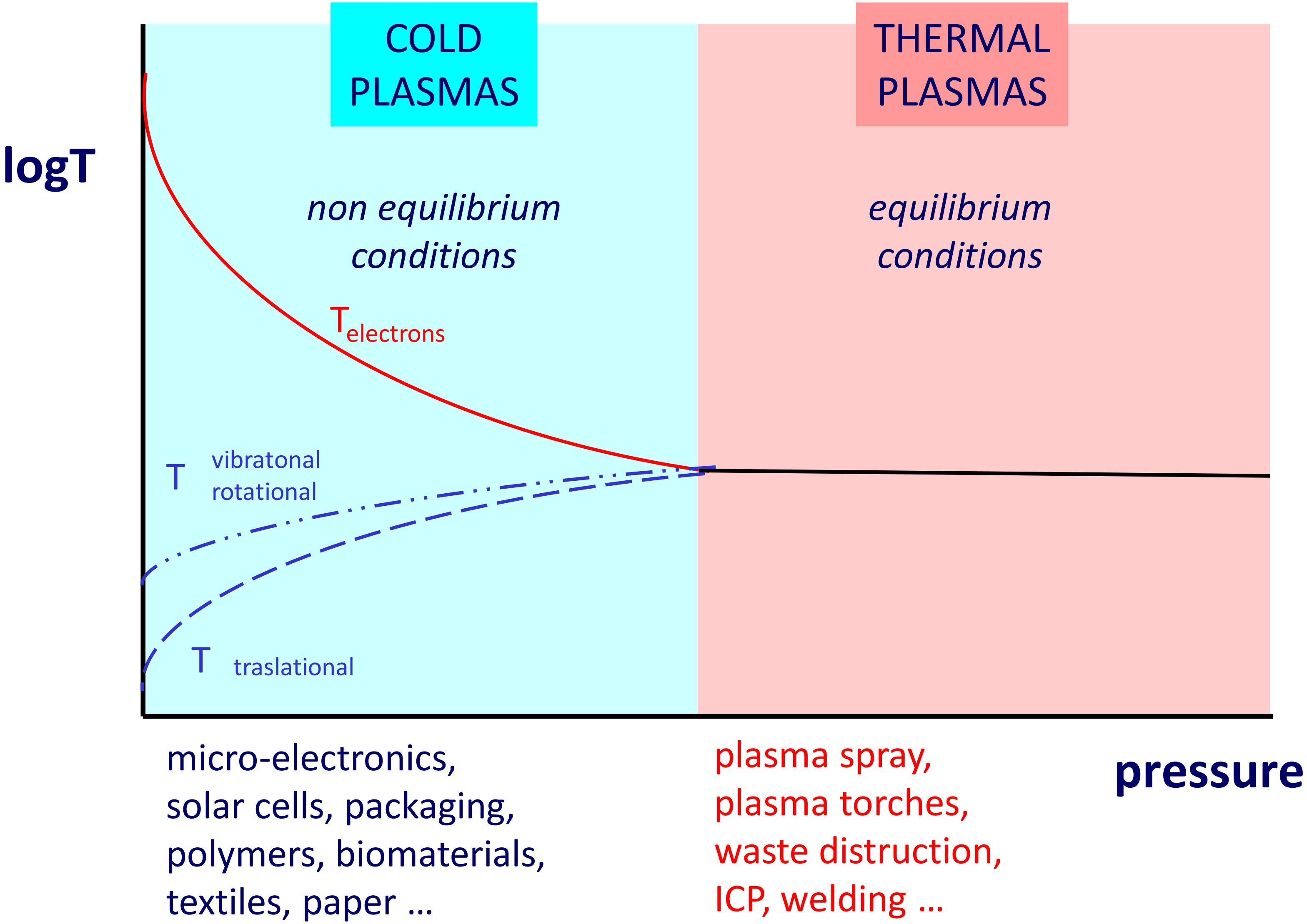
REACTORS & PROCESSES

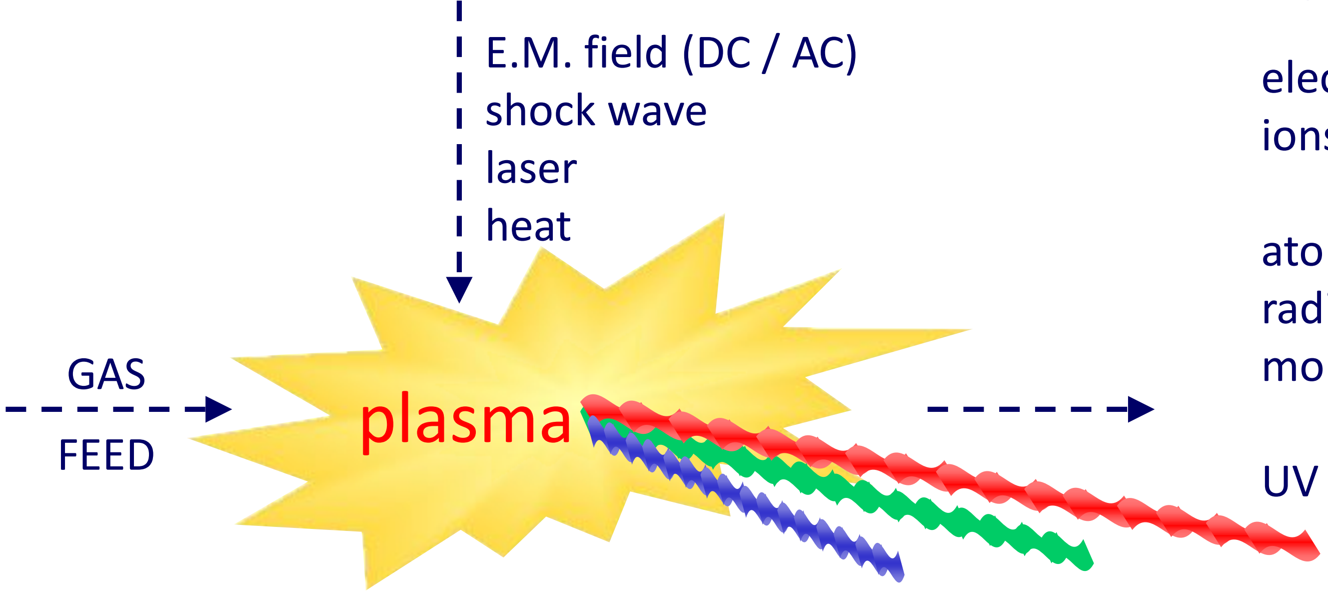


micro-electronics,
solar cells, packaging,
polymers, biomaterials,
textiles, paper …

plasma spray,
plasma torches,
waste distruction,
ICP, welding …

non eq. conditions can exist also at atmospheric pressure
***e.g.*, APGD, DBD plasmas**

COLD PLASMAS



ENERGY INPUT

E.M. field (DC / AC)
shock wave
laser
heat

GAS
FEED

plasma

ACTIVE SPECIES

electrons (0 - 10 eV)
ions

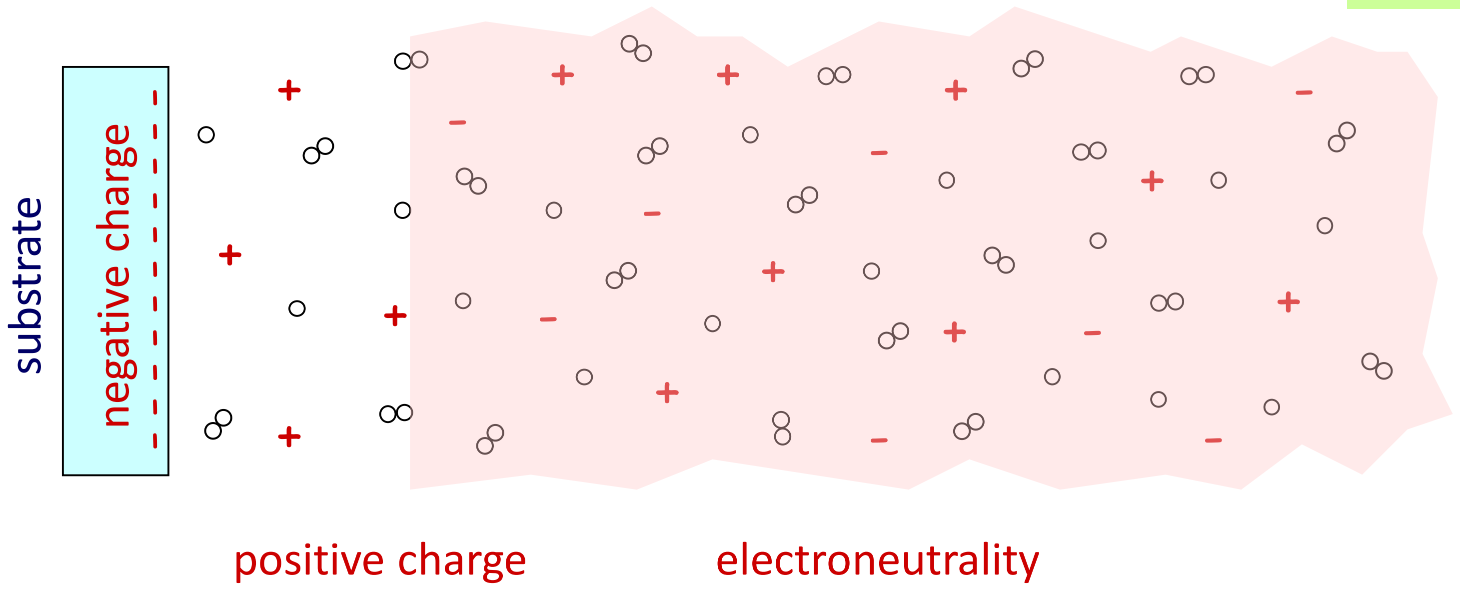
atoms
radicals
molecules

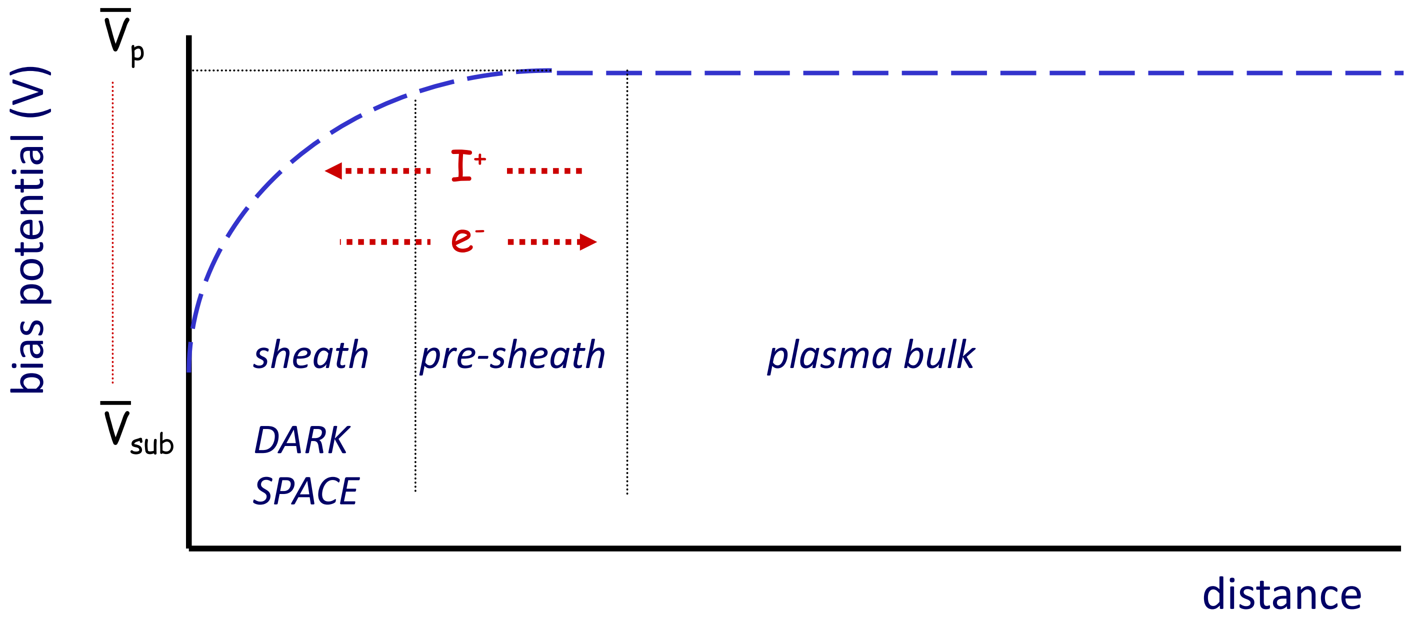
in different states

UV – VIS radiation

pressure,
feed flow rate
power input, frequency, pulsation,
residence time,
substrate temperature, bias, …

bias potential



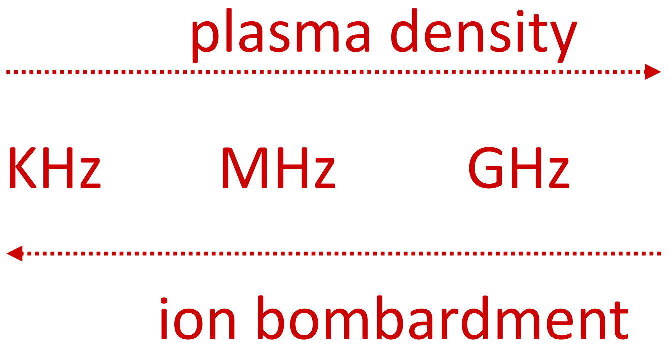


DC plasmas are not suitable for dielectrics, need internal electrodes, are not stable, offer a low plasma density.

Most plasma sources in LP regimes use radiofrequency (13.56 MHz)
or microwaves (2.54 GHz).

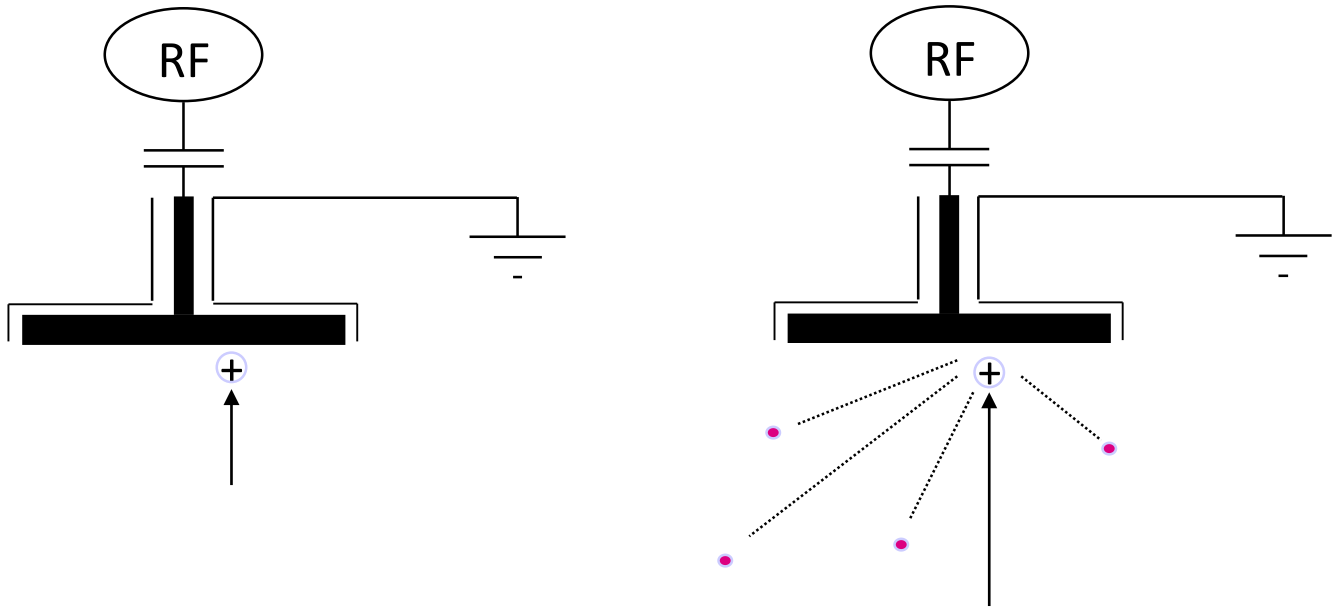
Audiofrequency (KHz) plasmas in LP regimes are characterized by an intense ion bombardment of the substrate (radiation damage), quite difficult to control.
In AP regimes KHz sources are most utilized

LP, Low Pressure
AP, Atm Pressure



In LP regimes

SPUTTERING



Low Energy Bombardment

activation of treatments

activation of PE-CVD

no surface damage

High Energy Bombardment

de-activation of PE-CVD

sputter-etching

surface damage

ejection of material
from the electrode

contamination

LOW-PRESSURE PLASMA CHEMISTRY
the arena

GAS PHASE
(0.01 – 10 Torr)

electroneutrality

$n_+ = n_- \rightarrow n_{I+} = n_{e-}$

ideal gas approximation

$PV = nRT$

mean free path 10 μm – 1mm

low number of e^- – neutral elastic collisions:

non equilibrium conditions

$T_e >> T_{el} > T_{rot}, T_{vib} > T_{trasl}$

PLASMA – SURFACE INTERACTIONS

Surfaces develop a negative charge respect to the plasma bulk:

electroneutrality does not hold near surfaces, and a “sheath” develops

positive ions bombard surfaces

\+

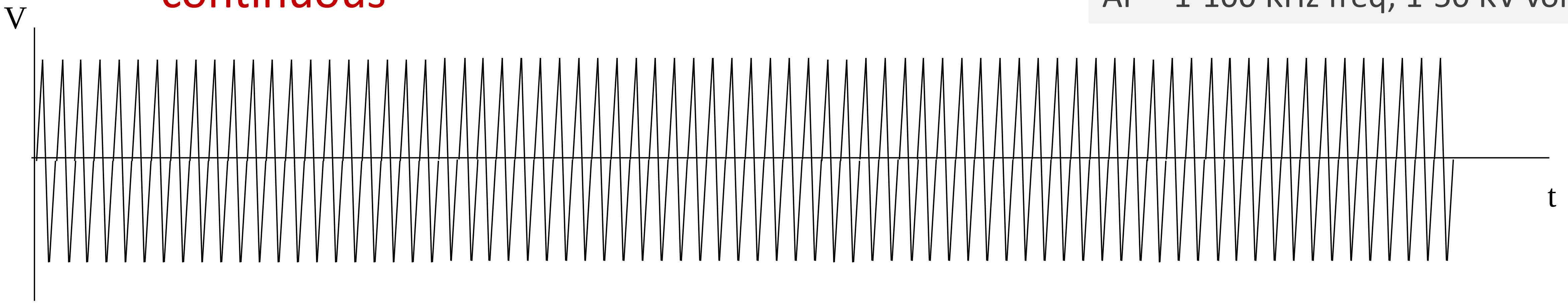
neutrals react with surfaces

Most applications of non equilibrium plasmas requires that the gas remains at room T. Since the low efficiency and number of elastic collisions at low P limit the energy transfer from free electrons to heavier species, it is quite easy to produce cold Low P gas discharges. With increasing pressure, however, the electron-species collision frequency increases, the energy transfer becomes more efficient, resulting in gas heating and plasma instabilities (e.g., sparks and arcs). **Many approaches are used to keep the gas cold in Atmospheric P discharges, namely:**

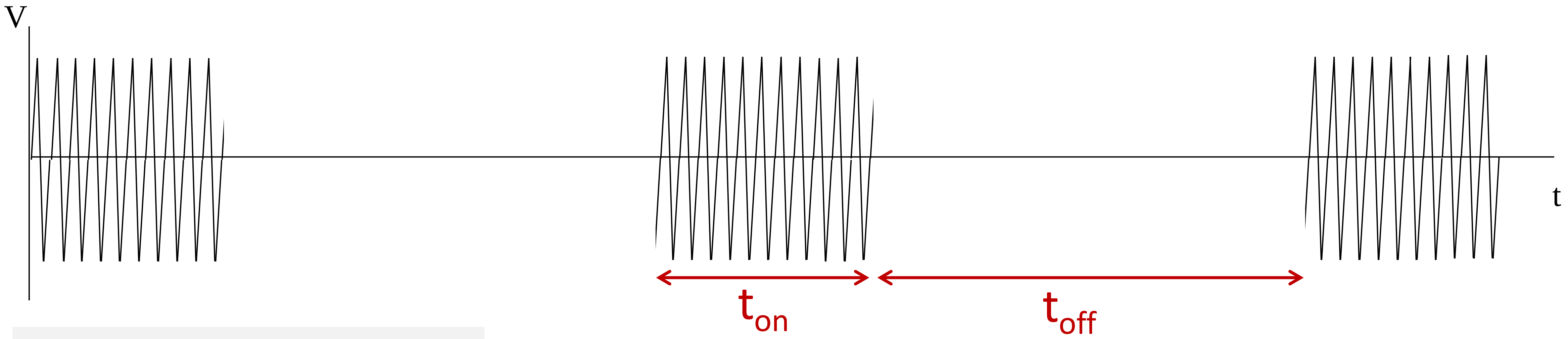
- **sharp electrodes, as in corona discharges;**
- **pulsing the plasma; μs-ns wide plasma pulses**
- **improved heat transfer;**
- **using gases (e.g., He) with high thermal conductivity;**
- **reduce the size of plasmas (e.g., micro-discharges);**
- **reduce the current with dielectric layers on the electrodes, as in Dielectric Barrier Discharges (DBD)**

continuous

AP 1-100 KHz freq; 1-50 KV volt.



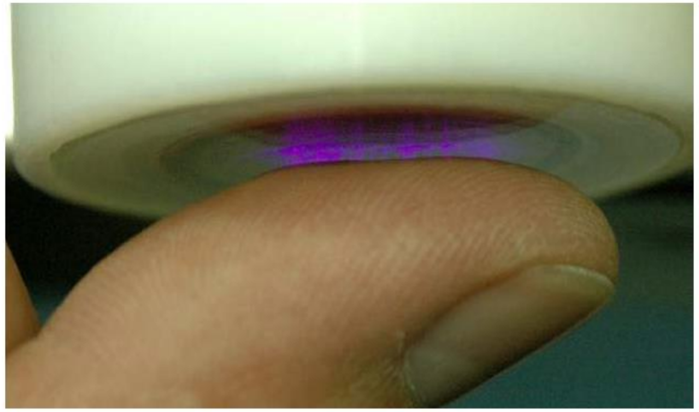
pulsed

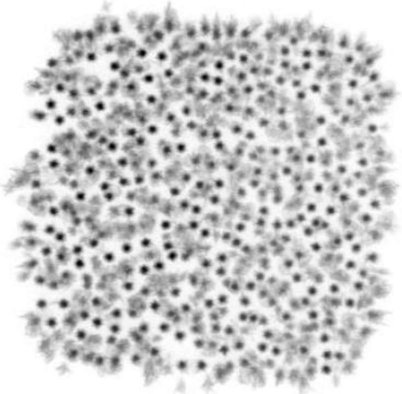


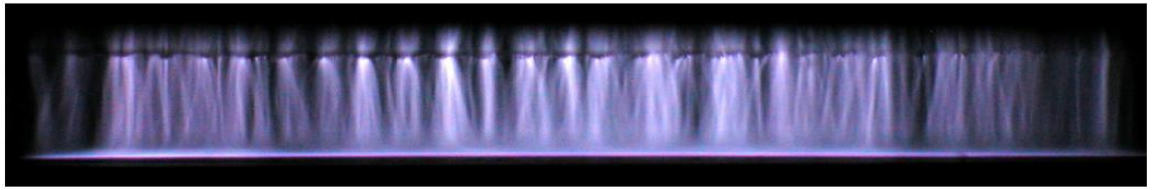
lower pulse width (μm, nm)
and higher V-rise speed
are desired to keep the gas cold

milli
micro
nanoseconds

Microdischarge Interaction and Structuring in Dielectric Barrier Discharges



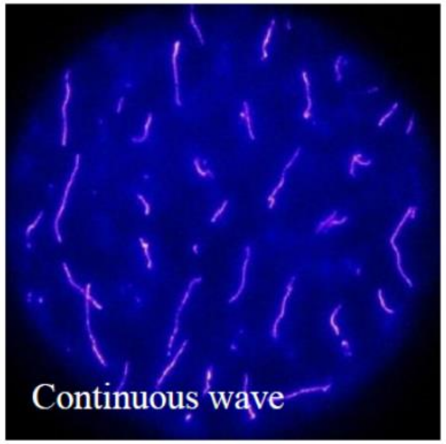




FE-DBD: Sinusoidal, Micro-pulsed, Nano-pulsed

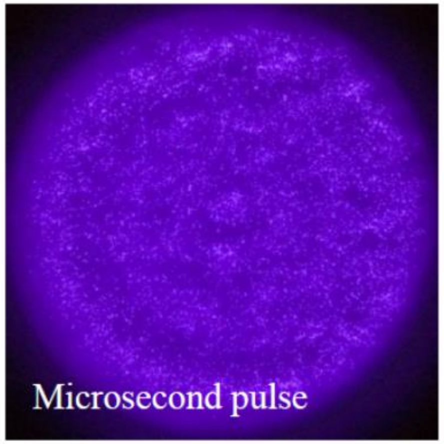
Continuous (sinusoidal)
Rise time: ~1 V / nsec
Sinusoidal wave

Filament temperature:
350-450K



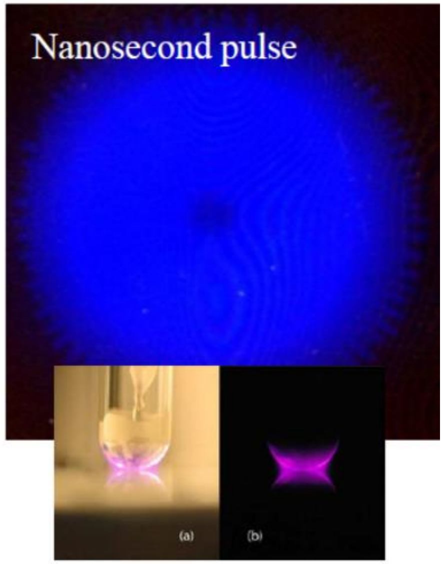
Microsecond-pulsed
Rise time: ~5 V / nsec
Pulse duration: ~2 µsec

Filament temperature:
320-420K

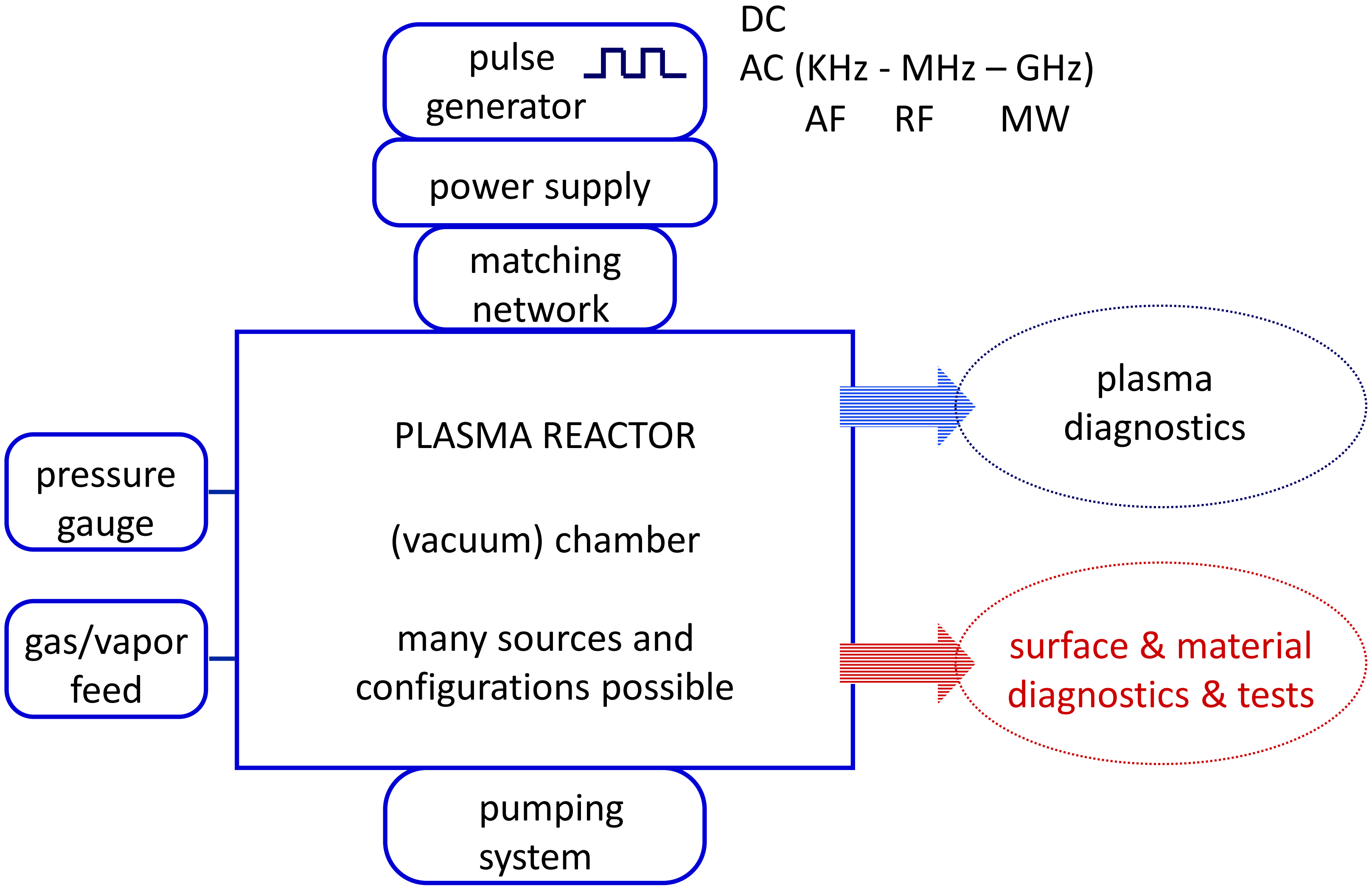


Nanosecond-pulsed
Rise time: ~3,000 V / nsec
Pulse duration: ~40 nsec

Rotational temperature:
~300K



PLASMA REACTORS LP/AP



pulse generator

power supply

DC
AC (KHz - MHz – GHz)
AF RF MW

matching network

PLASMA REACTOR

(vacuum) chamber

many sources and configurations possible

pressure gauge

gas/vapor feed

pumping system

plasma diagnostics

surface & material diagnostics & tests

PLASMA PARAMETERS: external and internal

“external” PARAMETERS

imposed from the operator

Pressure

Feed composition, flow rate, leaks

Field frequency, power density

Reactor configuration, materials, electrode geometry

Substrate position (*e.g.* glow *vs*. afterglow)

Duty cycle %, *time on*, *time off* in pulsed plasmas

Substrate temperature

Substrate *bias* potential

“internal” PARAMETERS

output from diagnostics

Fragmentation degree of the feed

Density and distribution of neutrals

Distribution energy (EEDF) and density (n_e) of electrons

Ionization degree

Residence time of the species

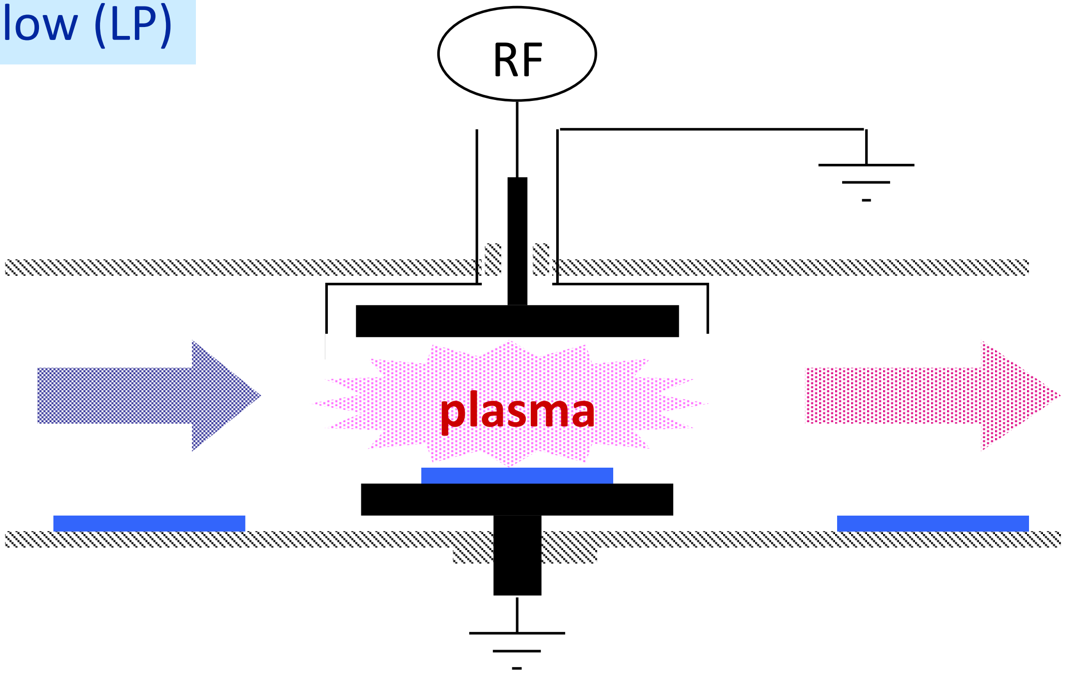
Process homogeneity

Positive-ion bombardment, sputtering

Deposition, etching, treatment rate

Contaminations

SUBSTRATE POSITION
glow vs afterglow (LP)

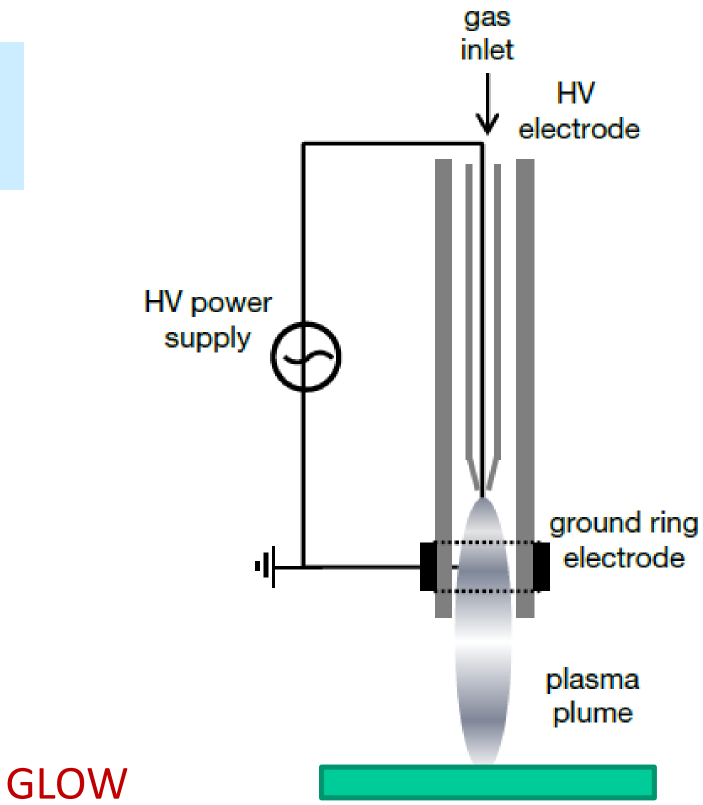


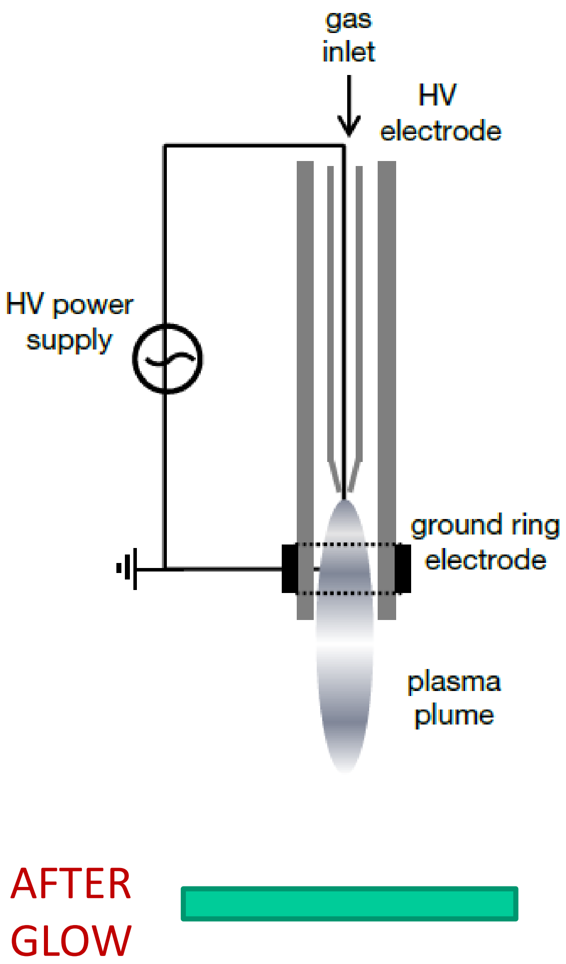
Preglow
no treatment

Glow
active species
ion bombardment
crosslinking
high rates
fragmentation

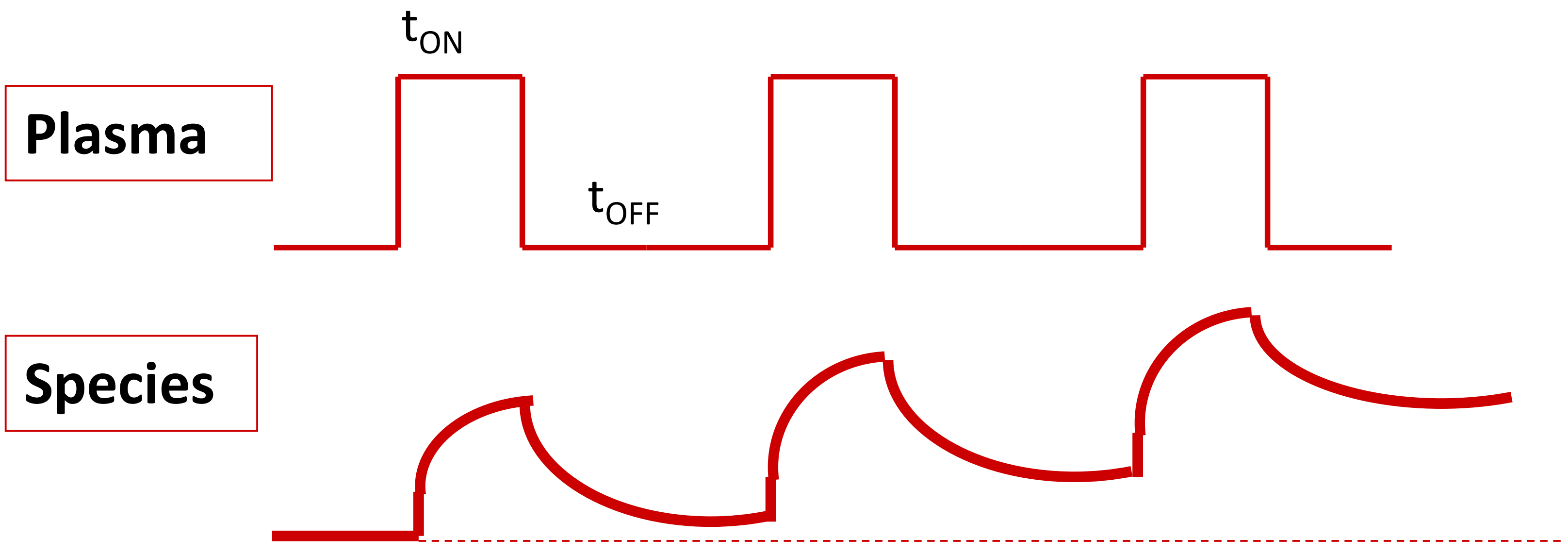
Afterglow
no electrons
no ions
no bias
long living species
mild treatments
selectivity
structure retention

SUBSTRATE POSITION
glow vs afterglow (AP)





POWER (bias) MODULATION



Modulation Parameters

Period = $t_{ON} + t_{OFF}$

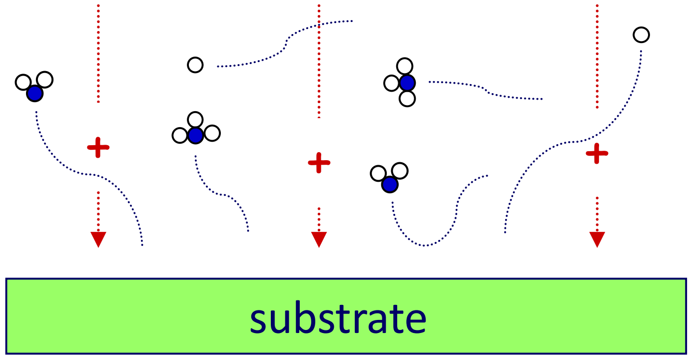
Duty Cycle = $(t_{ON}/\text{period}) * 100$

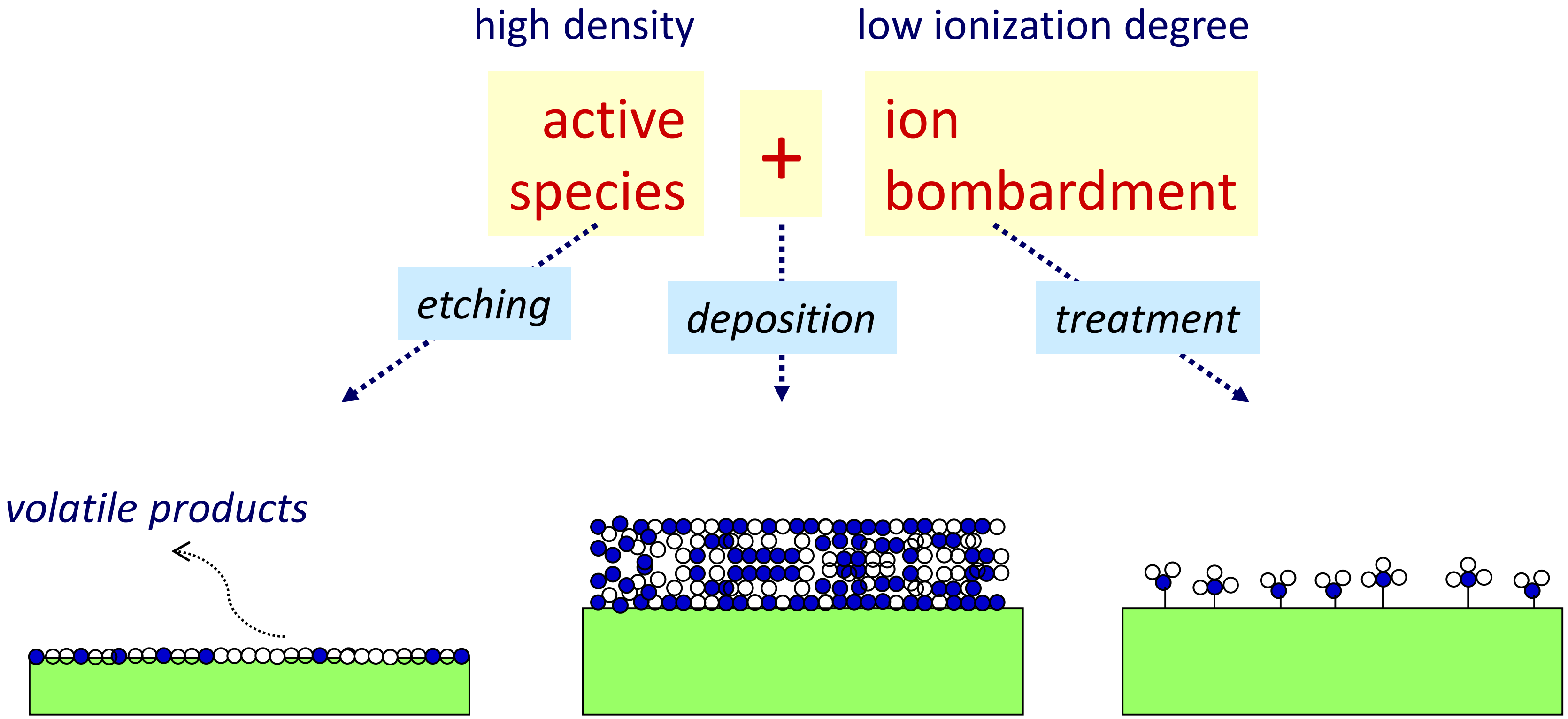
Effective power

$W_{eff} = W_{tot} \times DC$

PLASMA – SURFACE INTERACTIONS

Low P *synergistic action of active species and ion bombardment*





high density

low ionization degree

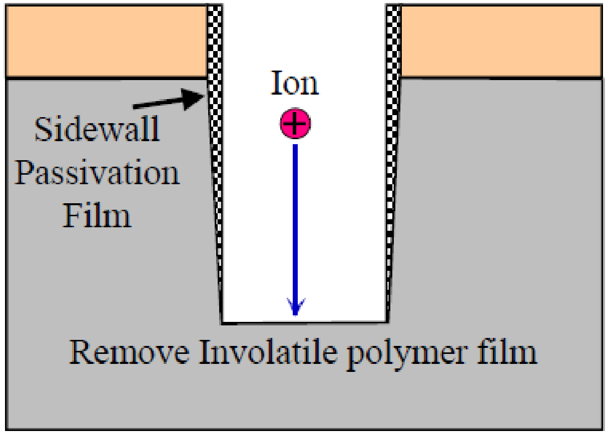
active species + ion bombardment

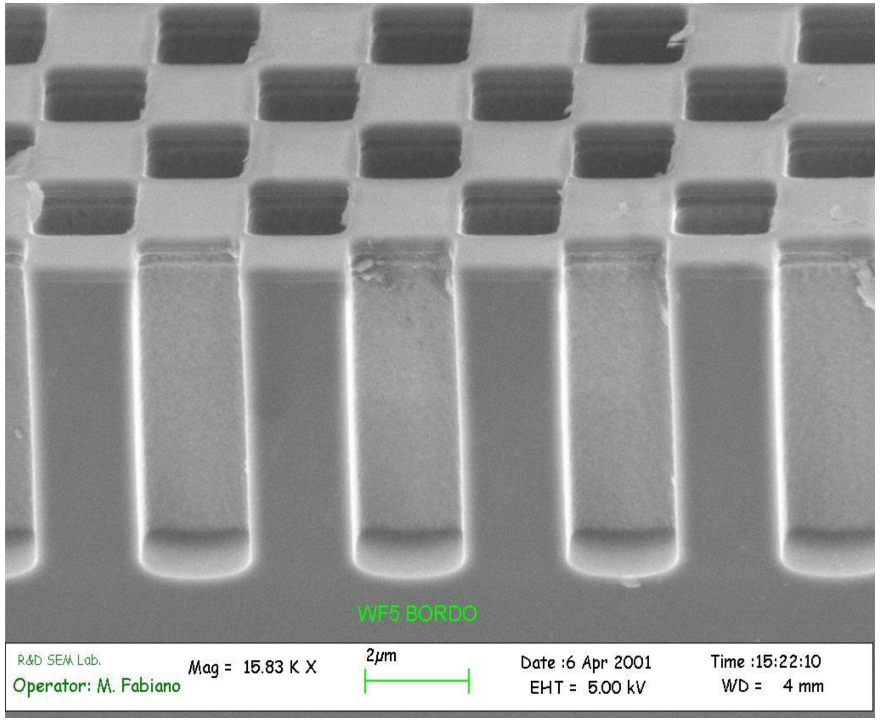
etching

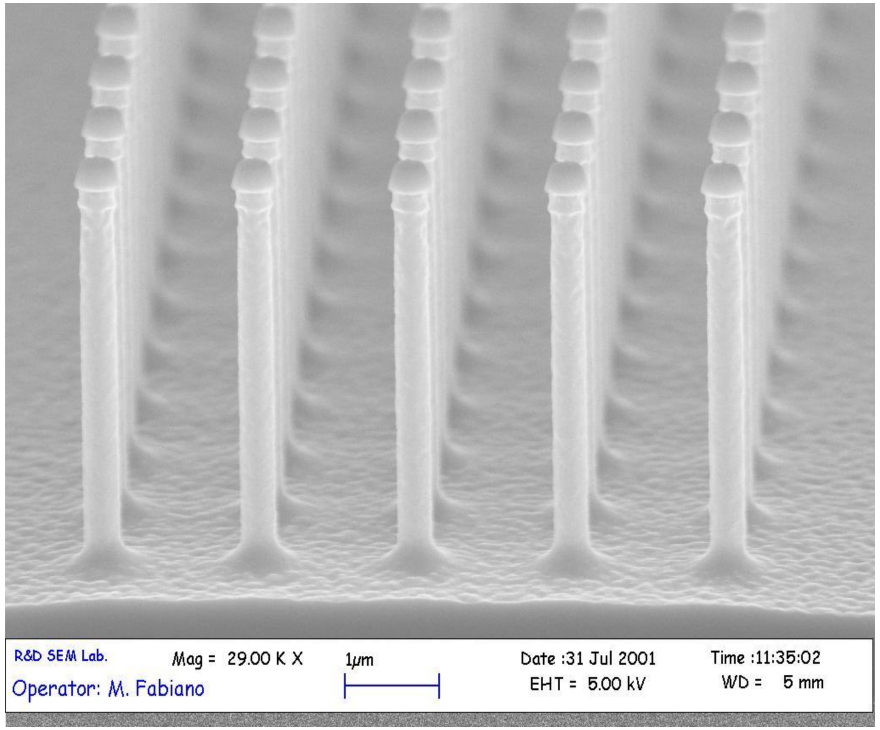
deposition

treatment

DRY ETCHING

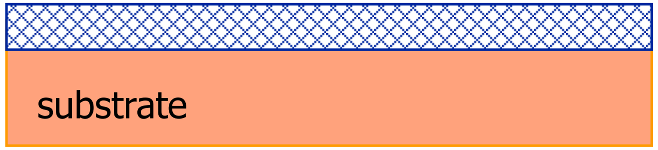

Ion
Sidewall Passivation Film
Remove Involatile polymer film


WF5 BORDO
R&D SEM Lab.
Operator: M. Fabiano
Mag = 15.83 K X
2μm
Date :6 Apr 2001
EHT = 5.00 kV
Time :15:22:10
WD = 4 mm


R&D SEM Lab.
Operator: M. Fabiano
Mag = 29.00 K X
1μm
Date :31 Jul 2001
EHT = 5.00 kV
Time :11:35:02
WD = 5 mm

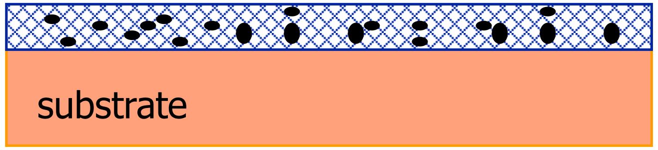
PE-CVD

dense, cross-linked coating



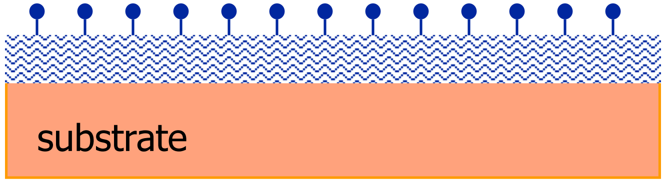
inorganic
DLC, SiOx, …

nano (bio) composite coating



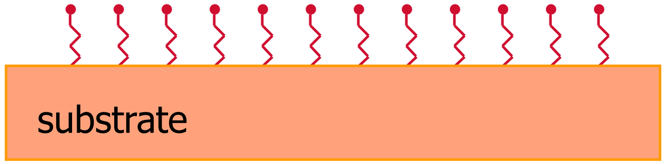
(bio) organic/inorganic
metal/ceramic clusters
embedded in a matrix

functional coating **(-COOH, -NH2, -OH, >C=O, …)**



organic
PEO-like, pdAA, teflon-like,
silicone-like …

high monomer structure retention



organic
teflon-like

modified thickness
10 – 1000 nm

CVD, Chemical Vapor Deposition

The precursor of the coating is in the gas phase.
The deposition/polymerization process can be initiated by an initiator molecule and/or by a hot filament, or by heating the substrate. (e.g., pyrolysis, i-CVD, etc)

PE-CVD, Plasma-Enhanced CVD

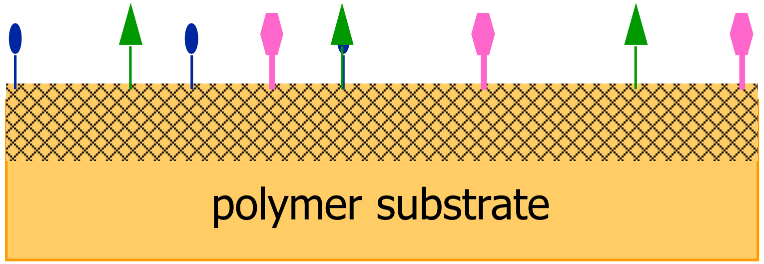
The precursor of the coating is in the gas phase.
The deposition process is initiated by fragmenting the "*monomer*" with an electric field (glow discharge). In case of organic monomers the jargon term *plasma polymerization* is utilized

PVD, Physical Vapor Deposition

The precursor of the coating is in the solid phase (filament, electrode).
The deposition process is initiated by heating a filament (evaporation) or by sputtering from an electrode bombarded by positive ions (glow discharge, ion gun, etc).

PLASMA TREATMENTS

grafting of functional groups



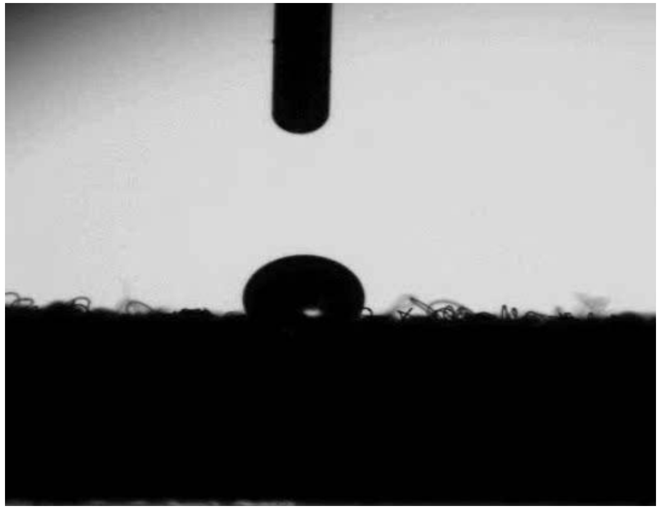
modified thickness
1 – 10 nm

surface modification (deposition, etching, grafting) plasma processes

can be considered nanotechnologies for the z axis

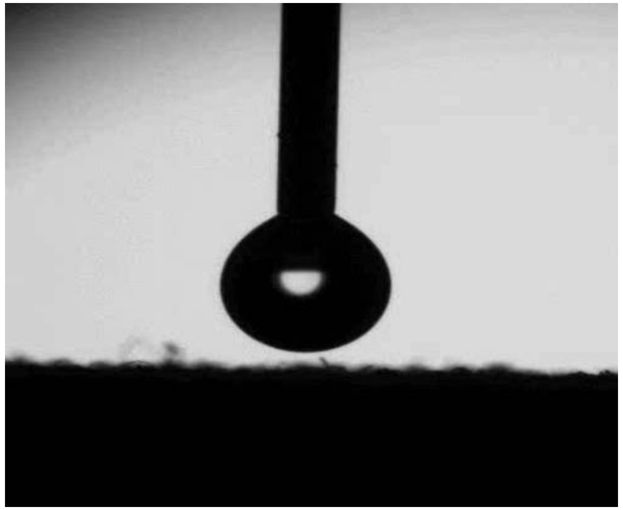
HYDROPHILIC TEXTILE

untreated

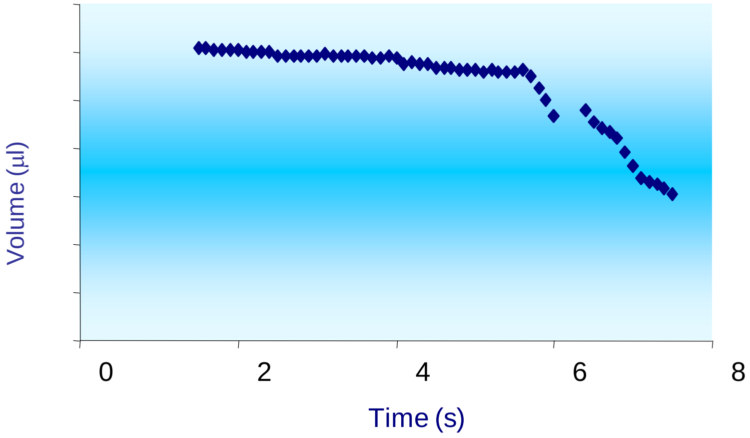


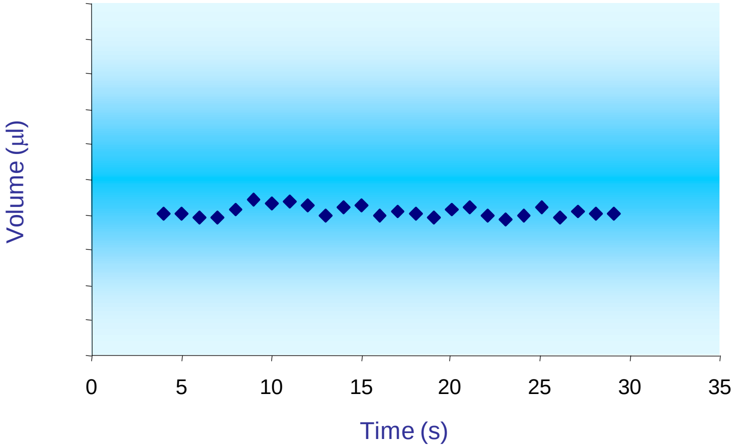
CF$_4$ plasma treated

WCA
122±3°



water adsorbtion kinetics





CF_4 → plasma → CF_x radicals + F atoms

CF_4 + O_2 → plasma → CF_{x-1} radicals↓ + CO, CO_2 + F atoms ↑

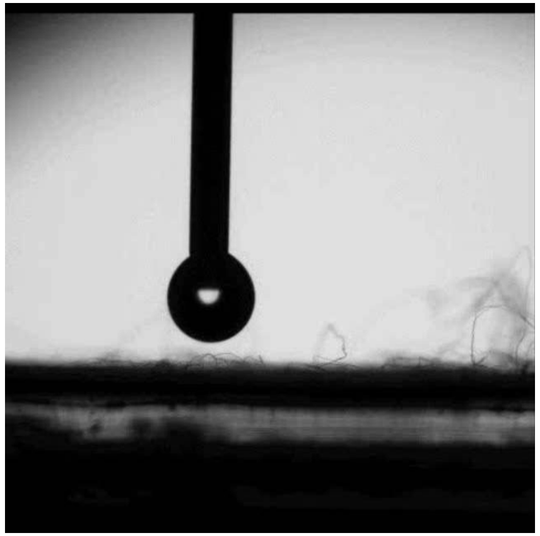
F atoms + pol. surf. → fluorinated (grafted) pol. surf.

CF_x radicals + pol. surf. → fluorinated (coated) pol. surf.

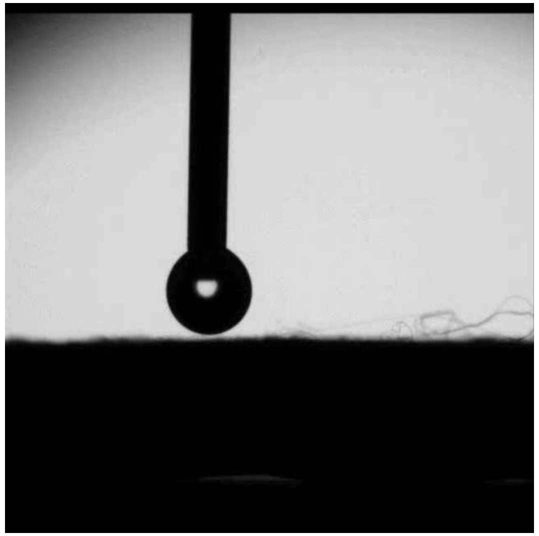
HYDROPHOBIC PBT WNW

untreated

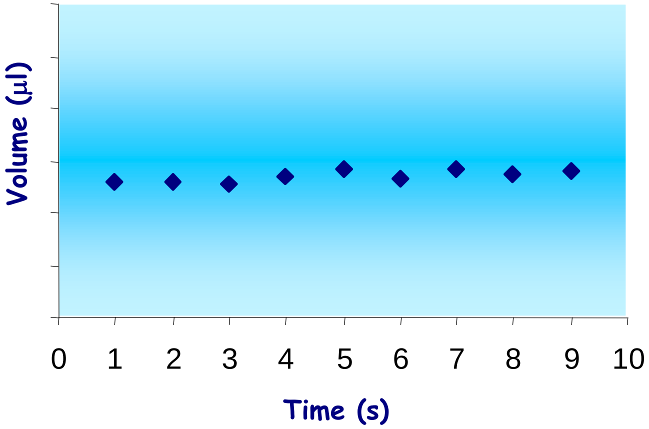
WCA 142±4°

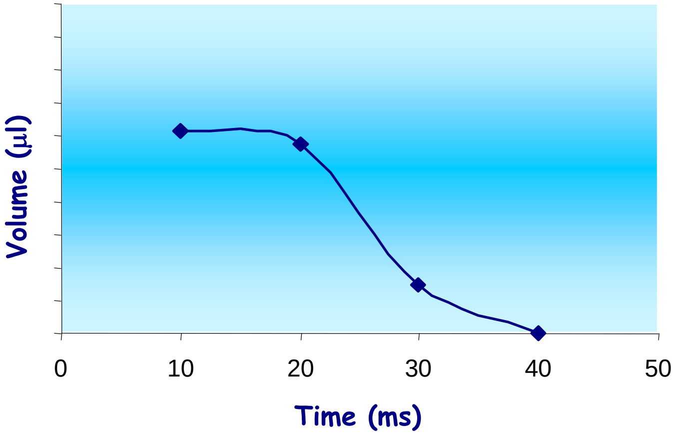


O_2 plasma treated



water adsorbtion kinetics





O_2 → plasma → $O_2^* + O_{atoms}$

$O_2^* + O_{atoms}$ + pol. surf. → oxidized (grafted) pol. surf.

$O_2^* + O_{atoms}$ + pol. surf. → oxidized (etched) pol. surf. + CO, CO_2, H_2O

SURFACE MODIFICATION OF MATERIALS WITH LOW PRESSURE PLASMA TECHNIQUES

active species interact with surfaces in three different processes

PLASMA (Dry) ETCHING

Ablation of materials (Si, SiO_2, III-V, II-VI, resists, polymers, metals, etc.) through reactions with active species forming volatile compounds.
ASHING: etching of polymers in O_2 plasmas.

PE-CVD PLASMA ENHANCED CHEMICAL VAPOR DEPOSITION

Inorganic (SiO_2, DLCs, diamond, a-Si:H, etc.) and organic (silicone-, PEO- teflon-like, etc.) coatings can be deposited.
PLASMA POLYMERIZATION is jargon name for PE-CVD of organic coatings;
where a MONOMER is used to feed the discharge.

PLASMA TREATMENTS

Modification of the topmost layers of materials (polymers) by grafting chemical groups ($-NH_2$, -COOH, -F, -OH…) and/or crosslinking surfaces with reactive (NH_3, CF_4, O_2, …) or inert (Ar, He,..) gases (CASING).

TECHNOLOGICAL APPLICATIONS OF COLD PLASMAS

Gas phase reactions

Production of Ozone; abatement of pollutants; vehicle exhaust gas treatments.

Light sources

Neon lights; High Intensity Discharge (HID) car lights; TV plasma displays.

Aerospace

Plasma-based space propulsion technologies; plasma-aided combustion; plasma actuators for airplane wings.

Surface modification processes of materials

Etching processes

Si, SiO_2 and other materials in Microelectronics for production of Ultra Large Scale (ULS) Integrated Circuits (IC);

Deposition of thin films

gas/vapor barrier layers in Food Packaging; protective anti-corrosion coatings on metals
hydrogenated amorphus Silicon (a-Si:H) photovoltaic coatings for solar cells;
diamond and diamond-like (DLC) hard coatings;
functionalization of very large area substrates (polymer webs, textiles, displays).

Treatments

grafting of polar groups on polymers for printing;
improving hydrophilicity and citocompatibility of polystirene cell-culture plates.

Plasma sterilization of materials

Plasma synthesis/functionalization of micro/nanoparticles

Synthesis of semiconductor nano-crystals; synthesis of carbon nanotubes;
functionalization of micro/nanoparticles.

Therapeutic uses of plasmas (Plasma Medicine)

Plasma-aided surgery; wound healing; cancer treatments; disinfection of teeth cavities in dentistry.

SURFACE PROPERTIES OF MATERIALS
TUNABLE
WITH PLASMA PROCESSES

adhesion

wettability/hydrophobicity

oleophobicity

gas/vapor barrier

permeability

biocompatibility

resistance to bacterial adhesion

chemical inertness

non fouling character

electrical conductivity

hardness (anti-scratch)

roughness, texture

refractive index

dyebility

color

corrosion protection

…

WHY NON EQUILIBRIUM PLASMAS ?

LOW TEMPERATURE PROCESSES FOR THERMOLABILE MATERIALS

SURFACE MODIFICATIONS, NO BULK ALTERATIONS

polymers, paper, textiles, ...

ADAPTABLE TO ANY SHAPE AND MATERIAL SUBSTRATE

webs, inside of small tubes, powders, granules, fibers, …

HIGH DENSITY OF ACTIVE SPECIES

comparable with high T gases and flames

TUNEABLE ION BOMBARDMENT

DRY TECHNOLOGY, NEGLIGIBLE IMPACT TO THE ENVIRONMENT

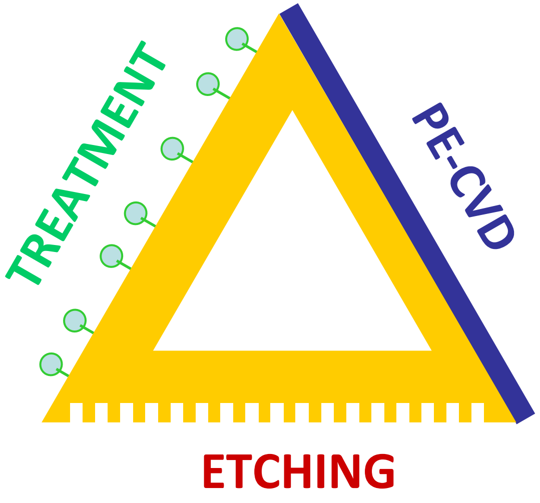
ATMOSPHERIC PRESSURE PROCESSES

SYNTHESIS OF AN ENTIRELY NEW CLASS OF SURFACES

TRANSFER TO INDUSTRIAL SCALE

PROCESS CONTROL POSSIBLE

INDUSTRIAL AREAS of COLD PLASMAS



MICROELECTRONICS
SEMICONDUCTORS
SOLAR CELLS
LIGHT SOURCES
OZONE PRODUCTION

- AUTOMOBILE
- FOOD PACKAGING
- TEXTILE
- BIOMATERIALS
- MICROFLUIDICS
- MEMS
- CLEANING
- STERILIZATION
- BIOLOGY
- ENVIRONMENT
- CATALYSIS
- MEDICINE
- POLYMERS
- PAPER
- WETTABILITY
- ADHESION
- METALLIZATION
- PRINTING, DYEING
- CORROSION PROTECTION
- CULTURAL HERITAGE
- COMPOSITES
- SENSORS
- OPTICS
- BUILDINGS

LOW T PLASMA PROCESSES: APPLICATIONS

ETCHING

Si, SiO_2, III-V & II-VI SC, resists, dielectrics, Al … for VLSI circuits;
cleaning; bioMEMS; sterilization; glass, PMMA for microfluidics, soft litography ….

PE-CVD (coatings)

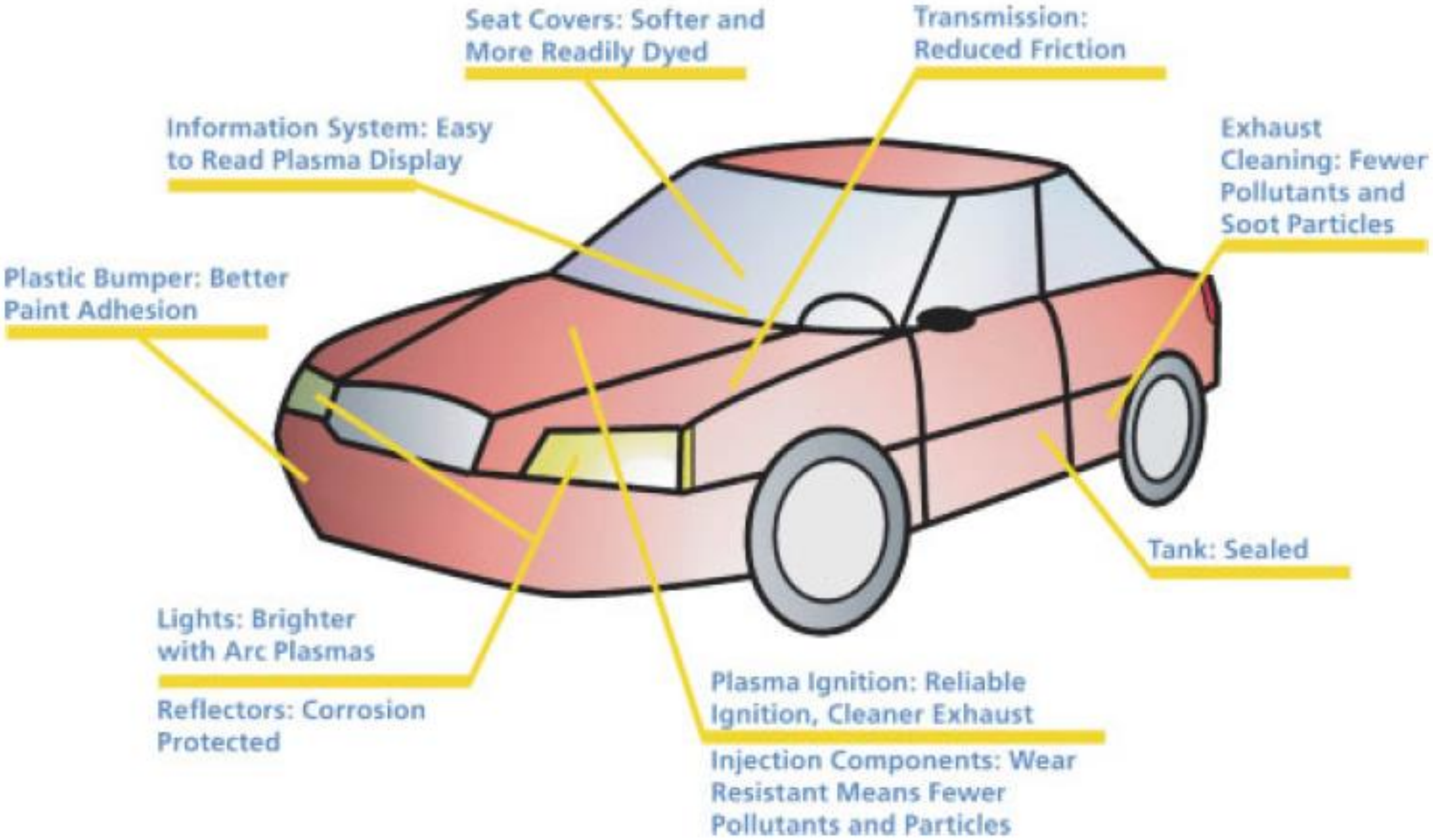
Gas barrier in food packages (webs, bottles, …) and OLED; corrosion protection on metals (car, …); protective for cultural heritage; low-k and high-k dielectrics for microelectronics; semiconductors for solar cells; anti-scratch, anti-reflective, colored for optics; water- oil-proof for paper and textiles; cell-adhesive, blood-compatible, protein and cell repulsive, bacterial-resistant for biomaterials; hydrophilic/hydrophobic; functional for (bio)molecule (enzymes, peptides, …) immobilization on biomedical surfaces and sensors; nanocomposite and bio-nanocomposite coatings, ….

TREATMENTS (grafting)

Improved adhesion of inks, dyes, glues, metals on polymers and textiles; anti-felting, anti-shrinking for wool;

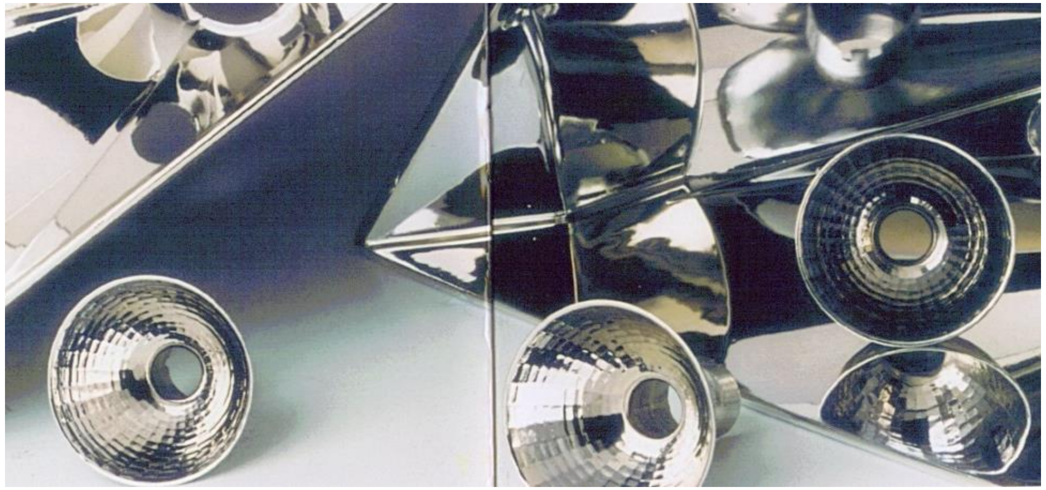
improving fiber- and particle-matrix adhesion in composite materials or scaffolds; hydrophilic/hydrophobic;

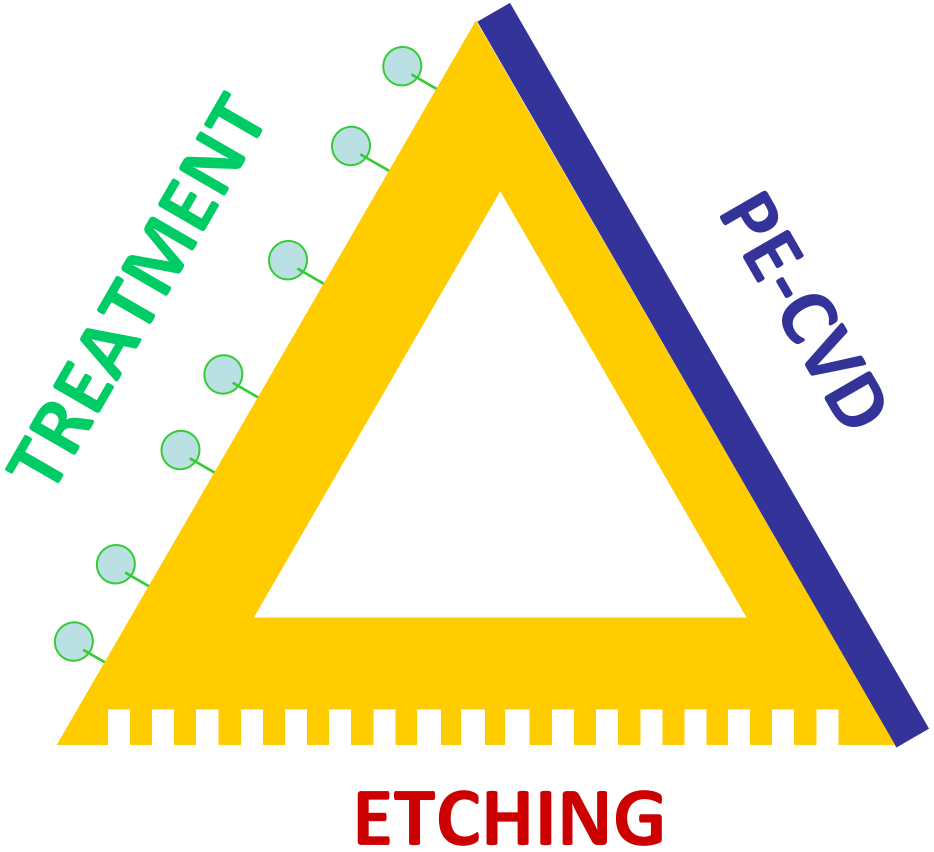
cell-adhesive, grafted groups to immobilize (bio)molecules on biomedical surfaces and sensors; …

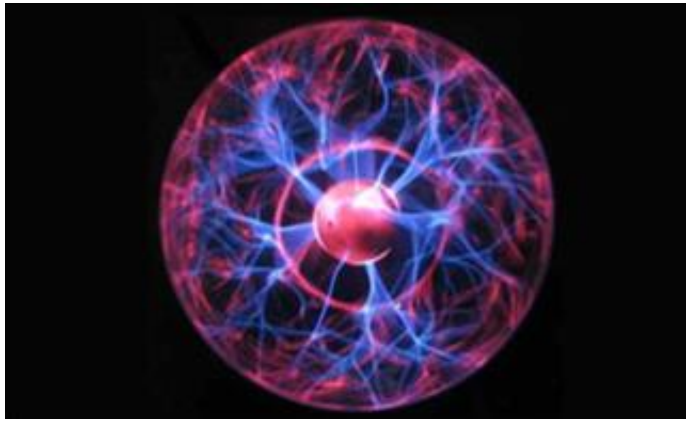


plasma
for the car

PE-CVD SiOx
“protecting seal” coatings
on Al-evaporated plastic car lights



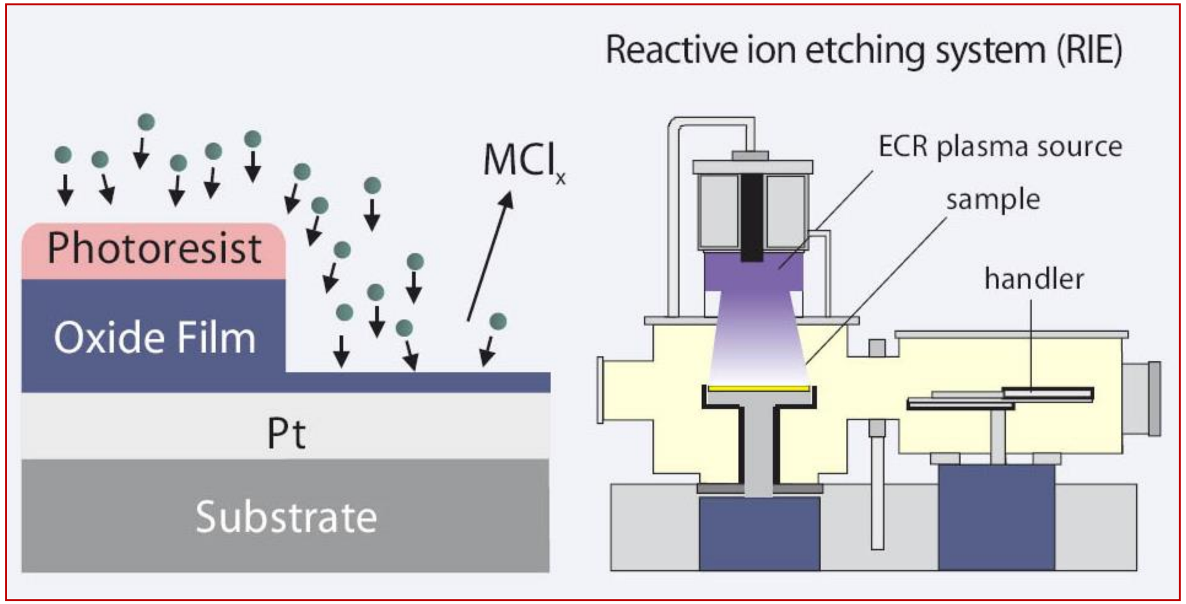

TREATMENT
PE-CVD
ETCHING



REACTOR CONCEPTS

Pietro Favia

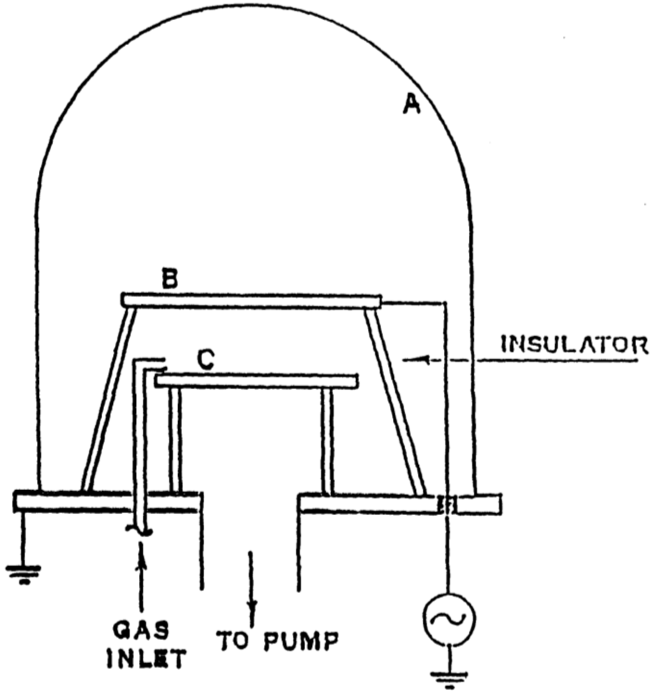
http://www.ion-med.com/how.asp



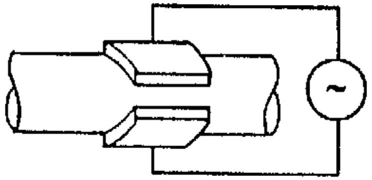
LOW P
PLASMA REACTORS:
popular configurations

INTERNAL ELECTRODES

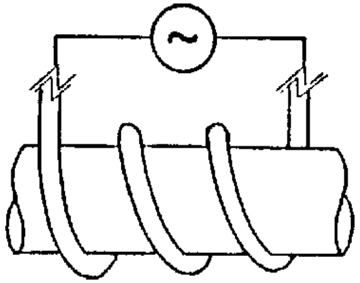
bell jar reactor



EXTERNAL COUPLING

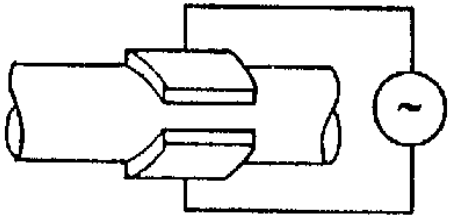


CAPACITIVE

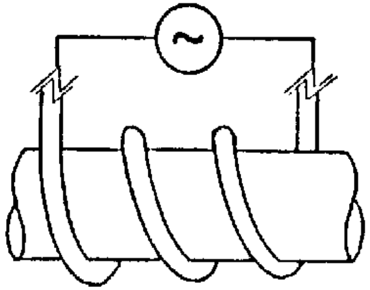


INDUCTIVE

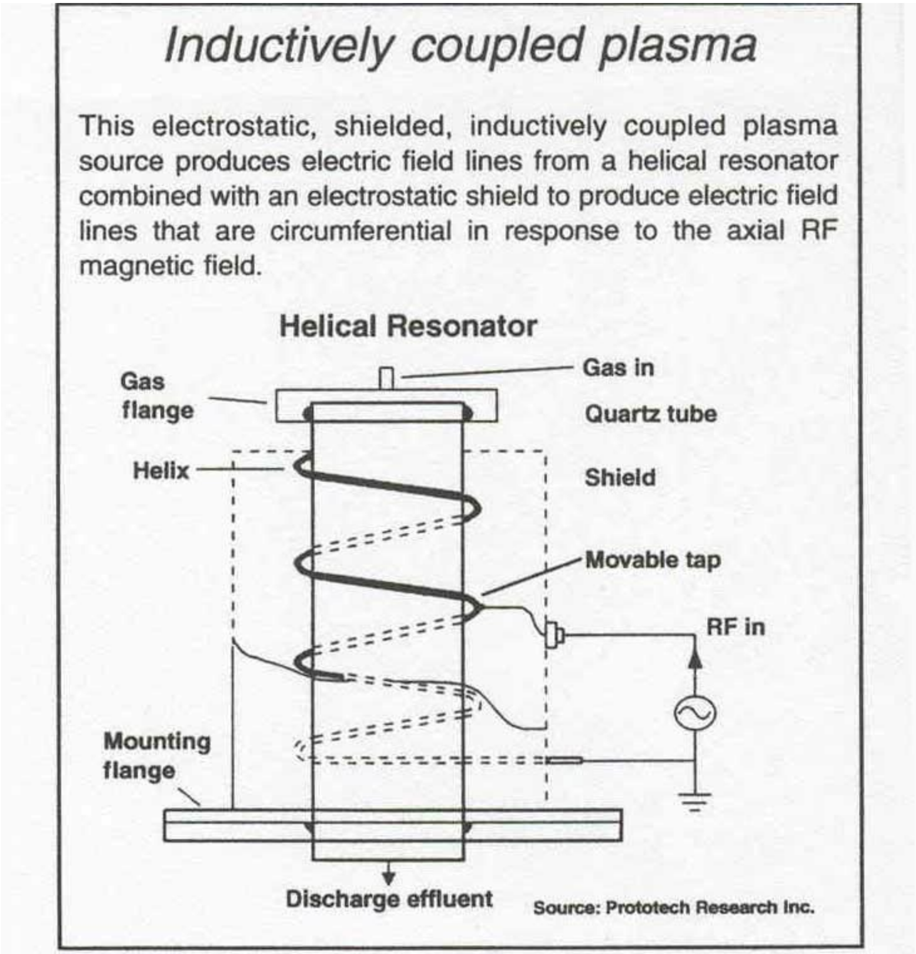
EXTERNAL COUPLING



CAPACITIVE



INDUCTIVE

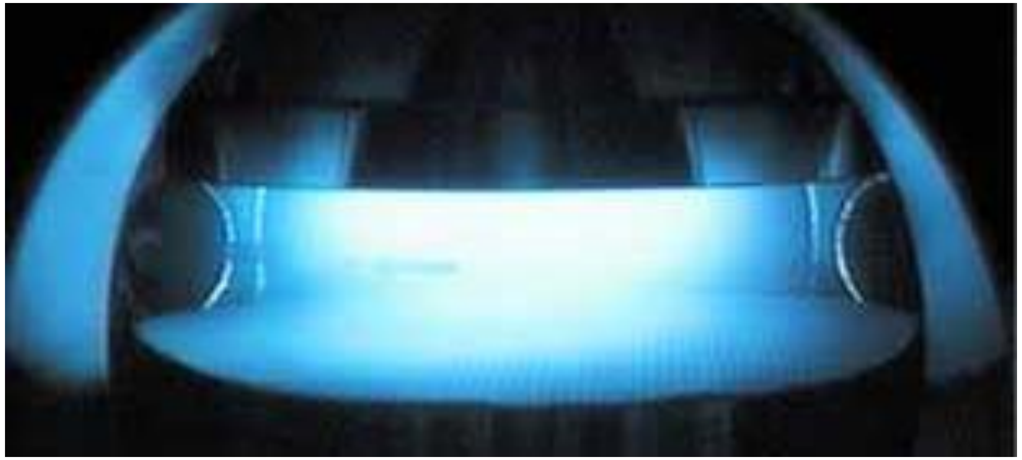


Inductively coupled plasma

This electrostatic, shielded, inductively coupled plasma source produces electric field lines from a helical resonator combined with an electrostatic shield to produce electric field lines that are circumferential in response to the axial RF magnetic field.

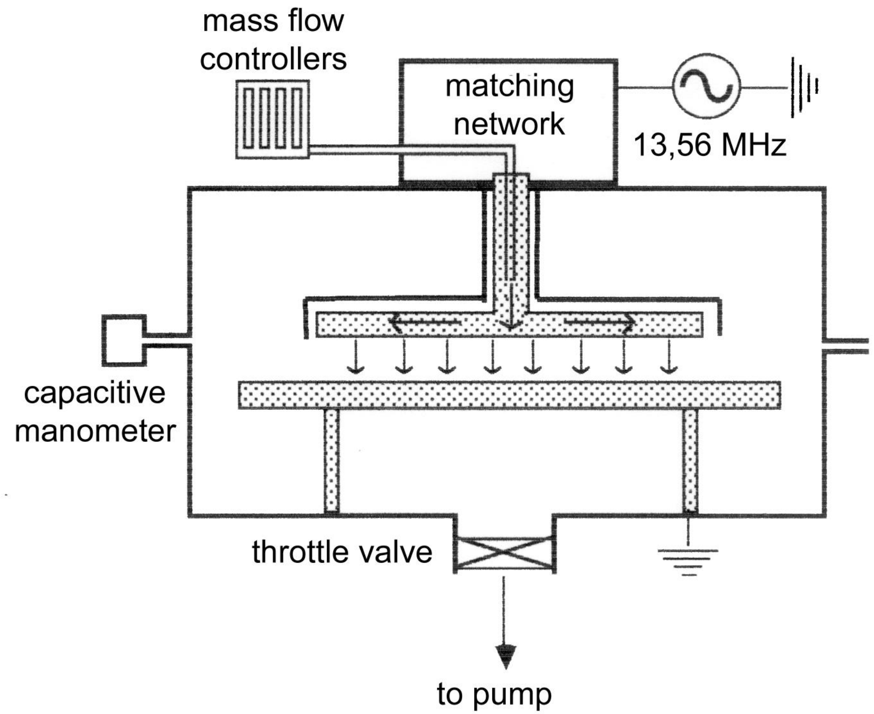
Helical Resonator

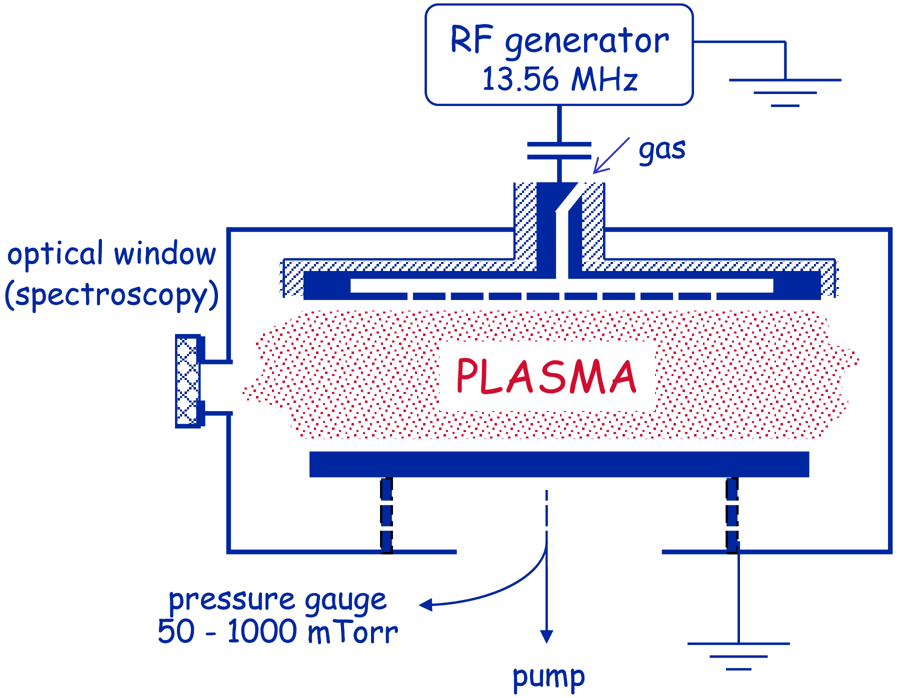
Source: Prototech Research Inc.



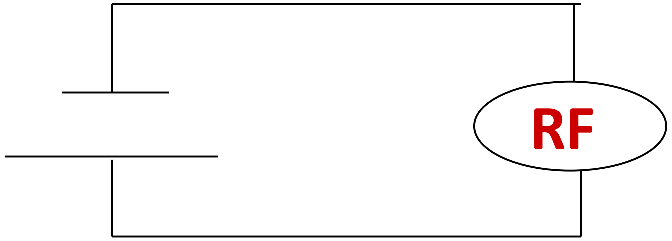
PARALLEL PLATE PLASMA REACTOR

internal electrodes

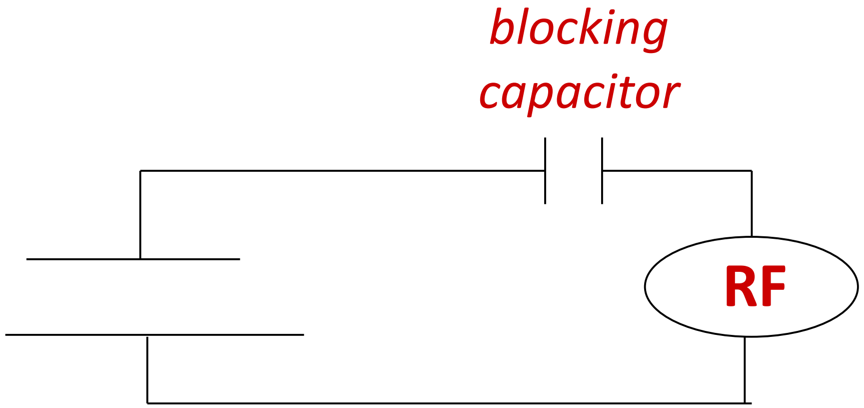




POTENTIALS IN A GLOW DISCHARGE
(oversimplified picture)



DIRECT COUPLING

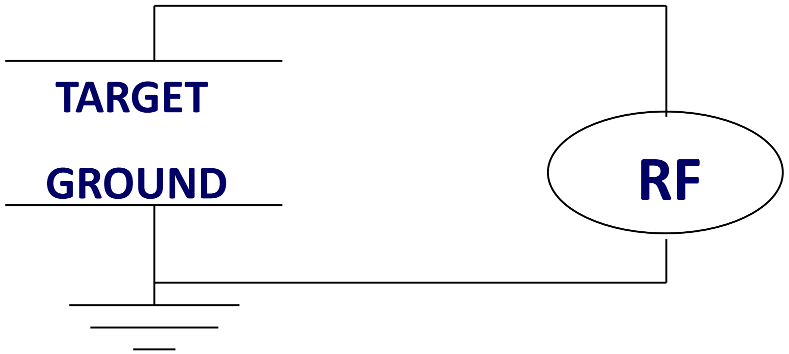


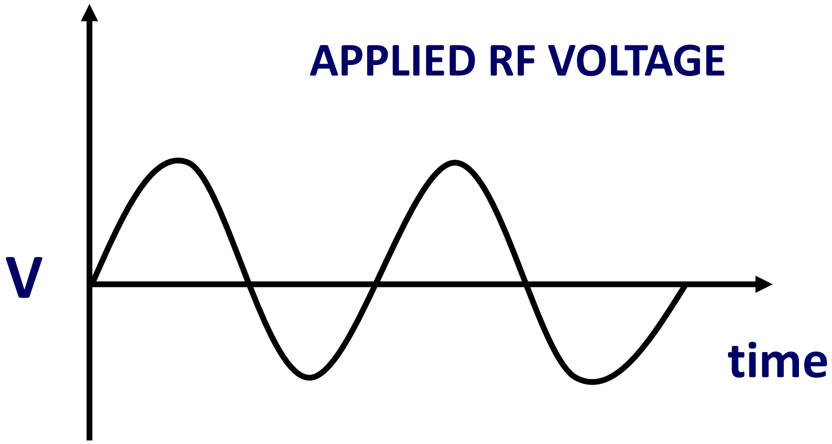
CAPACITIVE COUPLING

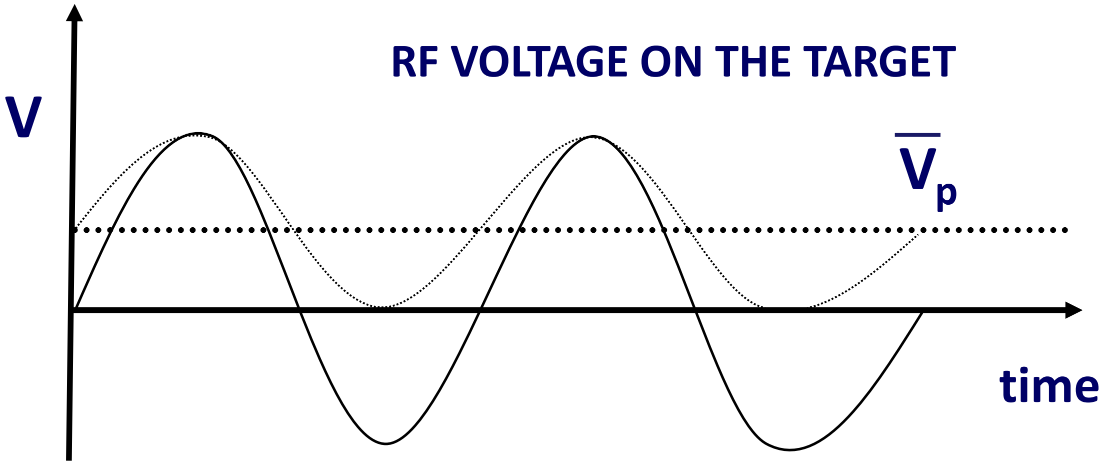
WITH THE BLOCKING CAPACITOR
NO NET CURRENT CAN FLOW IN THE CIRCUIT IN ONE RF CYCLE

$$I_{tot} = 0$$

DIRECT COUPLING



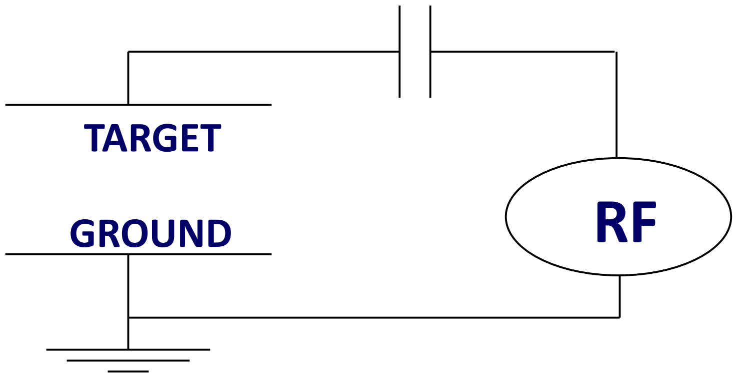

APPLIED RF VOLTAGE

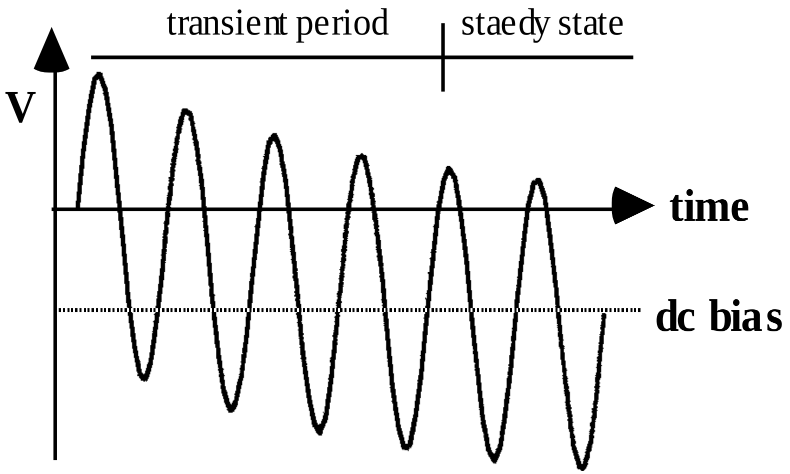

RF VOLTAGE ON THE TARGET

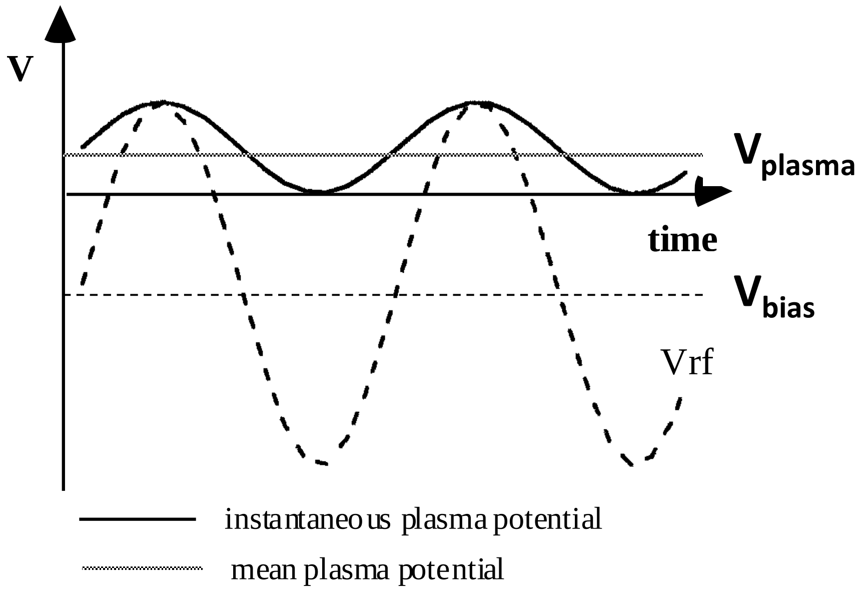
AVERAGE PLASMA POTENTIAL > 0 (e.g. Vp/2)

AVERAGE TARGET POTENTIAL = 0

CAPACITIVE COUPLING







THE SITUATION IS SIMILAR FOR A FLOATING SUBSTRATE

FLOATING POTENTIAL

AVERAGE POTENTIAL
ON AN ELECTRICALLY INSULATED SUBSTRATE

BIAS (or SELF) BIAS POTENTIAL

AVERAGE POTENTIAL OF A SUBSTRATE (ELECTRODE)
CONNECTED TO A RF POWER SUPPLY

AVERAGE PLASMA POTENTIAL

AVERAGE POTENTIAL OF THE BULK OF THE PLASMA

1. AC voltage overcomes the problem of charge which accumulates on a dielectric in the DC system.

The positive charge which accumulates due to ion bombardment during one half of the AC cycle can be neutralized by electron bombardment during the next half cycle. The frequency of AC must be high enough so the half period will be shorter than the charge-up time of the dielectric. Although this time will vary due to conditions and dielectric materials, for most applications the frequency must be above **100 KHz.**

2. Although there are a number of differences in the practical operation of AC plasmas, the principles of DC glow discharges can be applied to AC. One simply considers the AC as a rapidly reversing DC plasma.

At low frequency both electrons and ions can follow the field, so that a glow discharge is the same as DC, except that the polarity reverses twice each cycle. At high frequency the massive ions cannot respond to the frequency changes, whereas electrons can. By far the most common RF frequency used is 13.56 MHz, allowed by the FCC.

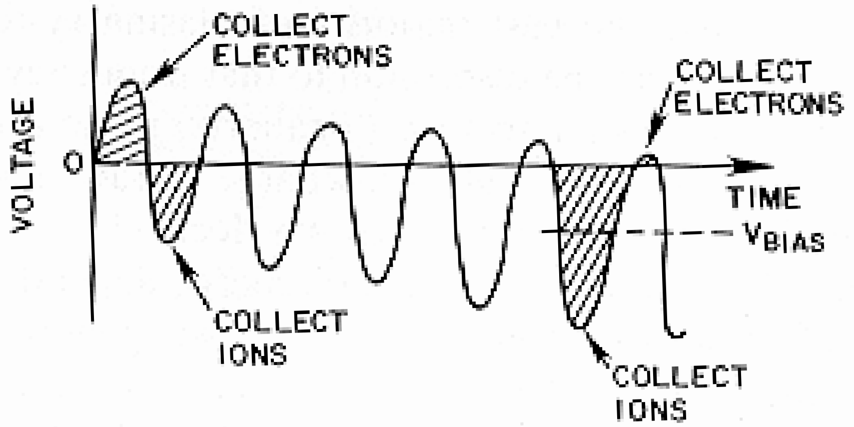
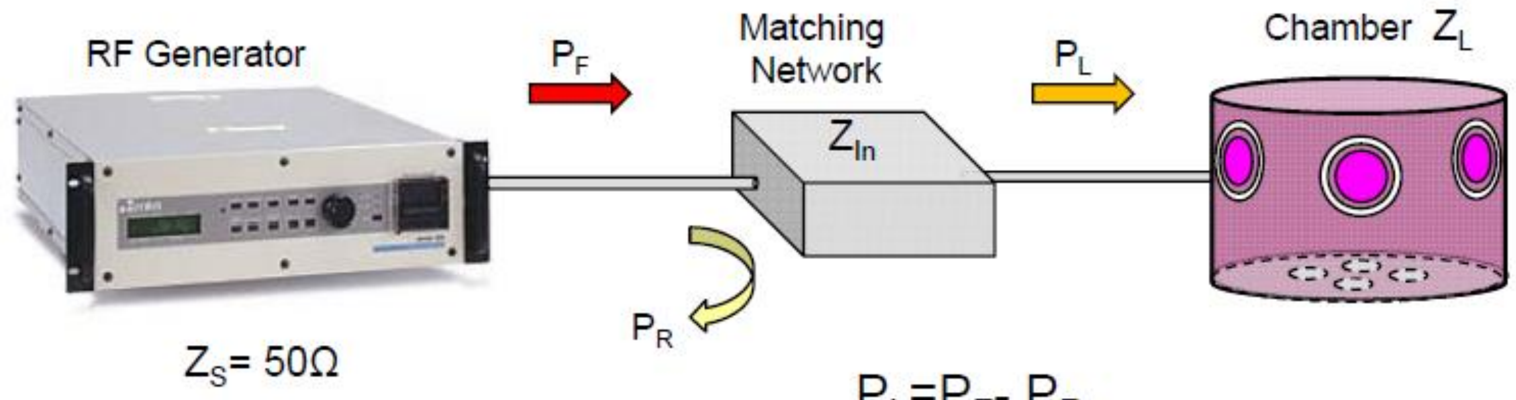


Fig. 9. The potential on the powered electrode of Fig. 8b as a function of time for the first several rf cycles.

MATCHING NETWORK

The matching network (manual/automatic) maximizes the power delivered to the plasma, reduces reflected power (standing waves) and protects the power supply.

A reactor could be operated also without the matching network; in practice the requested power density cannot be maximized without matching.

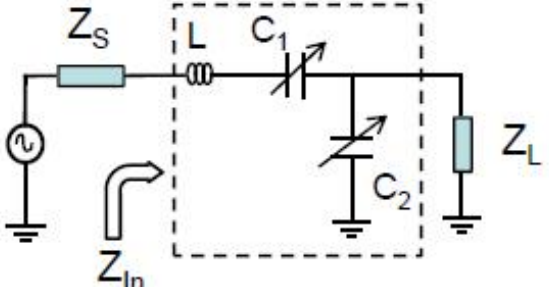


$$P_L=P_F- P_R$$

In general: $Z_L \neq Z_S$

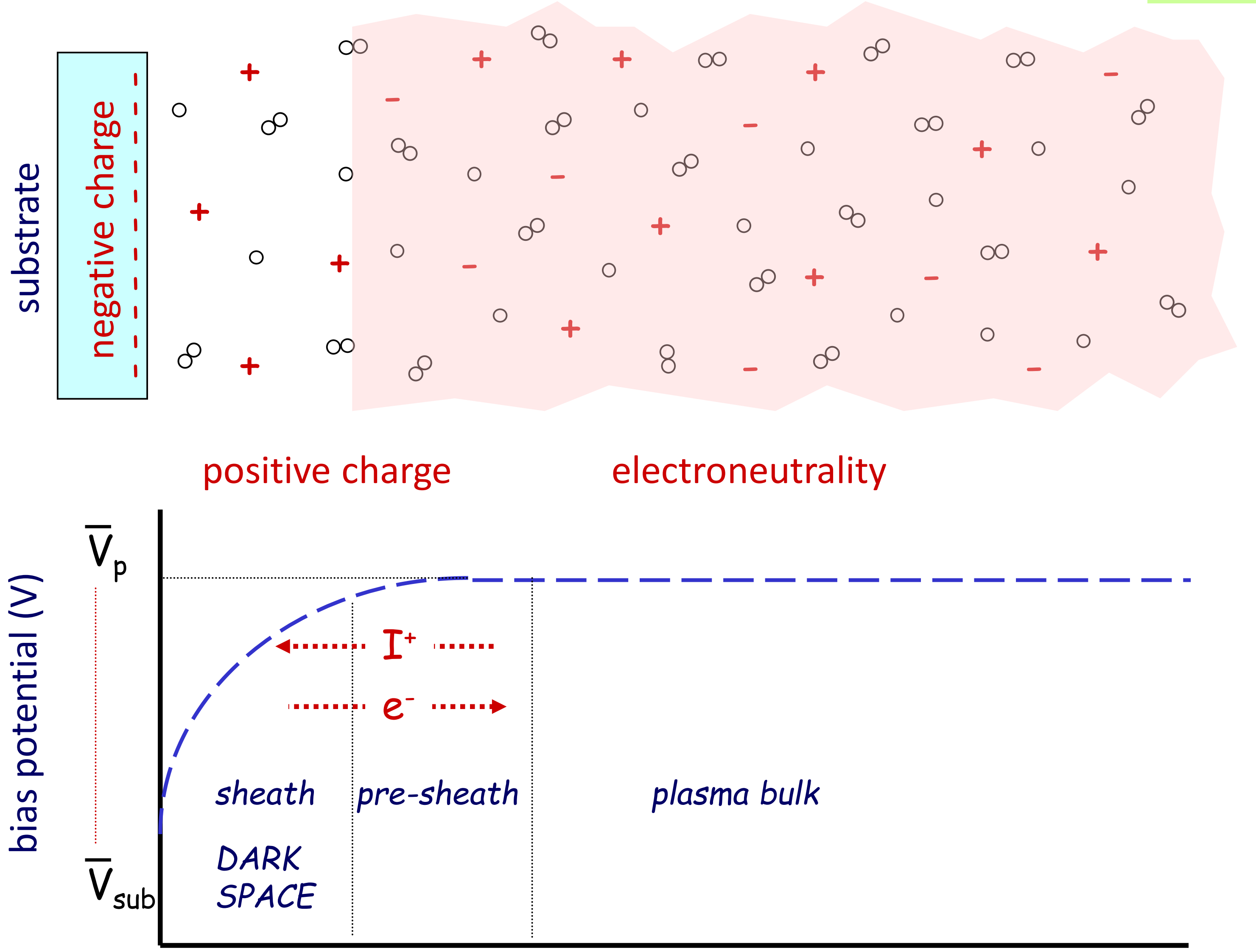
Purpose of Matching Network: $Z_{in} = Z_S$ to maximize power delivery from source.

Manual or Automatic Matching Network



L-type

bias potential



the thickness of the sheath increases with surface potential

- **at 13.56 MHz ions are affected by average potentials since, during the period they cross the sheath, RF polarity changes several times.**

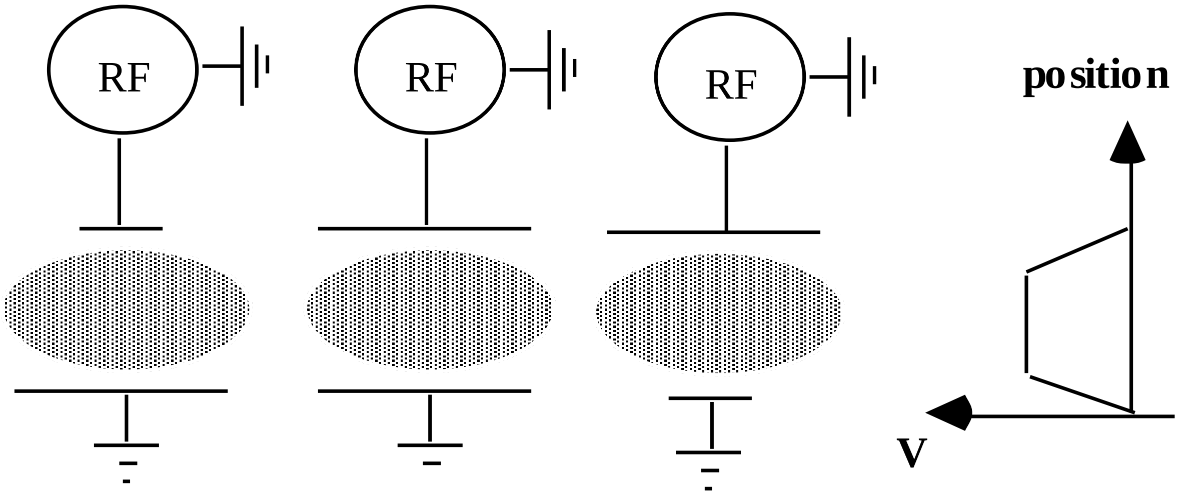
- **the surfaces in contact with the plasma are interested by positive ion bombardment because plasma bulk is the most positive region in the system.**

- **positive ion energy depends on system geometry, pressure, frequency, and a.c. peak-to-peak voltage.**

- **electrons reach surfaces with low energy for the decelerating effect of the sheaths.**

ION BOMBARDMENT INSIDE A PLASMA REACTOR

DIRECT COUPLING



PERFECT SIMMETRY

NO DIFFERENCE BETWEEN THE TWO ELECTRODES

CAPACITIVE COUPLING

the higher average potential drop (plasma-substrate) is experienced by the electrode with lowest area

Koenig & Meissel Law

$$\frac{V_1}{V_2} = \left(\frac{A_2}{A_1}\right)^n \qquad n = 1 - 4$$

Assumptions
(strong deviation at high P):

- ion current density equal at both electrodes;
- collisionless sheaths
- uniform plasma density

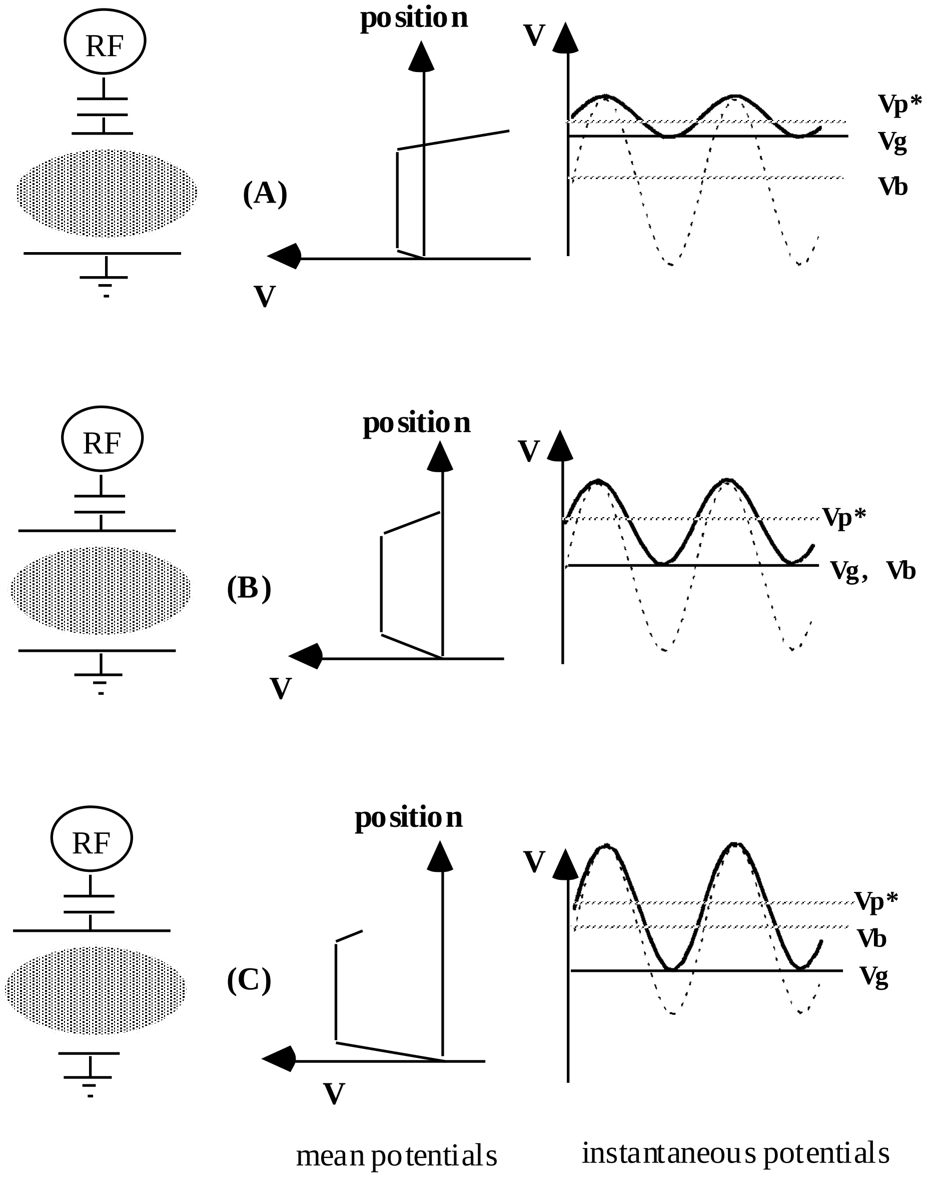
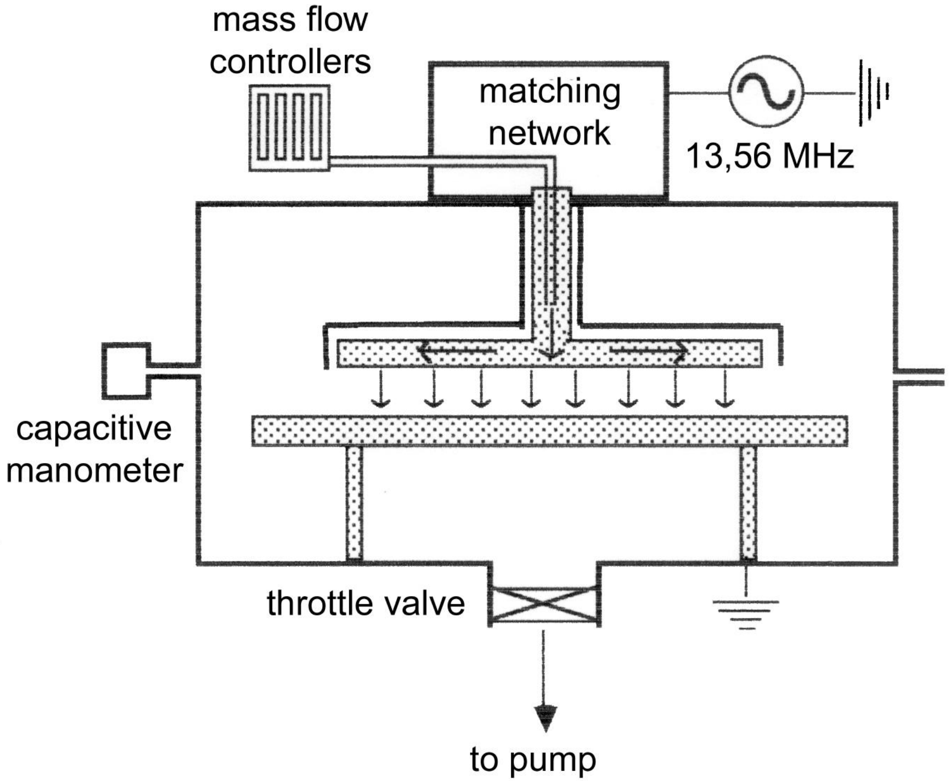


Figure 12. instantaneous and averaged potentials as a function of reactor geometry

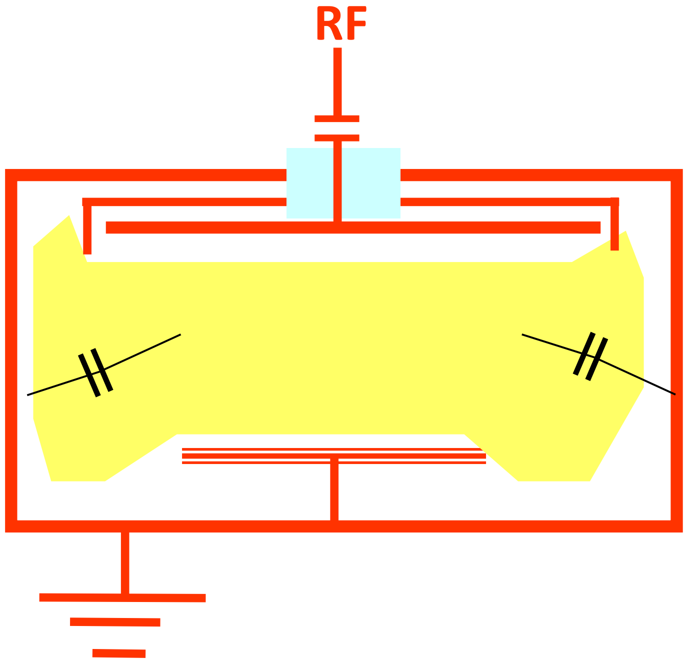
PARALLEL PLATE “DIODE” REACTOR

INTERNAL COUPLING



THE SYSTEM IS **ASYMMETRIC**
DUE TO THE REACTOR WALLS

walls put one of the many scale up problems

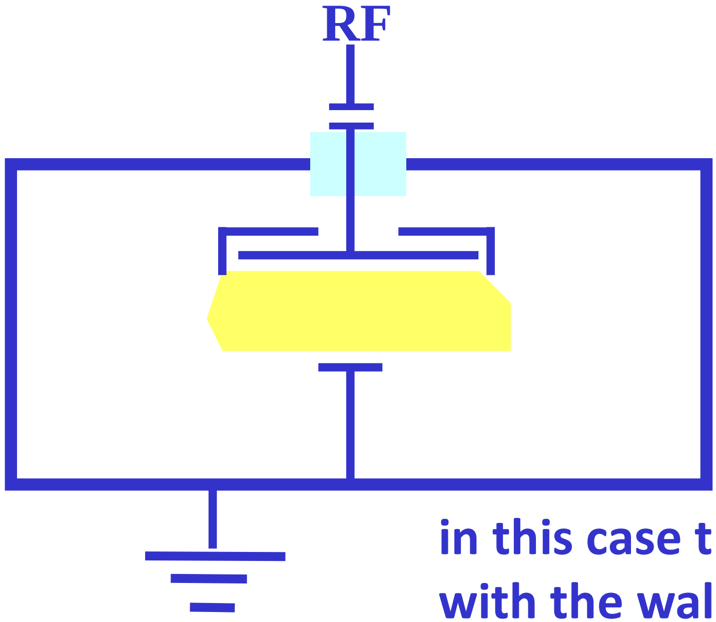


stray capacitance

lab scale

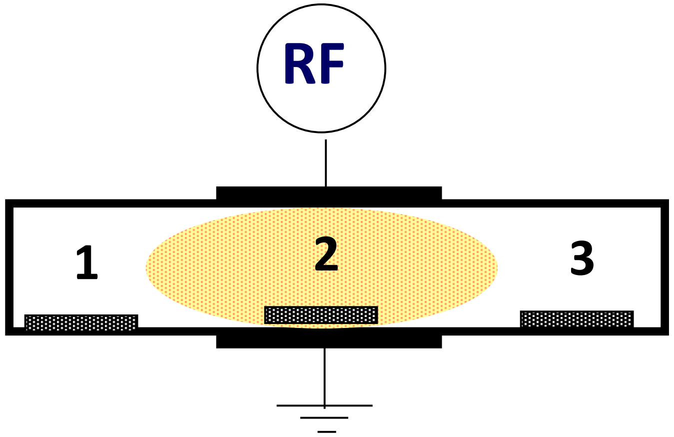
walls affect A_1/A_2 in a different way

large scale

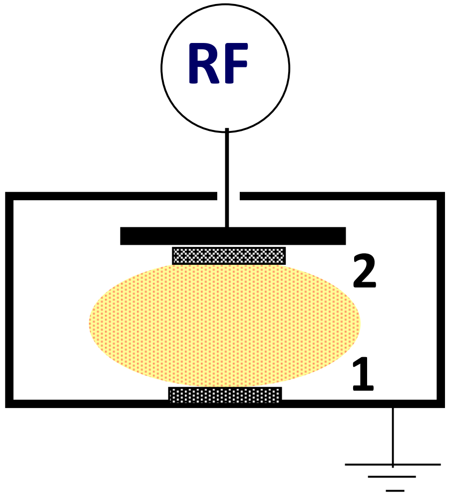


in this case the interactions with the walls are reduced

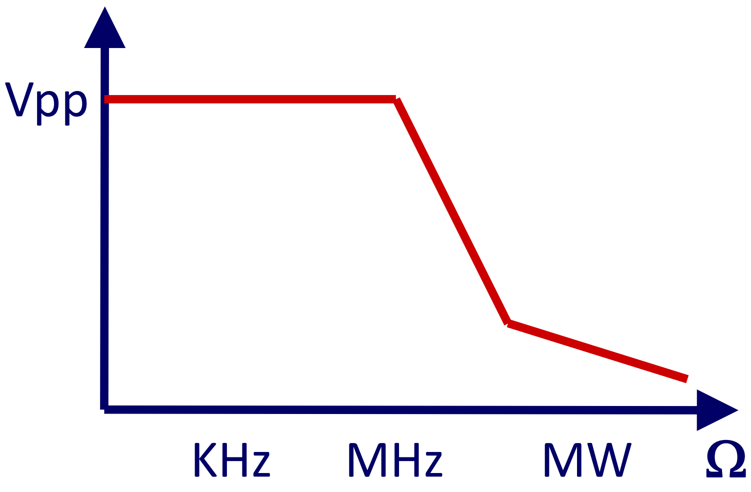
REACTOR GEOMETRY AND CHARACTERISTICS CONTROL THE PHYSICAL CONTRIBUTION TO THE PROCESS



substrate position



EFFECT OF RF FREQUENCY (ω) ON THE ION BOMBARDMENT



V_{pp}, V_p and V_{bias} increase by decreasing ω
KHz > MHz > GHz

Ion Transit Frequency (ITF, 0.9-2 MHz) is the frequency above which ions can't cross the sheath in less than half RF cycle

above ITF	I^+ are influenced by average potentials
below ITF	I^+ are influenced by instantaneous potentials

when ω < ITF (es KHz)

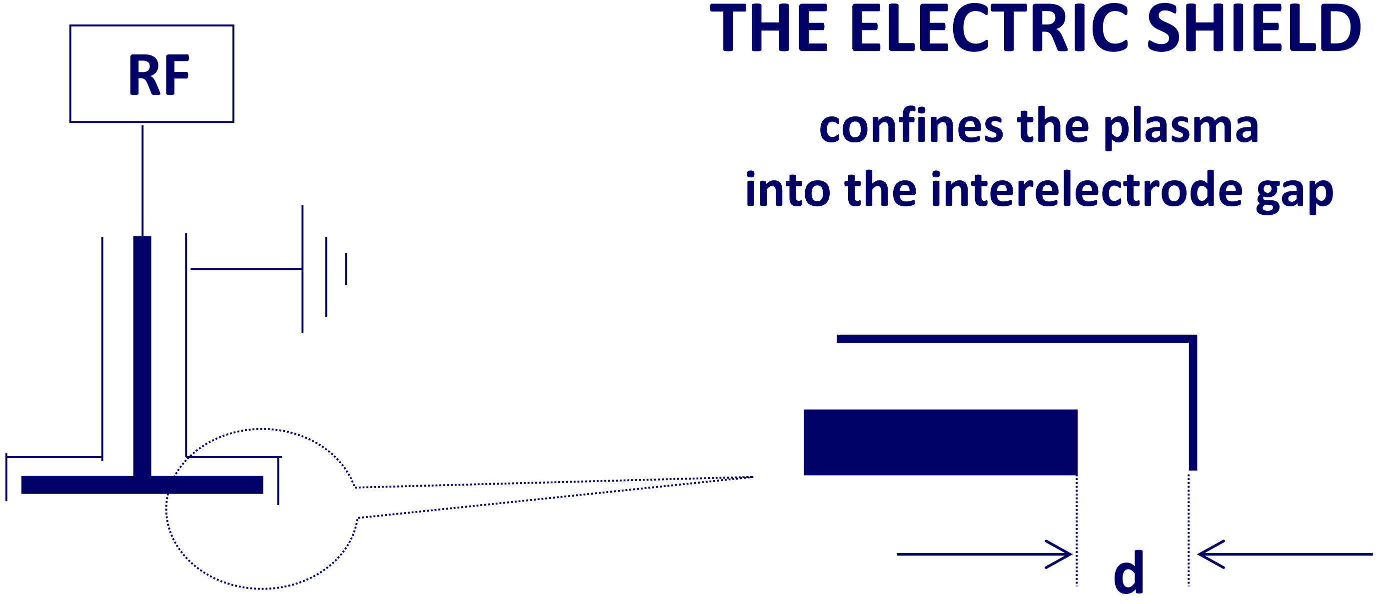
the ion bombardment becomes more energetic

the ion energy distribution function becomes broader

In the GHz, also electrons become unable to follow the oscillations of the electric field and are affected by average potentials

THE ELECTRIC SHIELD

confines the plasma
into the interelectrode gap



d = 0.5 – 3 mm

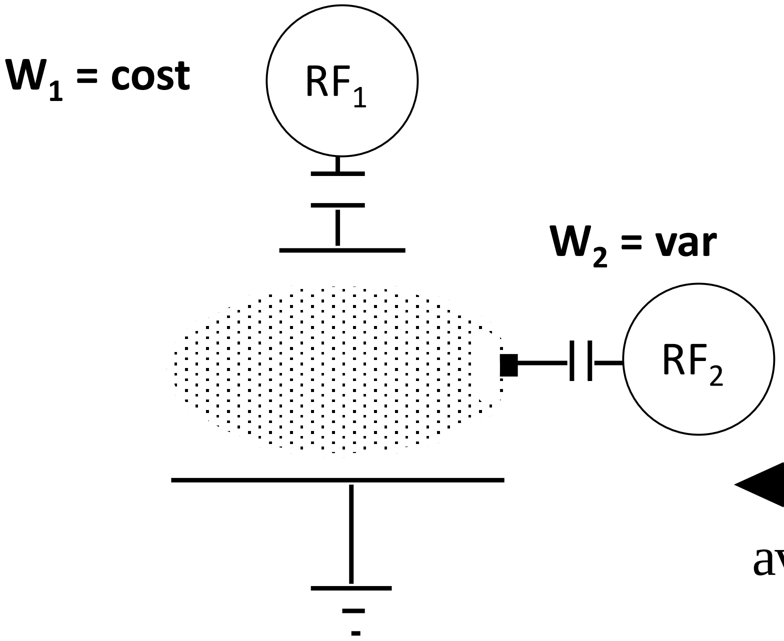
d (macroscopic, Paschen) is related to the Debye length (microscopic)

d must avoid discharge ignition with arcs and sparks

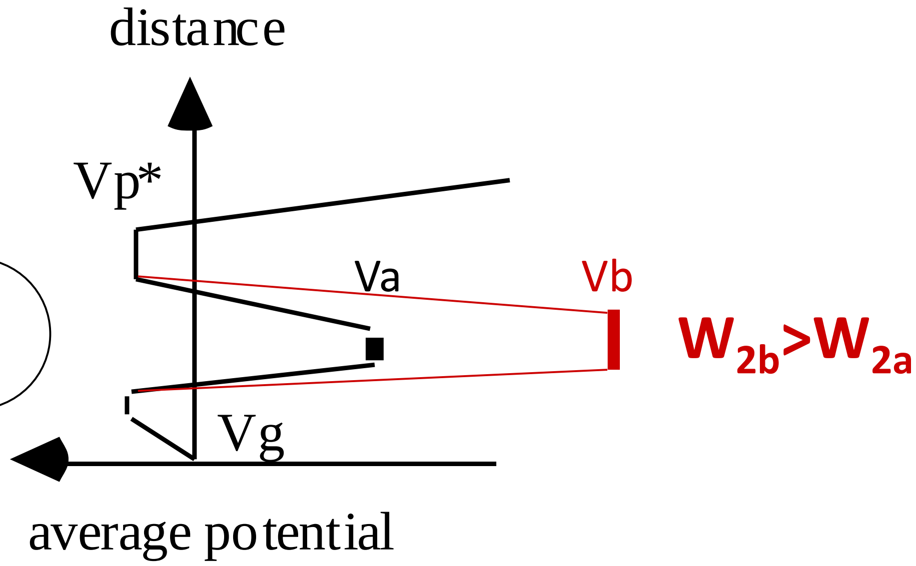
P↑ d↓

W↑ d↓

the surface potential of insulators can be tuned with an additional RF power supply



(A)



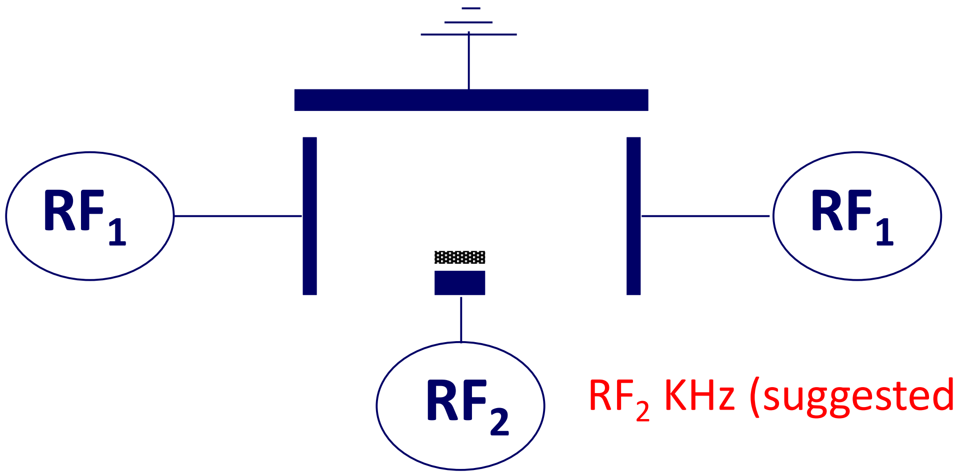
(B)

$W_1 >> W_2$

TRIODE REACTOR

DUAL FREQUENCY TRIODE REACTORS

THE ION BOMBARDMENT CAN BE TUNED INDEPENDENTLY FROM OTHER PARAMETERS



RF$_1$ 13.56 MHz
(also GHz)

RF$_2$ KHz (suggested), MHz

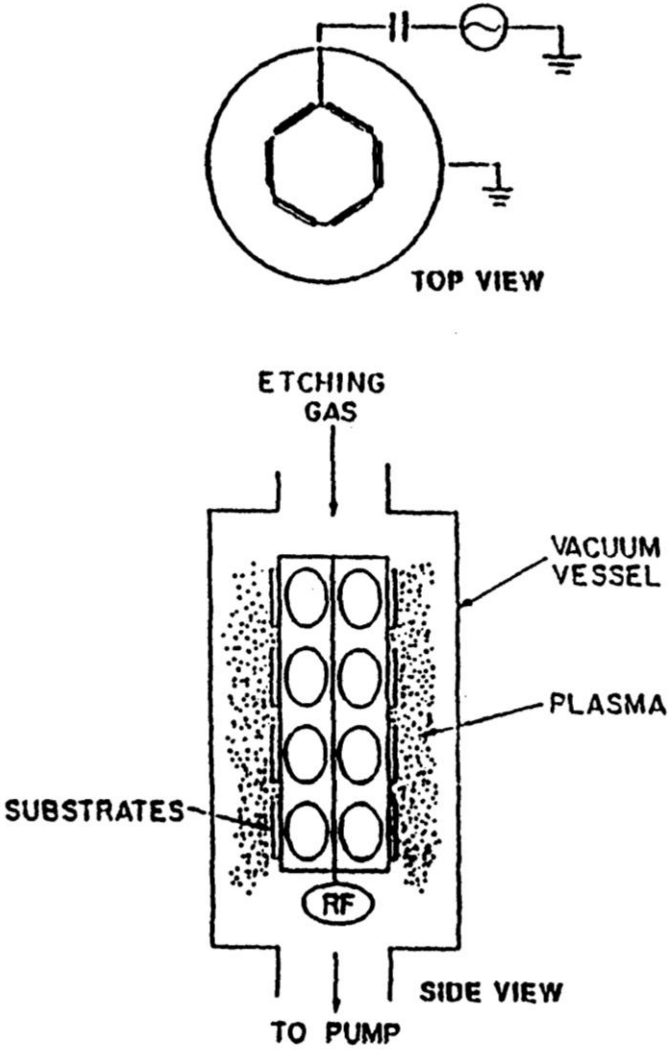
to reduce plasma perturbations the substrate electrode must be as small as possible

higher frequency
RF MW → **Plasma generation**
(low Vp, high I, high ne, N)

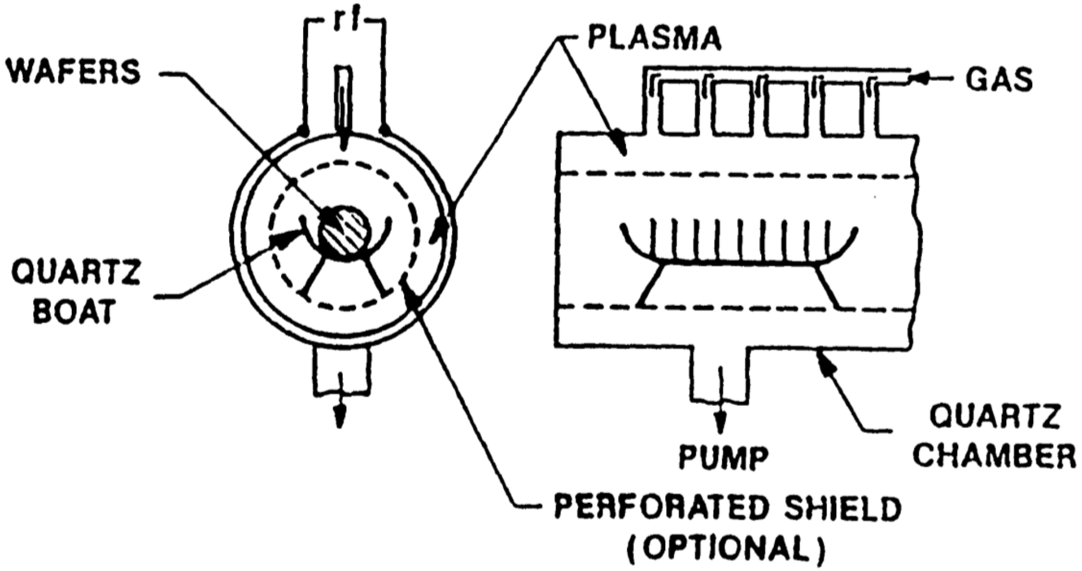
Lower frequency
AF → **Ion bombardment**
(high Vp, high Vb, low I)

THE HEXODE

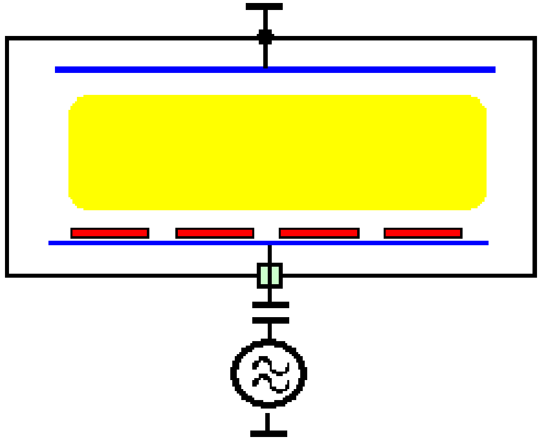
etching processes
in the 80s



BARREL REACTORS

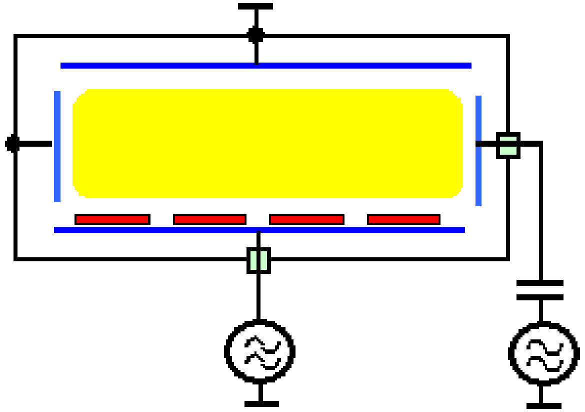


RIE

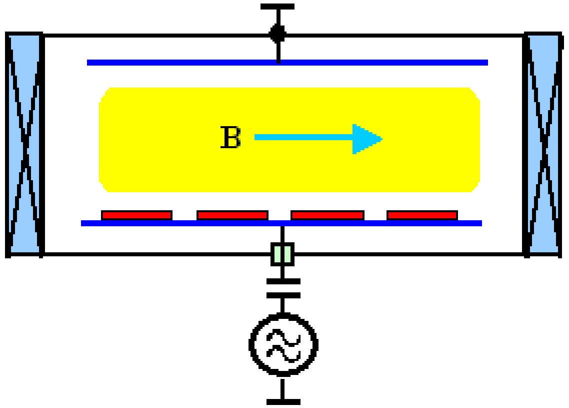


triode

TRIE

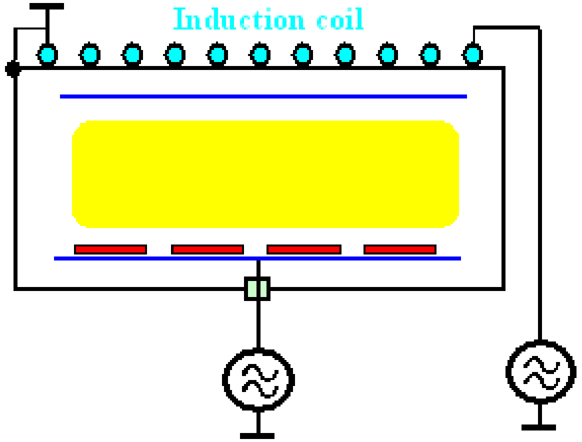


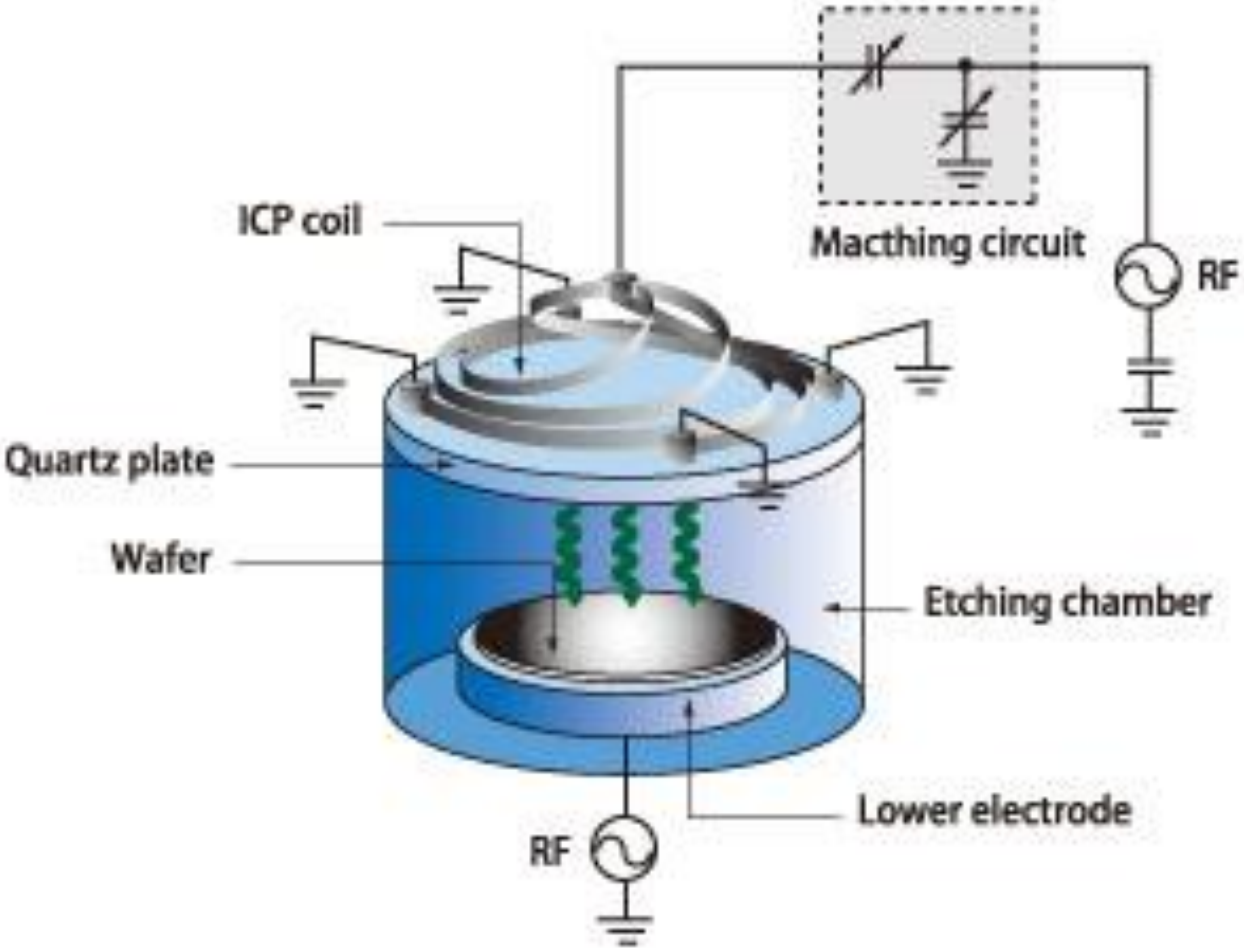
MRIE

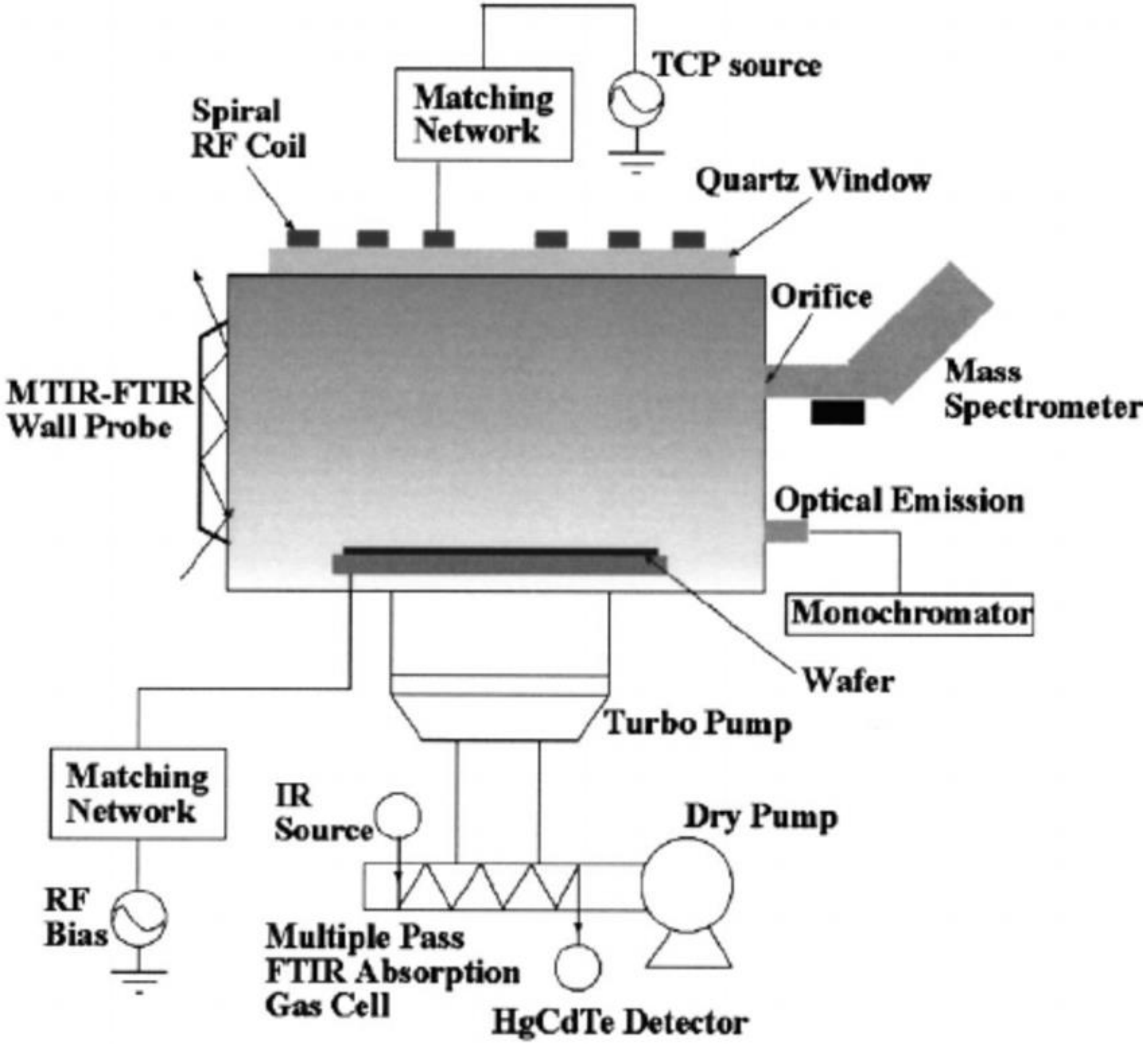


triode

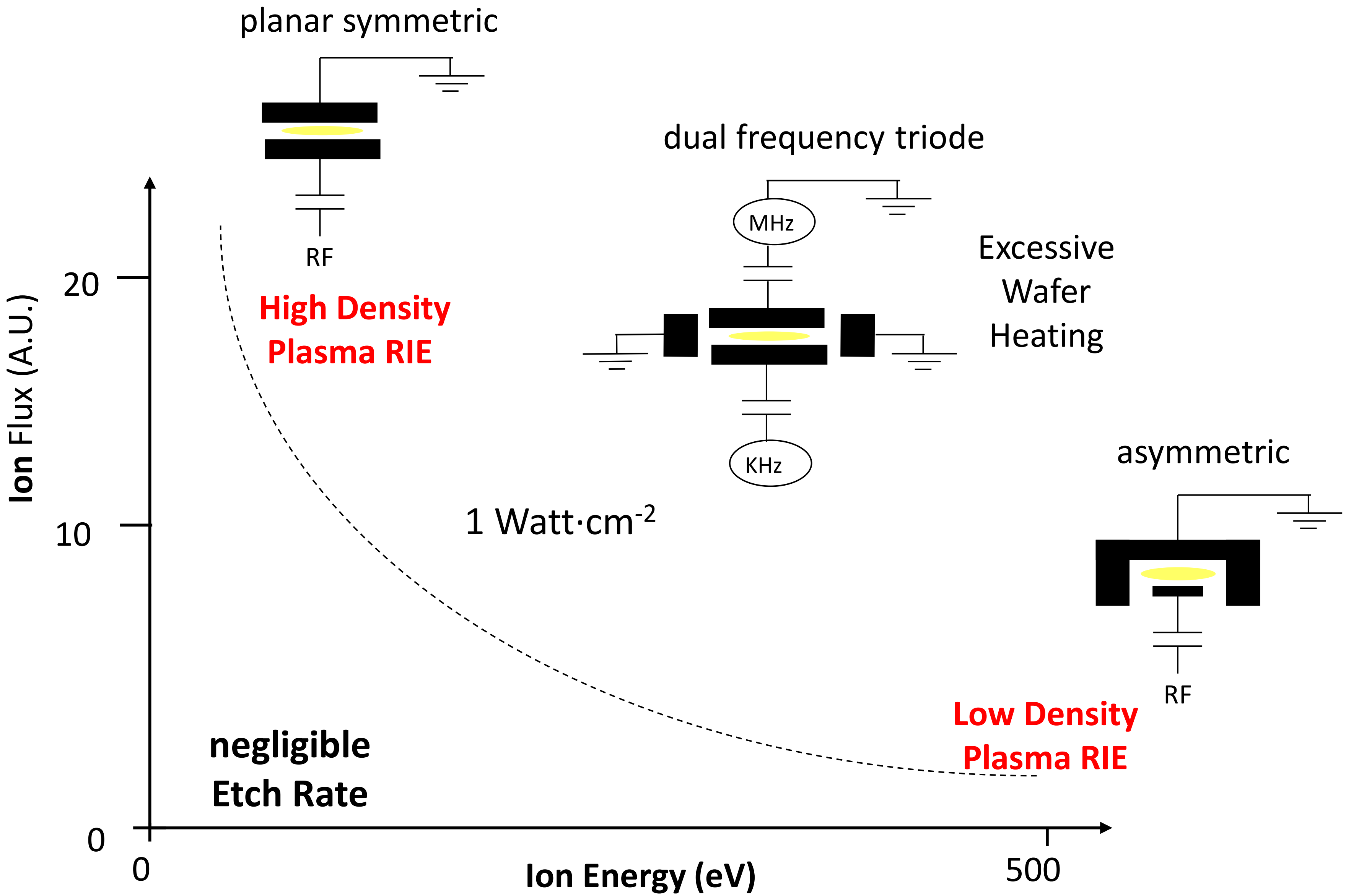
ICPE



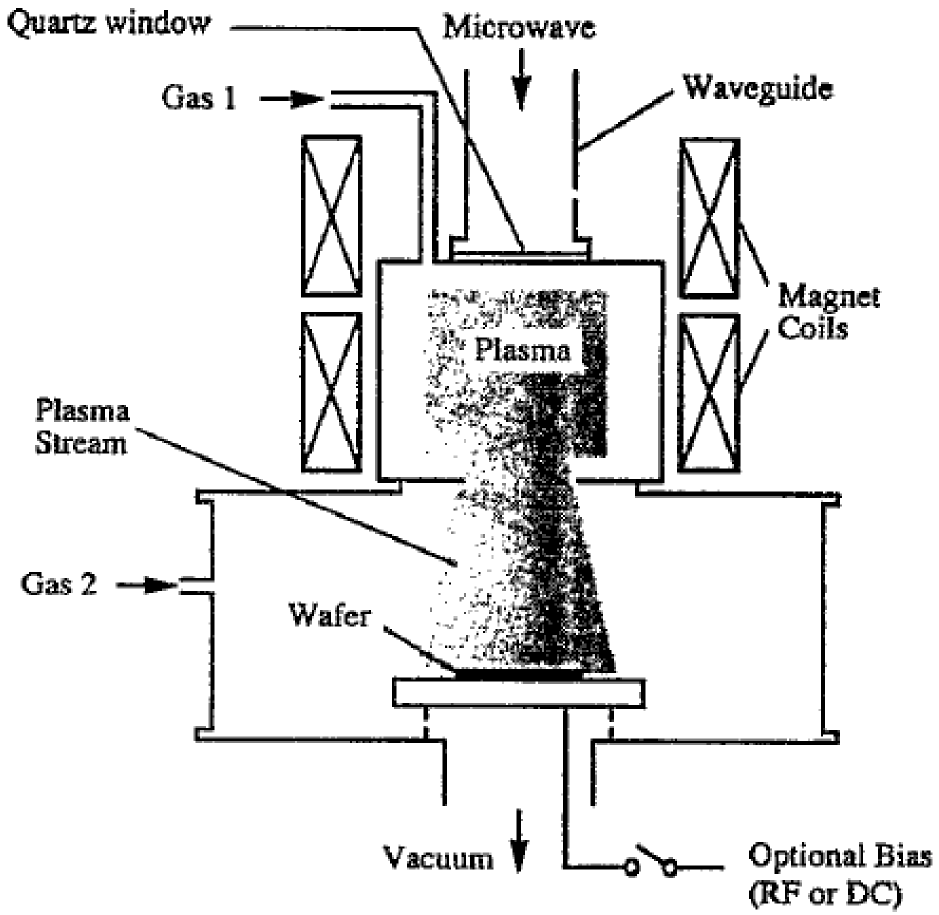

ICP coil
Macthing circuit
RF
Quartz plate
Wafer
Etching chamber
Lower electrode
RF


Spiral RF Coil
Matching Network
TCP source
Quartz Window
Orifice
Mass Spectrometer
MTIR-FTIR Wall Probe
Optical Emission
Monochromator
Wafer
Turbo Pump
Matching Network
IR Source
Dry Pump
RF Bias
Multiple Pass FTIR Absorption Gas Cell
HgCdTe Detector

ION ENERGY / FLUX POSSIBILITIES IN RIE



ECR PLASMA (Deposition)



triode

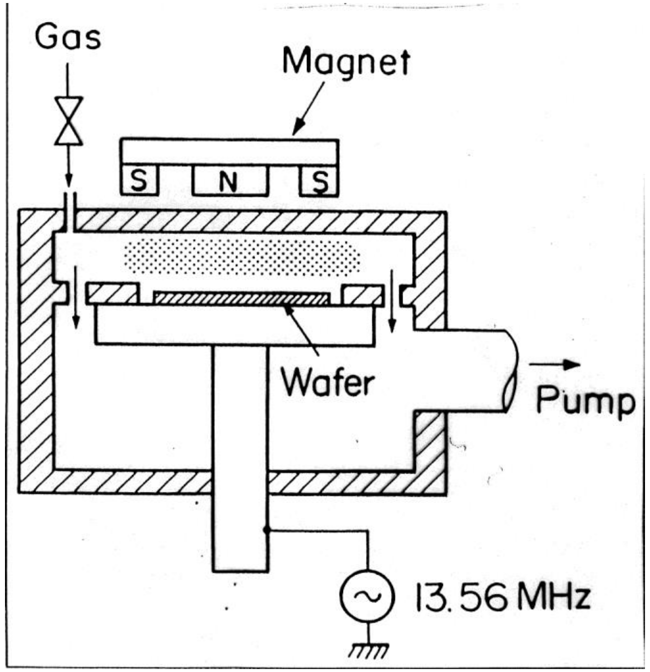
FIG. 7. Schematic of an ECR plasma source (reprinted with the permission of Plenum Press).

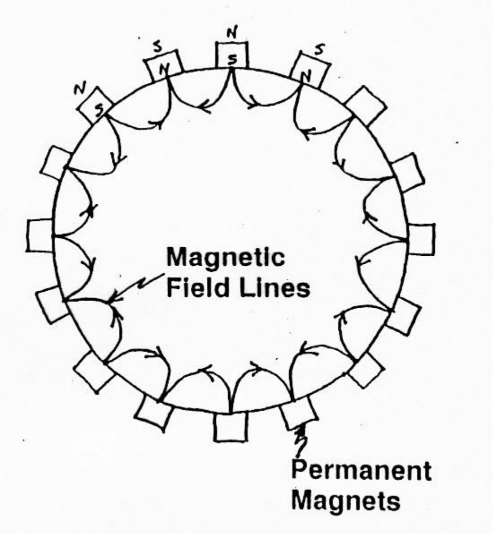
Industrial applications of low-temperature plasma physics*

Francis F. Chen†
University of California, Los Angeles, California 90024-1594

2164 Phys. Plasmas **2** (6), June 1995

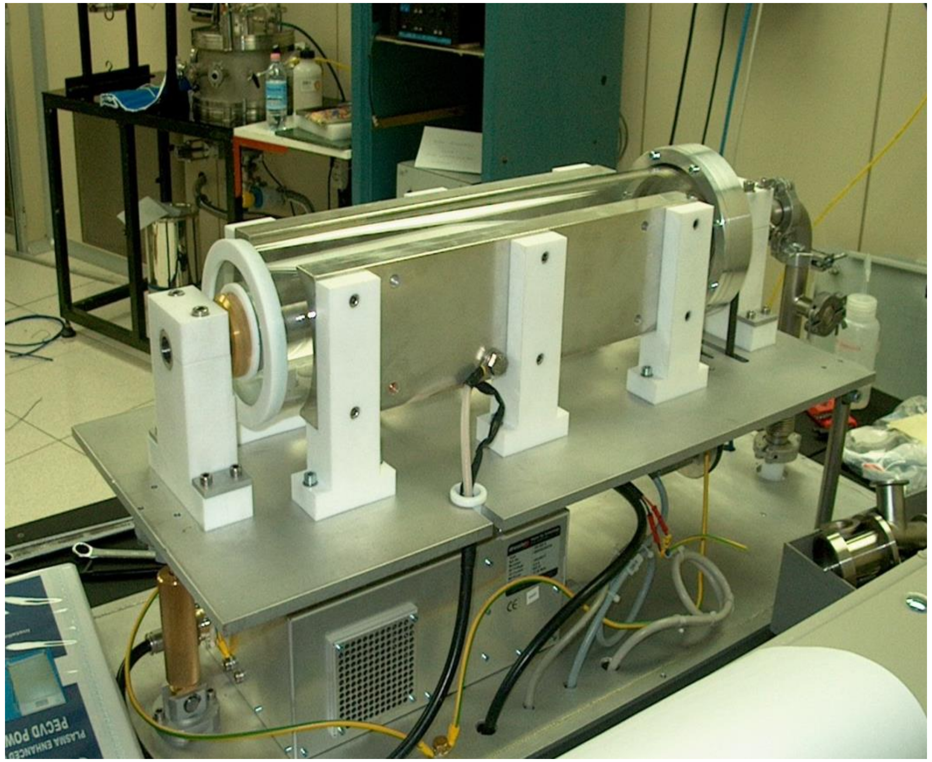
MAGNETRON


Gas
Magnet
S
N
S
Wafer
Pump
13.56 MHz

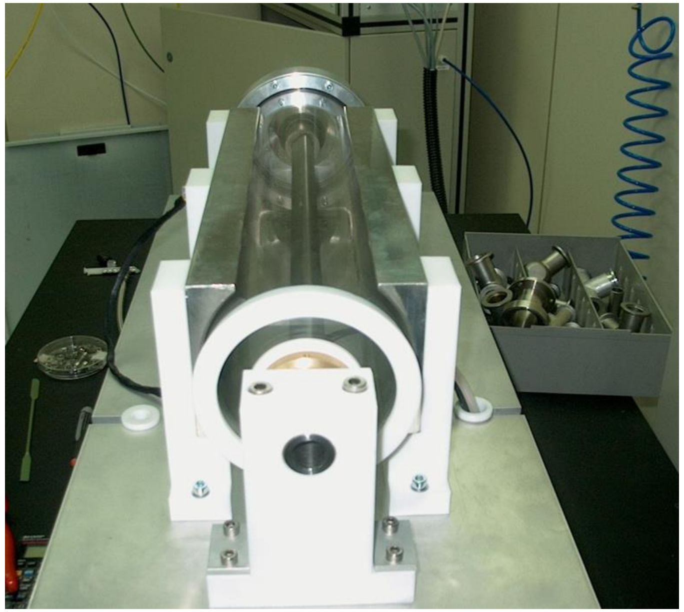

S
N
S
N
S
N
S
N
N
S
Magnetic
Field Lines
Permanent
Magnets

PLASMA SOLUTION srl
spin off dell'Università di Bari

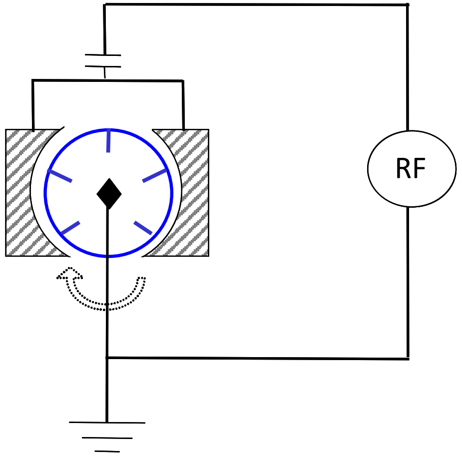
ROTATING REACTOR FOR GRANULES



side view



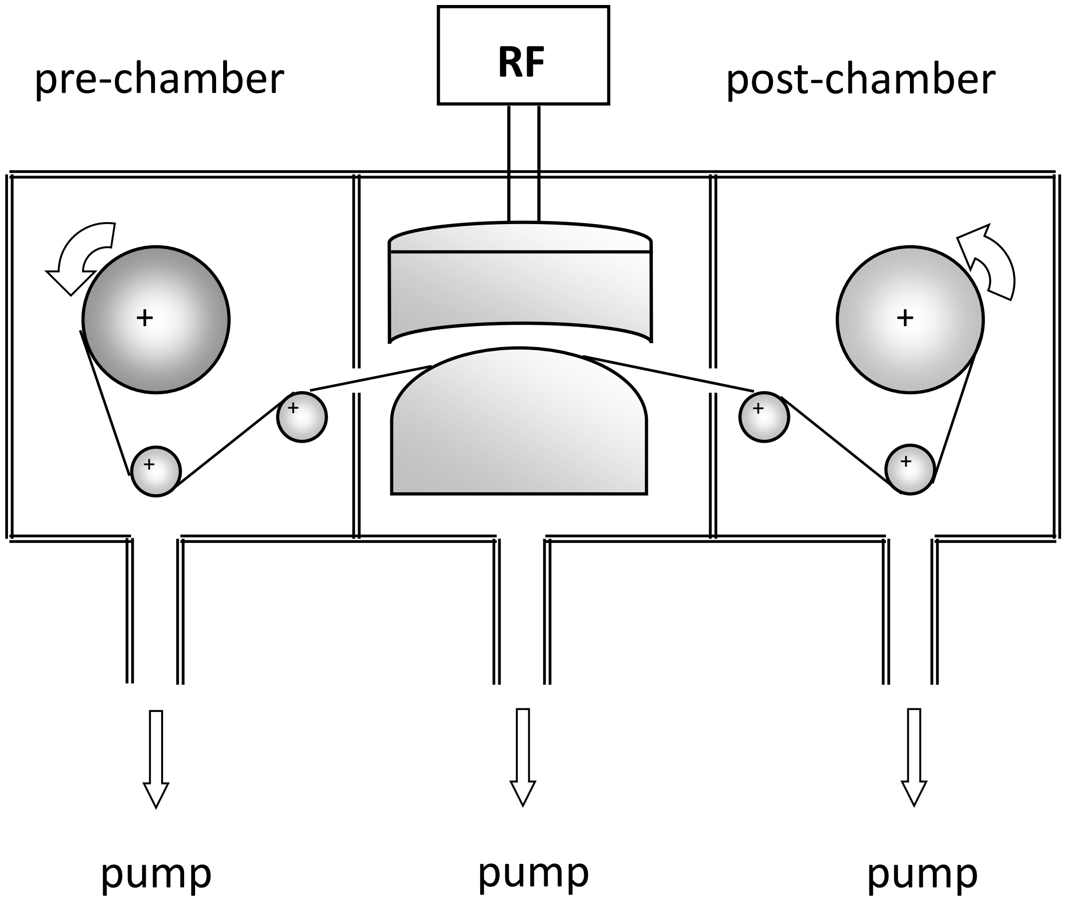
top view



Internal wing system to keep granules stirred during the process

WEB COATING

roll-to roll reactors

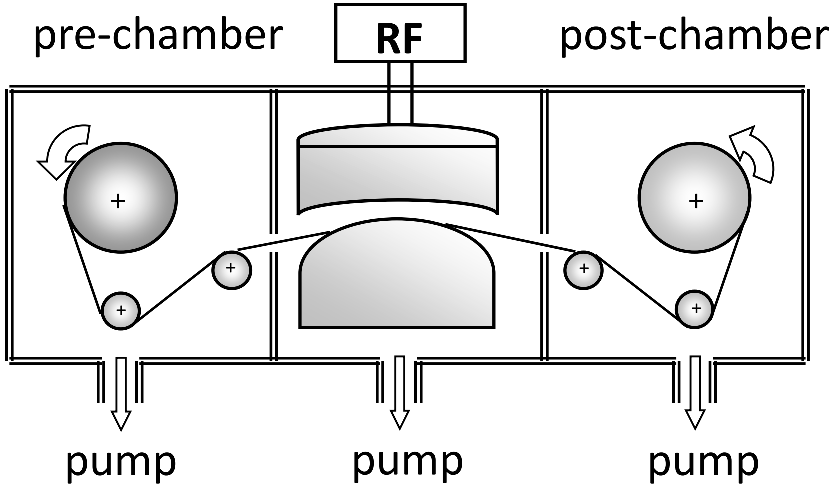


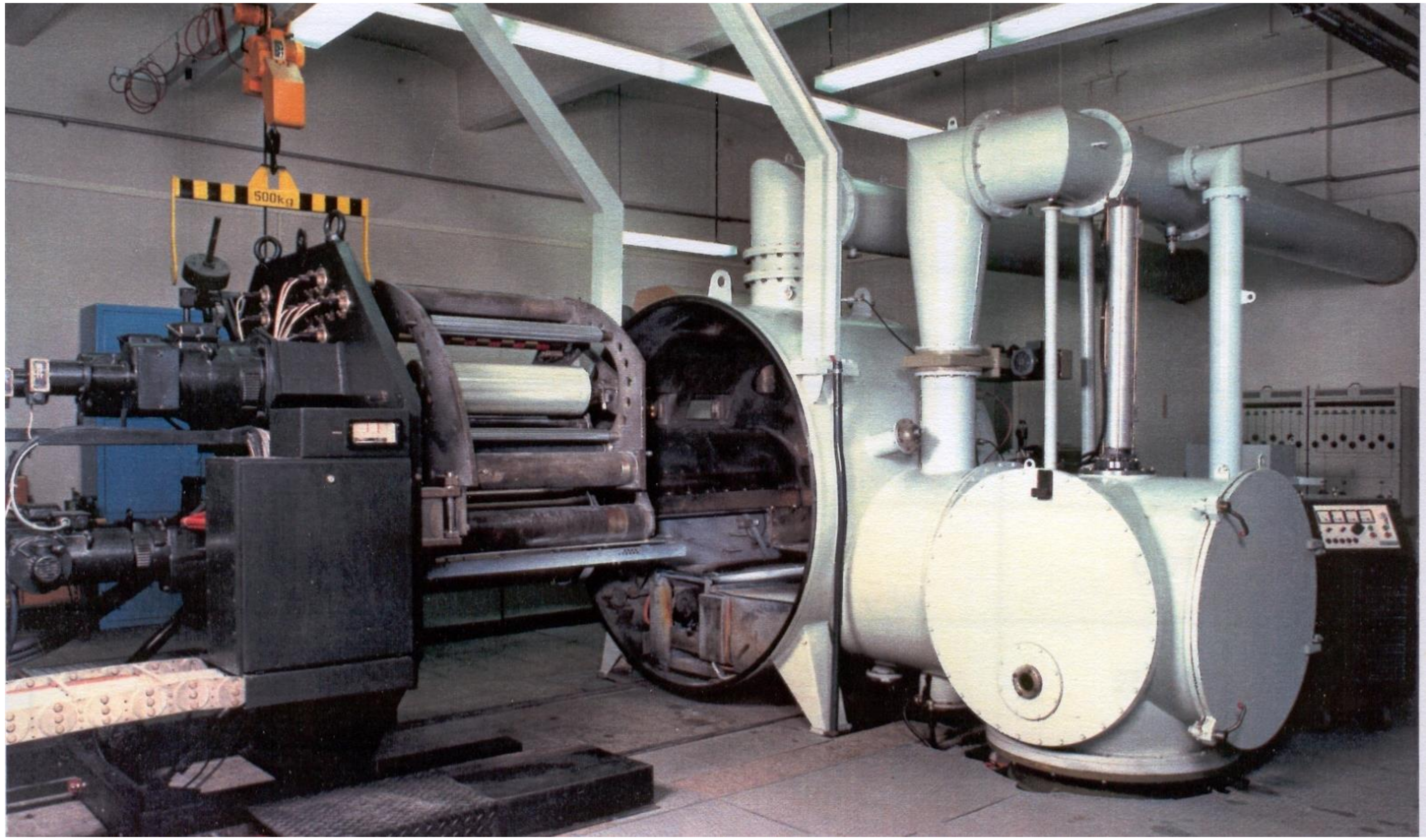
ADVANTAGES
- LOW COST PUMPS
- VERSATILITY OF TREATMENTS
- REDUCED MAINTENANCE

DISADVANTAGES
- LONG LOADING
- LONG WEB INSPECTION

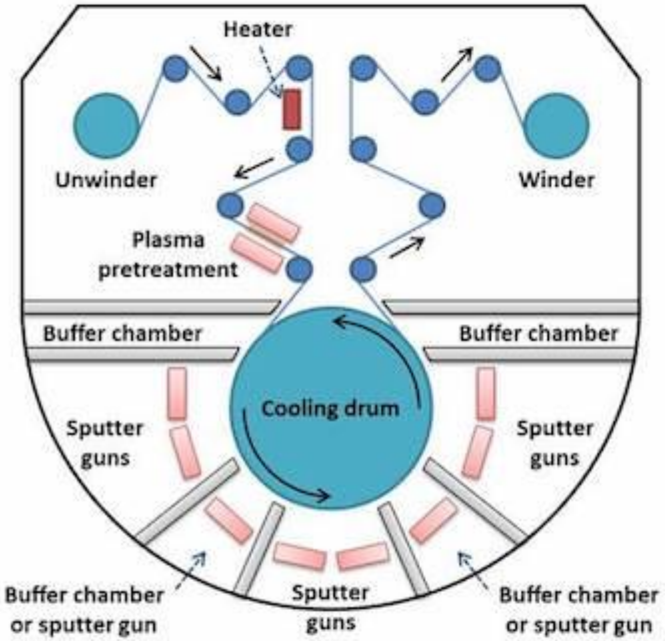
PLASMA REACTORS:

industrial web coater





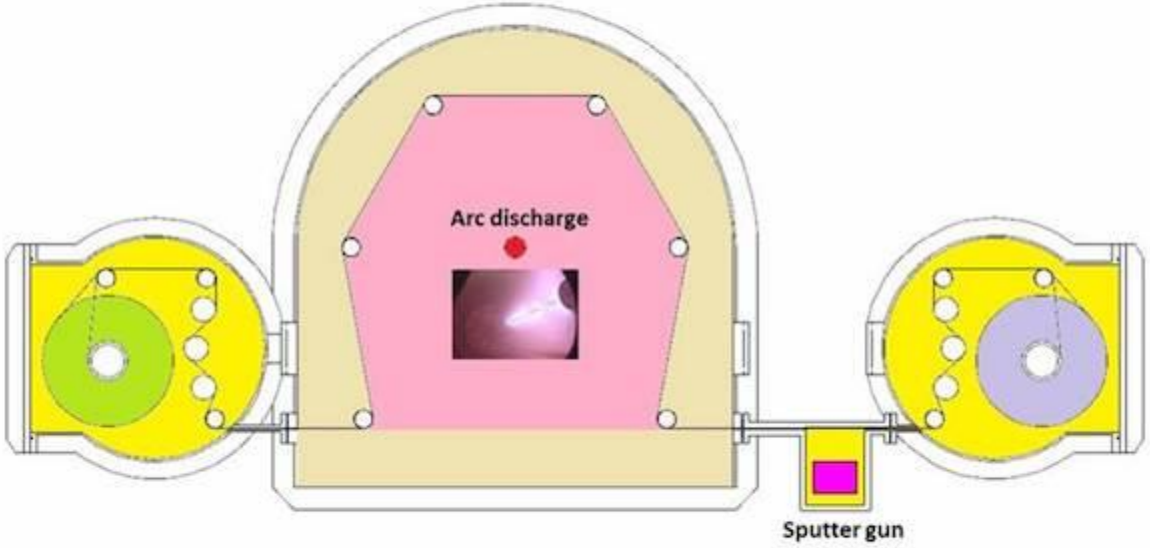
Conventional



- Conventional magnetron sputtering
- Complicated structure, high cost > $7,000,000
- Expensive target, low utility 30%
- Unstable reactive sputtering

VS.

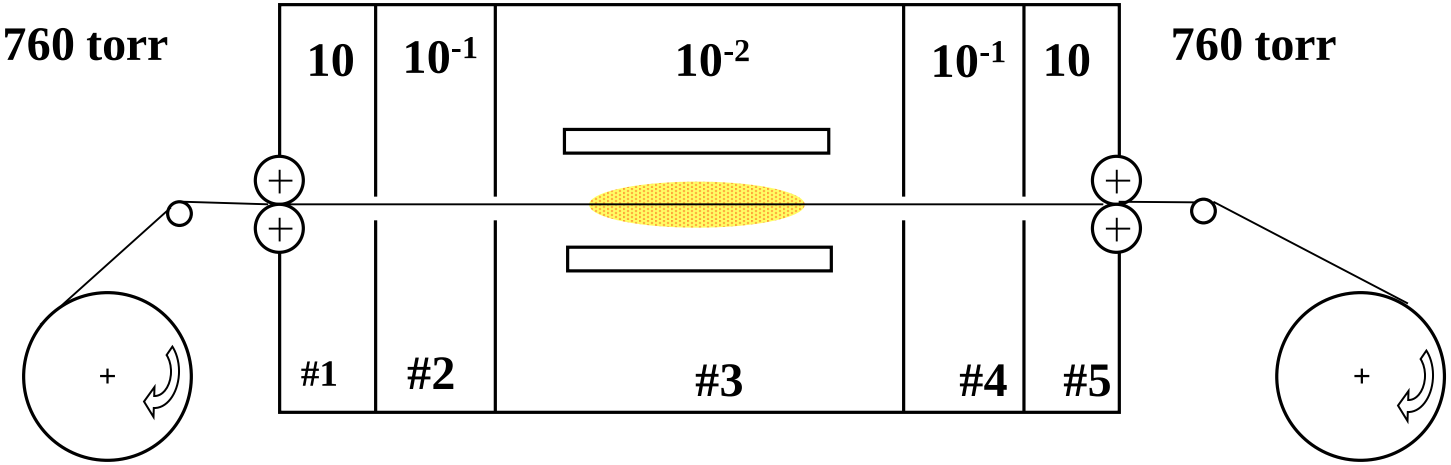
RollnCoat



- Patented hybrid plasma modular coating
- Simple structure, low cost ≈ $1,200,000
- Cheap target, high utility 70%
- Stable reactive arc deposition

WEB COATING AND TREATMENTS

AIR-VACUUM-AIR



ADVANTAGES

easy web inspection

loading without breaking vacuum

DISADVANTAGES

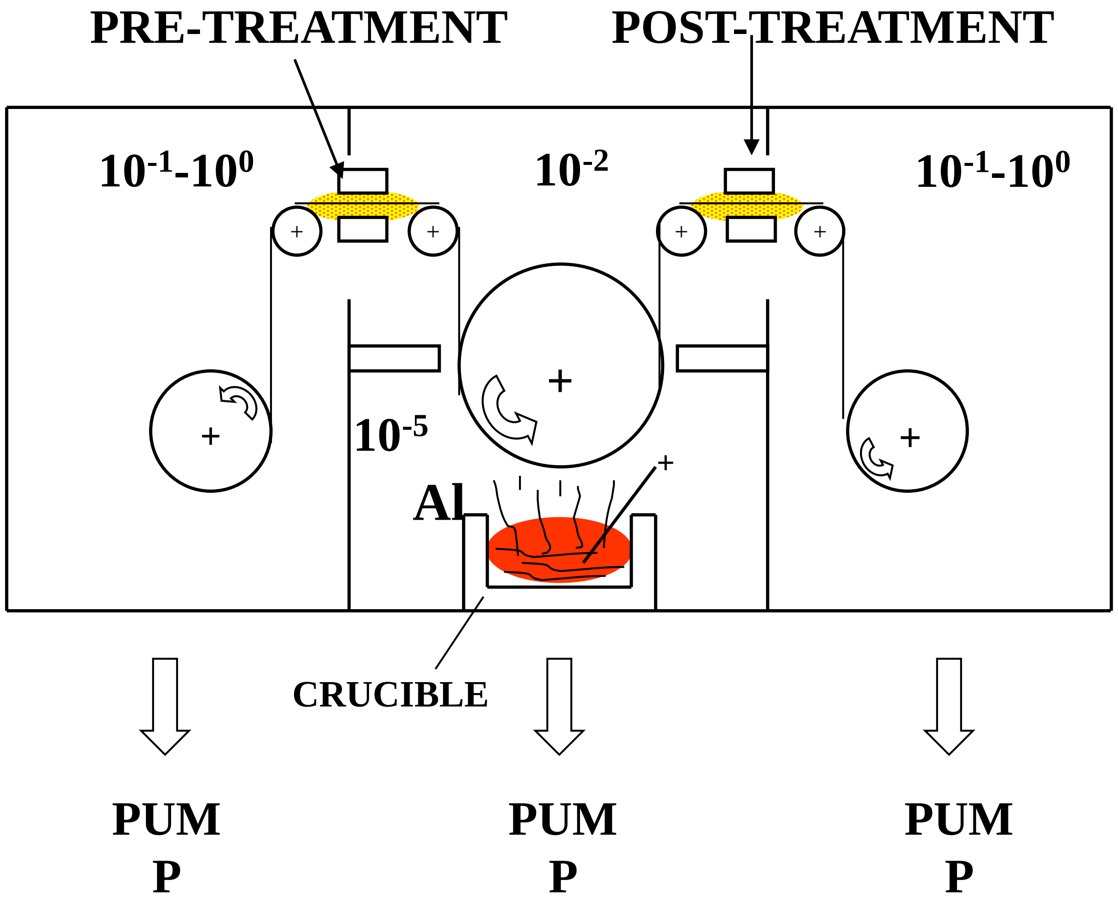
degassing and leaking

high pump cost

frequent maintenance

limited to air and O_2 treatments

PLASMA ASSISTED METALLIZATION



PRE-TREATMENT

POST-TREATMENT

10^{-1}-10^{0}

10^{-2}

10^{-1}-10^{0}

10^{-5}

Al

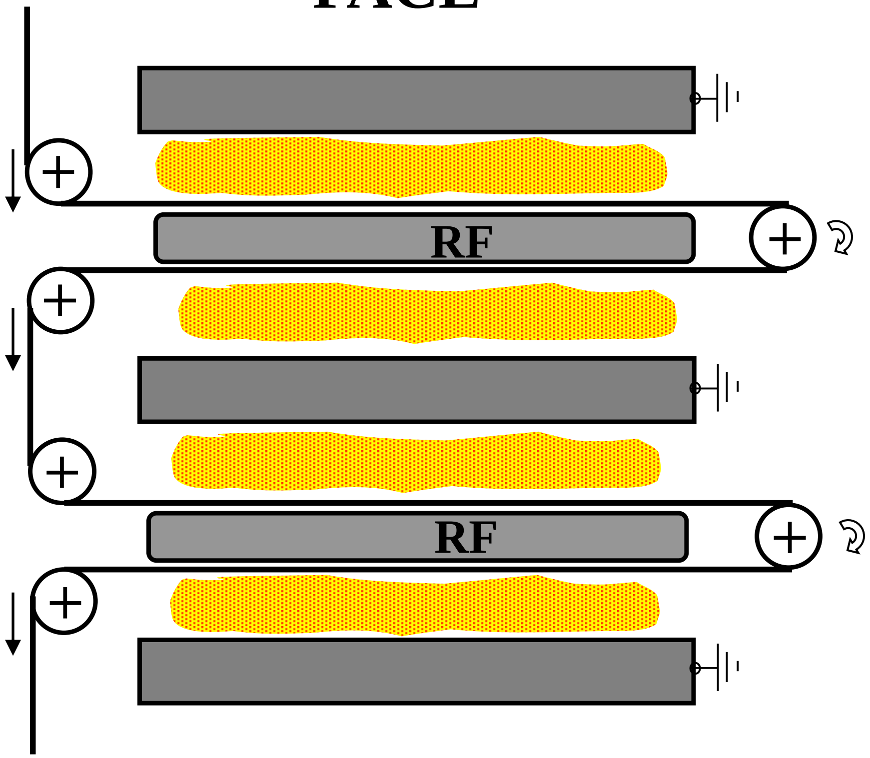
CRUCIBLE

PUMP

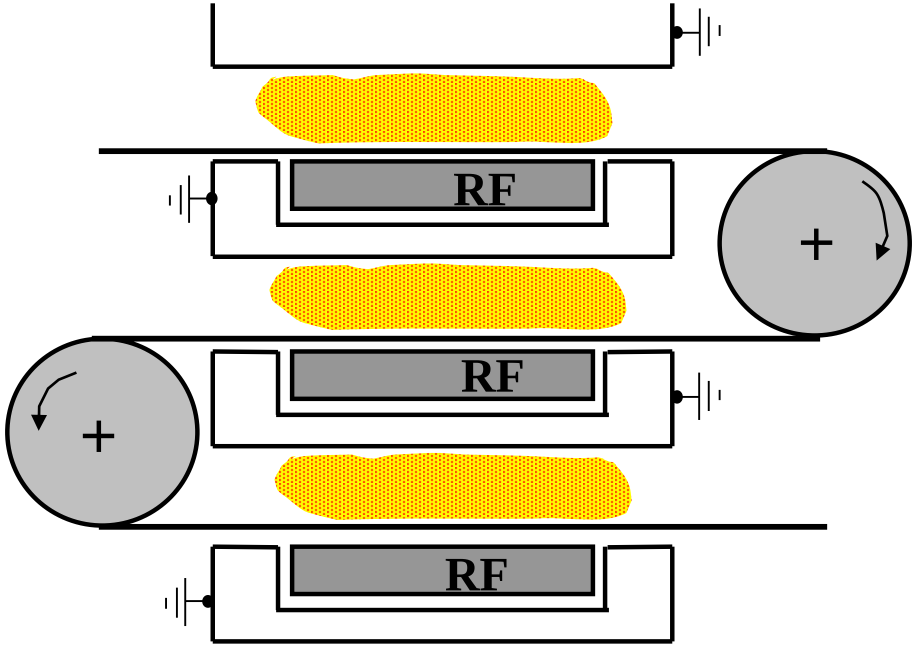
PUMP

PUMP

MULTIPLE SINGLE FACE



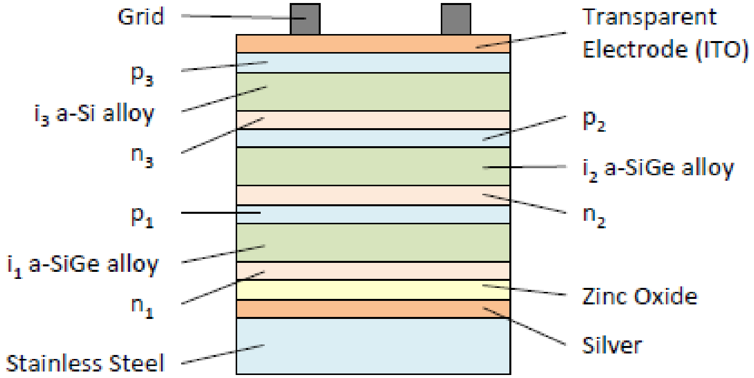
MULTIPLE DOUBLE FACE



LARGE SCALE PLASMA REACTORS

self-cleaning layers on glass → buildings

Industrial deposition system for the fabrication of DLC coatings for automotive parts and other applications. Each chamber contains six 1.6 m long electrodes. **(Courtesy of Hauzer Techno Coatings)**



Triple-junction solar cell

S. Guha, J. Yang, J. Non-Cryst. Sol. 2006

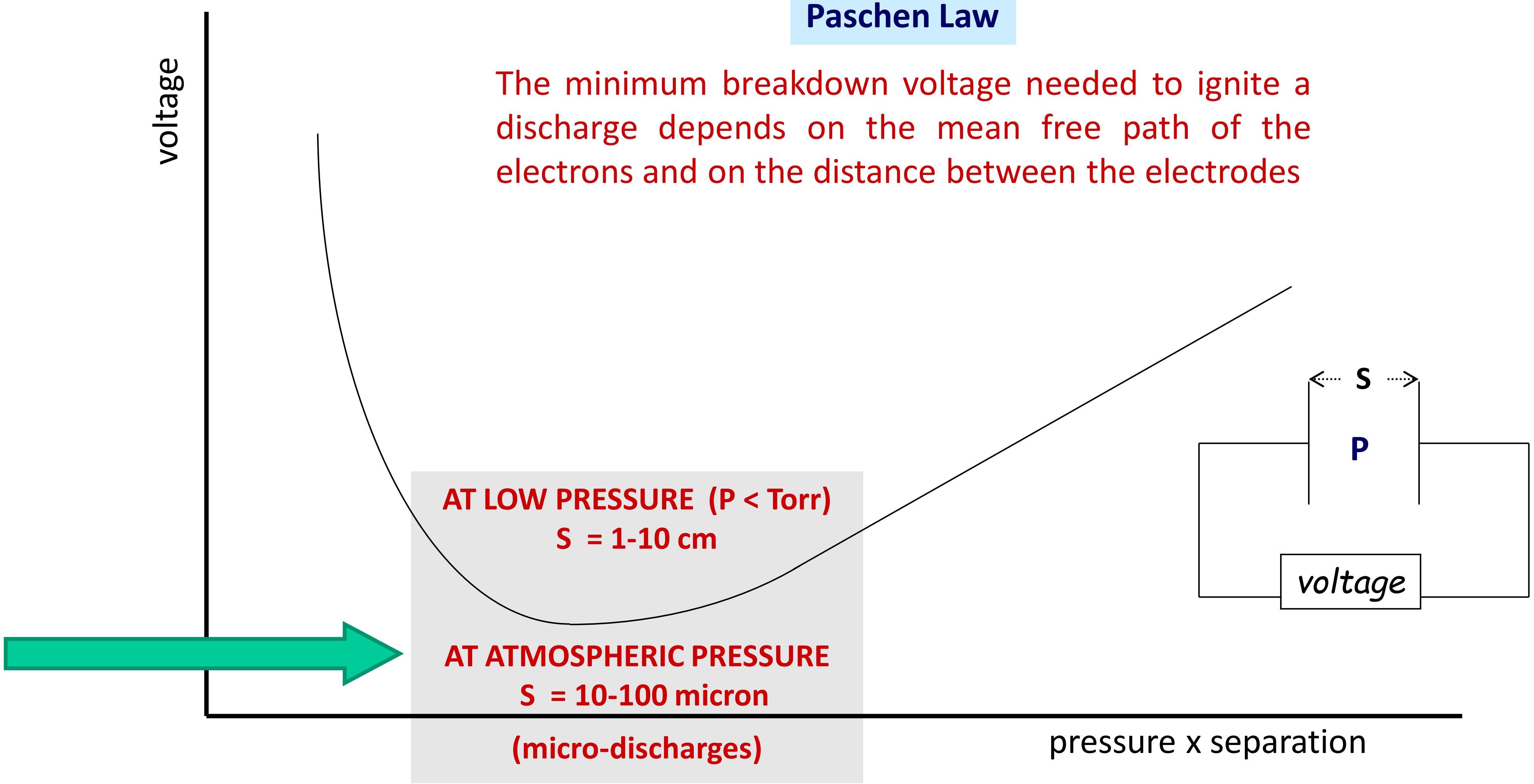
Large area roll-to-roll deposition system for the fabrication of triple-junction photovoltaic cells: 2,500m long, 36 cm wide and 125 µm thick SS foils; 4 compartments: a) washing, b) back reflector sputtering (Al, ZnO), c) PECVD of 9-layer triple junction – nc-Si and SiGe, d) AR coating – ITO.

System: 90m long, 3m tall, web speed 30 cm/min, 14,5 km of solar cells in 72 hrs.

(Courtesy of United Solar Ovonic, USA)

Paschen Law

The minimum breakdown voltage needed to ignite a discharge depends on the mean free path of the electrons and on the distance between the electrodes



AT LOW PRESSURE (P < Torr)
S = 1-10 cm

AT ATMOSPHERIC PRESSURE
S = 10-100 micron

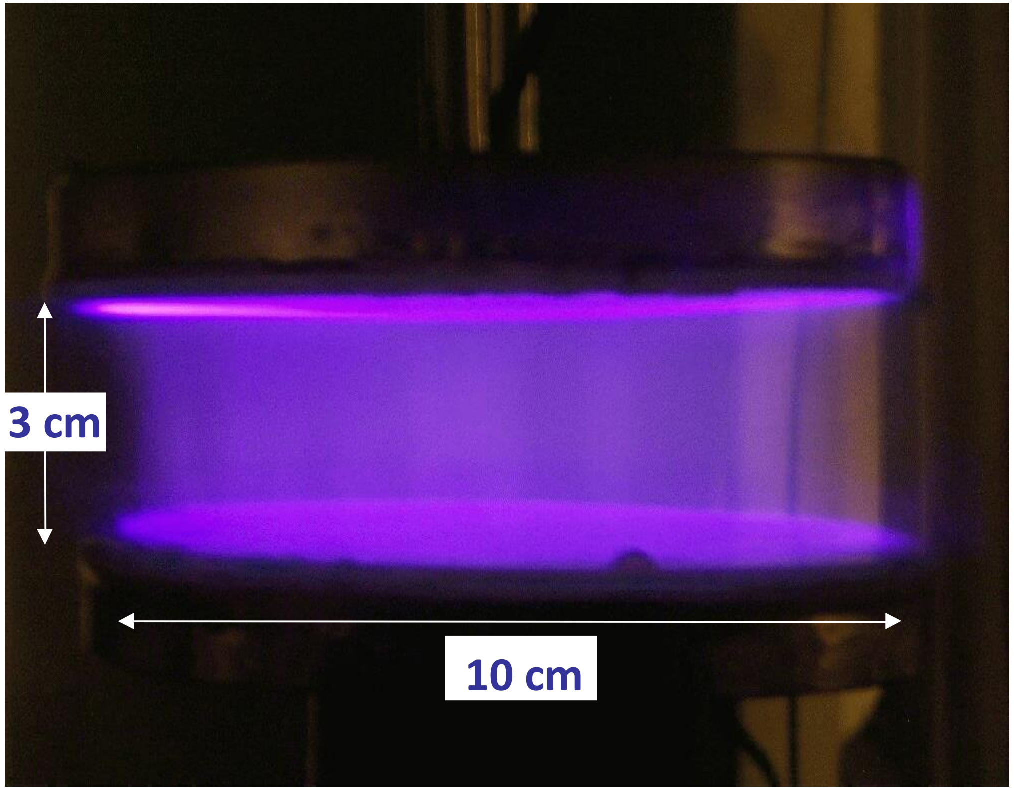
(micro-discharges)

Low PxS
electrons experience not enough ionizing collisions while travelling between electrodes

High PxS
due to the high collision frequency, electrons cannot accelerate enough to provide a minimum number of ionizing collisions

Atmospheric Pressure REACTORS and SOURCES

M. Laroussi, ODU 1999
He plus Air
DBD, f = 20 kHz

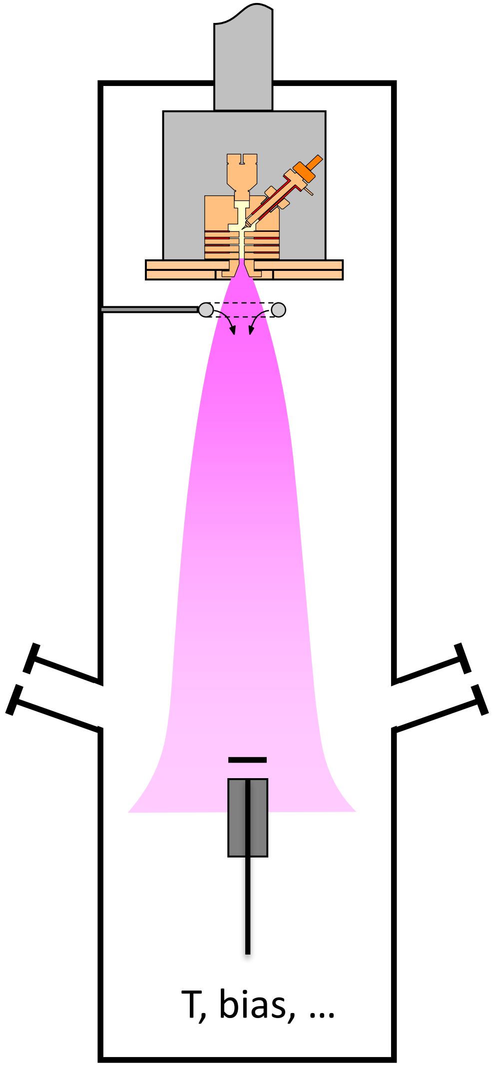


Most applications of non equilibrium plasmas requires that the gas remains at room T. Since the low efficiency and number of elastic collisions at low P limit the energy transfer from free electrons to heavier species, it is quite easy to produce cold Low P gas discharges. With increasing pressure, however, the electron-species collision frequency increases, the energy transfer becomes more efficient, resulting in gas heating and plasma instabilities (e.g., sparks and arcs).

Many approaches are used to keep the gas cold in Atmospheric P discharges, namely:

- **sharp electrodes, as in corona discharges**
- **pulsing the plasma; μs-ns wide plasma pulses;**
- **improved heat transfer; higher flow rates;**
- **using gases (e.g., He) with high thermal conductivity;**
- **reduce the size of plasmas (e.g., micro-discharges);**
- **reduce the current with dielectric layers on the electrodes, as in Dielectric Barrier Discharges (DBD)**

P. J. Bruggeman, Atmospheric Pressure Plasmas, in Low Temperature Plasma Technology: Methods and Applications, P. K. Chu, XinPei Lu ed, CRC, 2013



high press plasma
(~400 mbar)
cascaded arc

monomer injection

expansion
(0.2 mbar)

Plasma-surface
interaction
deposition or etching

Courtesy of Prof. M.C.M. “Richard” Van de Sanden, TUE, Eindhoven

The Expanding Plasma, PECVD of α-Si:H

12

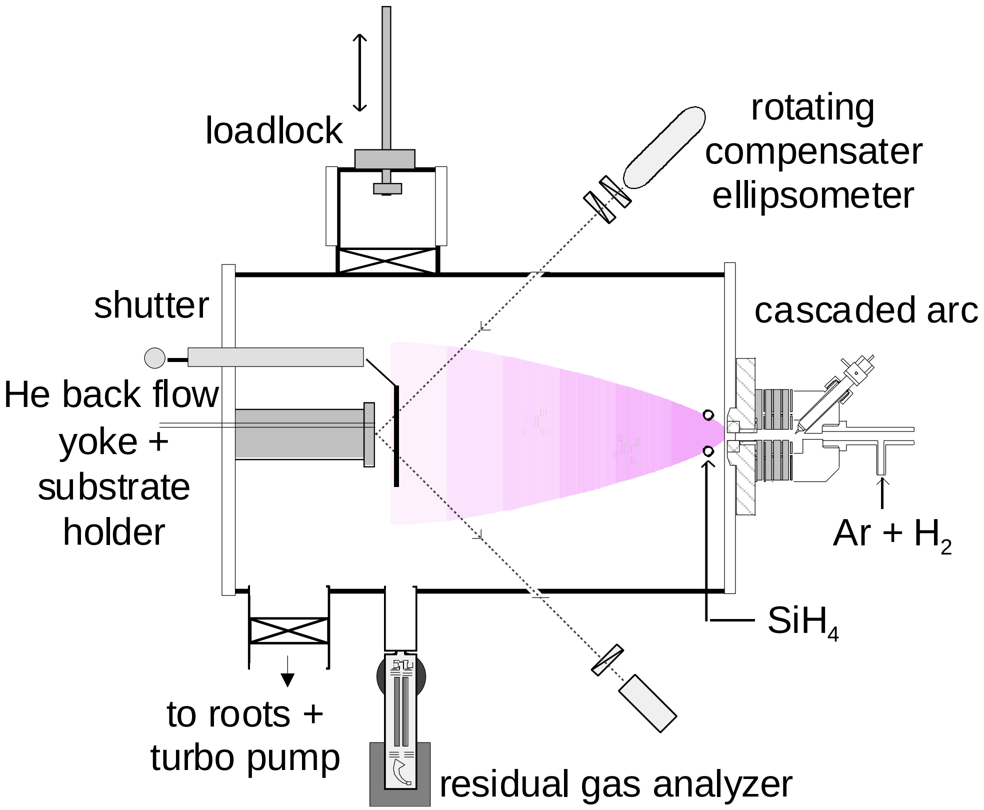
Real remote plasma:

Expansion of high-pressure Ar-H_2 plasma into low-pressure reactor→ SiH_4 dissociation

Large parameter range

Optimized conditions:

$H+SiH_4 \rightarrow SiH_3 + H_2$



Very high deposition rates: 10 nm/s. 400 nm within 1 minute!

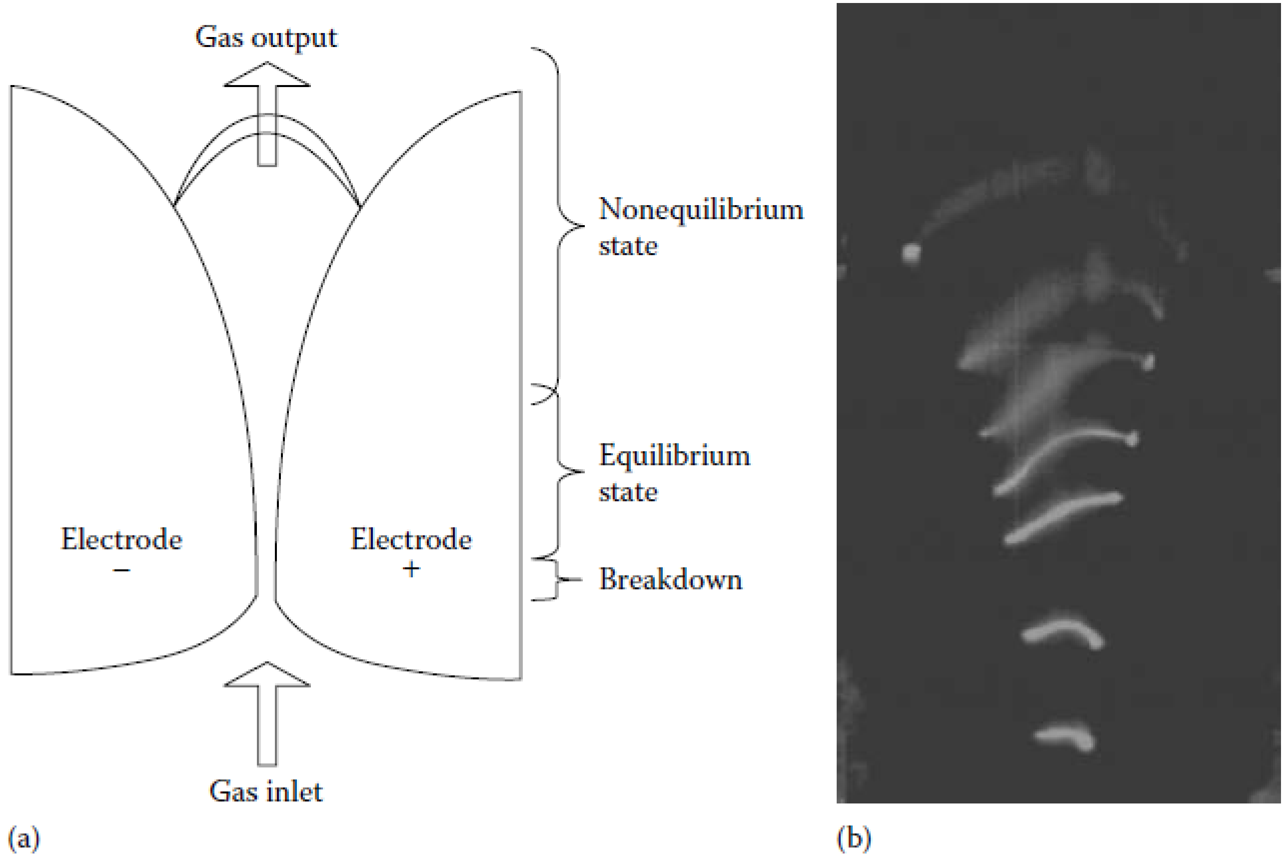
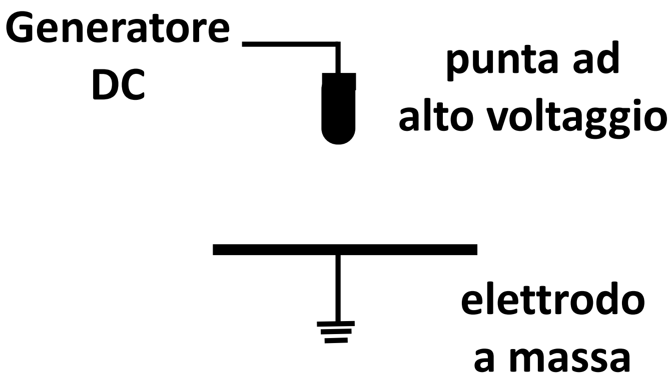


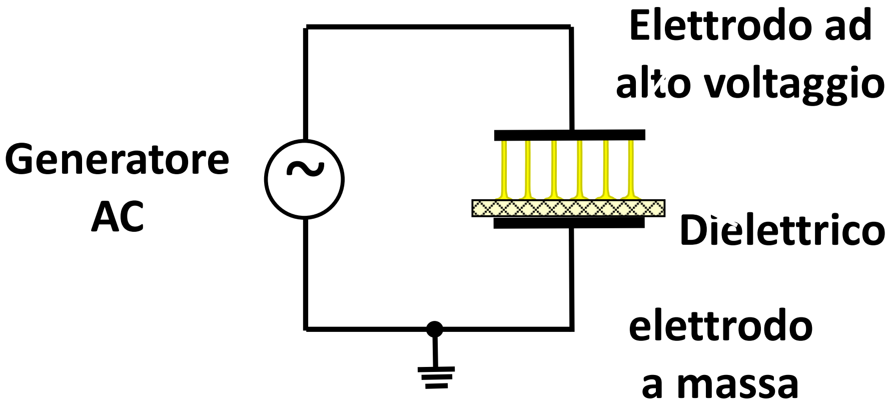
FIGURE 2.10 (a) Gliding arc electrode configuration with indication of the LTE and non-LTE region. (b) Superposition of snapshot images of a gliding arc discharge that illustrates the dynamic movement of the arc. (Reprinted with permission from Fridman, A., *Plasma Chemistry*, Cambridge University Press, Cambridge, 2008, © Cambridge University.)

Corona Discharges



- **elettrodi asimmetrici** per stabilizzare la scarica.
- **alti voltaggi, corrente continua**
- scarica omogenea, localizzata all’elettrodo piccolo, ad alto voltaggio, estesa verso l’elettrodo a massa. **forte disomogeneità spaziale**

Dielectric Barrier Discharges DBD



- almeno uno strato **dielettrico** fra gli elettrodi metallici.
- **alti voltaggi**, **corrente alternata**
- **microscariche** (~10 ns, r~0.1 mm) distribuite omogeneamente nello spazio e nel tempo su tutto l’elettrodo: **FILAMENTARY DBD**
- In opportune condizioni è possibile ottenere scariche omogenee come a bassa pressione: **GLOW DBD**

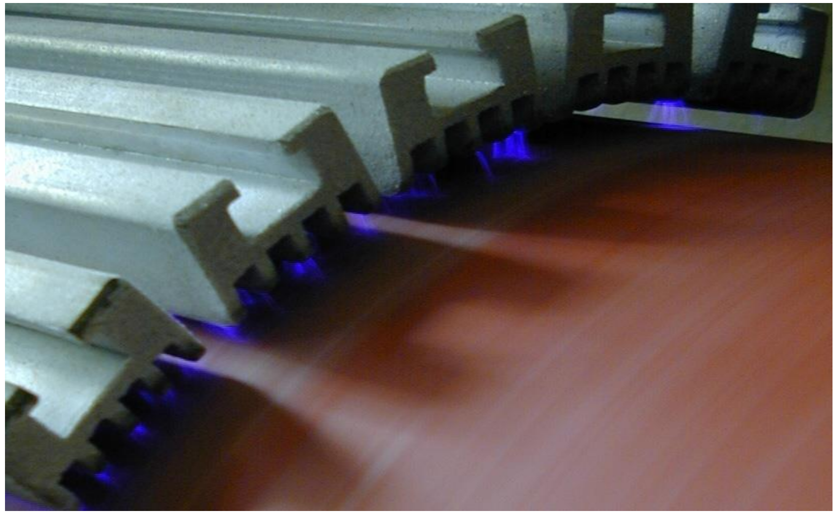
multi-tip pulsed corona discharge tested at LAPLACE-PRHE Laboratory.

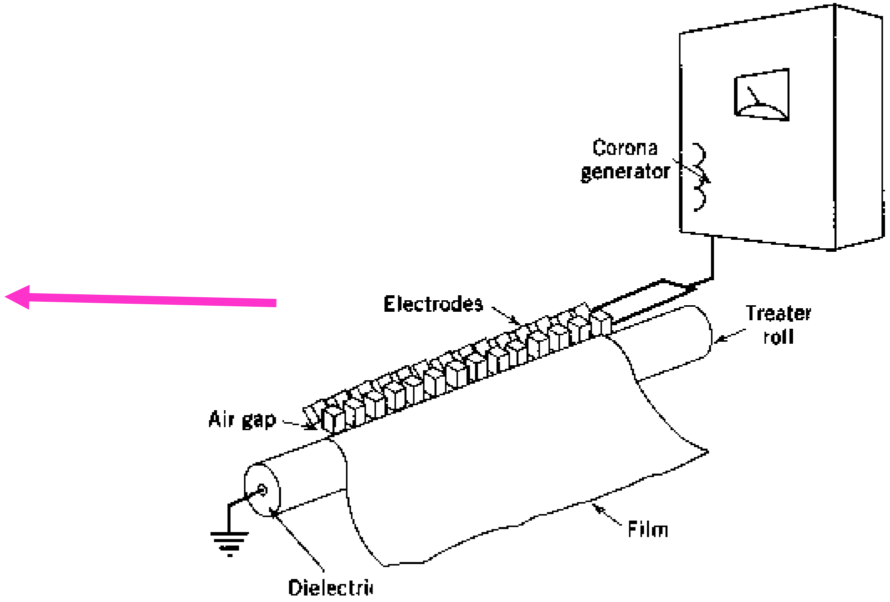
CORONA DISCHARGES IN AIR

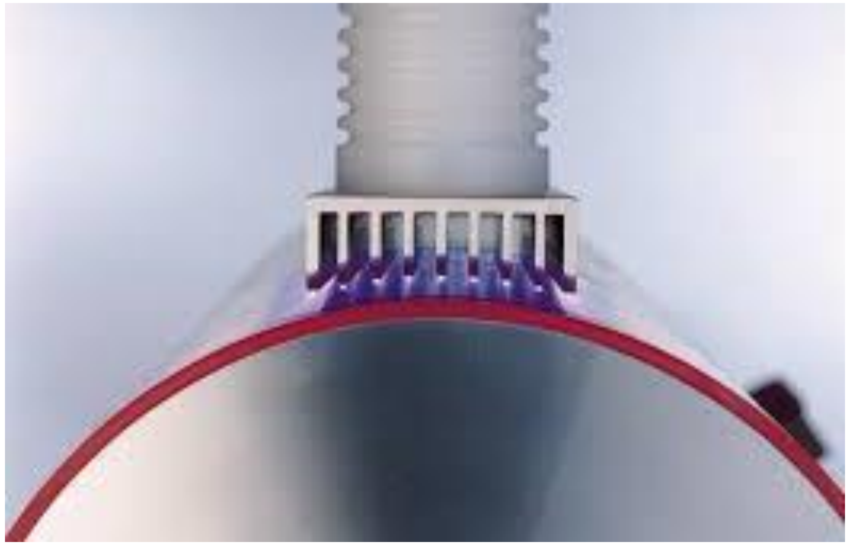
ACTIVATION OF POLYMERS
TO
PRINTABILITY
GLUEABILITY
DYEABILITY
WETTABILITY

Modifica superficiale di materiali

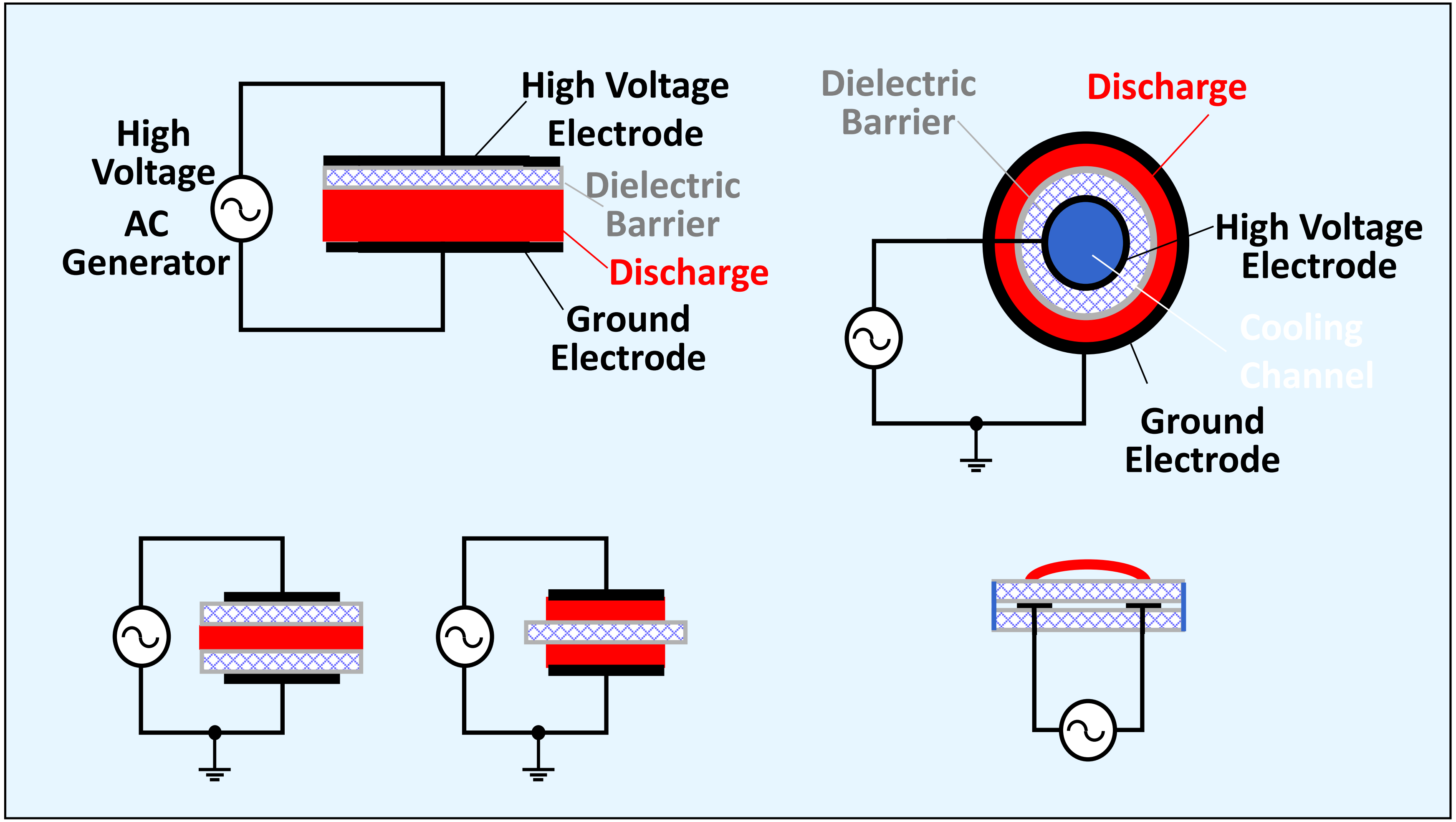
Trattamento di web polimerici per incrementarne bagnabilità e proprietà adesive





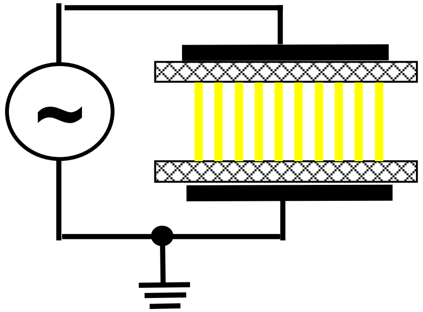


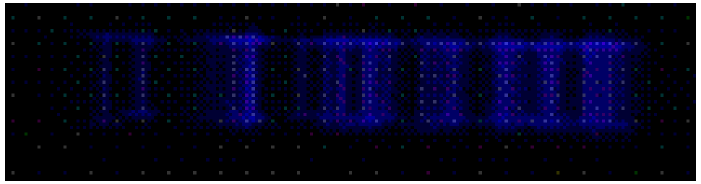
Dielectric Barrier Discharge (DBD) Configurations

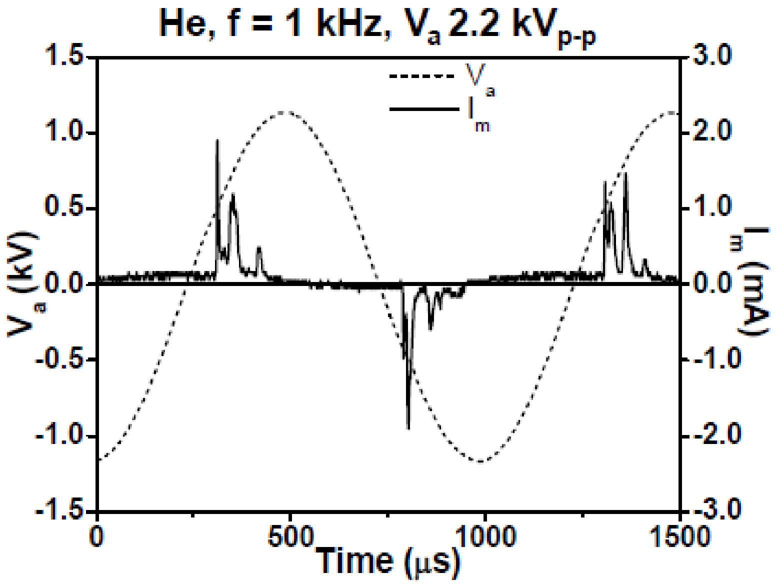


REGIMI DI SCARICA

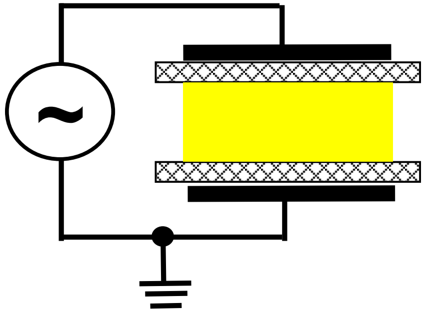
Filamentary discharge FDBD

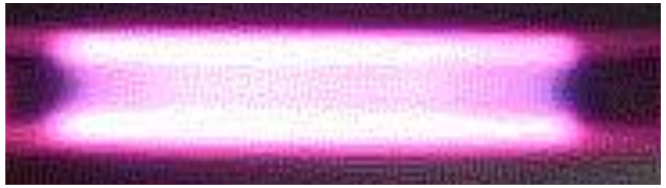


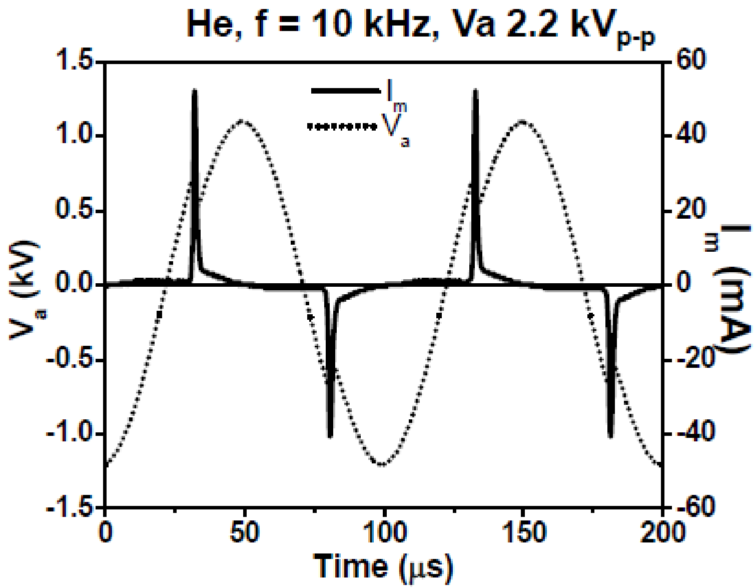


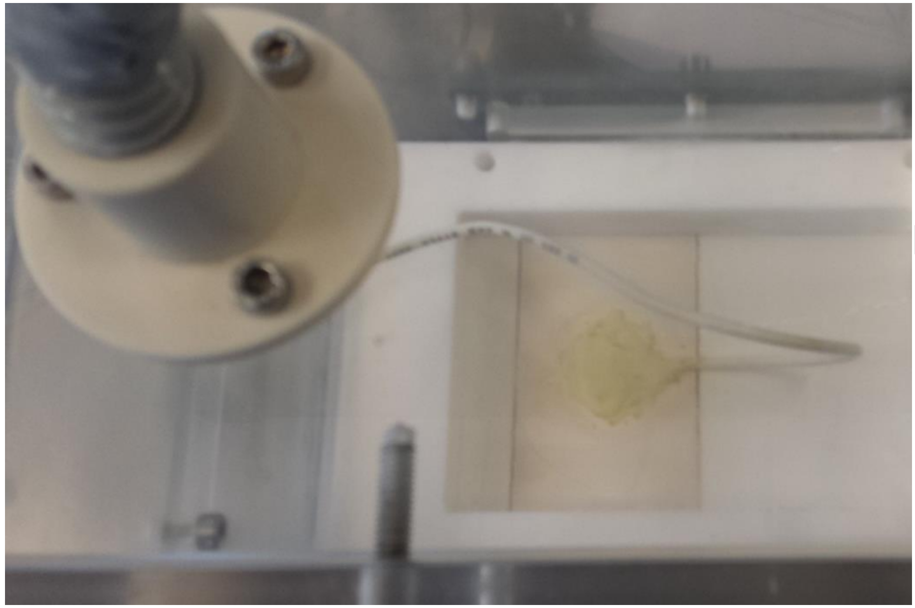


Glow discharge GDBD

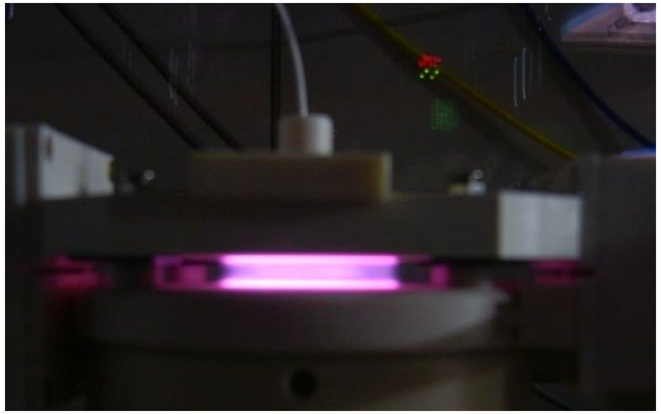


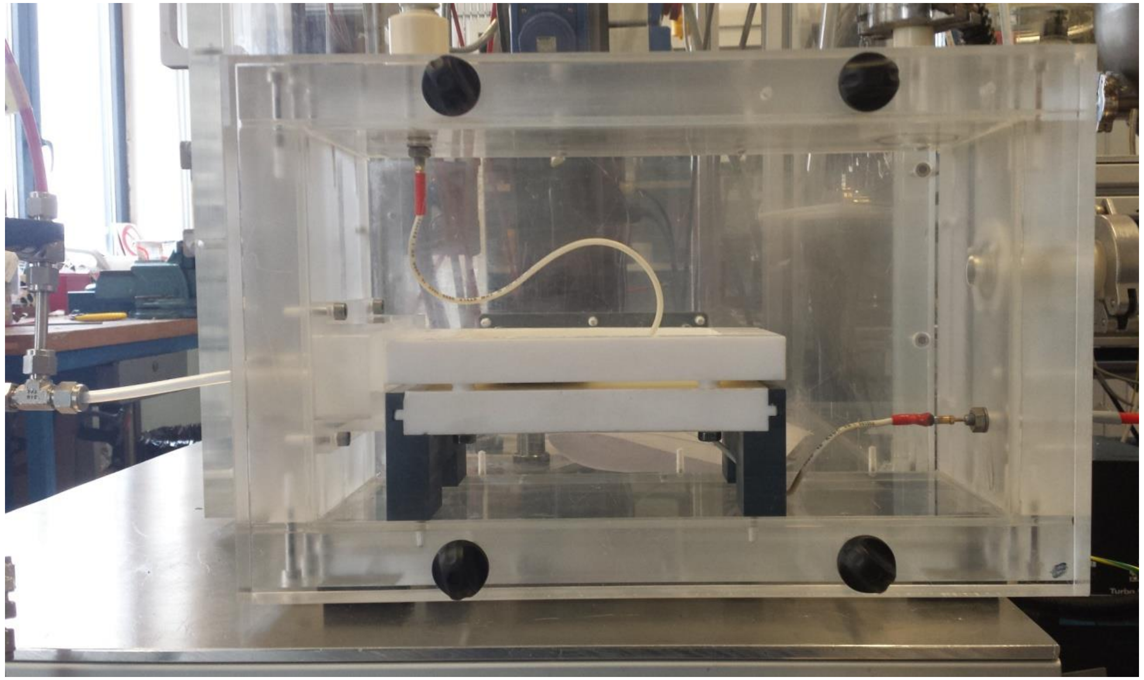


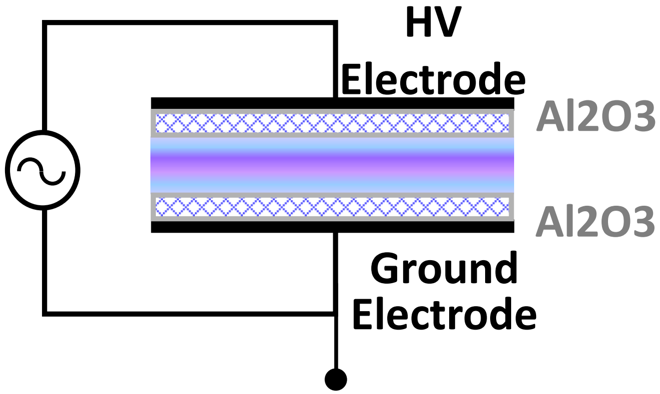




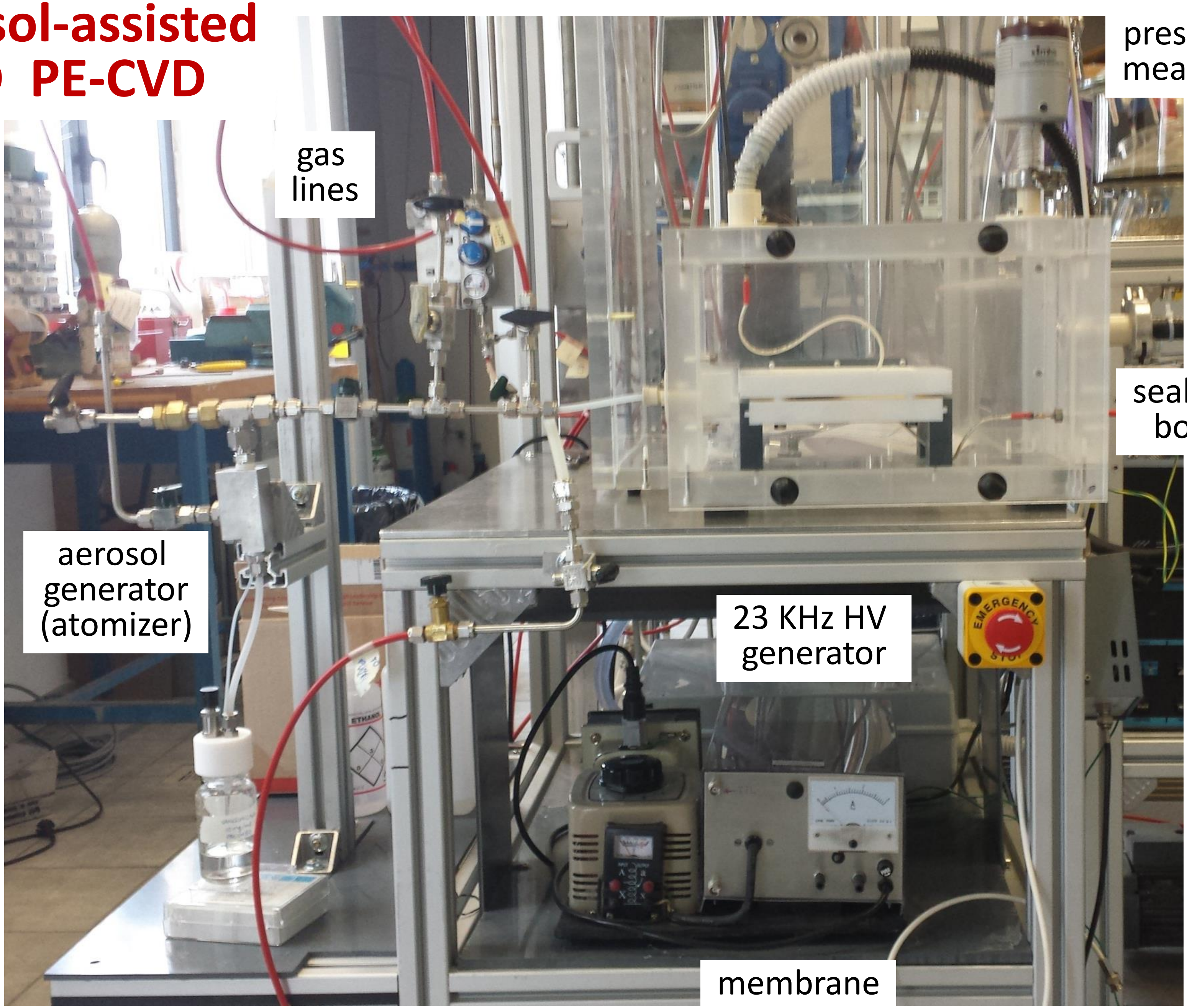
High Voltage Electrode







aereosol-assisted DBD PE-CVD



gas lines

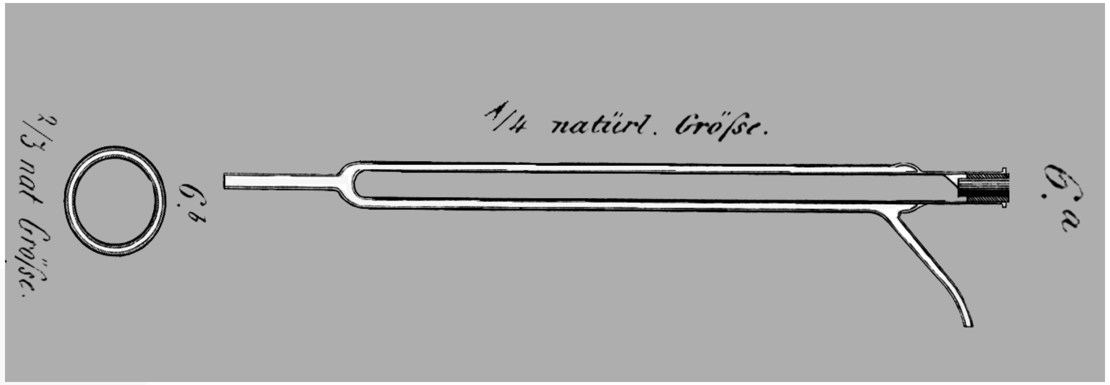
pressure measure

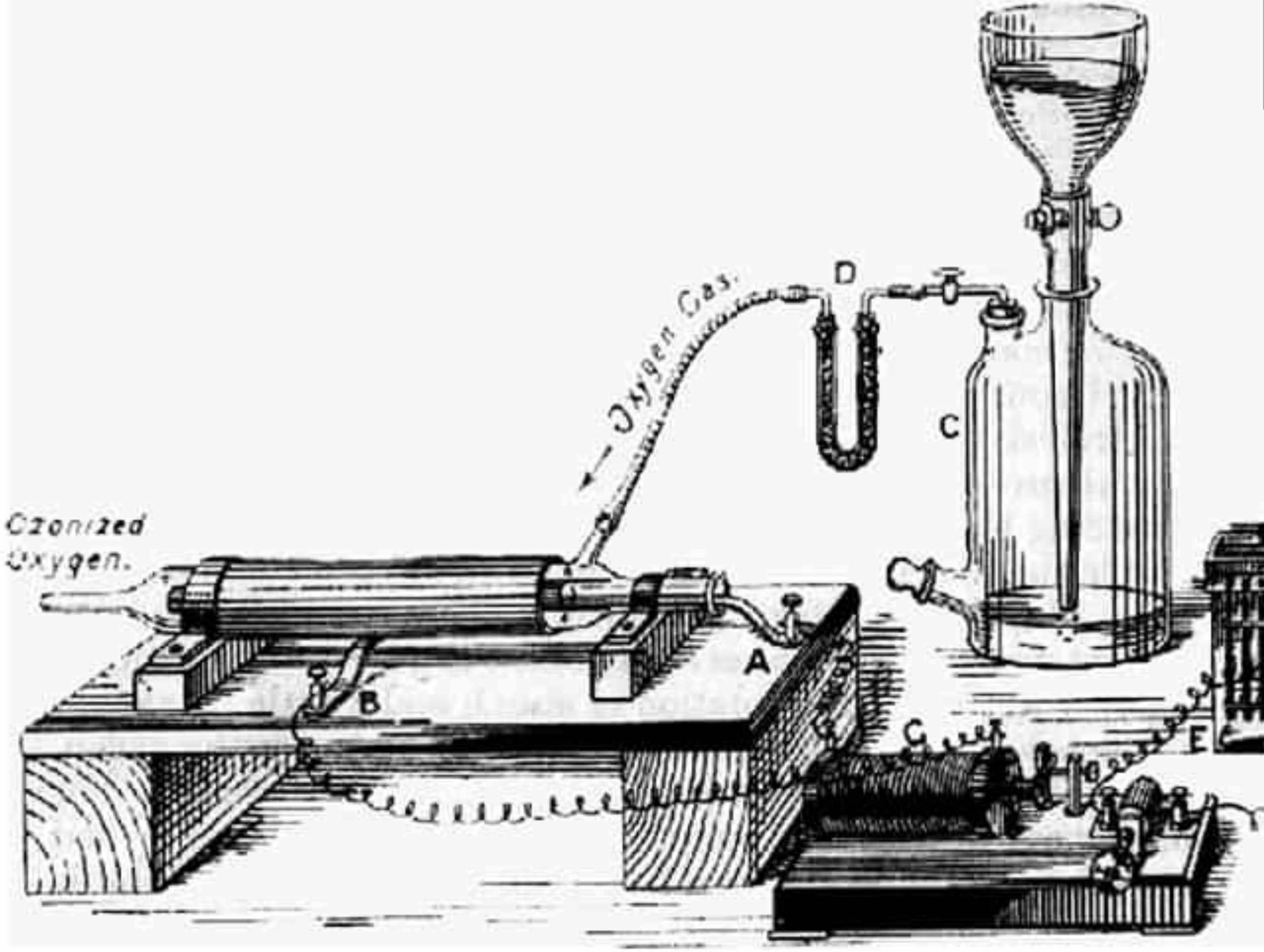
sealed box

aerosol generator (atomizer)

23 KHz HV generator

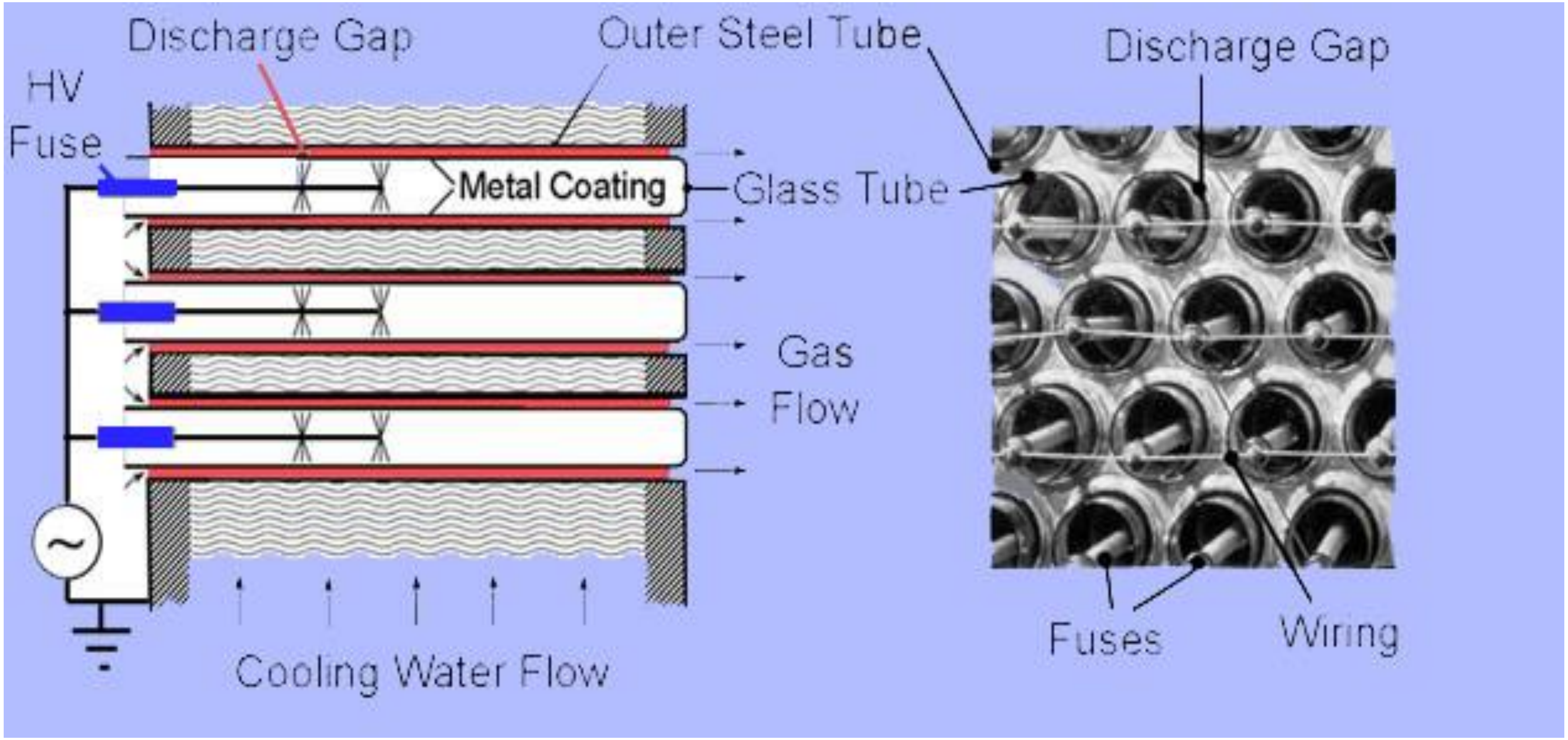
membrane pump



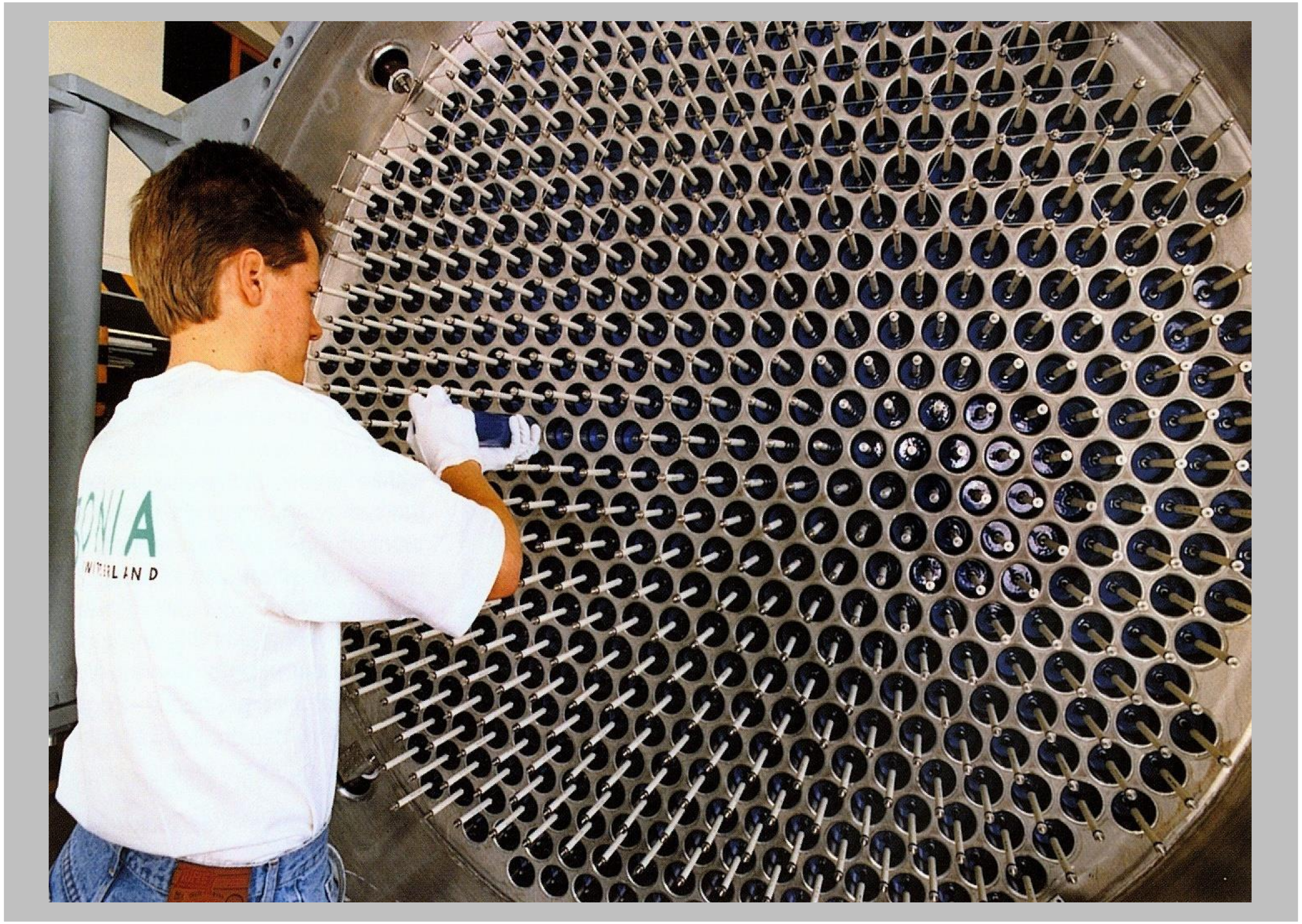


Historical Ozone Tube of W. Siemens 1857

Discharge Tubes in Ozone Generators



Ozonia AT Ozone Generator



Courtesy of Dr. Uli Kogelschatz

Plasma Jet

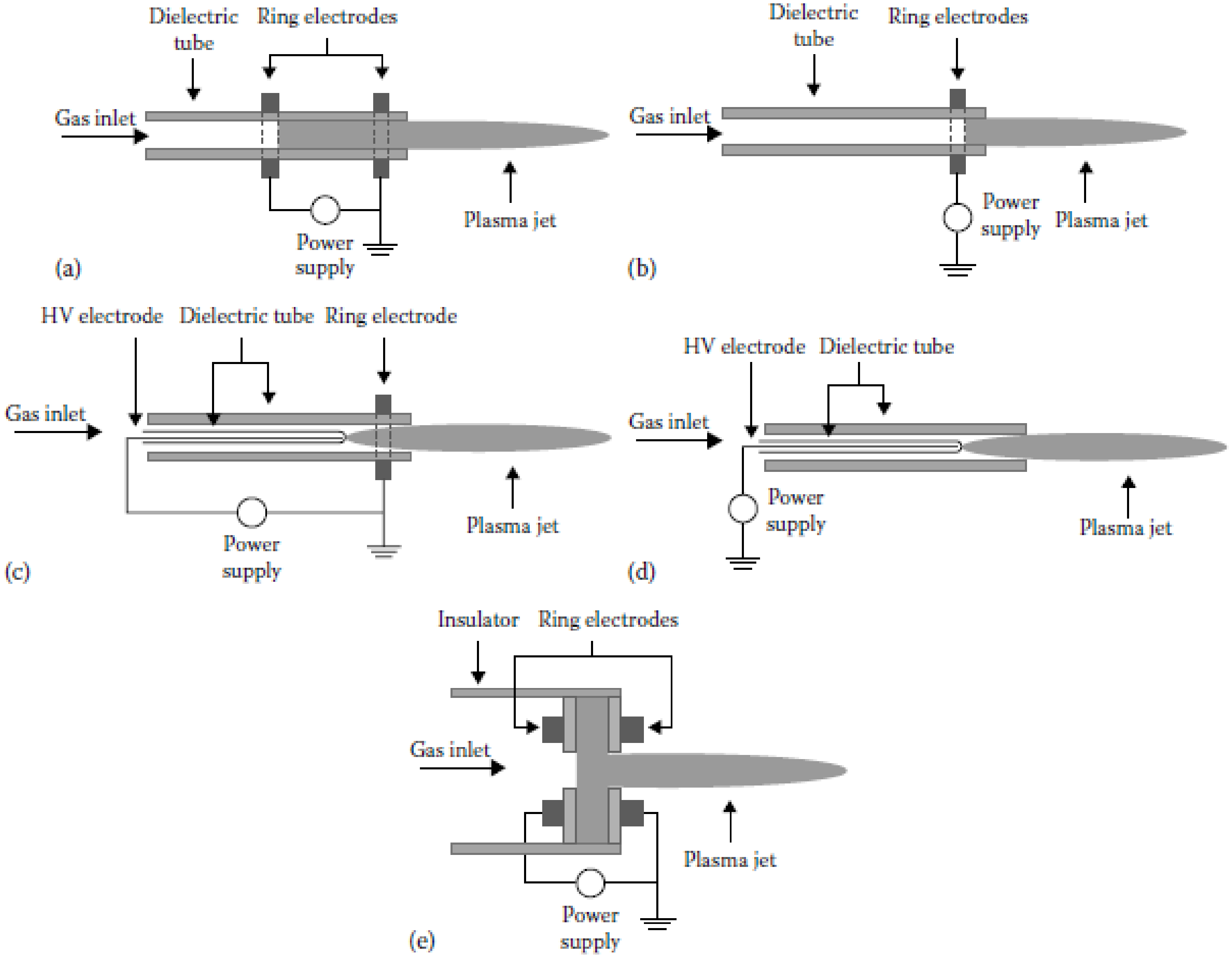


FIGURE 7.2 Schematic of a DBD plasma jet. (a) two ring electrodes DBD jet; (b) single electrode DBD jet; (c) electric field-enhanced two electrode DBD jet; (d) electric field-enhanced single electrode DBD jet; (e) plasma pencil.