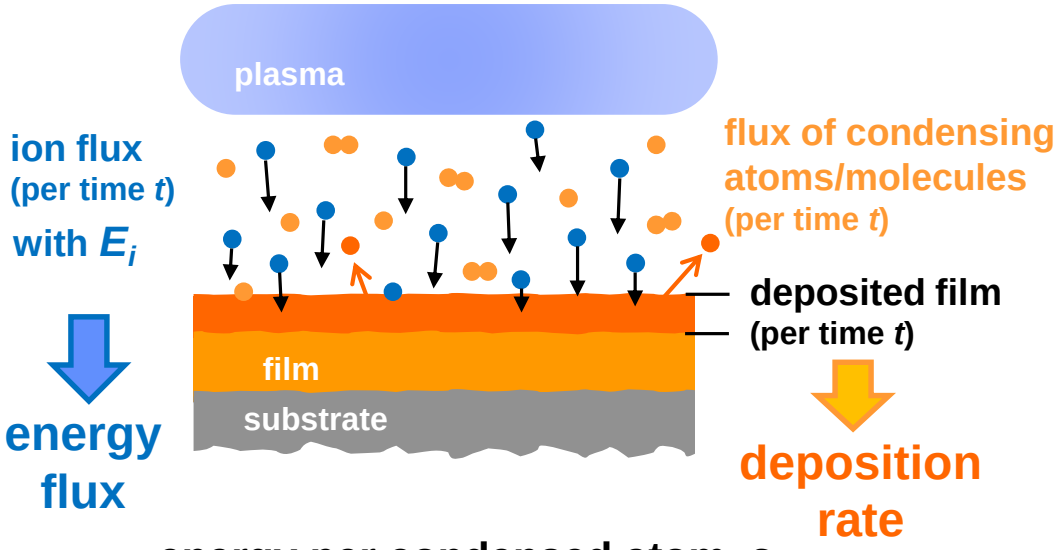
**'induced plasma polymerization'**

activation at the surface is considered as the rate-limiting step

P. Favia, R. Lamendola, **R. d'Agostino**, *Plasma Sources Sci. Technol.* 1, 1992, 59; A. von Keudell et al., *PSST* 9, 2000, 455

# Surface Processes

## Deposited energy – kinetic energy yielding non-equilibrium conditions

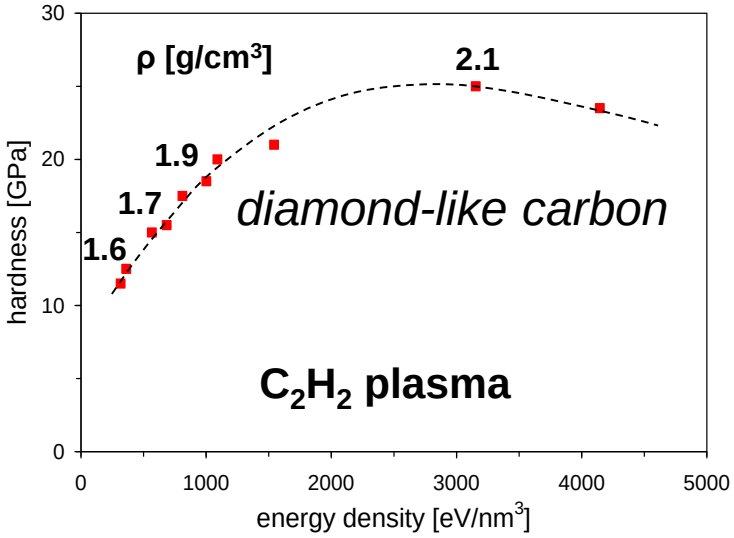



**energy per condensed atom, ε**

$$\varepsilon = E_i \cdot \Gamma_i \,/\, R$$

**(energy flux / deposition rate)**

**hardness of a-C:H depending on ε**




**number of atoms in volume (nm³):**

$$n_{atom} = \rho \frac{N_A}{M_{atom}} \frac{C_{atom} M_{atom}}{C_{atom} M_{atom} + C_i M_i}$$

→ **energy deposited into growing film at highly non-equilibrium conditions**

**e.g. a-C:H (DLC)**

**ρ = 2.1 g/cm³, 25 at% H ($C_i$ = 0.25, $C_{atom}$ = 0.75)**

**→ ~100 C atoms per nm³**

**→ for ε = 3000 eV/nm³: ~30 eV per C**


Y. Koval, *J. Vac. Sci. Technol.* B22 (2004) 843.
S. Engelmann, *Plasma Process. Polym.* 6 (2009).

# HMDSO Plasma Polymerization

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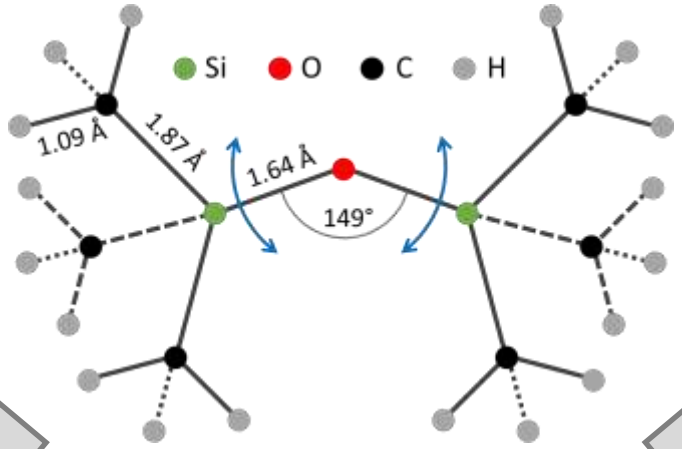
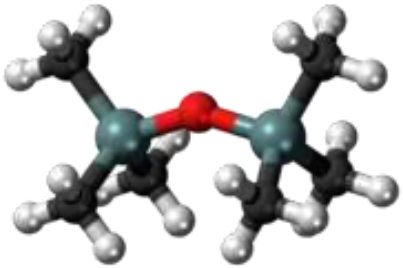
## Versatility, mechanism and applications

hexamethyldisiloxane

$SiO_2C_6H_{18}$



(+Ar)

$E_{pl}$ ↑

$+O_2$

PDMS-like coatings

**water repellence**

nanoporous SiO:CH coatings

**drug delivery**

quartz-like coatings

**barrier coatings**

**biomaterials / protein adsorption / microfluidics / sensors / packagings**

# HMDSO Plasma Polymerization

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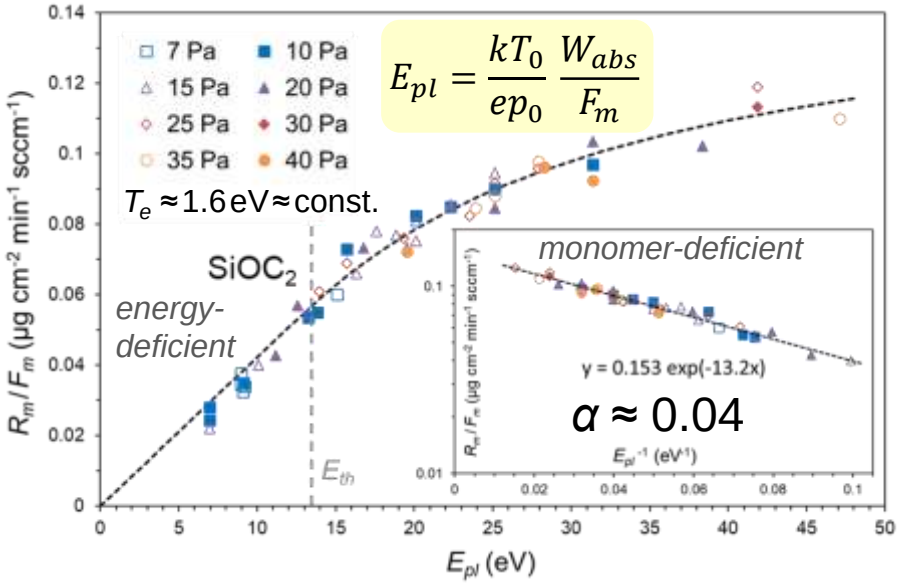
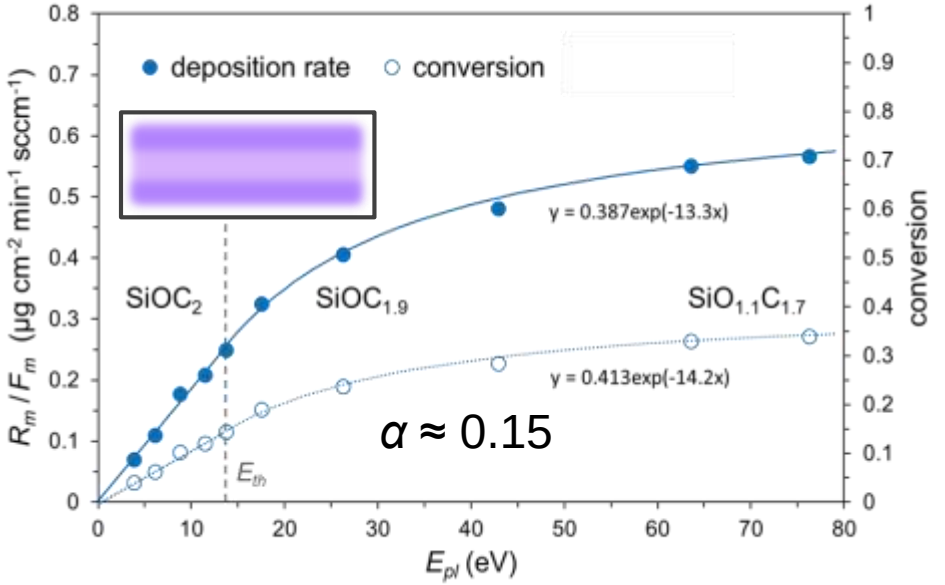
## Evaluation of mass deposition rates, $R_m$, in *energy-* and *monomer-deficient* regime

### RF CCP symmetric large (pure HMDSO)




### RF CCP symmetric small (pure HMDSO)




conversion of monomer into deposit

$$R_m/F_m = s\frac{M_{dep}}{N_A A_{dep}}\frac{p_0}{kT_0}c_a$$

s: sticking probability $M_{dep} \leq 74$ amu

D. Hegemann, **2013**, *J. Phys. D: Appl. Phys.* 46, 205204.

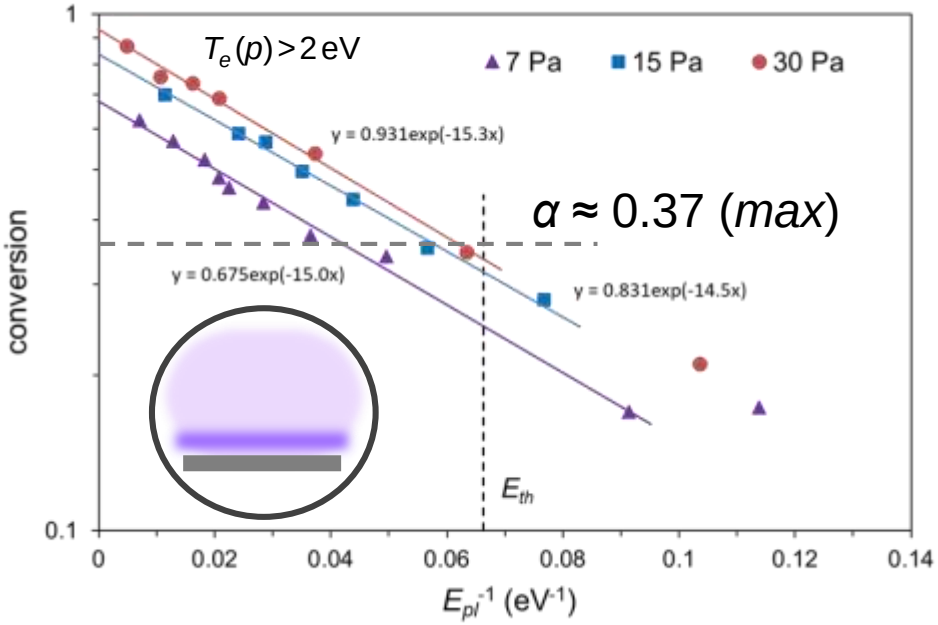
modified Arrhenius approach

$$c_a(E_{pl}) = \begin{cases} \alpha \cdot \frac{E_{pl}}{E_{th}}, & E_{pl} \leq E_{th} \\ \alpha \cdot exp\left(\frac{E_{pl} - E_{th}}{E_{pl}}\right), & E_{pl} > E_{th} \end{cases}$$

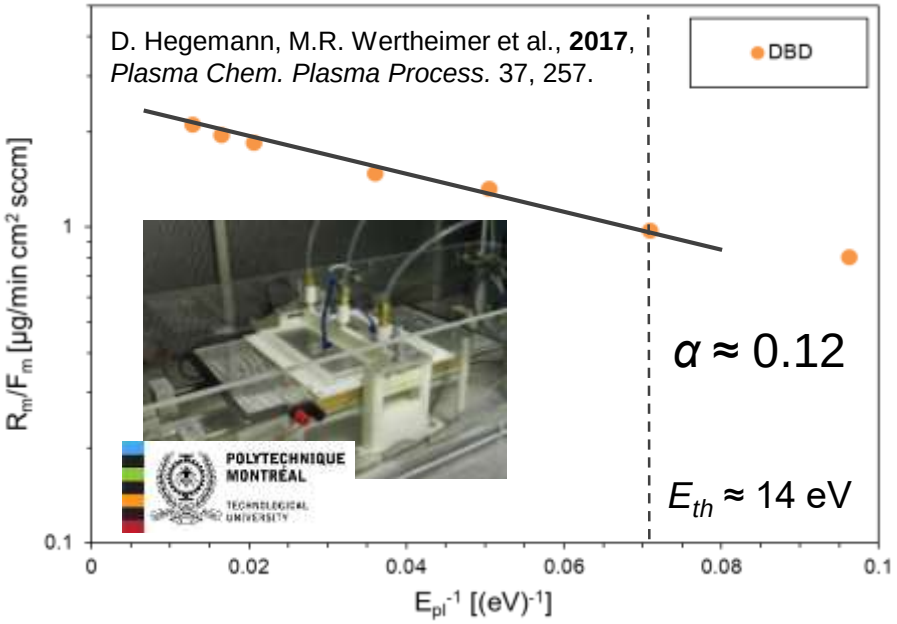
# HMDSO Plasma Polymerization

## HMDSO – conversion, mass deposition rates, and energy threshold, $E_{th}$

RF CCP asymmetric (HMDSO + Ar)




DBD 20 kHz (HMDSO + 10 slm Ar)



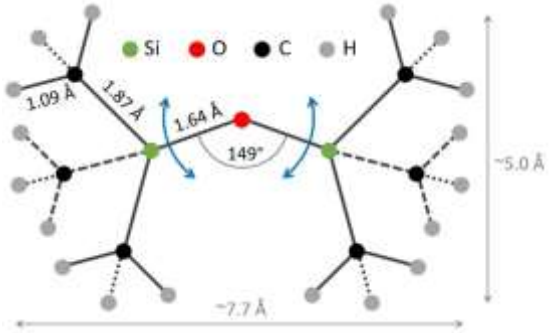

→ **linear increase in $R_m / F_m$ and $c_a$ up to $E_{th}$, Arrhenius behavior for $E_{pl} > E_{th}$**

→ **max. conversion requires s = 1 for film-forming species** (of 74 amu)

→ **$E_{th}$ = 14 ± 1 eV for HMDSO independent of plasma source and pressure**

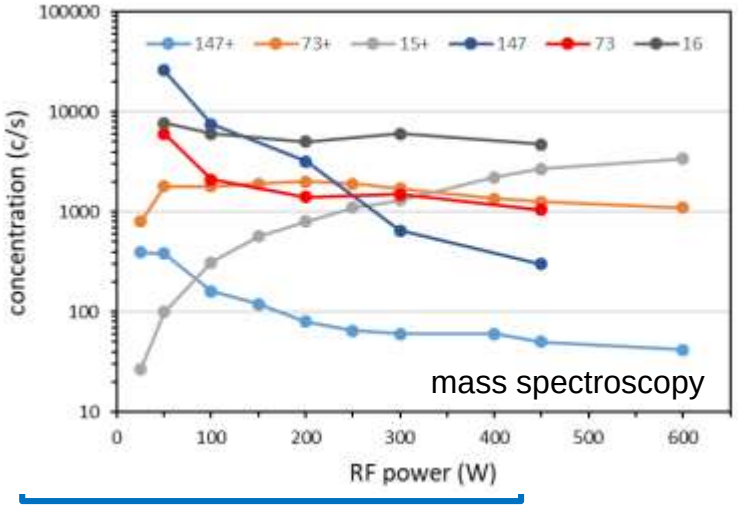
# HMDSO Plasma Polymerization

## HMDSO – proposed plasma chemical reaction pathway




bond strength of Si-$CH_3$ is reduced with Si-Si distance

→ only 147 amu detectable

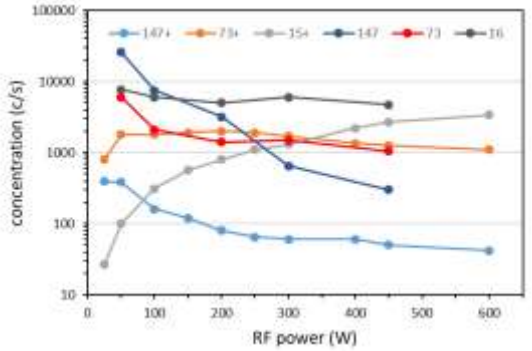



162 amu

$(CH_3)_3Si\text{-}O\text{-}Si(CH_3)_3$

vibr. ex. ***~0.1 eV***

$(CH_3)_3Si\text{-}O\text{-}Si(CH_3)_3$*




*dissociative ionization pathway*

$-CH_3$ ***3-5 eV*** → 147 $(CH_3)_3$*

$-CH_3$ ~10 eV → 147+ $(CH_3)_2Si\text{-}O\text{-}Si^+(CH_3)_3$

73 $-Si(CH_3)_3$ ***3-5 eV*** → **$(CH_3)_2Si\text{-}O$** ***13-15 eV***

73 $-Si(CH_3)_3$ **~6 eV** → $(CH_3)_2Si^+\text{-}O$ ~16 eV

73+ $-Si^+(CH_3)_3$ **~6 eV** → $(CH_3)_2Si\text{-}O$ ~16 eV

74 amu


R. Barni, S. Zanini, C. Riccardi, **2012**, *Advances Phys. Chem.* Vol. 2012, Article ID 205380.

D. Hegemann et al., **2020**, *Plasma Process. Polym.* 18, e2000176.

# HMDSO Plasma Polymerization

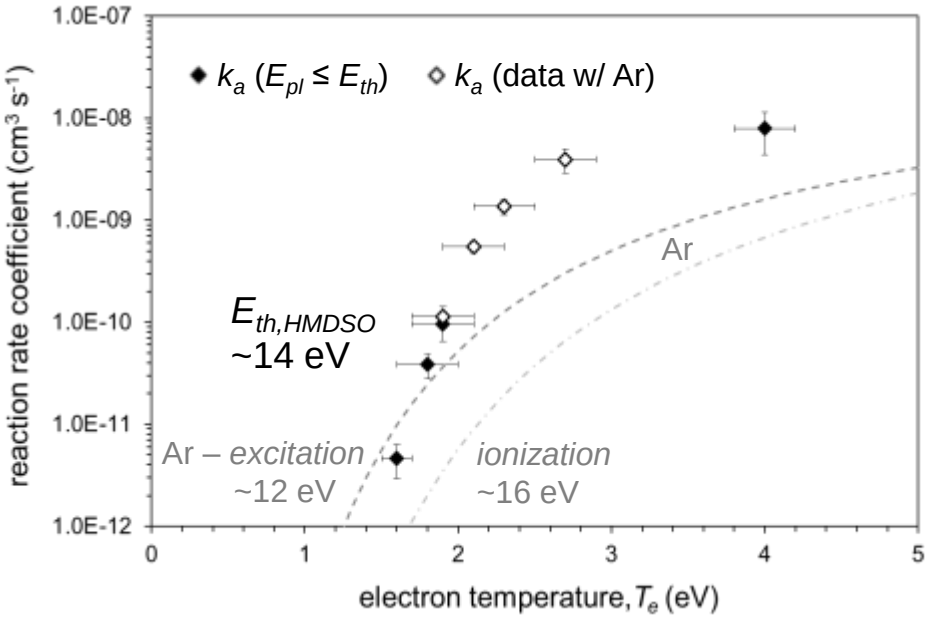
Empa
Materials Science and Technology

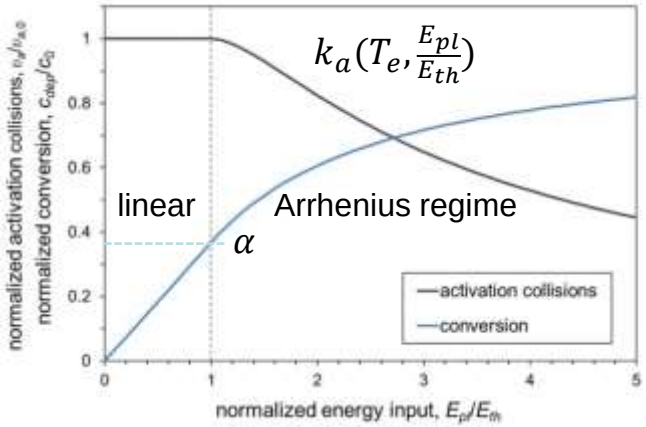
## Reaction rate coefficient for the combined average activation reaction

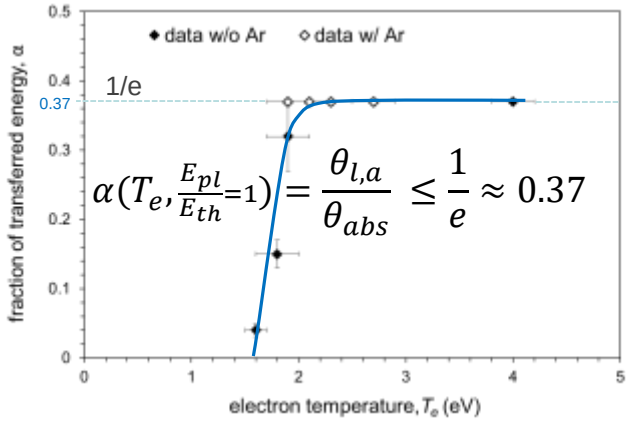
One averaged reaction pathway yielding activation reactions: $\nu \rightarrow \bar{\nu}_a$

$$\bar{\nu}_a = n_m k_a = \alpha(T_e)\frac{\theta_{abs}}{eE_{th}} \quad \text{for } E_{pl} \leq E_{th}$$

*energy-deficient*




D. Hegemann et al., *Plasma Process. Polym.* 18 (2020) e2000176

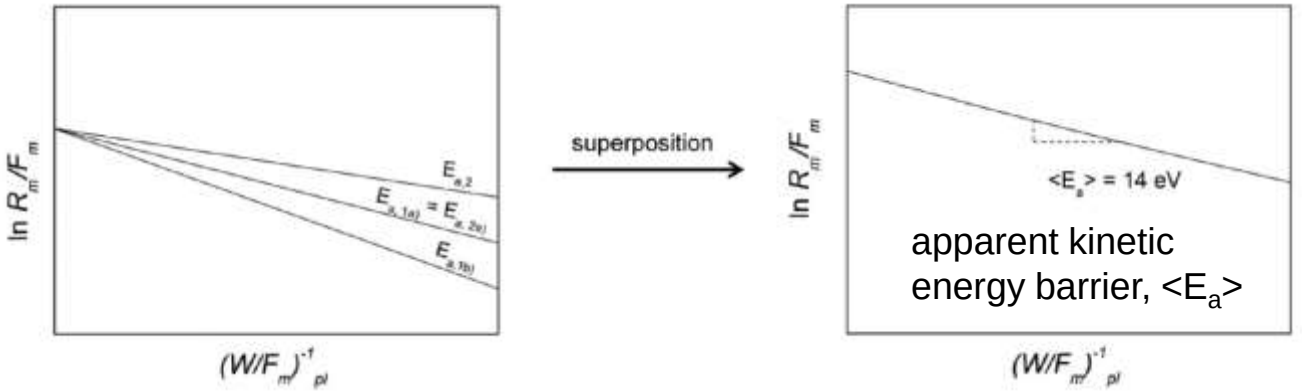
# Plasma Chemistry

## Macroscopic description of plasma-activated reactions in the gas phase

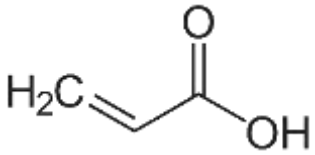
One lumped reaction rate coefficient for activation with corresponding $E_{th}$

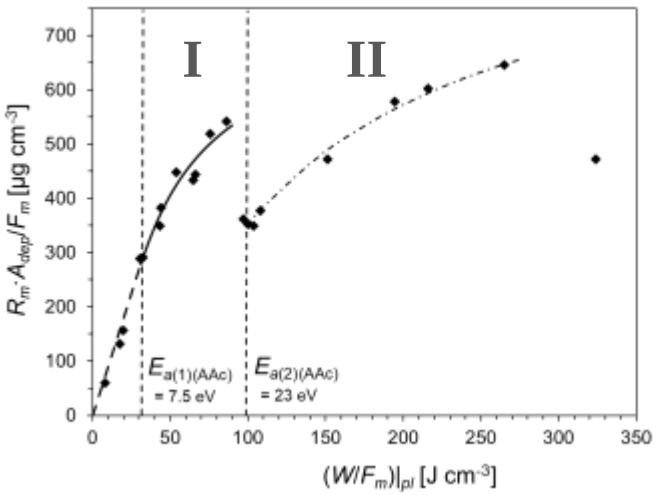
→ use of different
$k_a(T_e, E_{pl}/E_{th})$
for different $E_{th}$

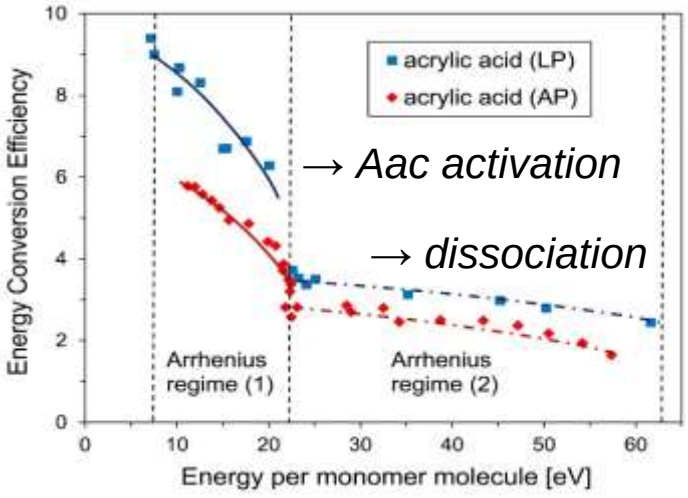
**HMDSO**




**acrylic acid (Aac)**




N. Blanchard et al., *Plasma Process. Polym.* 12 (2015) 32; D. Hegemann, et al., *Plasma Process. Polym.* 13 (2016) 834

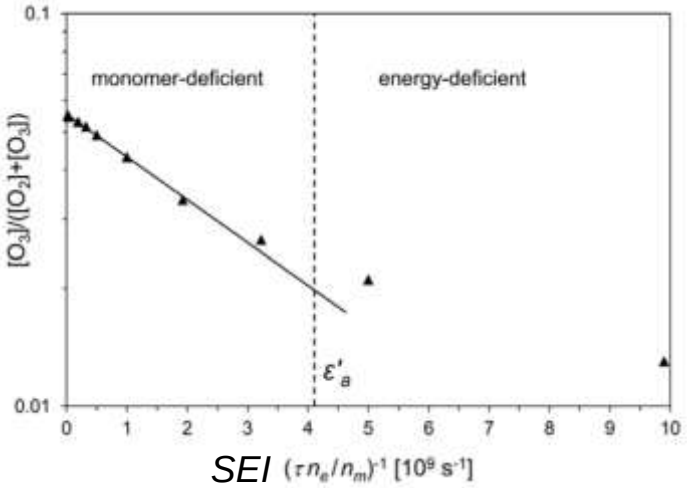
# Plasma Chemistry

Empa
Materials Science and Technology

## Macroscopic description of plasma-activated reactions in the gas phase

Reaction rate coefficients $k_a(T_e, E_{pl}/E_{th})$ according to macroscopic model

ozone generation




Also an interesting approach for plasma-chemical gas conversion?

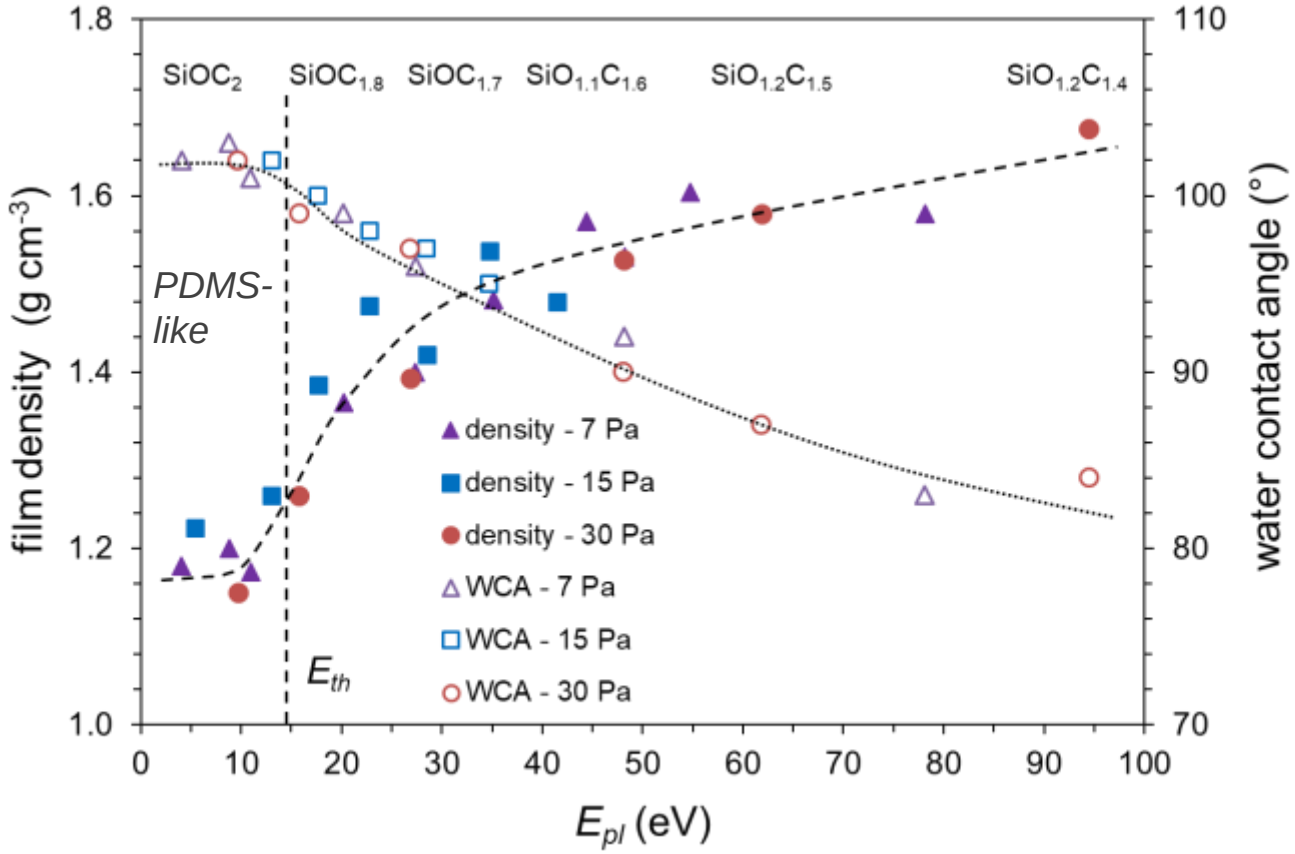
→ optimize conversion and energy efficiency

→ Let's come back to Plasma Polymerization in Industrial Applications…

# HMDSO Plasma Polymerization

Empa
Materials Science and Technology

## Film density and hydrophobicity of HMDSO-derived plasma polymer films




reduced hydrocarbon content
→ $CH_3$ abstraction in gas phase

(post-plasma) O incorporation
→ increased radical density

→ **film density largely scales with energy per monomer particle in gas phase**

→ **plasma-state polymerization through $\cdot(CH_3)_2$–Si–O$\cdot$ bi-radicals**

# Industrial Applications

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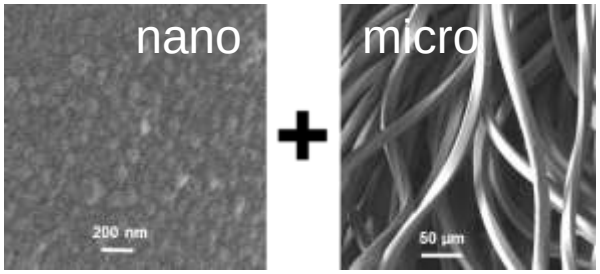
Materials Science and Technology

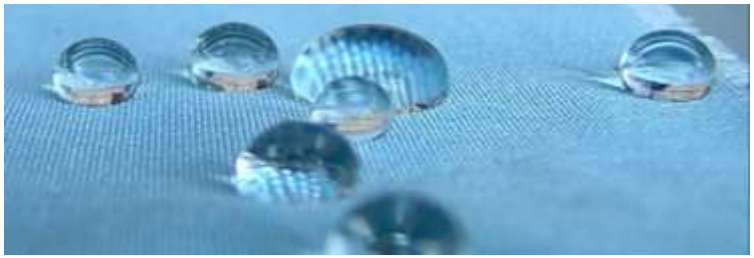
## Hydrophobic PDMS-like plasma polymer films on textiles

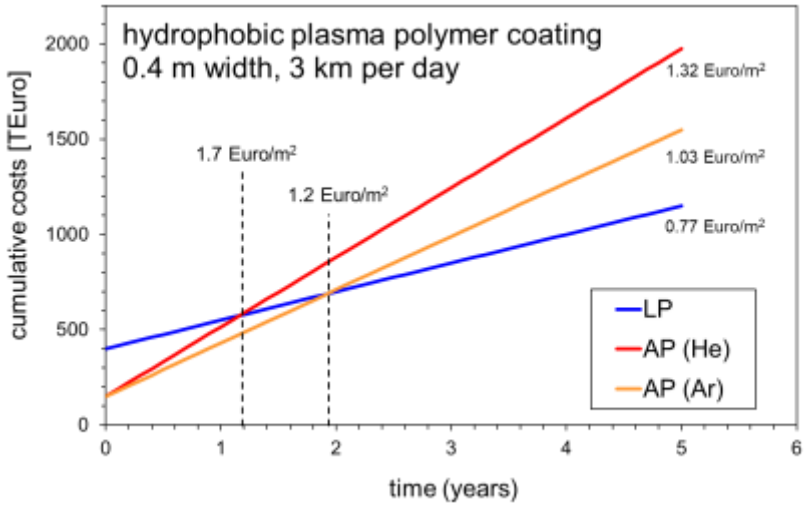
**hardness: ~1 GPa** (crosslinked)
→ **abrasion resistance**

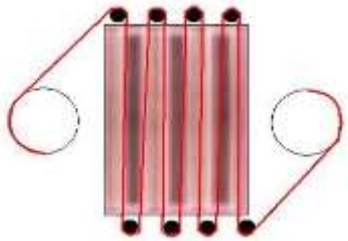
**thickness: <100 nm**

**washing fastness: >30 times**





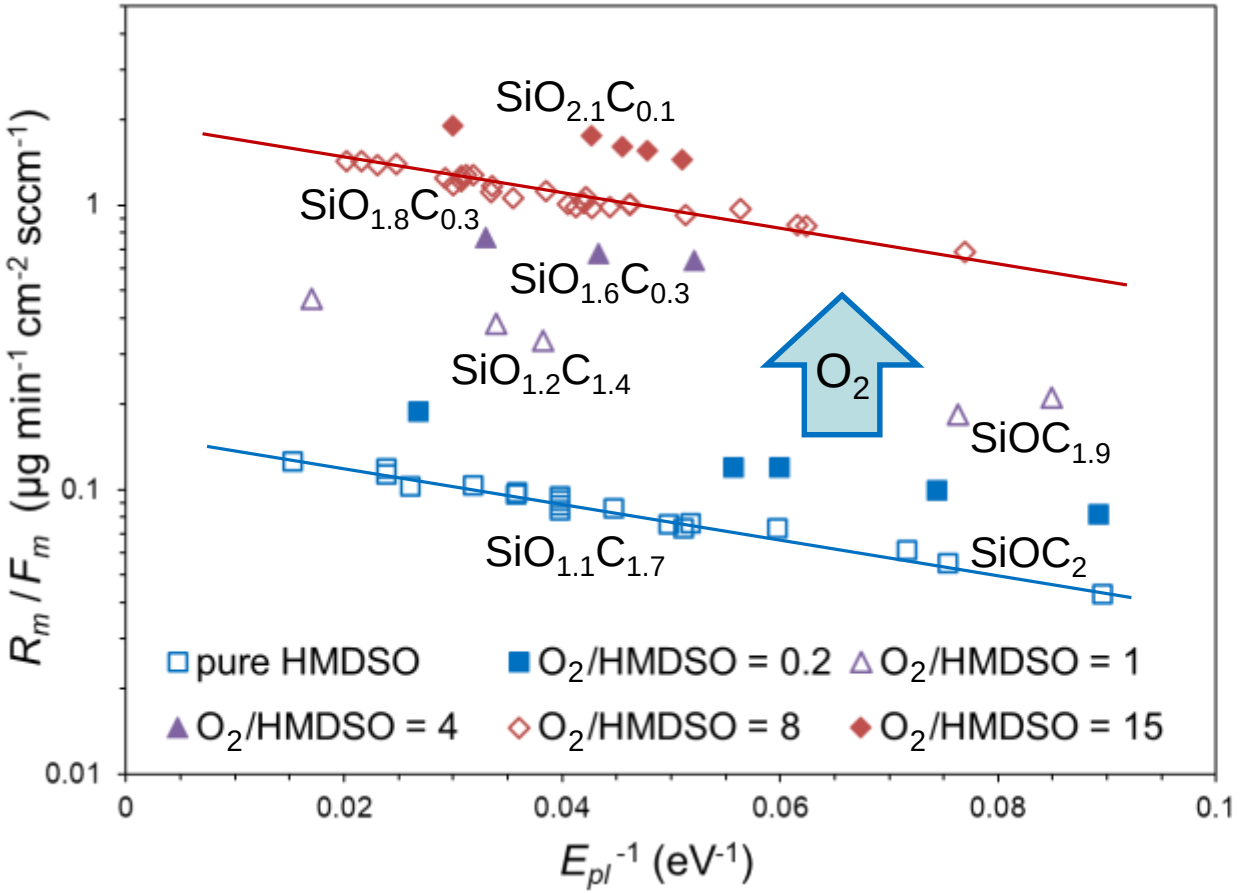


**1.60 m width**
**15 m plasma length**

→ **outdoor textiles; wound bandages**

# HMDSO Plasma Polymerization

## Admixture of oxygen to HMDSO plasma




enhanced conversion through activation of HMDSO by O* (beside electron impact)

oxidation of hydrocarbons
→ CO, $CO_2$, $H_2O$

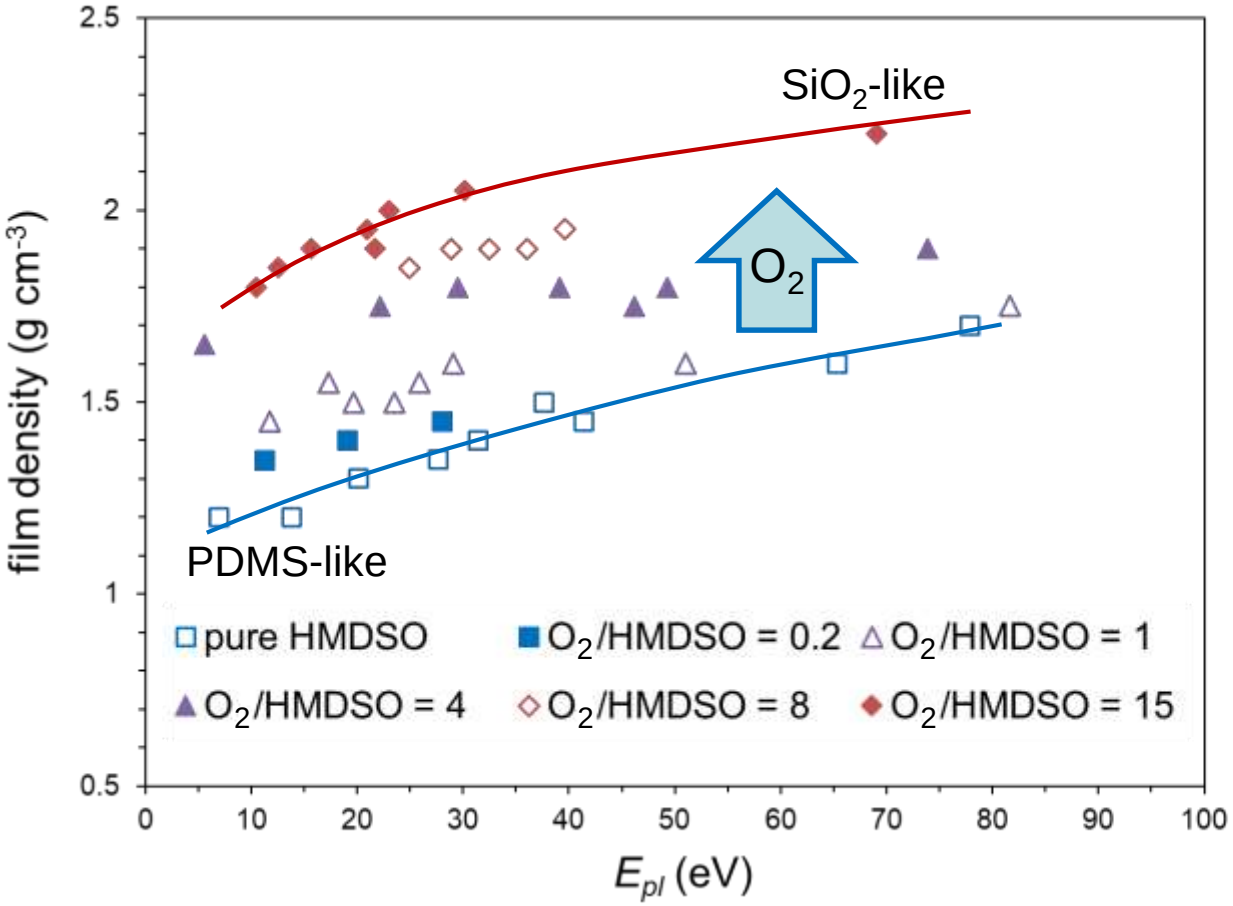
O incorporation

$$E_{pl} = \frac{kT_0}{ep_0} \frac{W_{abs}}{F_m + 0.6 \cdot F_{O2}}$$

→ **addition of oxygen picks up energy, maintaining the basic reaction pathway**

# HMDSO Plasma Polymerization

## HMDSO plasma vs. $O_2$/HMDSO plasma




higher Si-O coordination
→ denser structure

O incorporation

D. Hegemann et al., *Surf. Coat. Technol.* 174-175 (2003) 253

$$E_{pl} = \frac{kT_0}{ep_0} \frac{W_{abs}}{F_m + 0.6 \cdot F_{O2}}$$

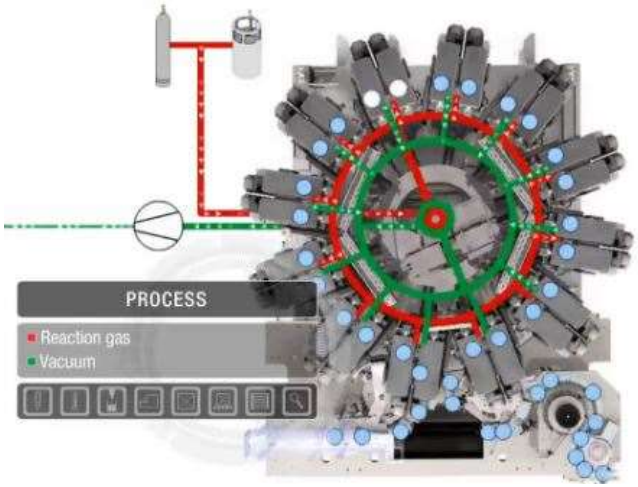
→ **film density largely scales with energy per monomer particle in gas phase**

# Industrial Applications

## $SiO_2$ barrier coatings – inert barrier technology (ibt) by Greiner Packaging

$O_2$ + HMDSO 20:1, 40 mbar, MW → ca. 15 nm coating inside bottle

barrier improvement factor >10
→ shelf life extended by **3 months**
**($H_2O$ + -Si-O-Si- → -Si-OH + HO-Si-)**

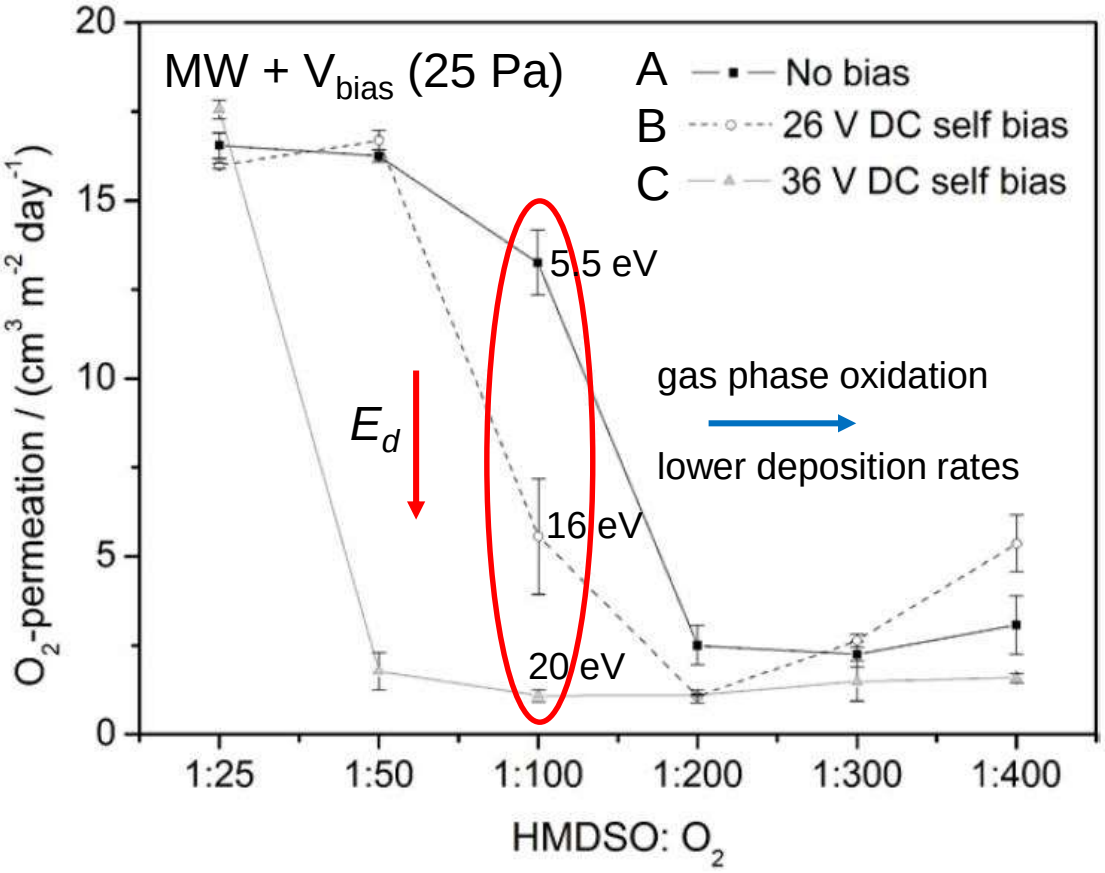


**KHS Plasmax**
**Hamburg / D**

**40’000 bottles per hour**
**in a continuous process**

# Industrial Applications

## $SiO_2$ barrier coatings – OTR depending on $O_2$/HMDSO ratio and bias




$\Gamma_i$ = ~$10^{16}$ $cm^{-2}$ $s^{-1}$

$E_i$ = ~3 / 9 / 11 eV (A / B / C)

$R_{dep}$ = 0.9 nm $s^{-1}$

deposited energy:

$$\varepsilon[\mathrm{eV\ nm^{-3}}] = \frac{E_i \Gamma_i}{R_{dep}[\mathrm{nm\ s^{-1}}]}$$

$\varepsilon$ = ~330 / 1000 / 1200 eV $nm^{-3}$ (A / B / C)

$SiO_2$ → ~60 atoms per $nm^3$

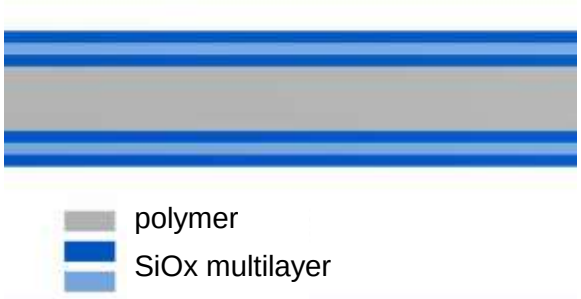
$E_d$ = **5.5 / 16 / 20 eV** per atom

**→ barrier coatings from $O_2$/HMDSO require sufficient high gas ratio and $E_d$**

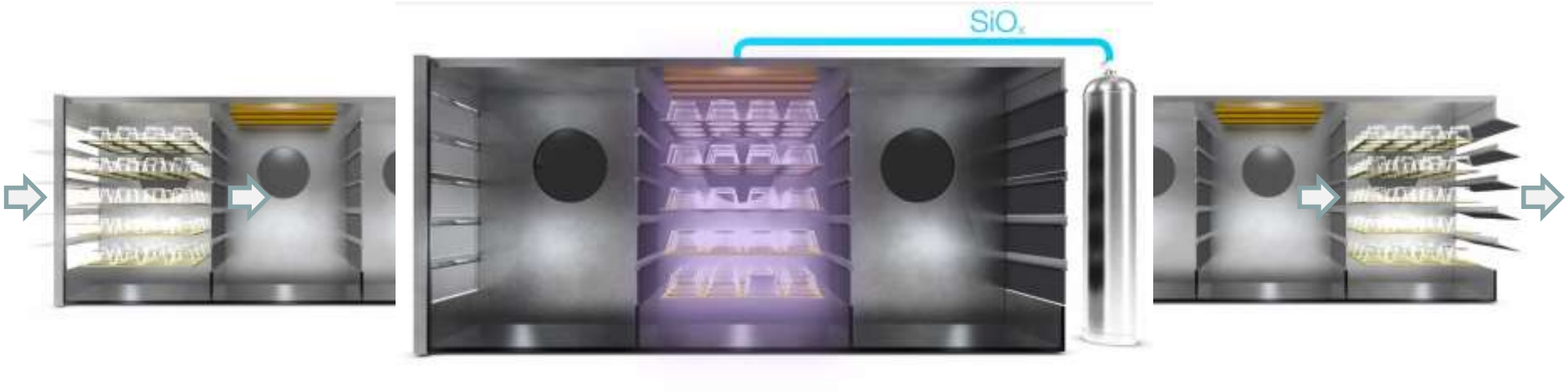
C.N. Liu et al., *J. Phys. D: Appl. Phys.* 46, 2013, 084015; S. Steves et al., *J. Phys. D: Appl. Phys.* 46, 2013, 084013

# Industrial Applications

## $SiO_2$ barrier coatings – inert barrier technology (ibt) by Greiner Packaging




https://www.greiner-gpi.com/en/technology/barrier-technology/ibt-inert-barrier-technology/




→ **nano-scaled multilayer coatings** (adhesion + barrier)

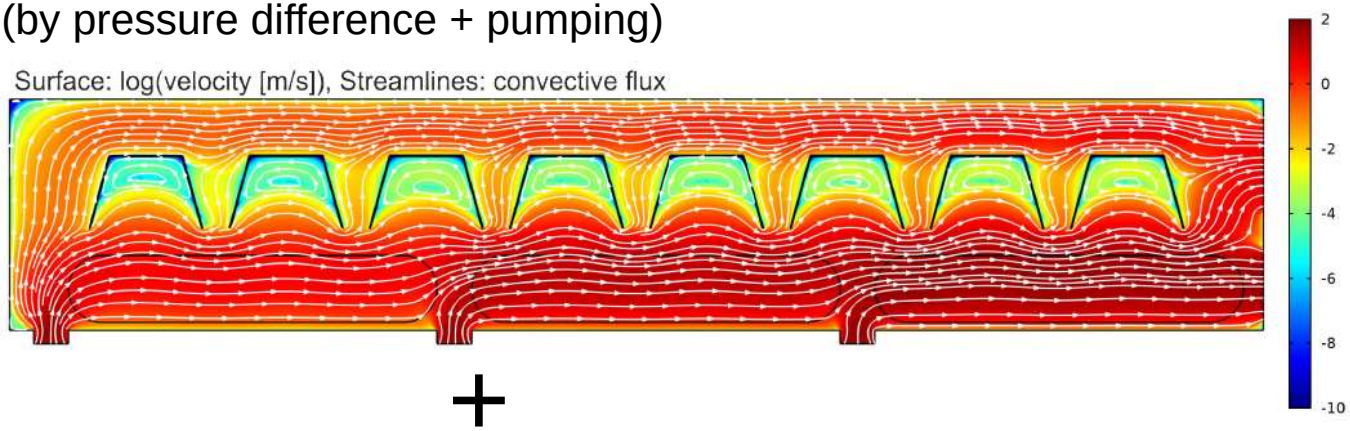
# Industrial Applications

## $SiO_2$ barrier coatings – simulation of flux of film-forming species

Simplified numerical simulation model for plasma polymer deposition

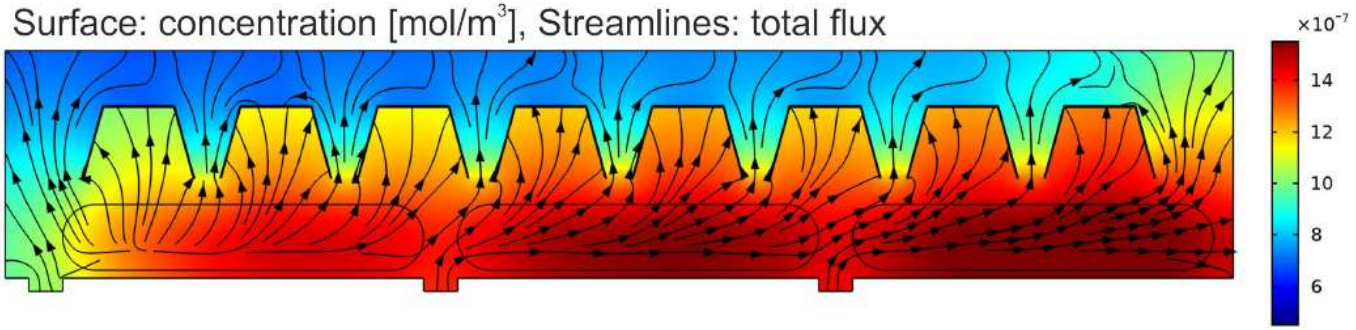
1) convective flux (by pressure difference + pumping)

COMSOL multiphysics




+

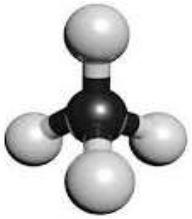
2) diffusion of film-forming species (as created in plasma according to macroscopic model)



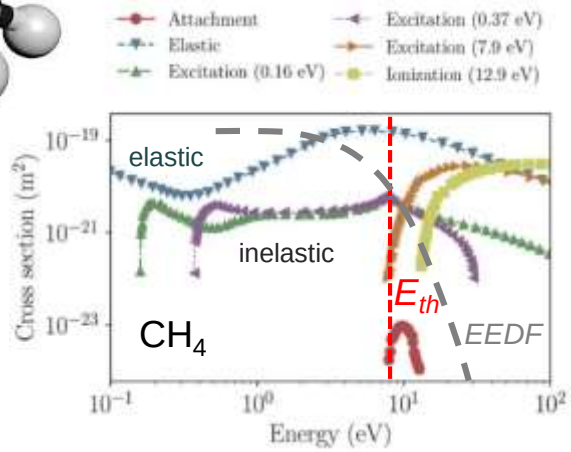

→ **optimization of coating uniformity** (for complex geometries)

# Hydrocarbon PPFs

## Plasma polymerization of methane, $CH_4$

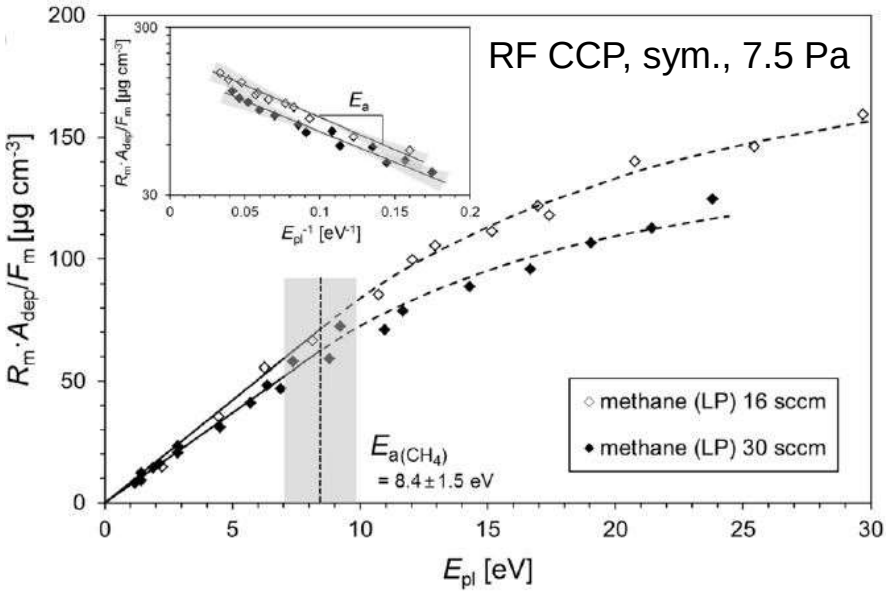


### Expectation




| Reaction ($CH_4$ + e) | Excitation threshold $E_m$ [eV] | |
|---|---|---|
| → $CH_4(\nu_{24})$ + e | | 0.162 |
| → $CH_4(\nu_{13})$ + e | | 0.361 |
| → $CH_3$ + H + e | | 9.0 |
| → $CH_2$ + $H_2$ + e | film-forming species | 10.0 $E_{th}$ |
| → CH + $H_2$ + H + e | | 11.0 |
| → C + 2$H_2$ + e | | 12.0 |
| → $CH_4^+$ + e + e | | 12.6 |
| → $CH_3^+$ + H + e + e | | 14.3 |

### Experiment




*electron impact gas phase reactions*

$CH_4 \rightarrow CH_4^* \rightarrow {}^{\bullet}CH_3, {}^{\bullet}CH_2, {}^{\bullet}CH$ (S)

*surface reactions*

${}^{\bullet}CH_2 + H \rightarrow {}^{\bullet}CH + H_2$

T. Minea et al., Plasma Process Polym. 16 (2018) e1800087; M. Bauer et al., J. Appl. Phys. 98 (2005) 073302

# Hydrocarbon PPFs

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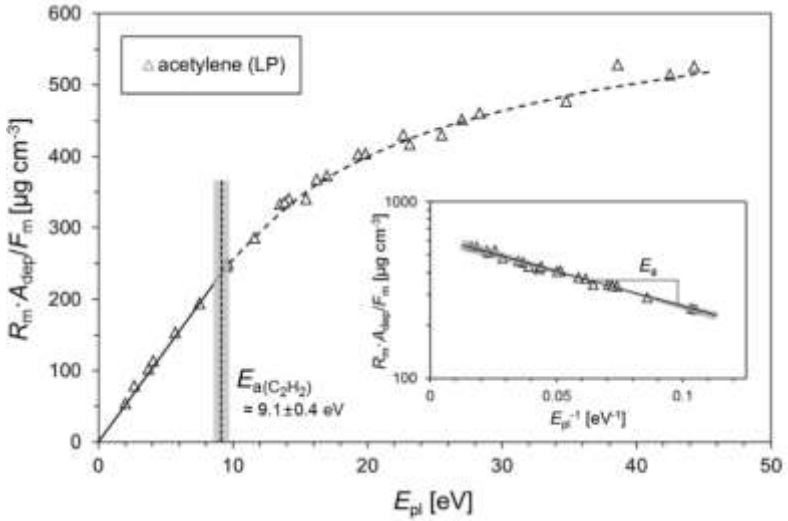
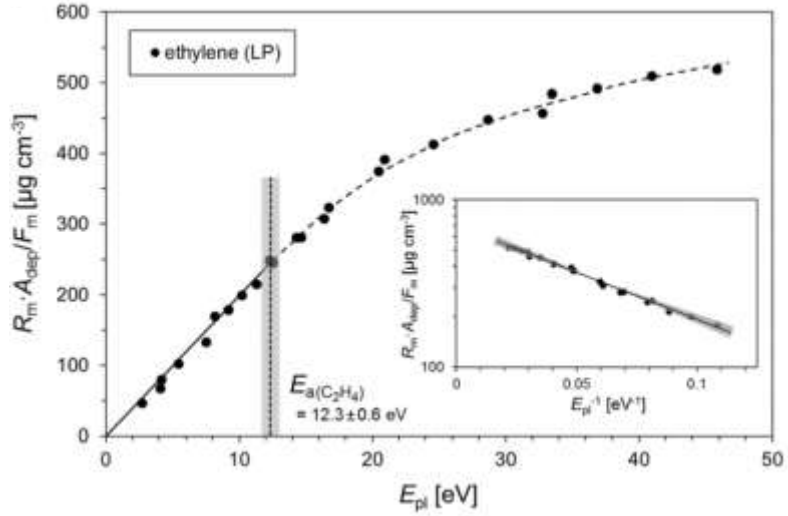
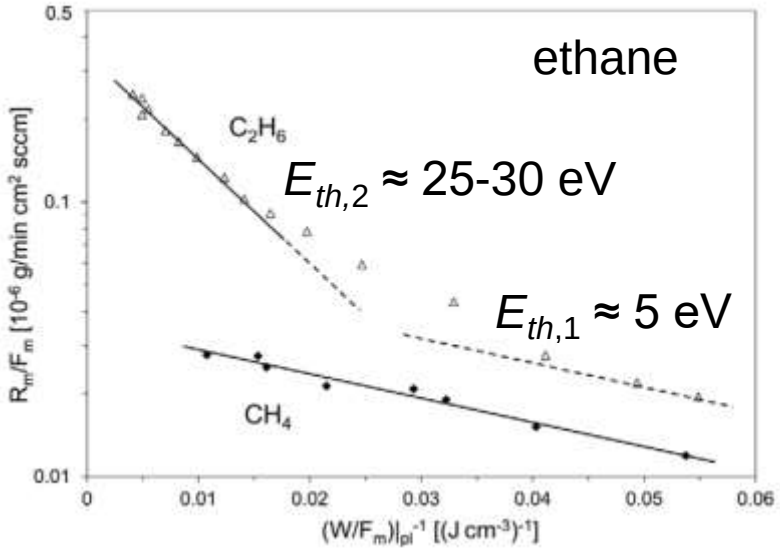
## Plasma polymerization of further hydrocarbon gases




$E_{th,1}$ : $C_2H_6 \rightarrow C_2H_4$ ($^{\bullet}CH_2$–$^{\bullet}CH_2$) + $H_2$

→ double deposition rate compared to $CH_4$

$E_{th,2}$ and 4x higher $R_m$ of $C_2H_x$ compared to $CH_4$ indicate different plasma chemistry


D. Hegemann et al., *Phys.Chem.Chem.Phys.* 21 (2019) 8698

D. Hegemann, *J. Phys. D: Appl. Phys.* 46 (2013) 205204

# Hydrocarbon PPFs

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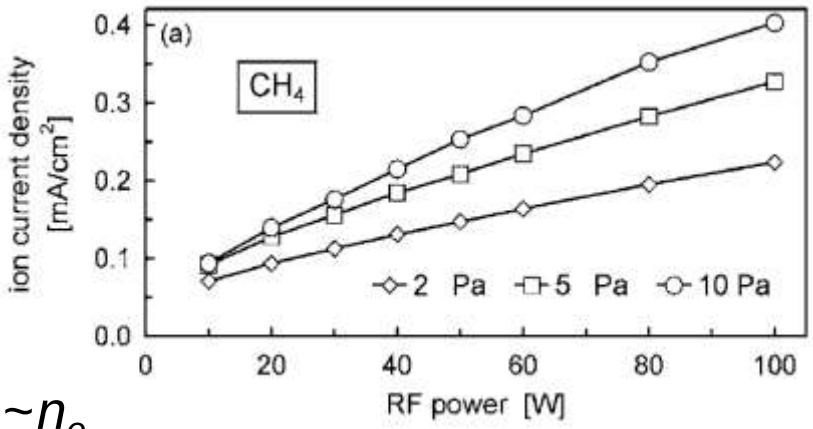
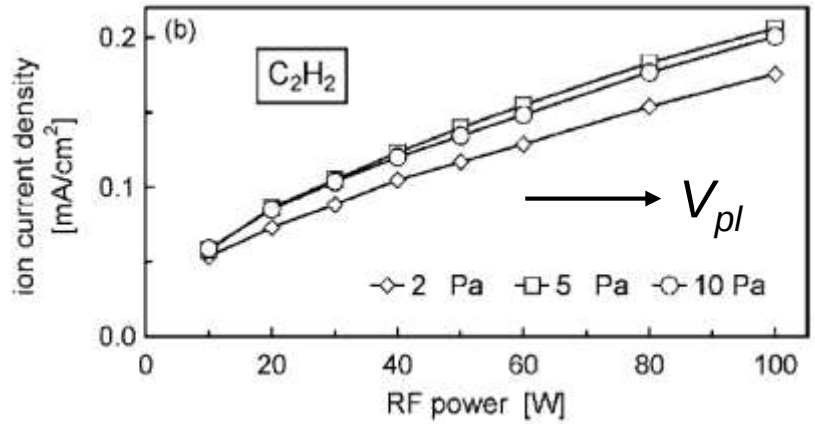
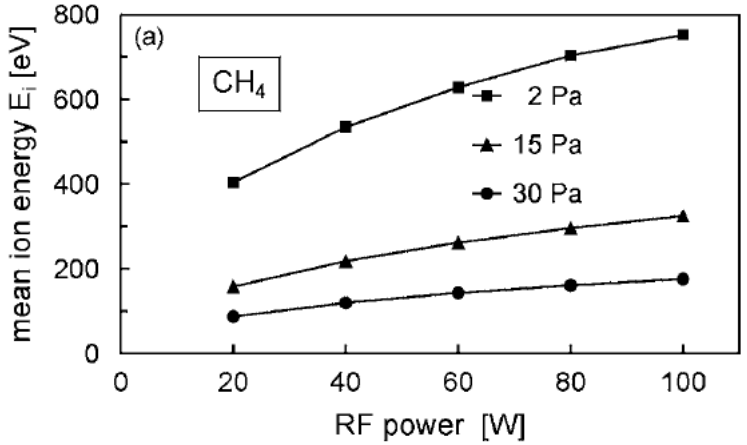
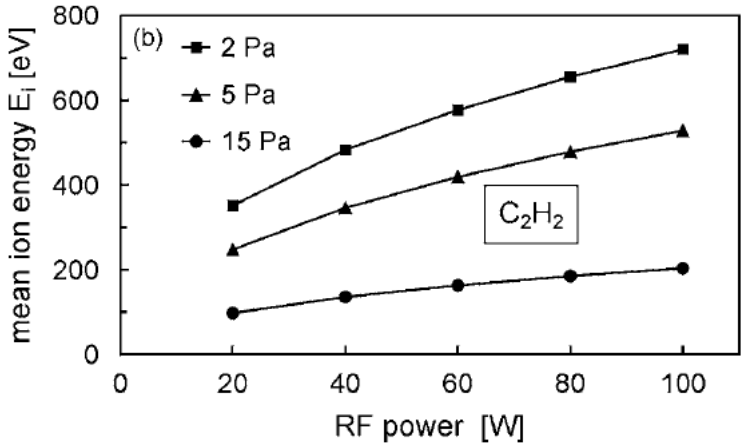
## Role of plasma chmistry and deposited energy for DLC – $CH_4$ vs. $C_2H_2$




$\sim n_e$



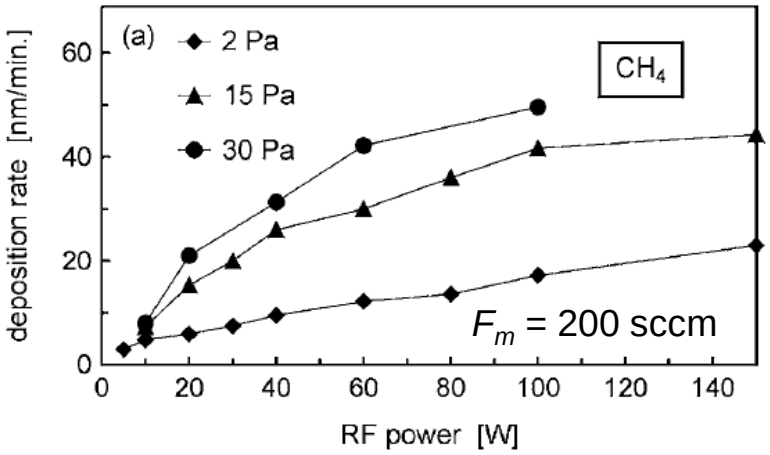



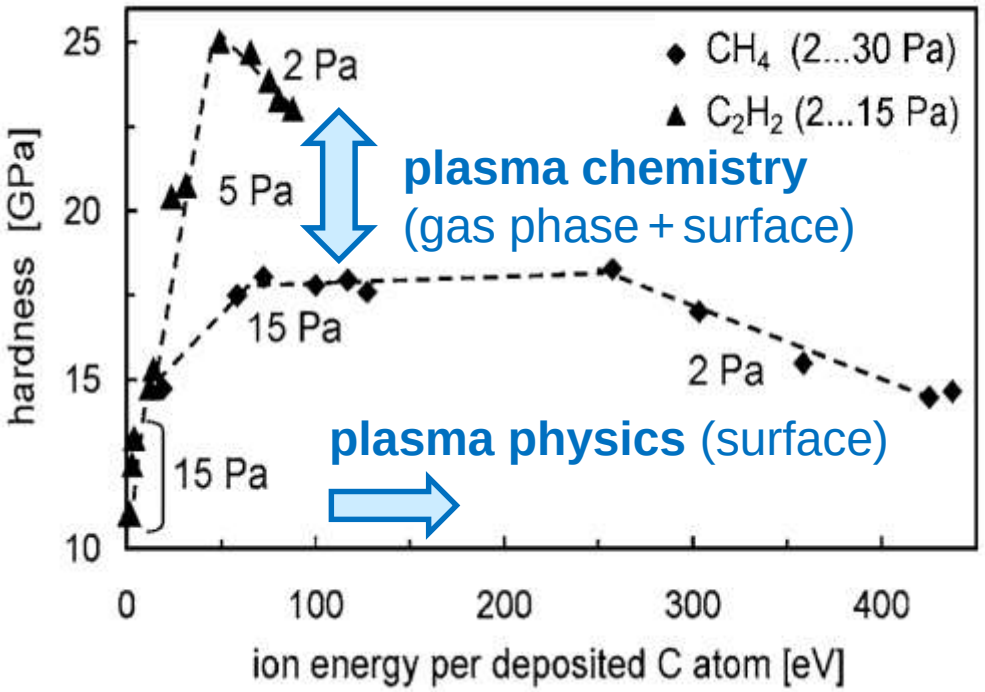

S. Peter, K. Graupner, D. Grambole, F. Richter, *J. Appl. Phys.* 102 (2007) 053304.

# Hydrocarbon PPFs

## Role of plasma chmistry and deposited energy for DLC – $CH_4$ vs. $C_2H_2$




energy flux per deposition rate $\varepsilon = \frac{E_i \Gamma_i}{R_{dep}}$




→ **enhanced deposition rate and hardness for $C_2H_2$-derived DLC**

S. Peter et al., *J. Appl. Phys.* 102 (2007) 053304.

# Industrial Applications

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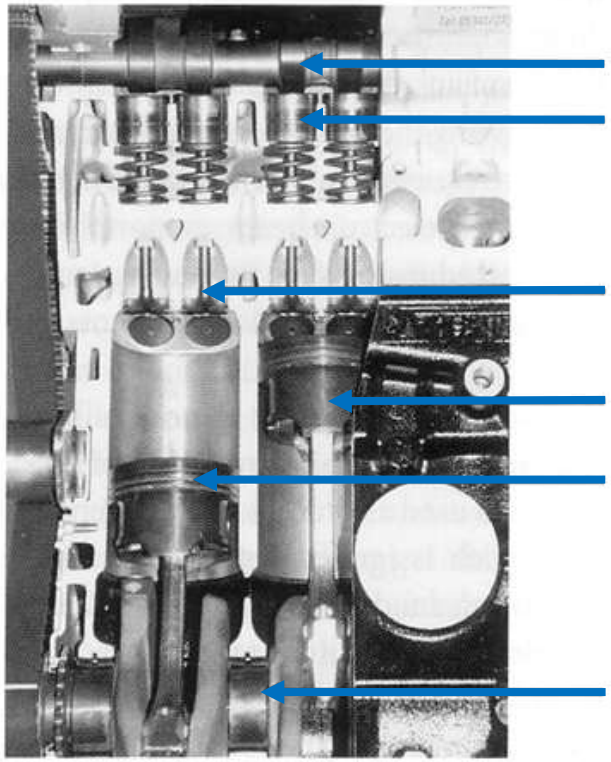
## DLC on tools and engine parts

*diamond-like carbon*

**$C_2H_2$ plasma, 2 Pa → ca. 1 µm**

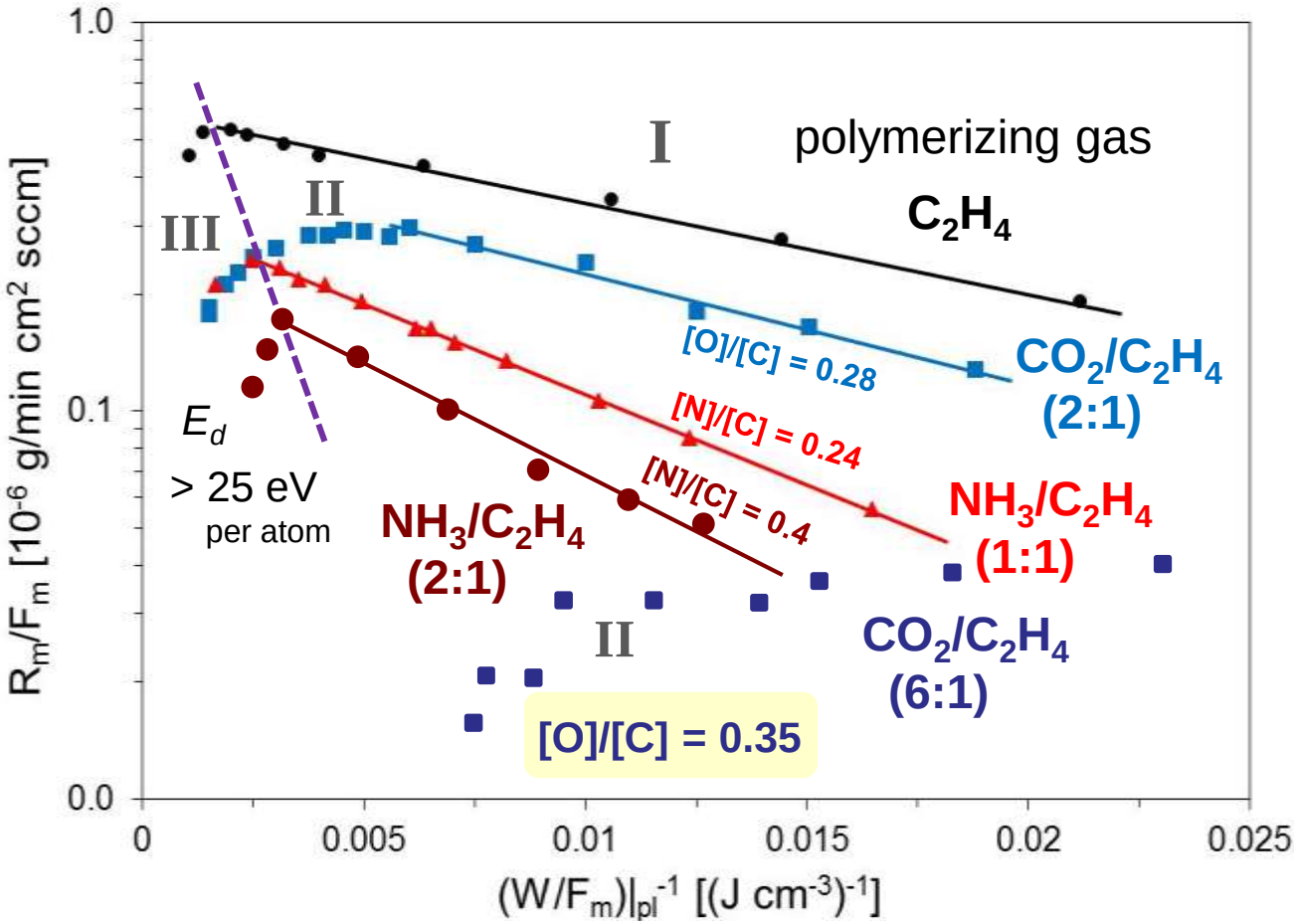



**→ friction reduction and wear protection**

**→ adhesion-promoting interlayers required, e.g. Cr- or CrNi-based**

# Functional PPFs

## Deposition rate of functional plasma polymers from $C_2H_4$ (+$CO_2$/$NH_3$)




RF CCP, sym., 10 Pa

**I**: quasi-Arrhenius
(same chemical reaction pathway)

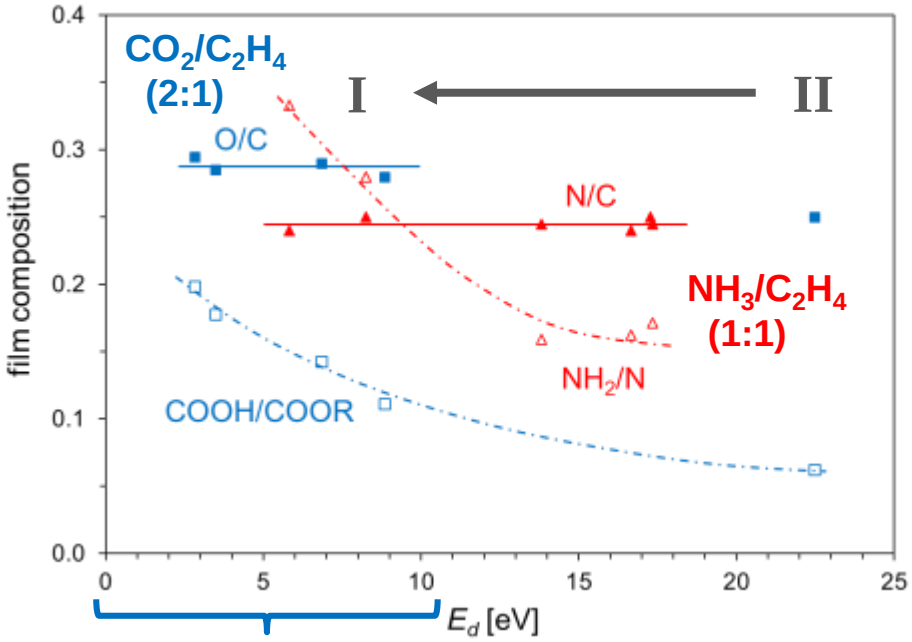
**II**: plasma chemically induced change
→ O formation
(only for $CO_2/C_2H_4$)

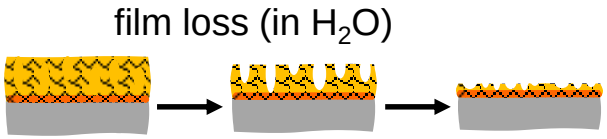
**III**: ion-assisted etching
(reduced *s* or $M_{dep}$)

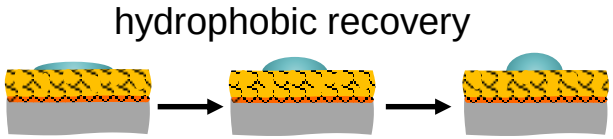
D. Hegemann, E. Körner, S. Guimond et al., *PPP* 7, **2010**, 889; D. Hegemann, U. Schütz, E. Körner, *PPP* 8, **2011**, 689.

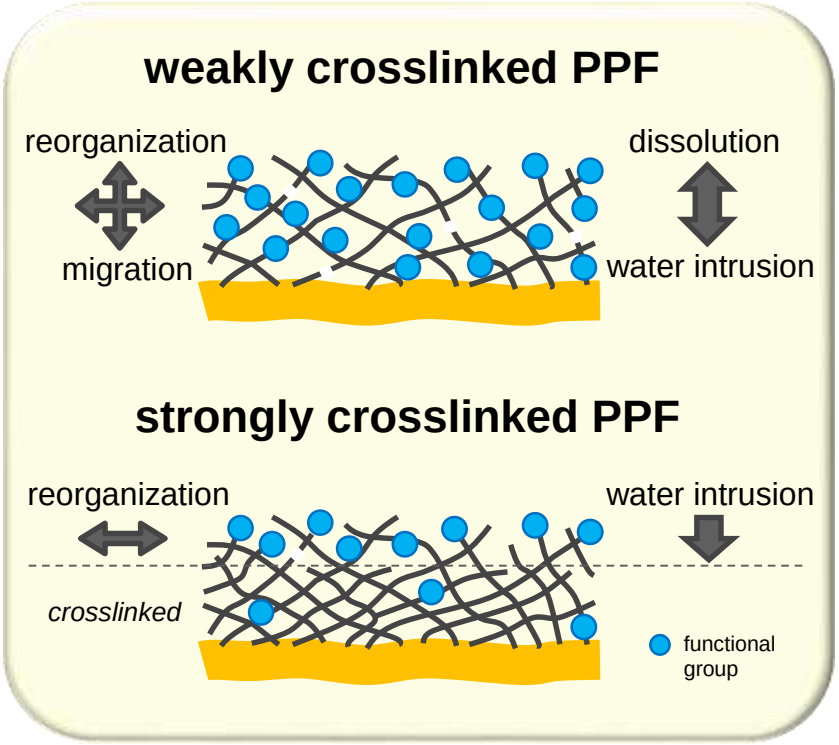
# Functional PPFs

## Stability issues with highly functional plasma polymer films




→ **vertical chemical gradient PPFs**

**(crosslinked base layer + 1-2 nm functional surface)**

Hegemann et al., *APL* 101, **2012**, 211603; Hegemann et al., *Langmuir* 32, **2016**, 651; Hegemann et al., *PPP* 15, **2018**, e1800090.

# Industrial Applications

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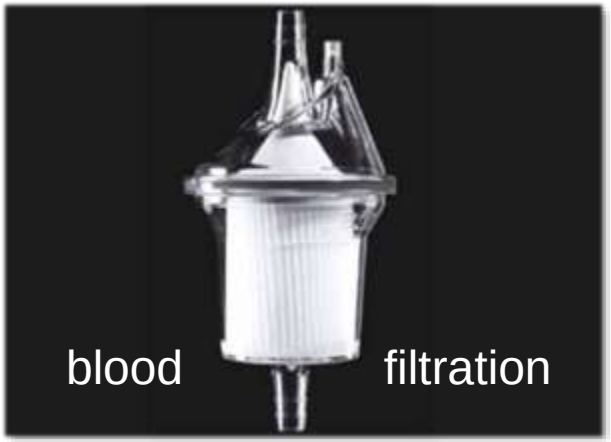
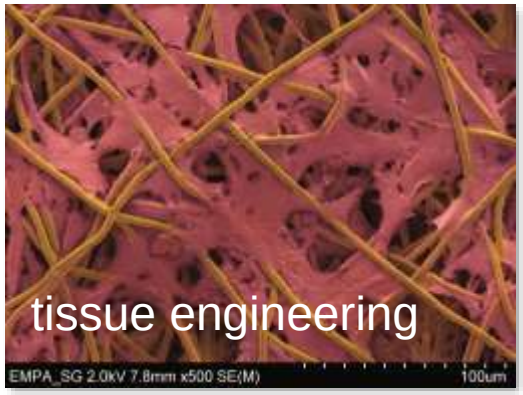
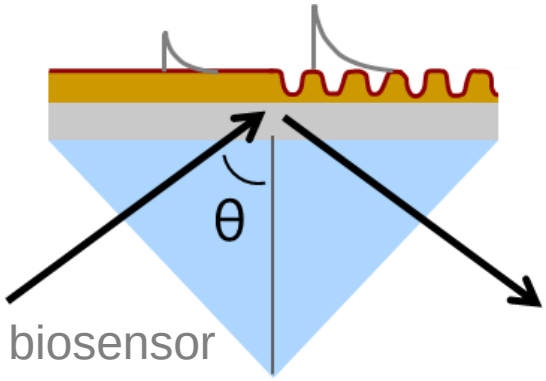
## Functional C:H:O plasma polymer films

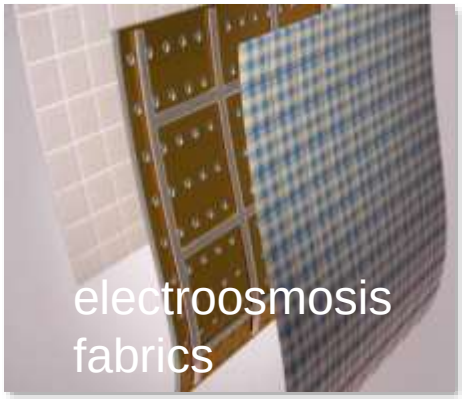
cutlery basket




On the way from development to product…



# Conclusions

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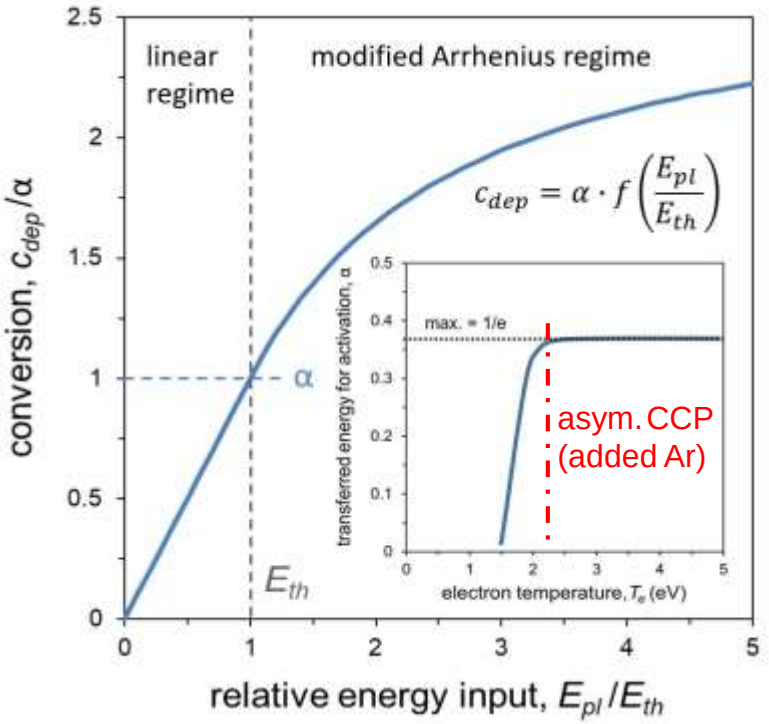
## Plasma Polymerization in Industrial Applications

- Plasma polymerization
  - → microscopic/macroscopic
  - → energy transfer *α* and *SEI*
  - → chemical reaction pathway
  - → gas phase/surface processes
- Control of film properties
  - → fragmentation/densification




- Economic robust ’tool’ for diverse industrial applications
  - → ’simple’ process optimization and control

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Materials Science and Technology

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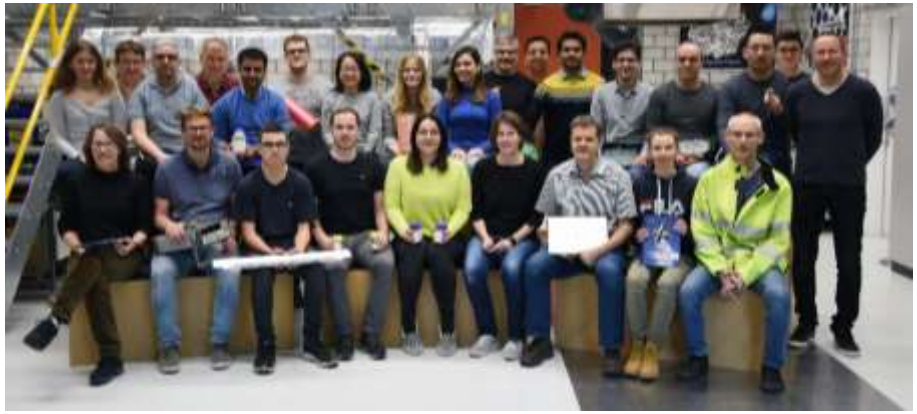

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FNSNF

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Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Commission for Technology and Innovation CTI

- **Open position for PostDoc** (as well as master thesis, internships)

D. Hegemann, E. Bülbül, B. Hanselmann,
U. Schütz, M. Amberg, S. Gaiser,
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