chimica inorganica industriale
PROCESSI INDUSTRIALI VIA PLASMA

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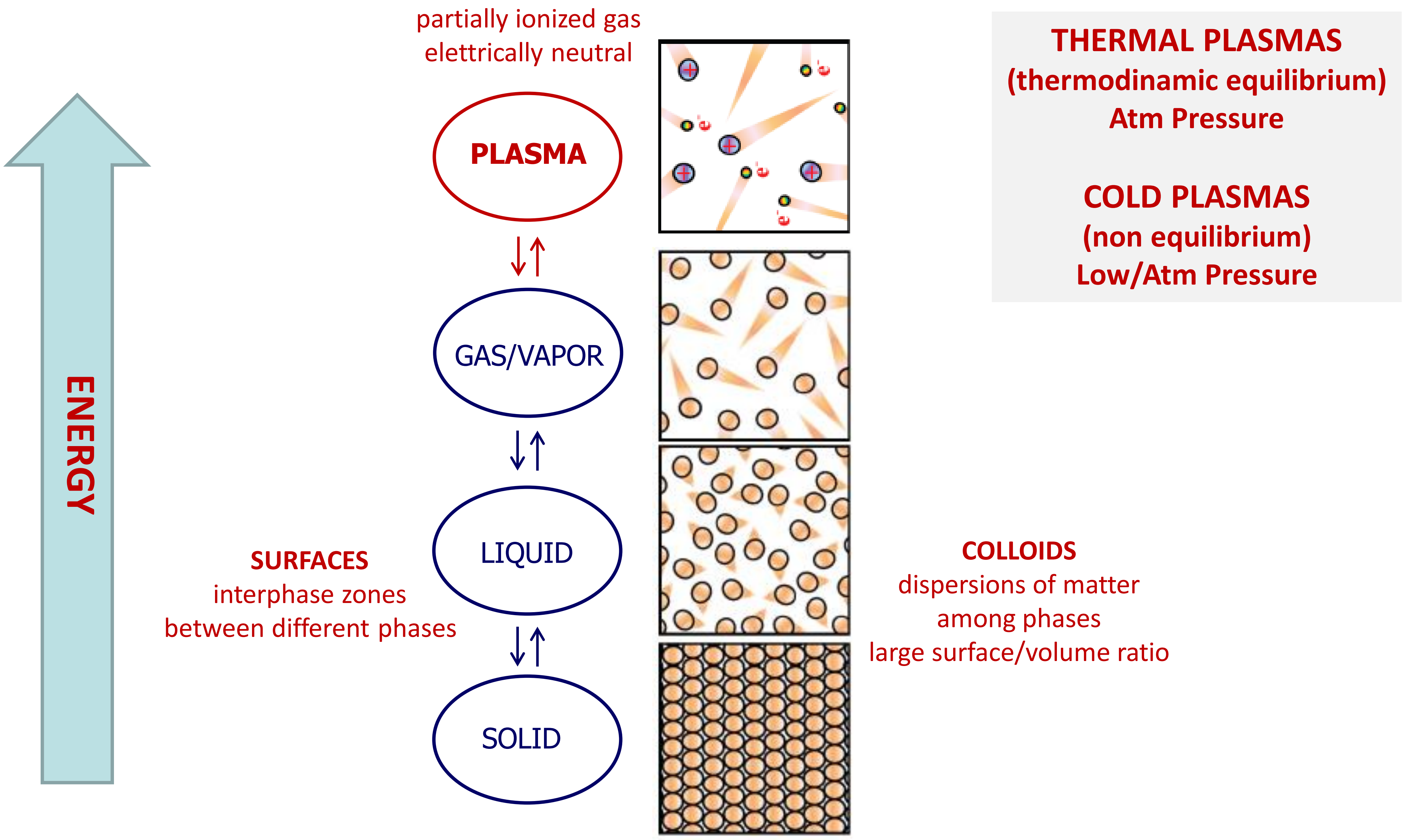

ENERGY
partially ionized gas
elettrically neutral
PLASMA
GAS/VAPOR
LIQUID
SOLID
SURFACES
interphase zones
between different phases
THERMAL PLASMAS
(thermodinamic equilibrium)
Atm Pressure
COLD PLASMAS
(non equilibrium)
Low/Atm Pressure
COLLOIDS
dispersions of matter
among phases
large surface/volume ratio

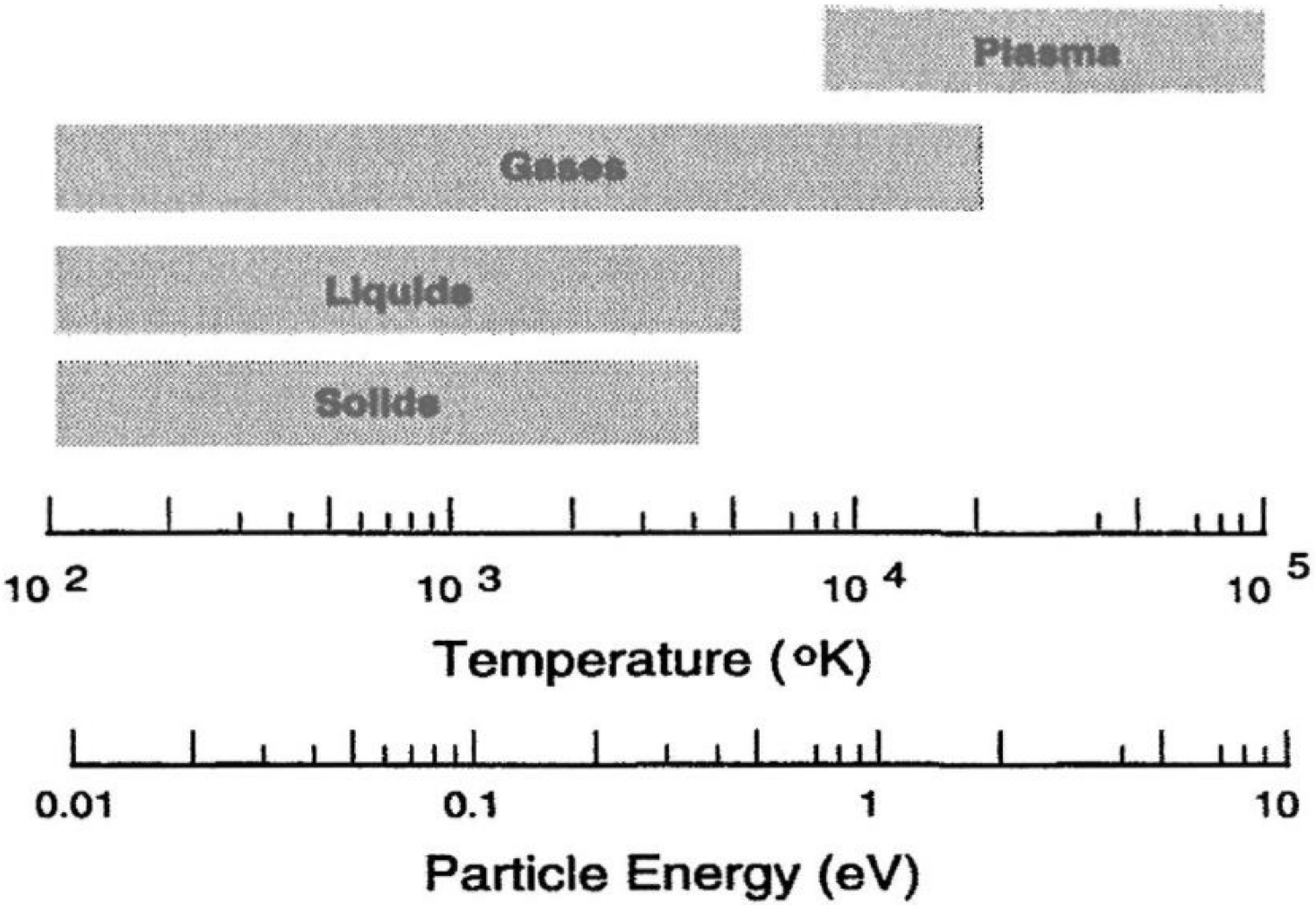


Fig. 1-1 State of matter versus temperature.

1928
I. LANGMUIR INTRODUCES THE WORD "PLASMA"

I. Langmuir, *Oscillations in Ionized Gases*
Proc. Nat. Acad. Sci. 14, 627, Aug 1928

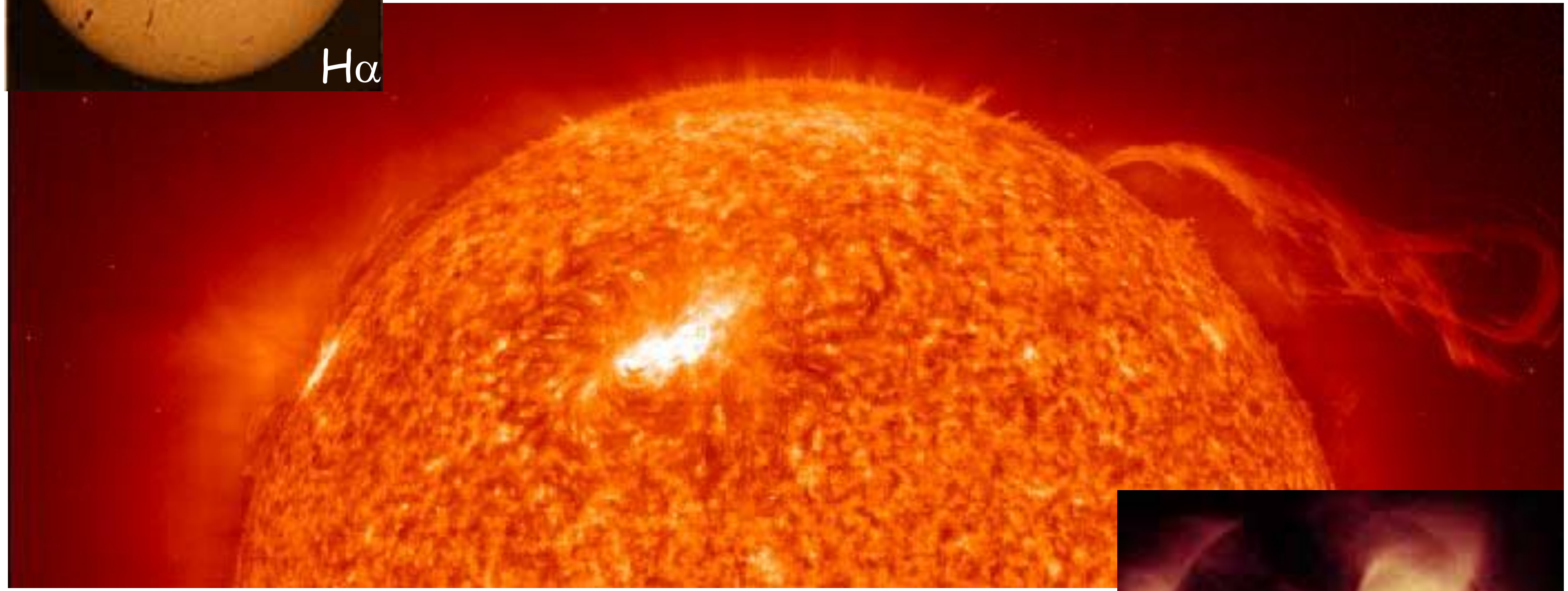
"Except near the electrodes, where there are sheaths containing very few electrons, the ionized gas contains ions and electrons in about equal numbers, so that the resultant space charge is very small. We shall use the name plasma to describe this region containing balanced charges of ions and electrons."

Irving Langmuir
(1881-1957)

Nobel Laureate in Chemistry 1932

... for his discoveries and investigations in surface chemistry ...

THEROMONUCLEAR PLASMA



PLASMA CALDO

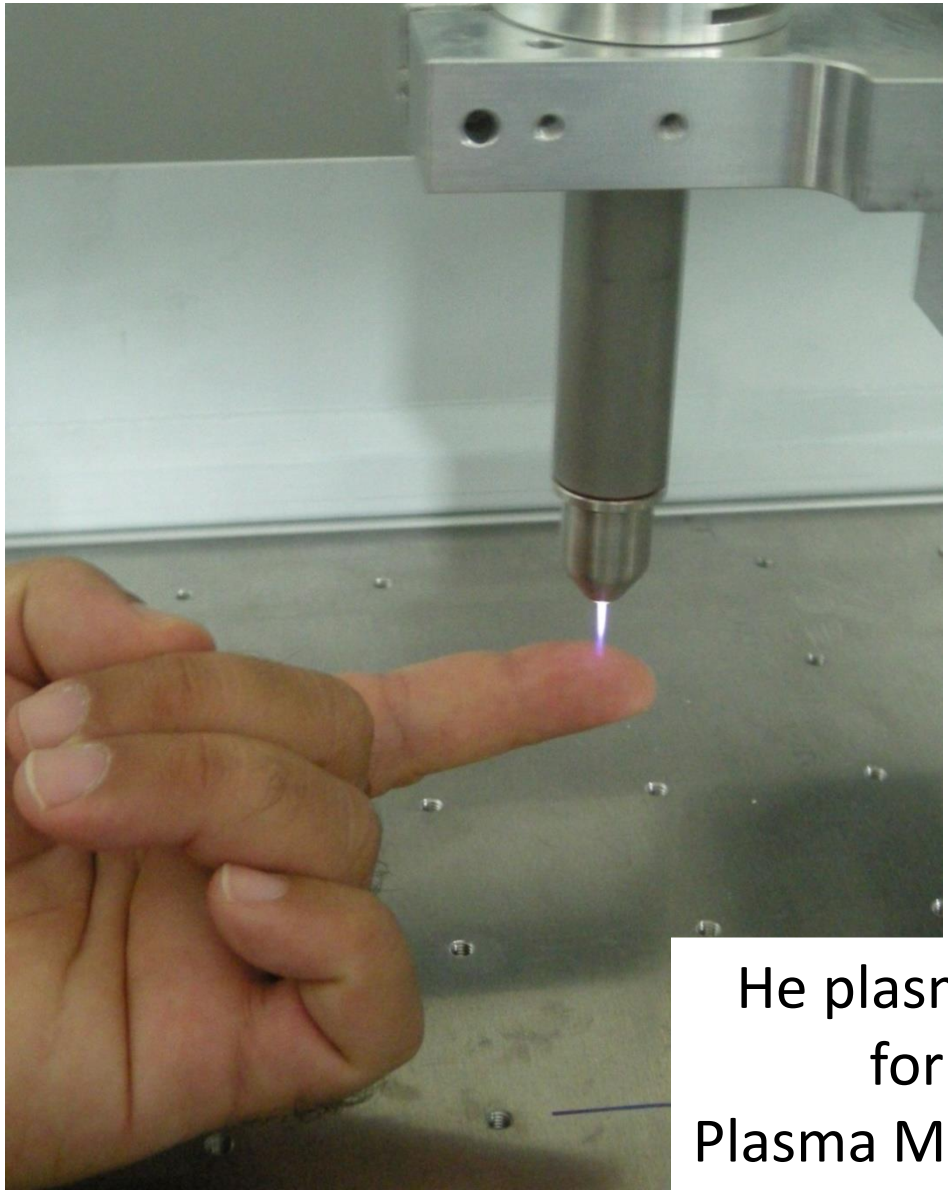
PLASMA FREDDO

PLASMA CALDO

PLASMA FREDDO

PLASMA CALDO

PLASMA FREDDO



He plasma jet
for
Plasma Medicine

PLASMA DEPOSITION/TREATMENTS atmospheric pressure

REALLY COLD !

THE 4th STATE OF THE MATTER: *birth of a concept*

V sec B.C. Empedocles defines EARTH, AIR, WATER, FIRE as the 4 elements

XVII century First observations of lightnings

XIX century German scientists find that electric discharges in hydrocarbon gases originate oily droplets

1857 Siemens develops the first Ozone generator, mainly used for water purification

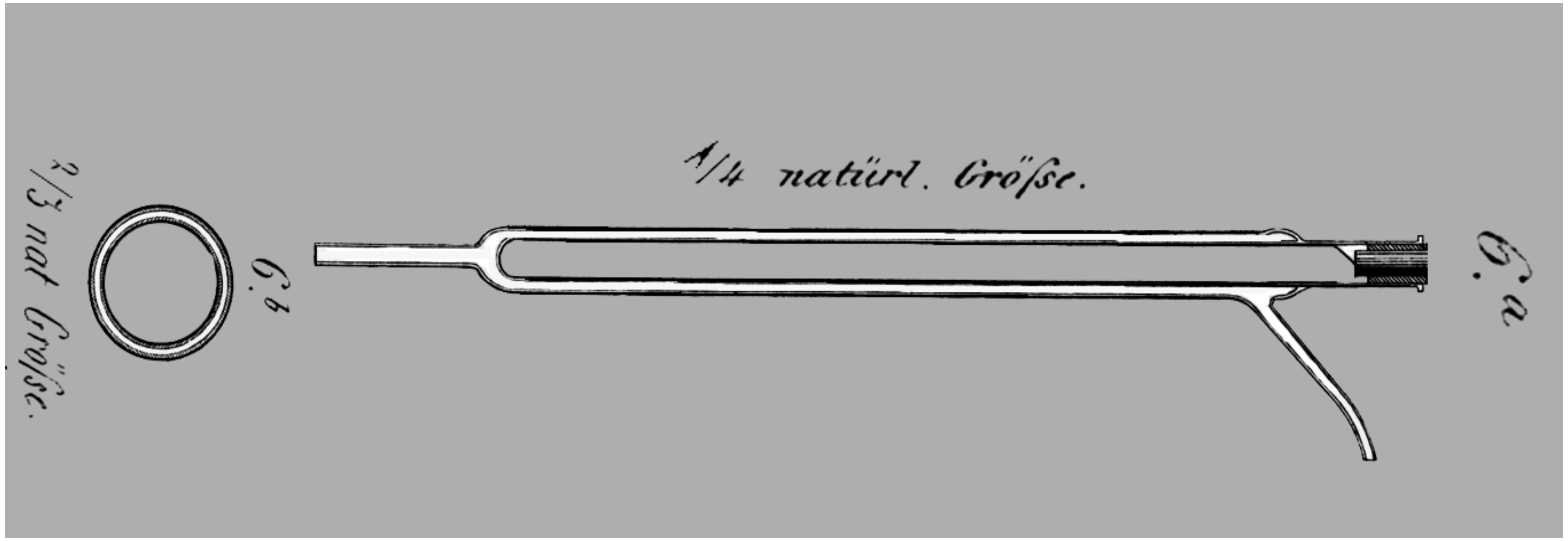
1879 W. Crookes defines the state of a ionized gas as "… a world where matter may exist in a 4th state …".

1910 G. Claude exhibits neon lights in public at the Paris Motor Show

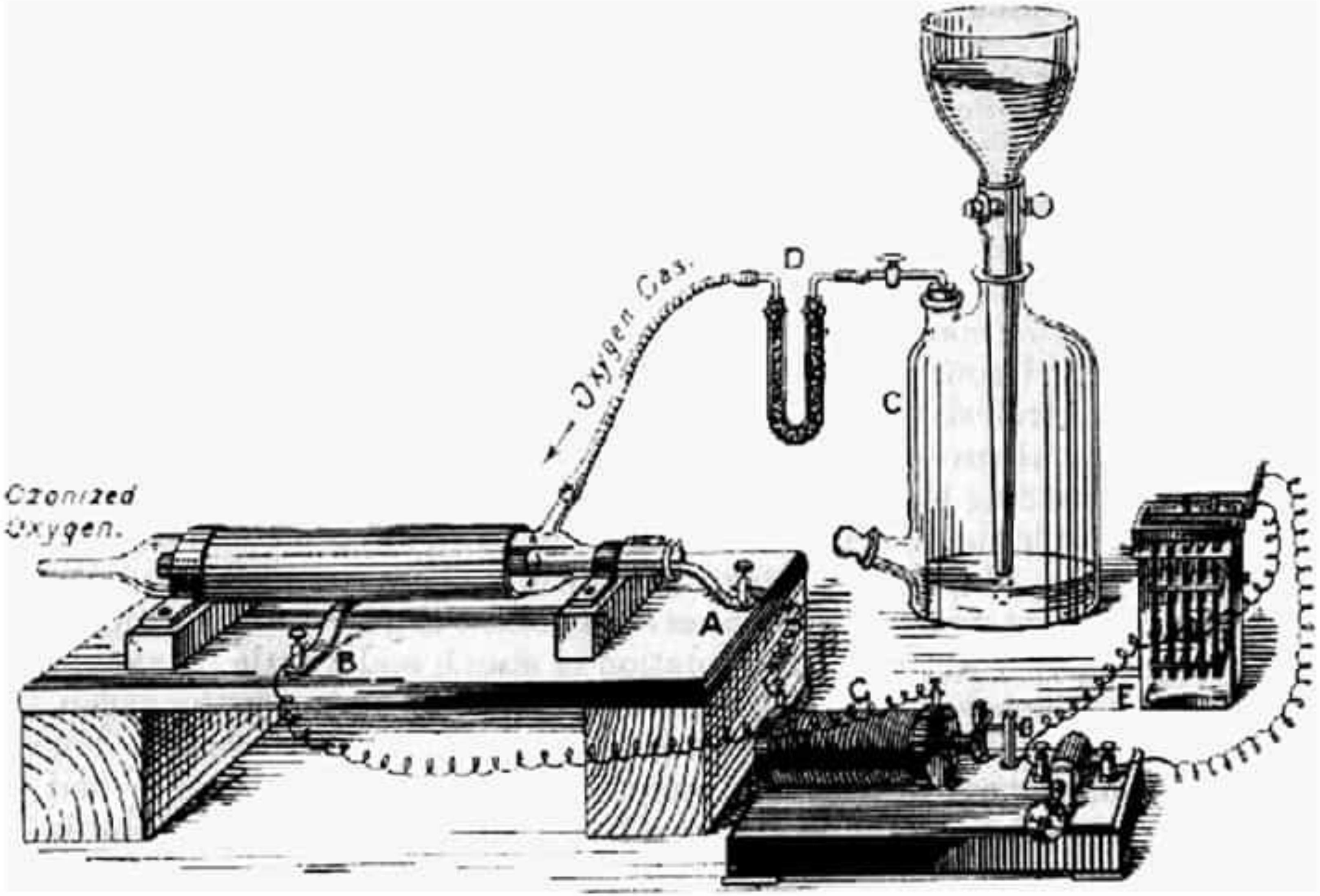
1928 I. Langmuir uses the word plasma to define a neutral ionized gas made of electrons, ions atoms and molecules as the "4th state of the matter".

late XIX, first half XX sec DC/AC low pressure gas discharges and flames are used to investigate the structure of atoms and molecules by means of Emission Spectroscopy

Historical Ozone Tube
of W. Siemens 1857

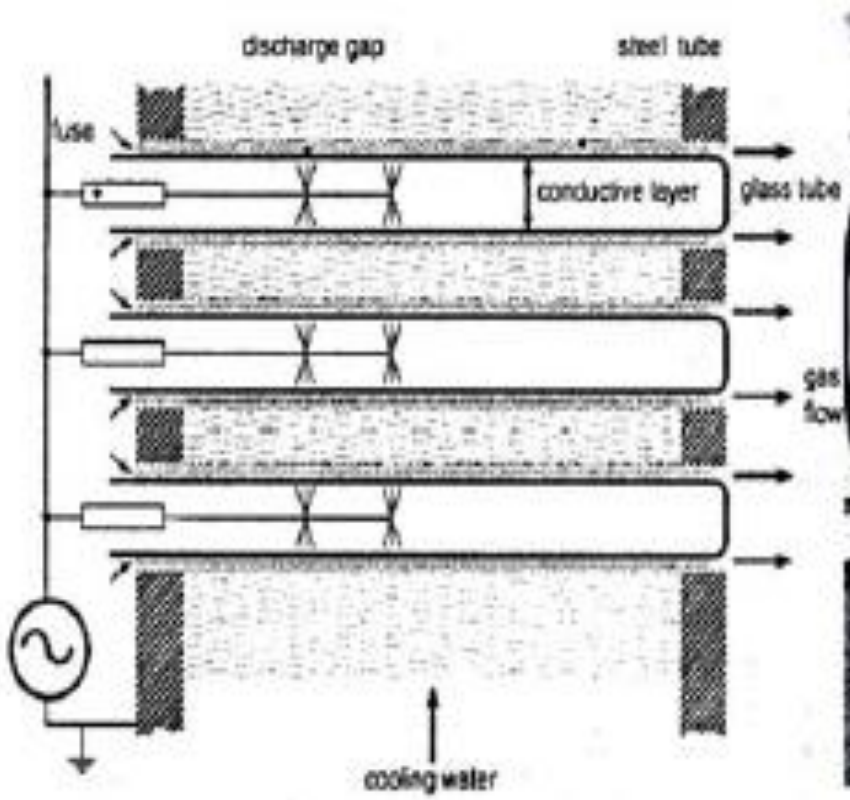


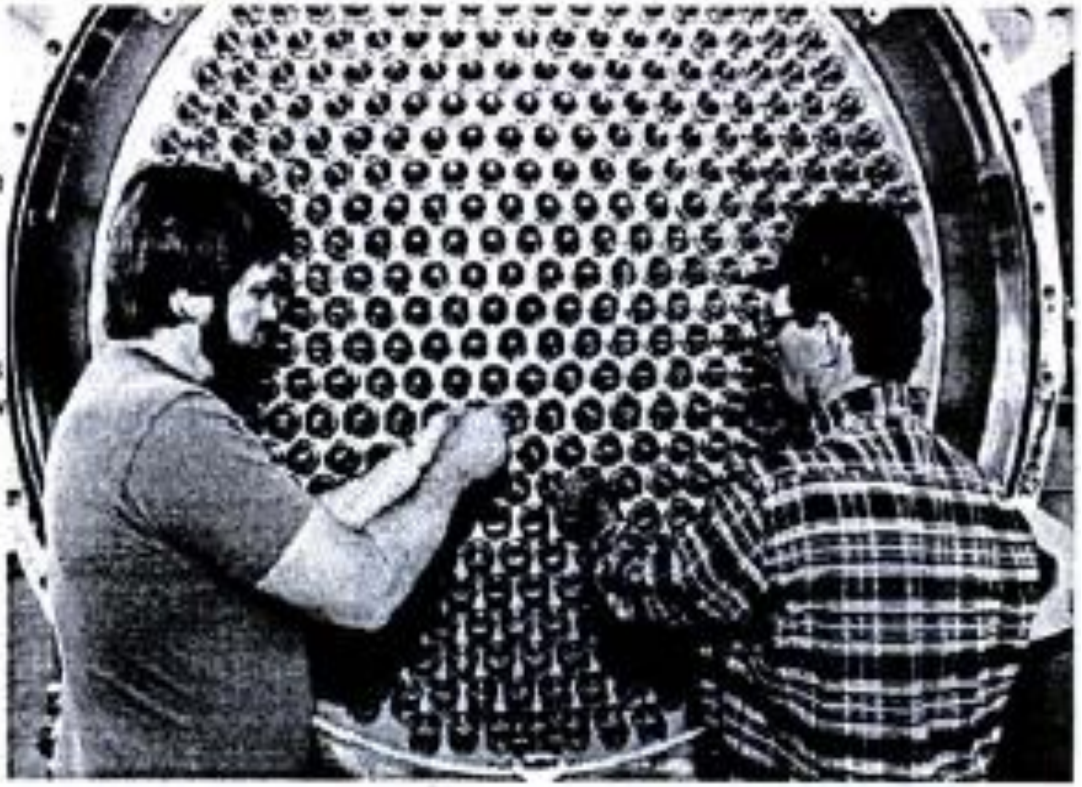
Poggendorff's Annalen der Physik und Chemie
102 (1857), 66-122



Ozonized
Oxygen.
← Oxygen Gas.
D
C
A
B
C
E

applicazioni delle Dielectric Barrier Discharge: O_3





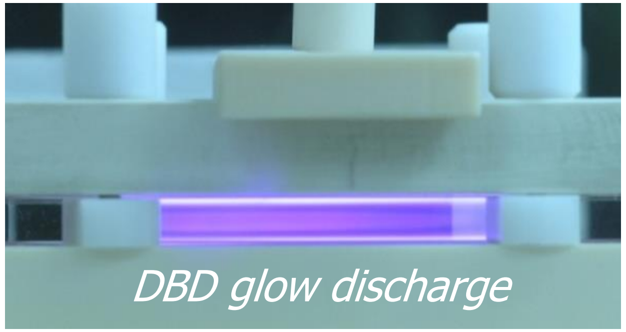
generatore di O_3
Los Angeles
Aqueduct Filtration Plant

$$O_2 + O + M \rightarrow O_3^* + M \rightarrow O_3 + M$$

i generatori sono in grado di produrre centinaia di Kg/h di ozono

per trattamento delle acque e sbiancamento della polpa di legno

COLD PLASMAS

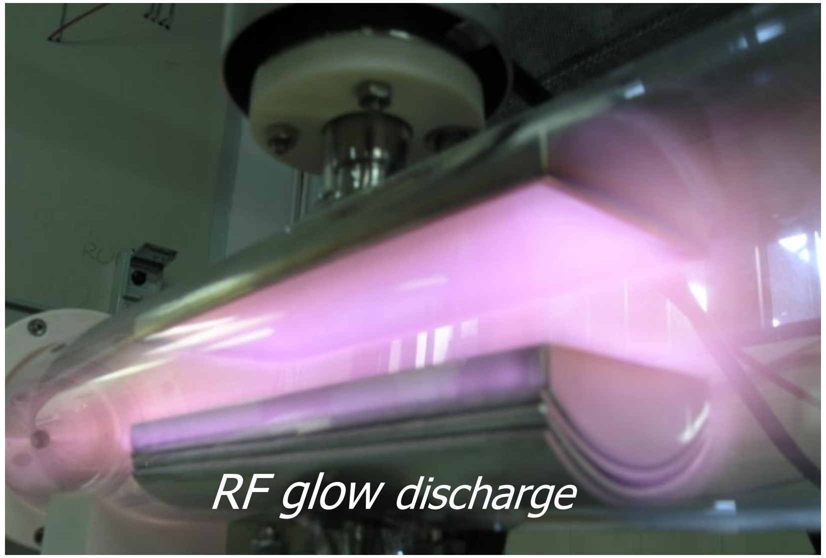

DBD glow discharge

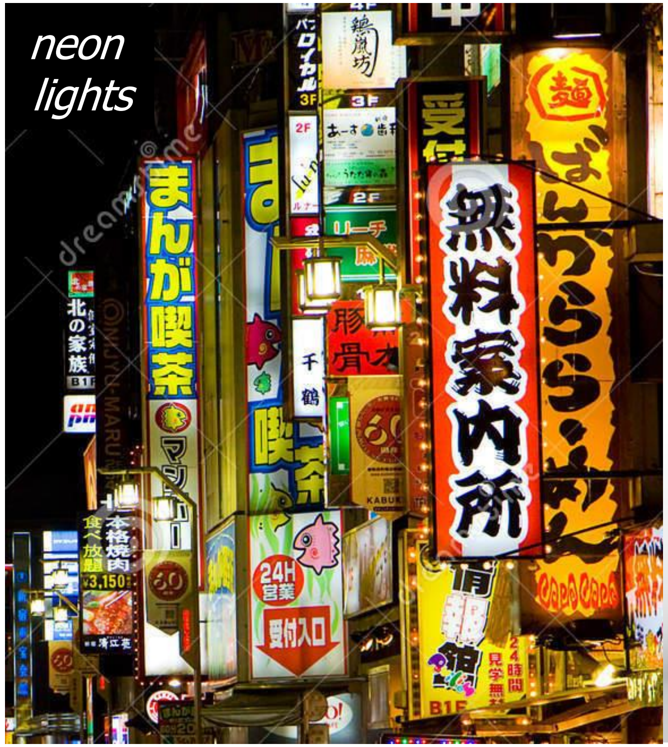

HID car lights


plasma ball


plasma jet


aurora borealis


RF glow discharge



neon lights


plasma TV

THE 4th STATE
OF THE MATTER:
developments and maturity

50'-60's
- Plasma chemistry for producing chemicals
- First depositions of thin films
- Miller experiment

70's
- First plasma etching processes
- Equilibrium/non equilibrium debate
- Deposition of α-Si:H

80's
- Solar cells (α-Si:H) produced
- Microelectronics at large
- Other applications start

90's
- Extreme miniaturization in microelectronics
- Polymers, textiles, packaging, biomaterials, paper, composites, MEMS,… sterilization …

2000
- Micro- , nano- surface plasma-engineering in different fields
- Large area easy processing
- Old processes in new fields; plasmas very common also in low-tech fields

2010 →
- Plasma Medicine (Agriculture, Food, …)

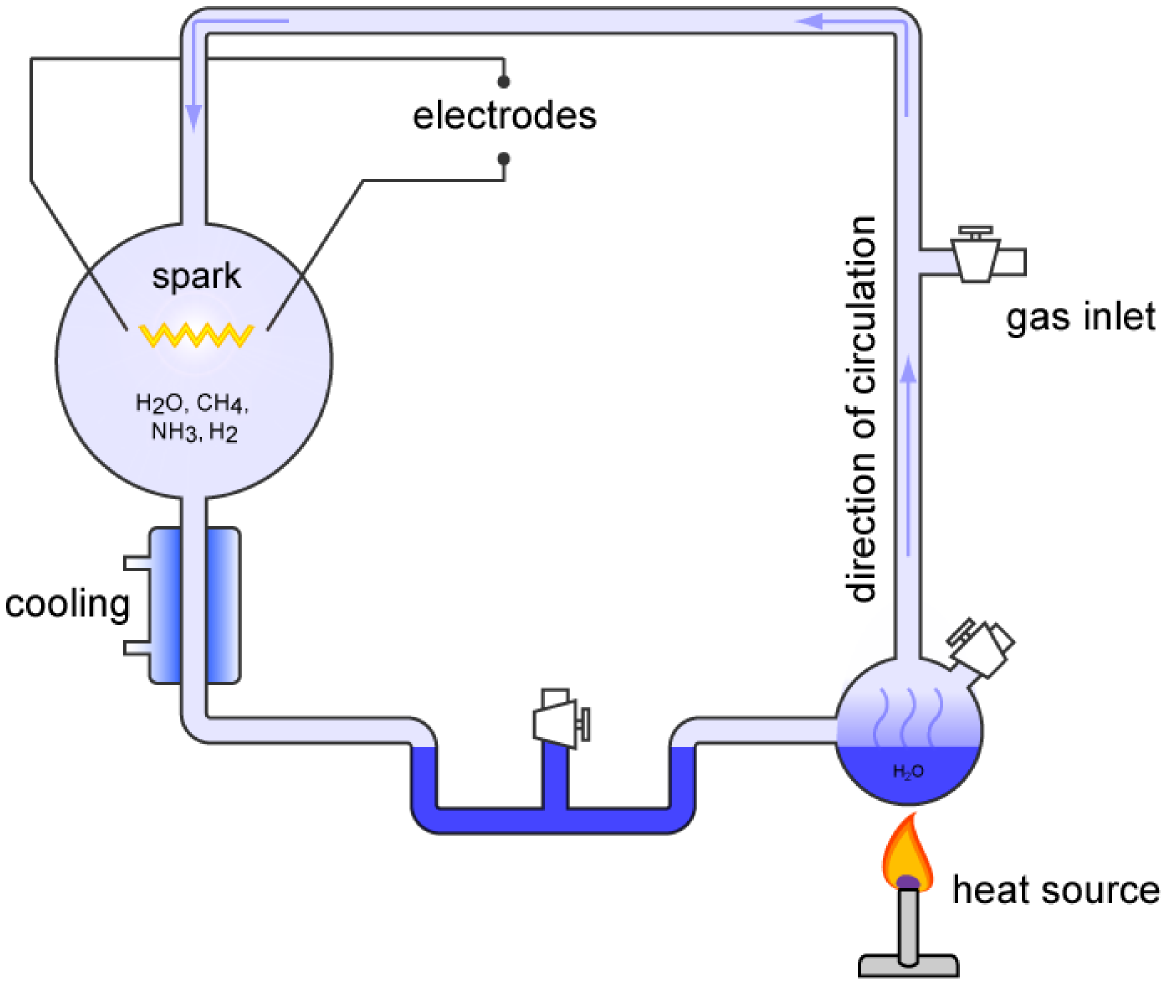
PLASMAS
AND THE ORIGIN OF LIFE

"A Production of Amino Acids Under Possible Primitive Earth Conditions

Stanley L. Miller
G. H. Jones Chemical Laboratory
University of Chicago, Chicago, Illinois"
Science, Vol. 117 p.528 (1953)

"Production of org Compounds under Primitive Earth Conditions"

Stanley L. Miller
G. H. Jones Chemical Laboratory
University of Chicago, Chicago, Illinois"
J. Am Chem Soc. Vol. 77,9 p.2351ff (1955)



plasma (spark) processing

of the pristine atmosphere on EARTH

a mixture of H_2O, CH_4, NH_3 and H_2

amino acids were produced in the discharge !

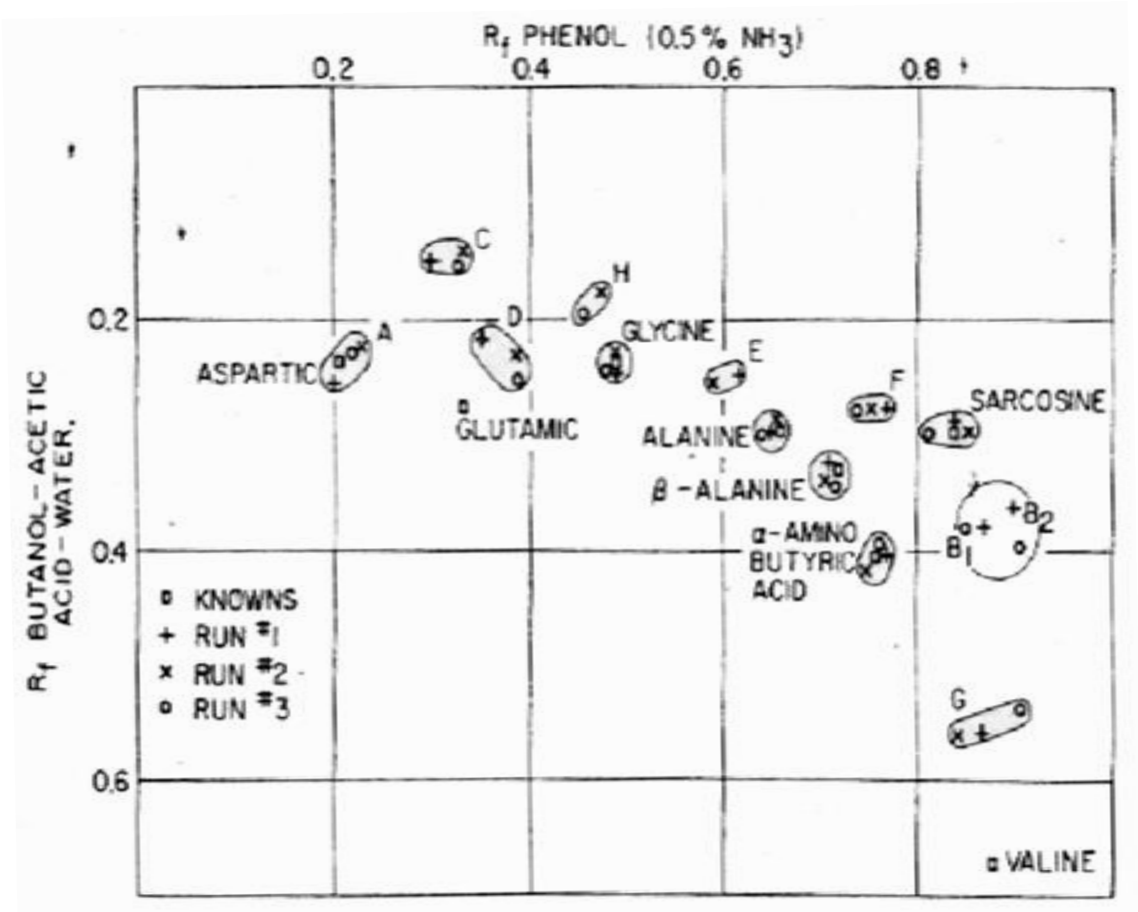
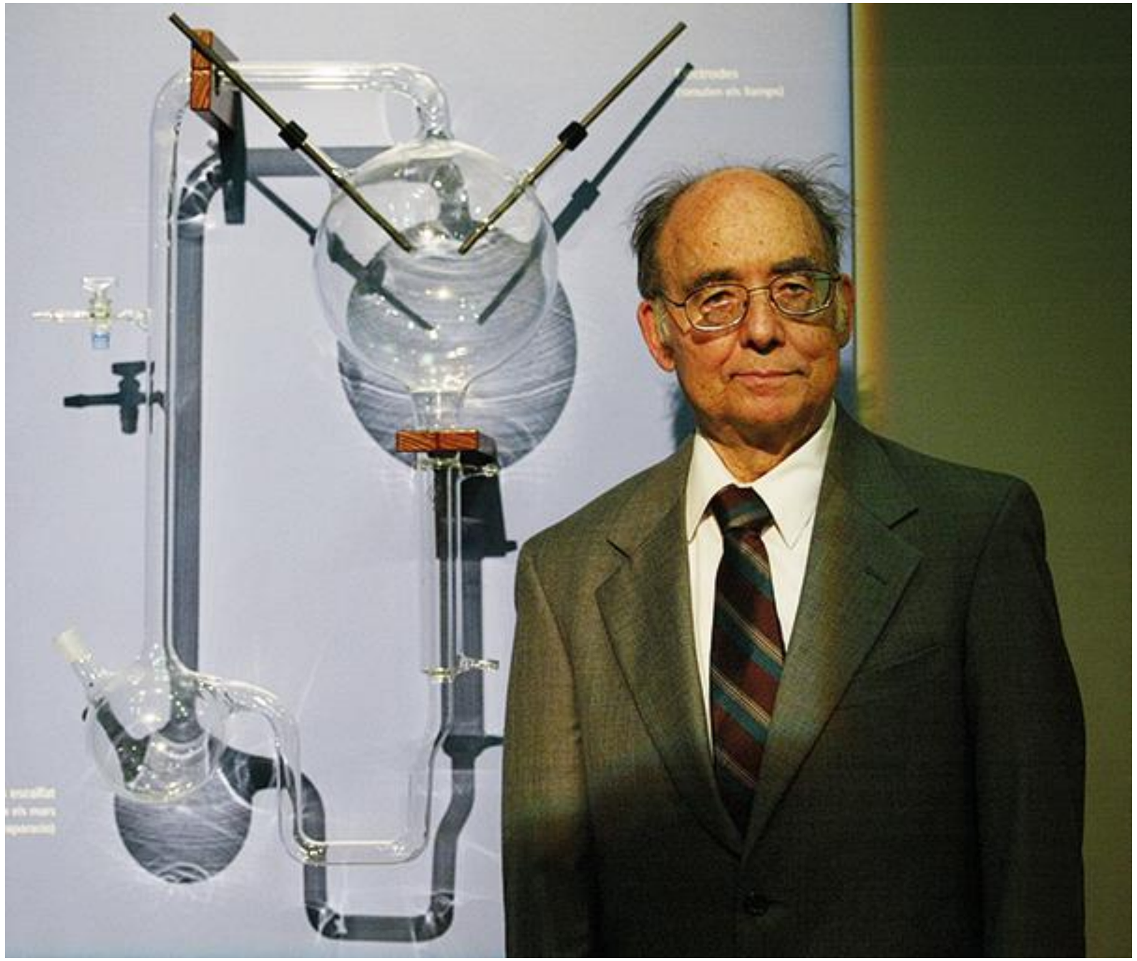
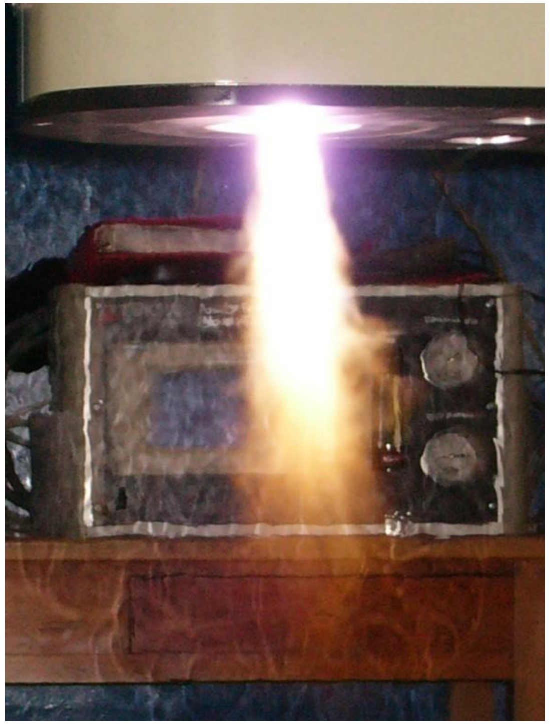
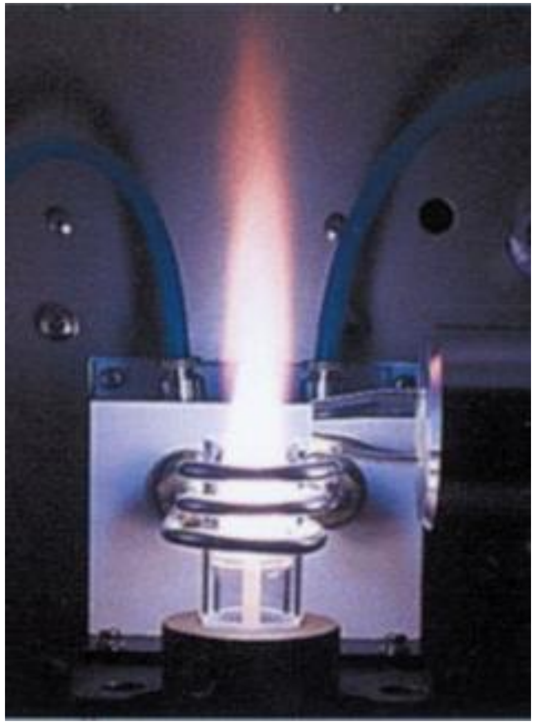


Fig. 8.—Paper chromatography of the amino acids.





THERMAL PLASMAS



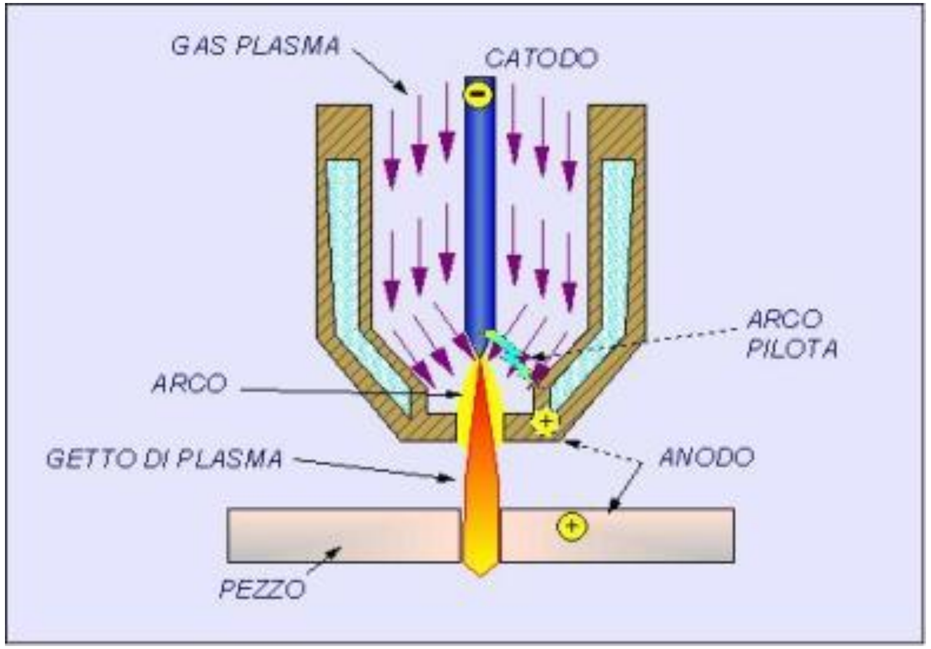
welding, cutting, metallurgy,
plasma spray deposition,
ICP spectroscopy,
waste abatment

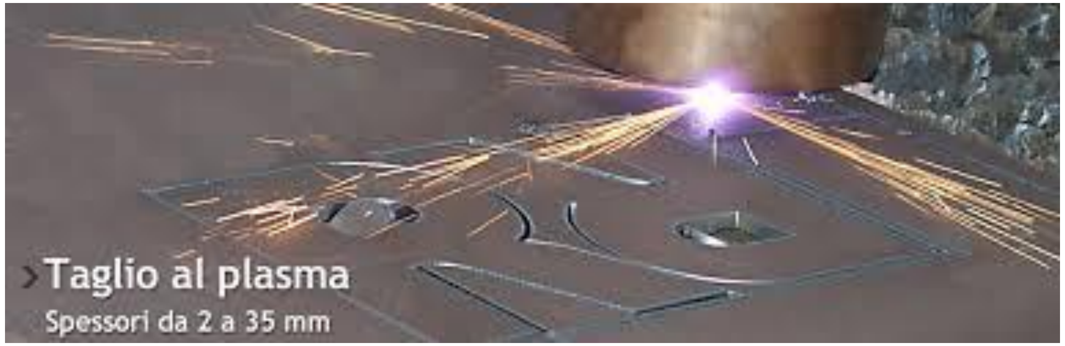
TAGLIO A PLASMA

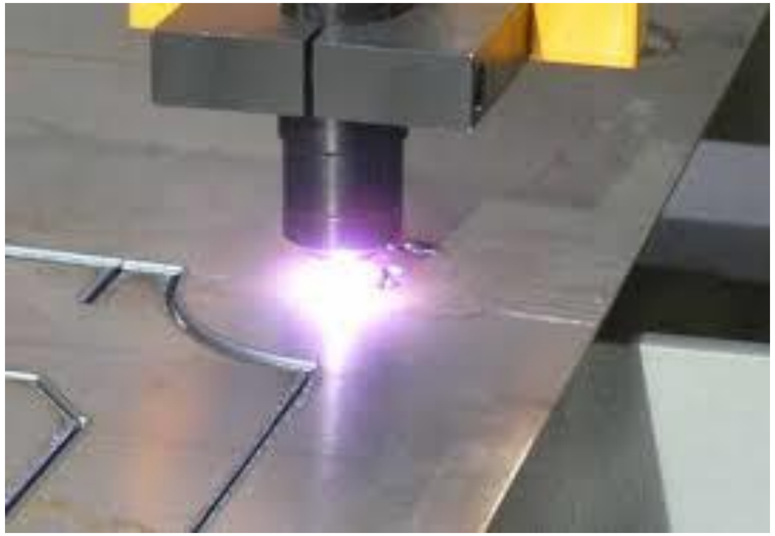
metalli

aria compressa

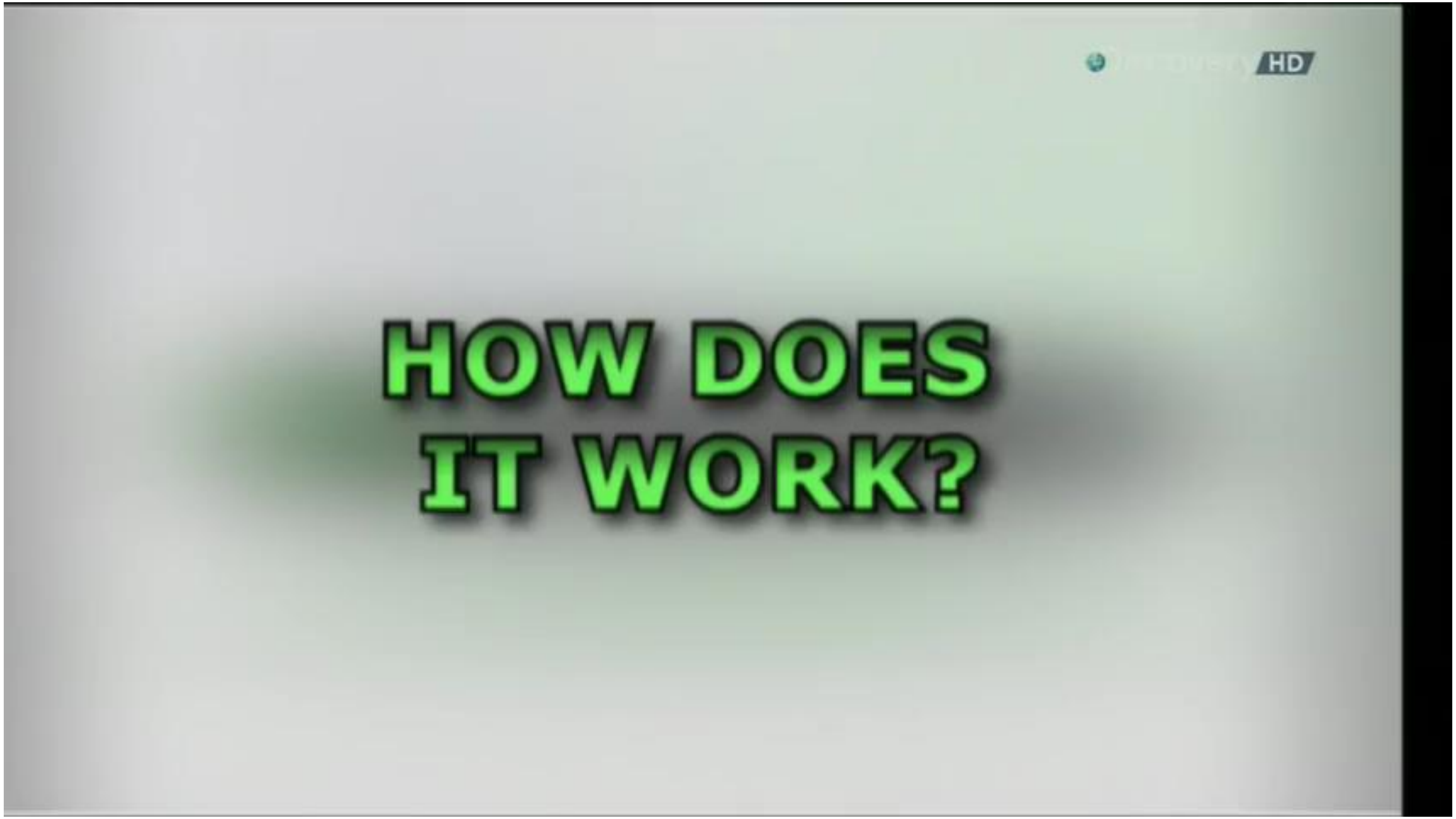
T 10^4 K



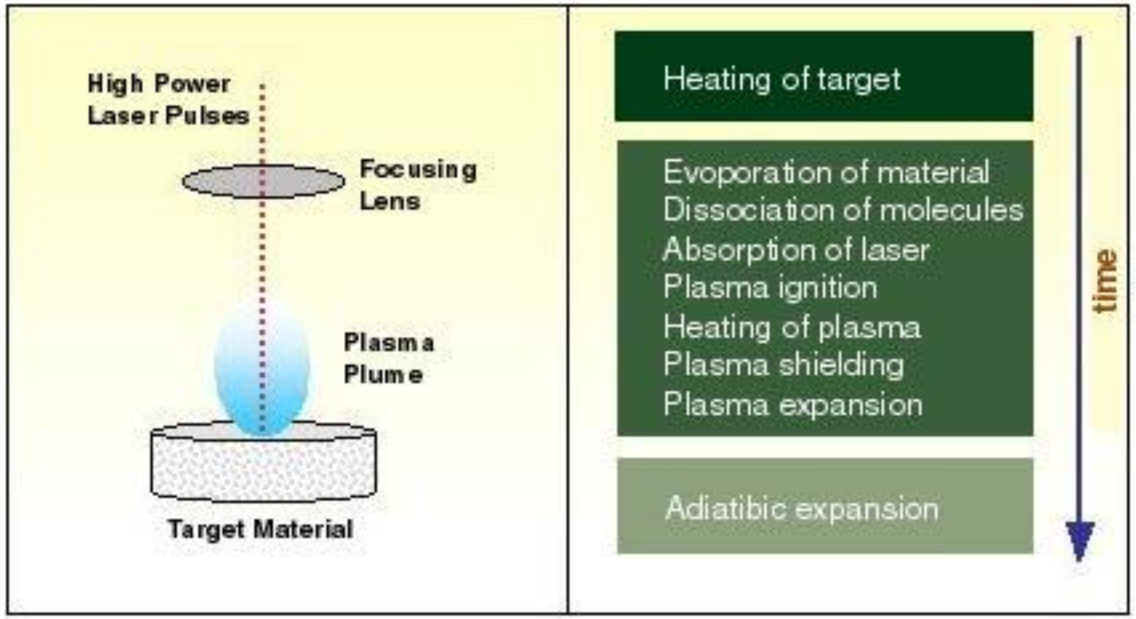




taglio al plasma
video

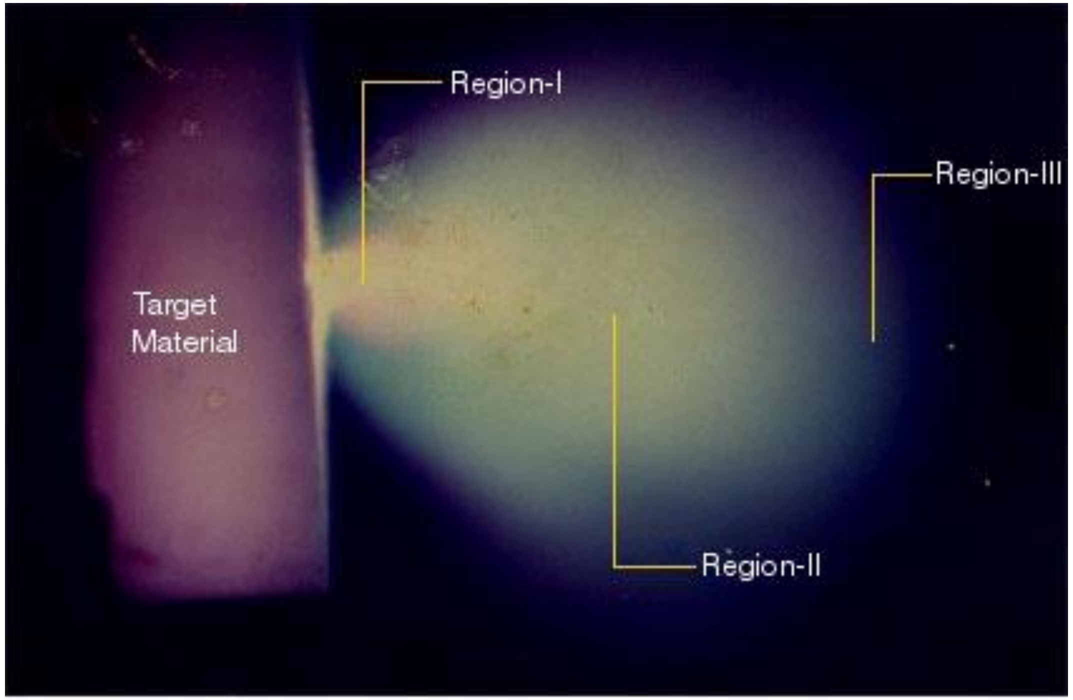


LASER INDUCED PLASMA



Evolution of laser induced plasma from a target material

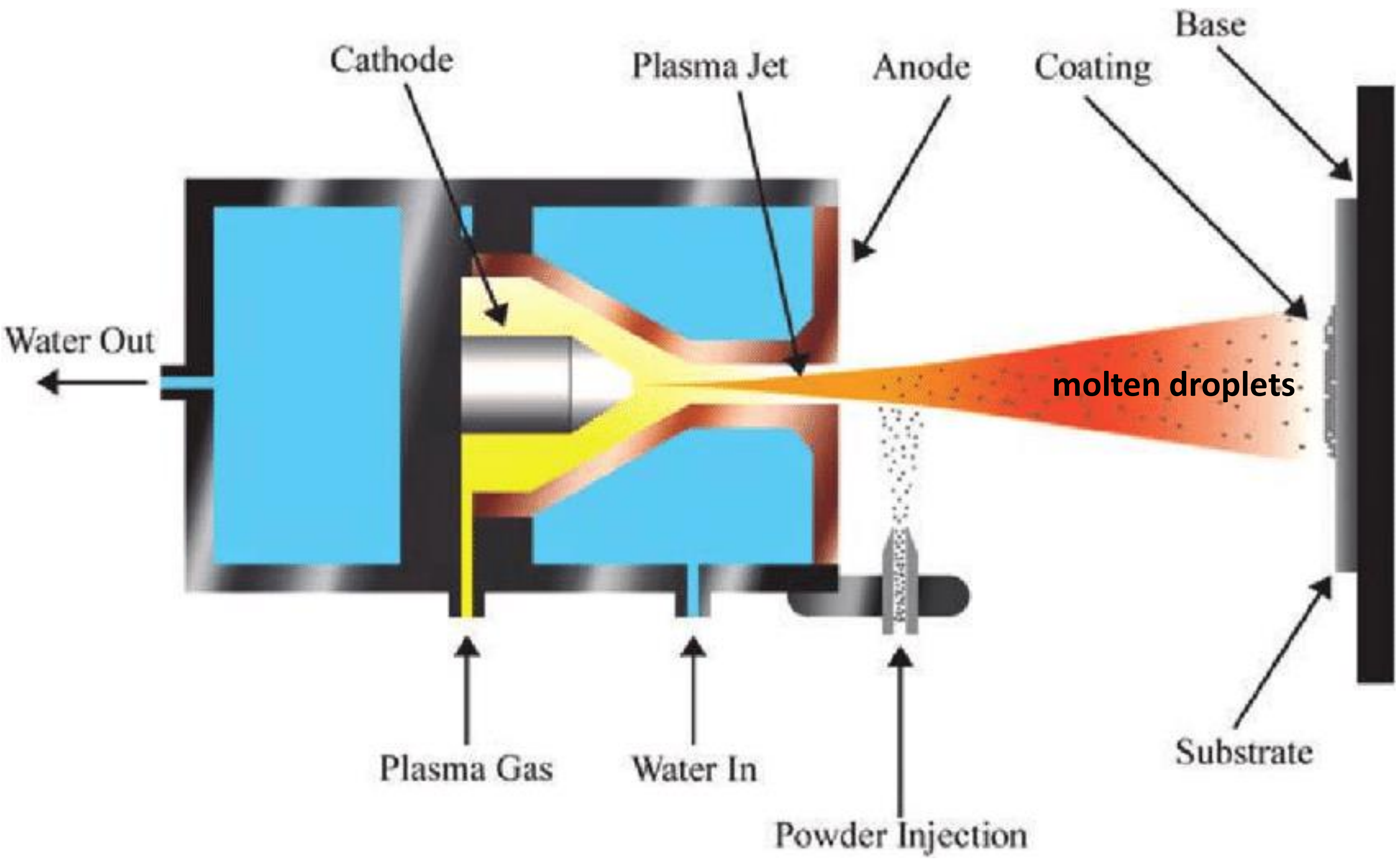
a plasma can also be obtained when high-density energy is supplied to a liquid or a solid by a laser or by an electric field strong enough



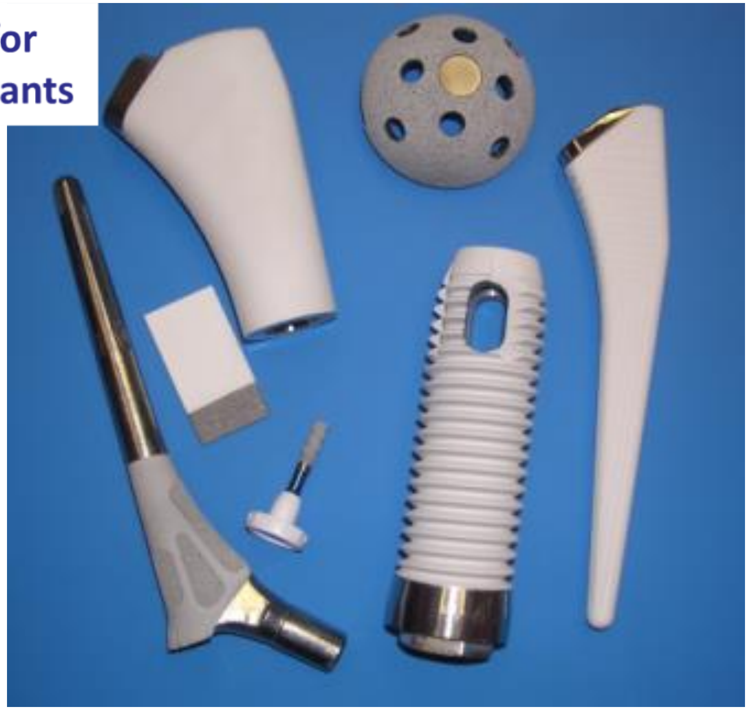
Laser produced plasma plume from a metal target

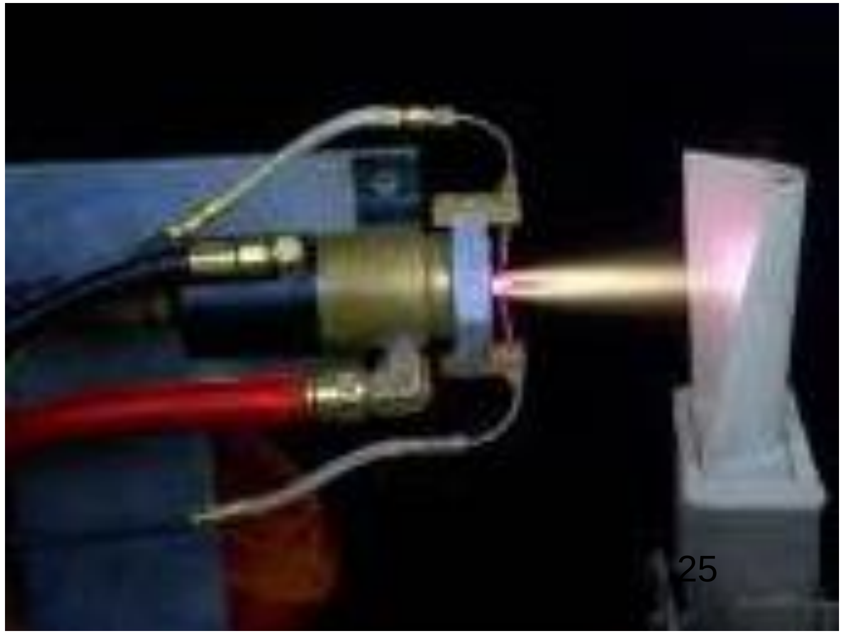
PLASMA SPRAY

thermal plasmas for materials

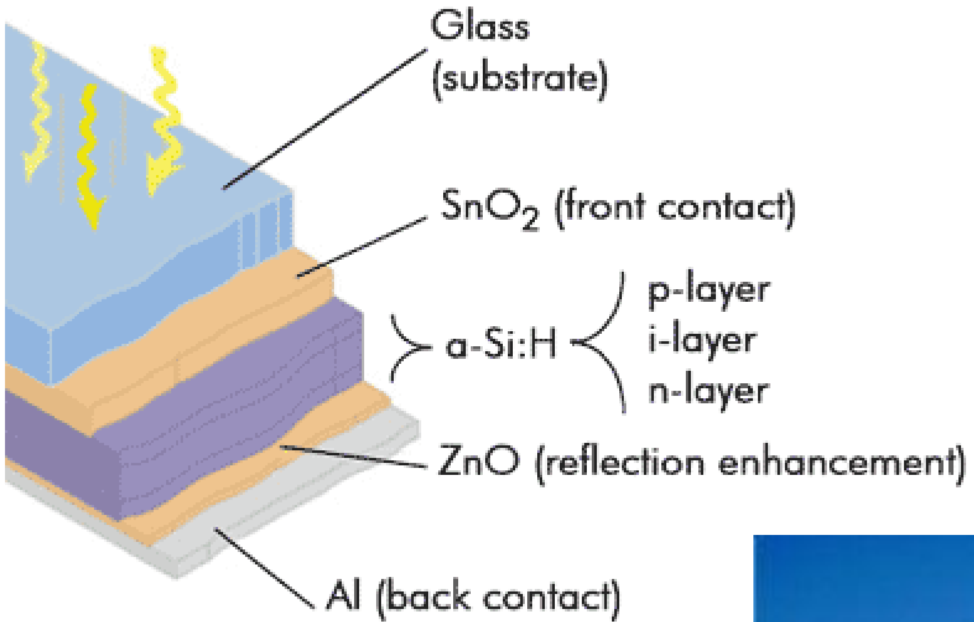


hydroxyapatite coatings for orthopedic and dental implants





re-entry plasma sheath

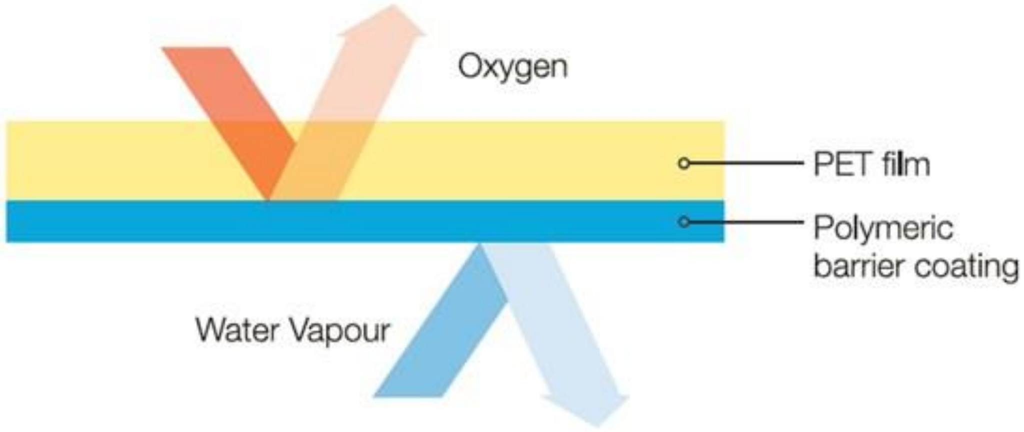


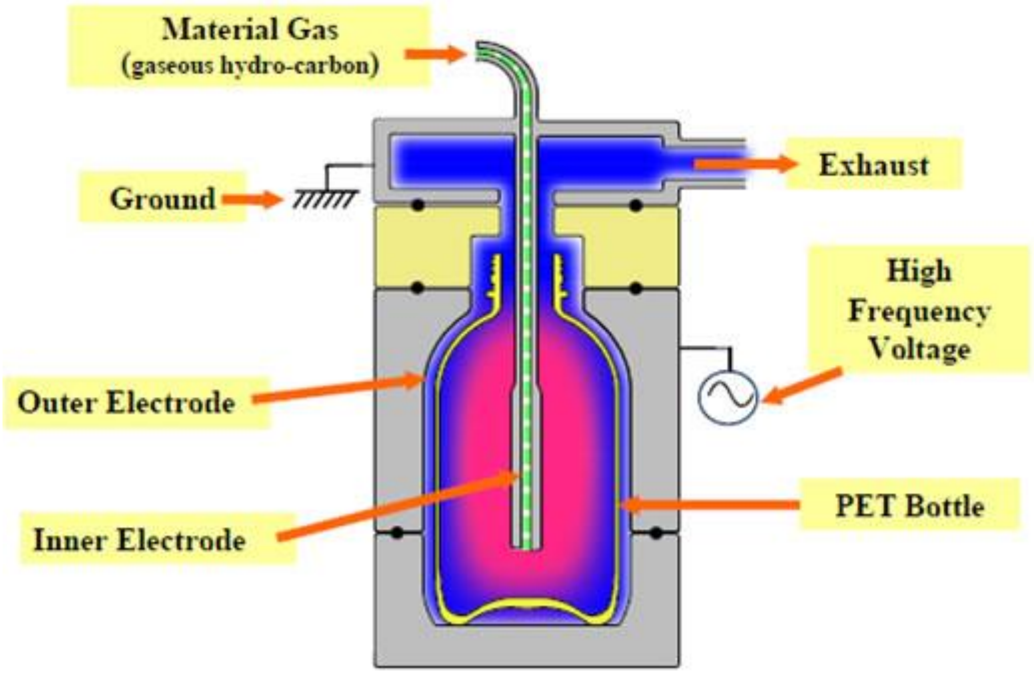
PLASMA DEPOSITED

ACTIVE LAYERS

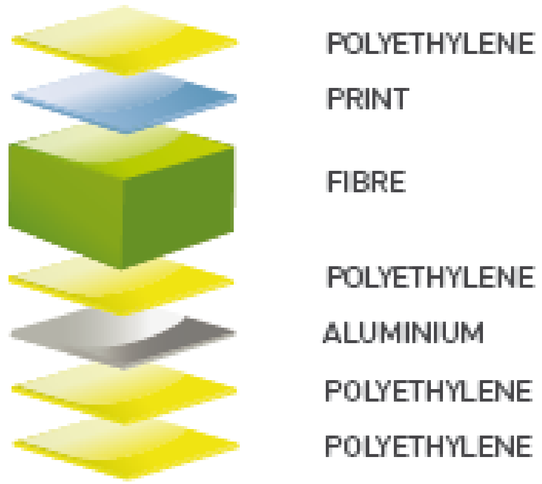
IN SOLAR CELLS

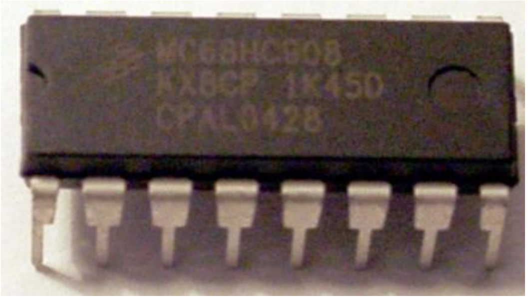
gas barrier coatings

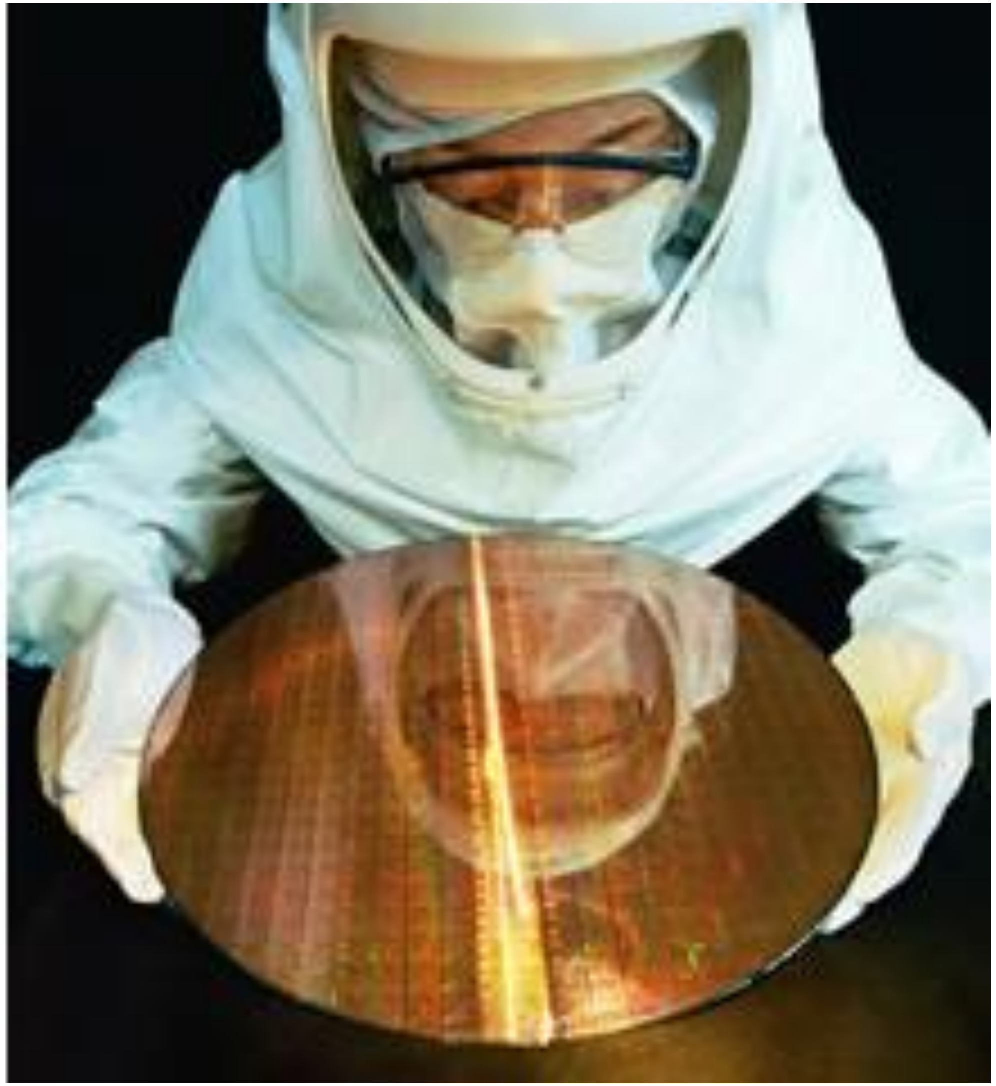


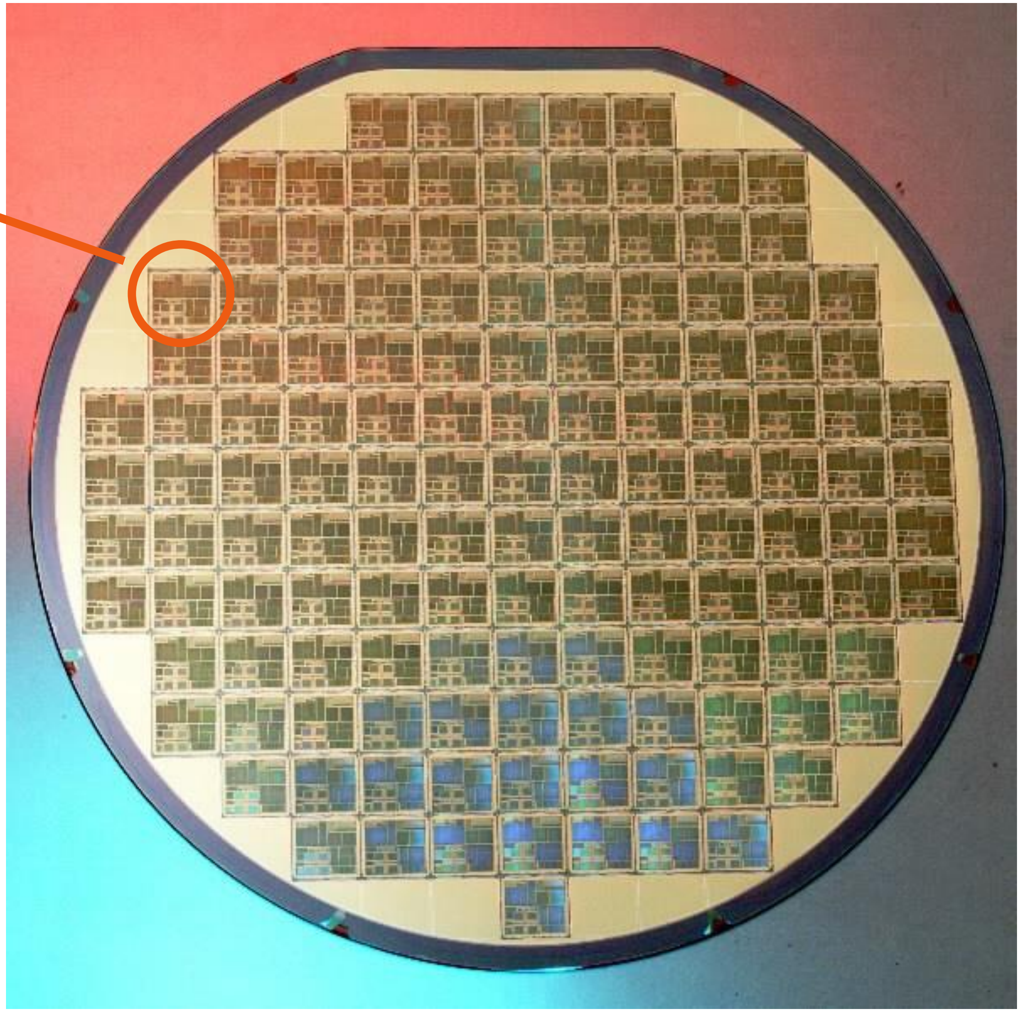


THE LAYERS OF A BEVERAGE CARTON



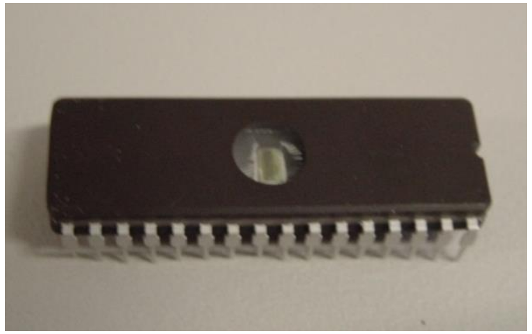


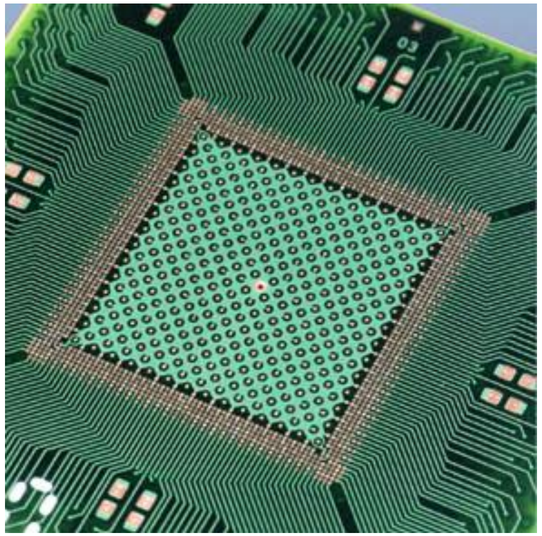


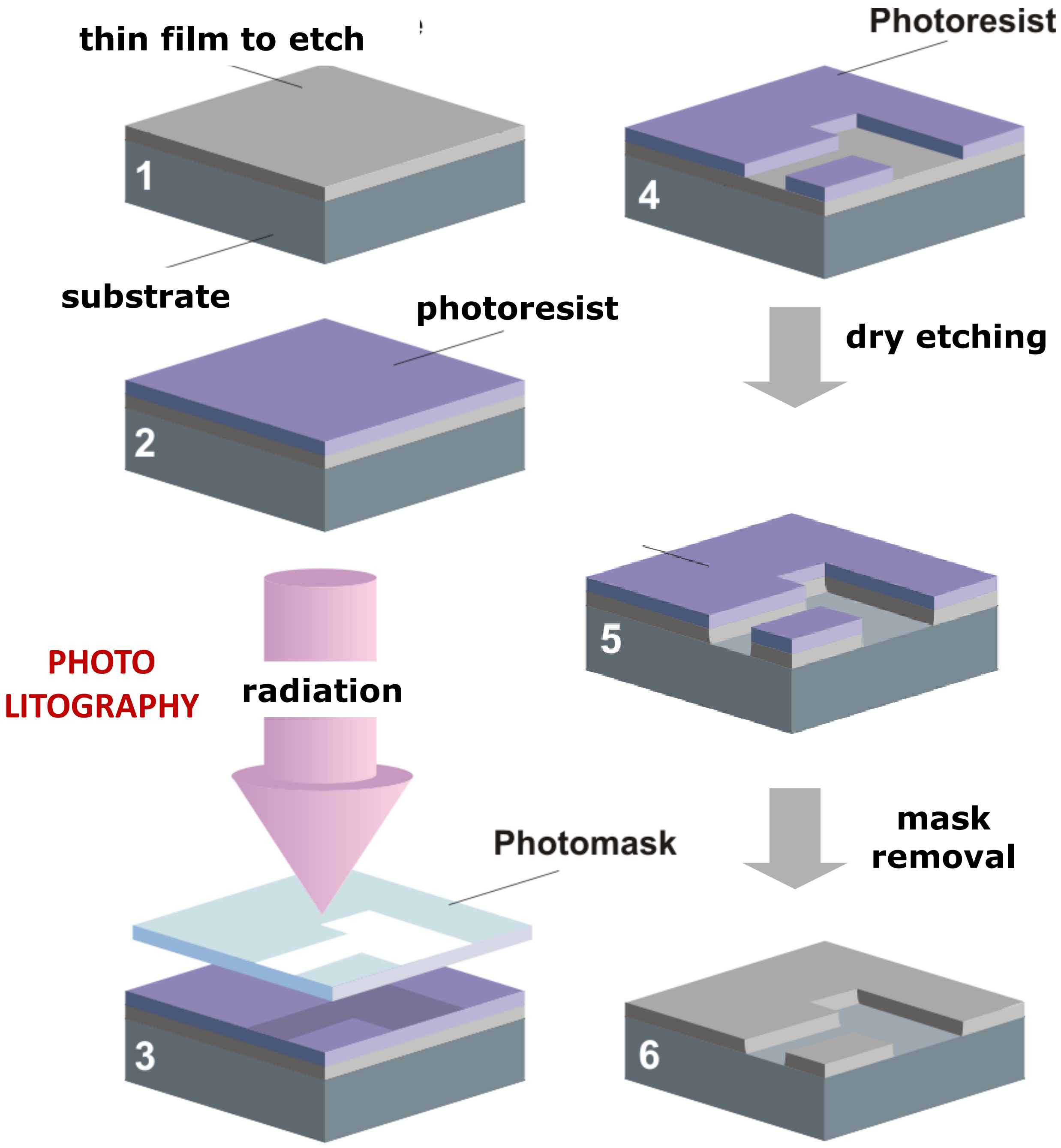


CIRCUITI INTEGRATI
IN MICRO ELETTRONICA

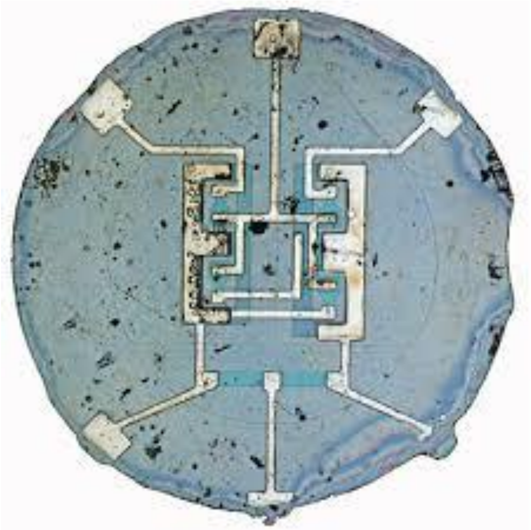
PLASMA (DRY) ETCHING

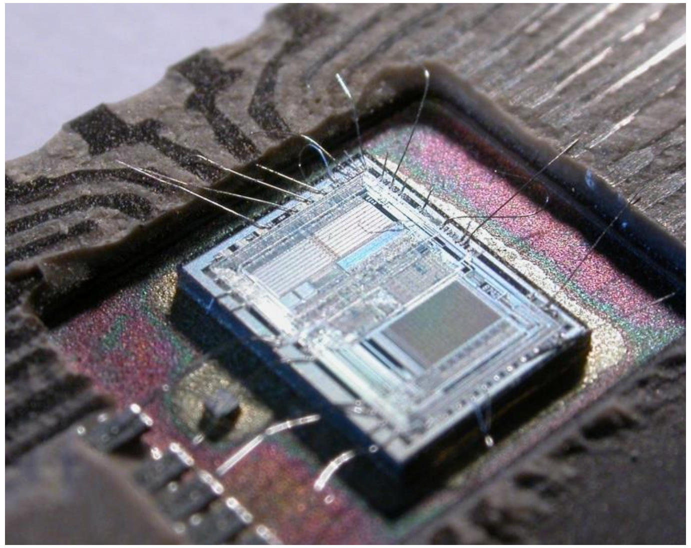


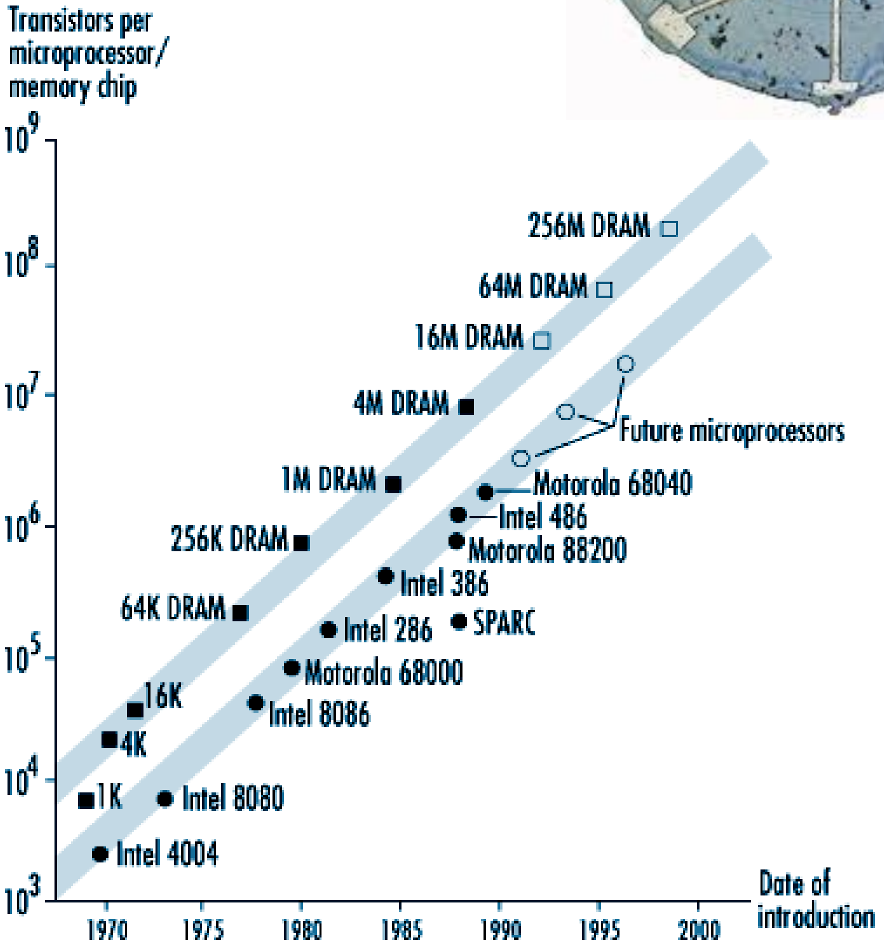


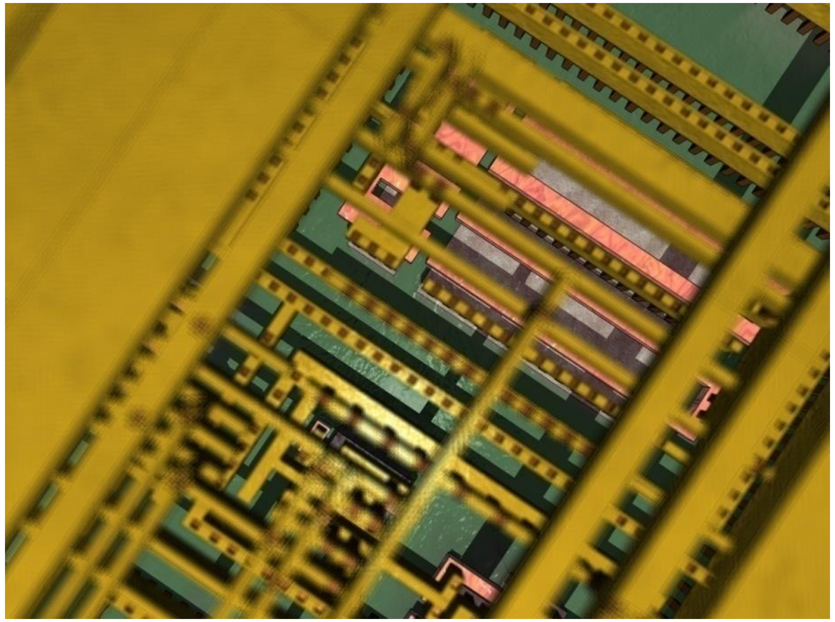


Integrated Circuits









"Moore's law" observes that, for computer hardware, the number of transistors in an integrated circuit doubles approximately every 2 years. The law is named after **Gordon E. Moore**, co-founder of **Intel Corporation**, who first described the trend in 1965 and stated it in 1975. His prediction has proven to be accurate, the law is used in SC industry to guide long-term planning and to set R&D targets.

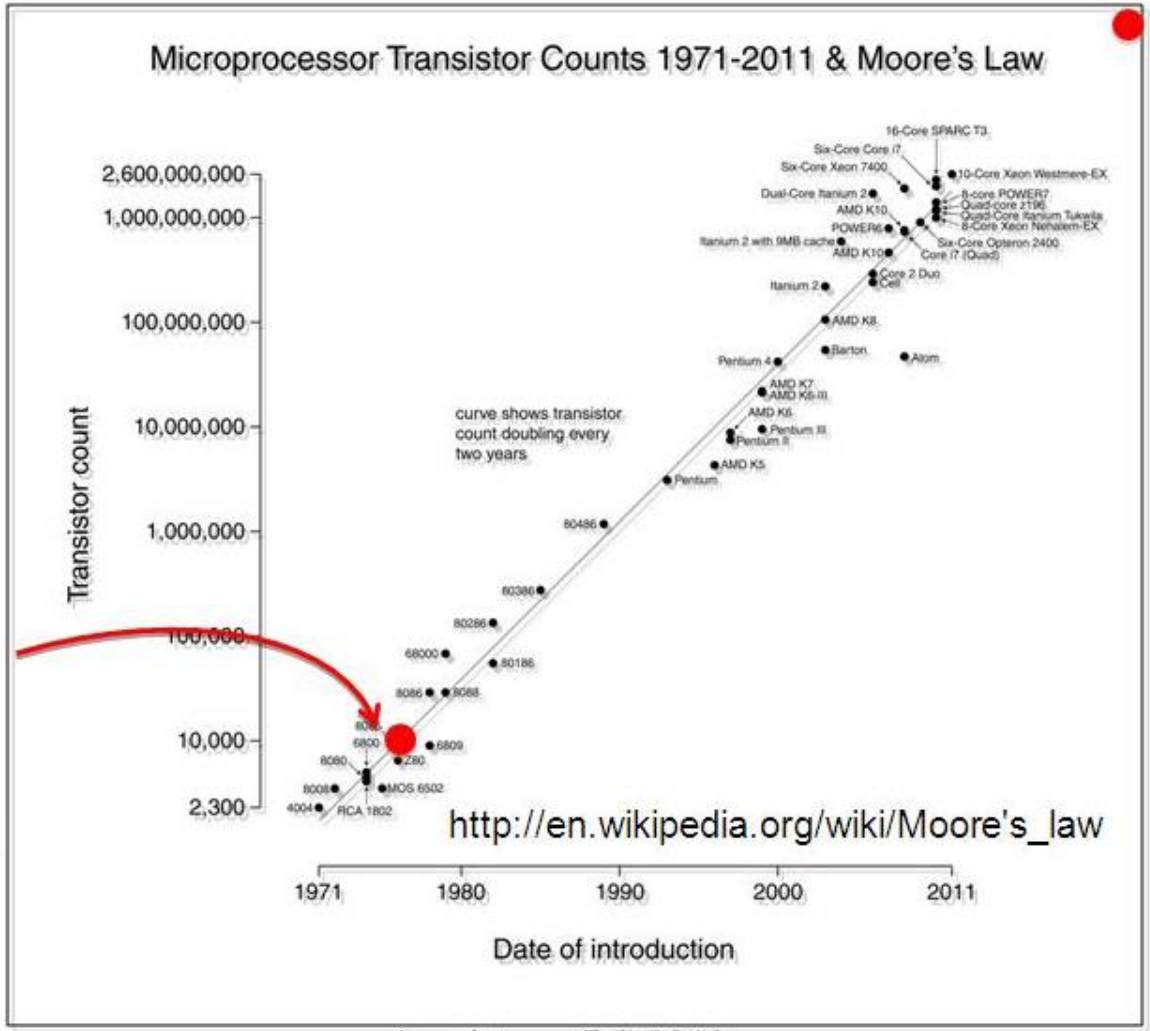
The capabilities of many digital electronic devices are linked to Moore's law: quality-adjusted microprocessor prices, memory capacity, sensors and number/size of pixels in digital cameras. All of these improve at roughly exponential rate. This improvement has dramatically enhanced the effect of digital electronics in global economy. Moore's law describes a driving force of technological and social change, productivity, and economic growth in the late 20^{th} / early 21^{st} centuries.

The period is often quoted as 18 months because of Intel executive **D. House**, who predicted that chip performance would double every 18 months (a combination of the effect of more transistors). Although this trend has continued for about 60 years, "Moore's law" has to be considered an observation, not a physical law, expected to continue until at least 2015/20. The 2010 update to the **International Technology Roadmap for Semiconductors** predicted that growth will slow in 2013, when transistor counts and densities will start to double “only” every 3 years.

Moore's Law

$L = 5000$ nm

Micro-electronics

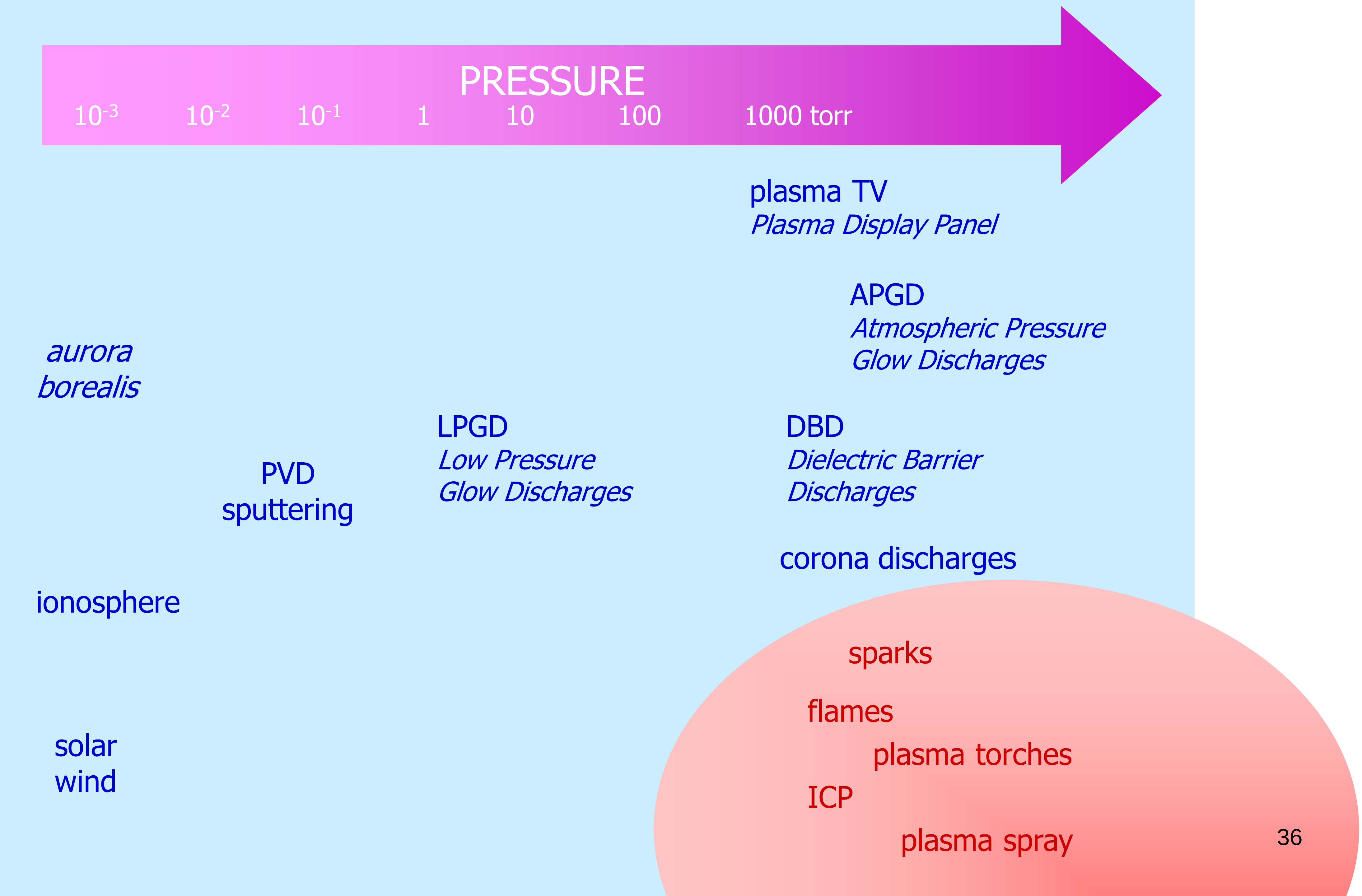


$L = 5$ nm

Nano-electronics

Computing efficiency
Computations per kilowatt-hour
1e+16
1e+15
1e+14
1e+13
1e+12
1e+11
1e+10
1e+9
1e+8
1e+7
1e+6
1e+5
1e+4
1e+3
1e+2
1e+1
1e+0
Computations per KWh (log scale)
SiCortex SC5832
DELL Dimension 2400
IBM PS/2 E &
SUN SS1000 x8
486/25 and 486/33 desktops
Dell OptiPlex GXI
Apple Macintosh
Compaq Deskpro 386/20e
IBM PC
IBM PC/XT
IBM PC/AT
Cray I
DEC PDP-11/20
Apple IIe
Commodore 64
SDS 920
Altair 8800
Univac III
R2 = 98.3%
Univac I
Univac II
EDVAC
ENIAC
1945
50
55
60
65
70
75
80
85
90
95
2000
05
10
Year
Source: Jonathan Koomey

1993 vs 2013


PRESSURE
10-3 10-2 10-1 1 10 100 1000 torr
plasma TV
Plasma Display Panel
APGD
Atmospheric Pressure
Glow Discharges
aurora
borealis
LPGD
Low Pressure
Glow Discharges
DBD
Dielectric Barrier
Discharges
PVD
sputtering
corona discharges
ionosphere
sparks
flames
plasma torches
ICP
plasma spray
solar
wind

APPLICATIONS OF COLD PLASMAS

OZONE PRODUCTION *(since XIX century)*

LIGHTS

MODIFICATION OF SURFACE PROPERTIES
etching, deposition of thin films, grafting

TV DISPLAYS

STERILIZATION

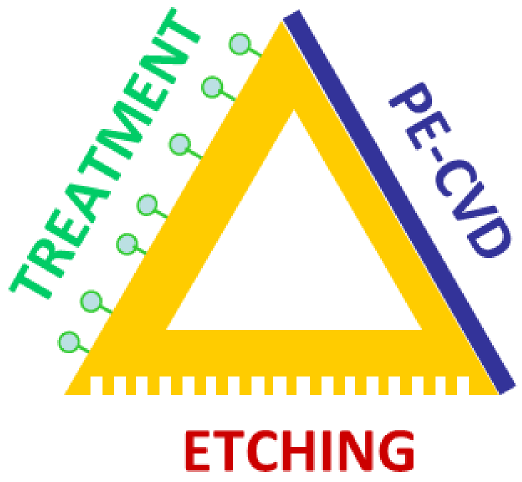
SYNTESIS OF NANOMATERIALS
Carbon nanotubes (CNTs), semiconductor (SC) nanocrystals

PLASMA MEDICINE (food, agriculture, ...)

PLASMA SCIENCE AND TECHNOLOGY

first applications

- LIGHT SOURCES
- OZONE PRODUCTION
- MICROELECTRONICS
- SEMICONDUCTORS
- SOLAR CELLS
- 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
- AGRICULTURE



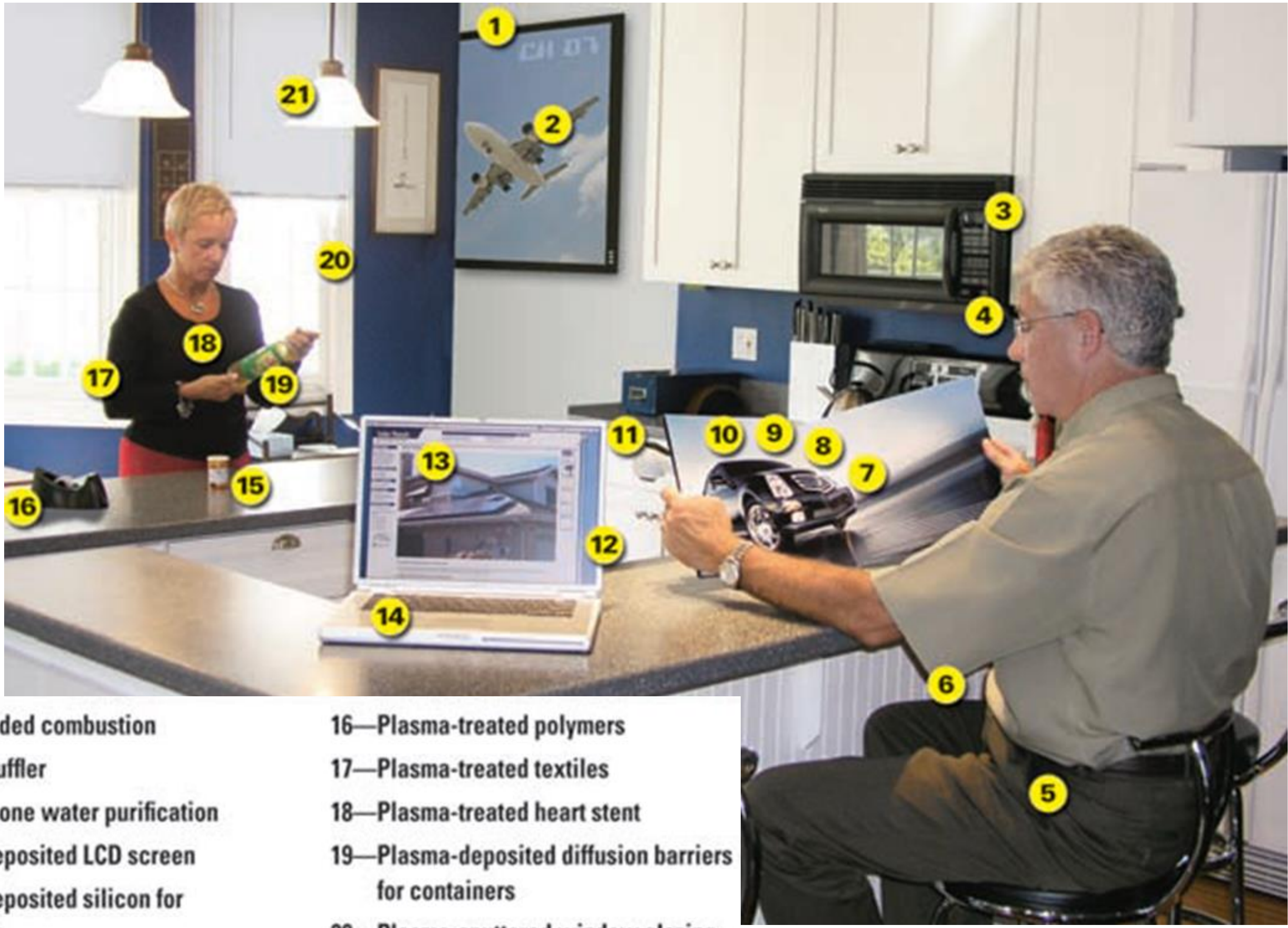
IN MATERIAL SCIENCE TECHNOLOGY NON EQUILIBRIUM «COLD» PLASMAS ALLOW

- **SURFACE ALTERATIONS OF PROPERTIES**
- **AT ROOM TEMPERATURE**
- **WITH NO BULK MODIFICATION**

Plasma Science Technology

Materials Science

Surface Engineering



Plasma Science: Advancing Knowledge in the National Interest
Plasma 2010 Committee, Plasma Science Committee,
National Research Council (2007), The National Academies Press

01—Plasma TV
02—Plasma-coated jet turbine blades
03—Plasma-manufactured LEDs in panel
04—Diamondlike plasma CVD eyeglass coating
05—Plasma ion-implanted artificial hip
06—Plasma laser-cut cloth
07—Plasma HID headlamps
08—Plasma-produced H_2 in fuel cell
09—Plasma-aided combustion
10—Plasma muffler
11—Plasma ozone water purification
12—Plasma-deposited LCD screen
13—Plasma-deposited silicon for solar cells
14—Plasma-processed microelectronics
15—Plasma-sterilization in pharmaceutical production
16—Plasma-treated polymers
17—Plasma-treated textiles
18—Plasma-treated heart stent
19—Plasma-deposited diffusion barriers for containers
20—Plasma-sputtered window glazing
21—Compact fluorescent plasma lamp

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IOP Publishing

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Topical Review

The 2017 Plasma Roadmap: Low temperature plasma science and technology

I Adamovich[1], S D Baalrud[2], A Bogaerts[3], P J Bruggeman[4], M Cappelli[5], V Colombo[6], U Czarnetzki[7], U Ebert[8,9], J G Eden[10], P Favia[11], D B Graves[12], S Hamaguchi[13], G Hieftje[14], M Hori[15], I D Kaganovich[16], U Kortshagen[4], M J Kushner[17], N J Mason[18], S Mazouffre[19], S Mededovic Thagard[20], H-R Metelmann[21], A Mizuno[22], E Moreau[23], A B Murphy[24], B A Niemira[25], G S Oehrlein[26], Z Lj Petrovic[27], L C Pitchford[28], Y-K Pu[29], S Rauf[30], O Sakai[31], S Samukawa[32], S Starikovskaia[33], J Tennyson[34], K Terashima[35], M M Turner[36], M C M van de Sanden[9,37] and A Vardelle[38]

J Phys D Appl Phys 50, 323001, 2017

CONSENSUS PAPER

Plasma Process Polym. 2019;**16**:e1800118.
https://doi.org/10.1002/ppap.201800118

PLASMA PROCESSES AND POLYMERS

The future for plasma science and technology

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Dirk Uhrlandt[1] | Milan Šimek[3] | Kostya (Ken) Ostrikov[4,5] |
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The application of gas discharge plasmas has assumed an important place in many manufacturing processes. Plasma methods contribute significantly to the economic prosperity of industrialized societies. However, plasma is mainly an enabling method and therefore its role remains often hidden. Hence the success of plasma technologies is described for different examples and commercial areas. From these examples and emerging applications, the potential of plasma technologies is discussed. Economic trends are anticipated together with research needs. The community of plasma scientists strongly believes that more exciting advances will continue to foster innovations and discoveries in the first decades of the 21st century, if research and education will be properly funded and sustained by public bodies and industrial investors.

LOW PRESSURE

ATMOSPHERIC PRESSURE

COLD PLASMAS

THERMAL PLASMAS

PLASMA

- partially ionized gas
- equal number of positive and negative charged particles
- uniform charge density
- thermodynamic equilibrium or non-equilibrium

GLOW DISCHARGE

- partially ionized gas
- not uniform charge density
- in some zones (walls, surfaces) the neutrality is not respected
- always in non-thermodynamic equilibrium