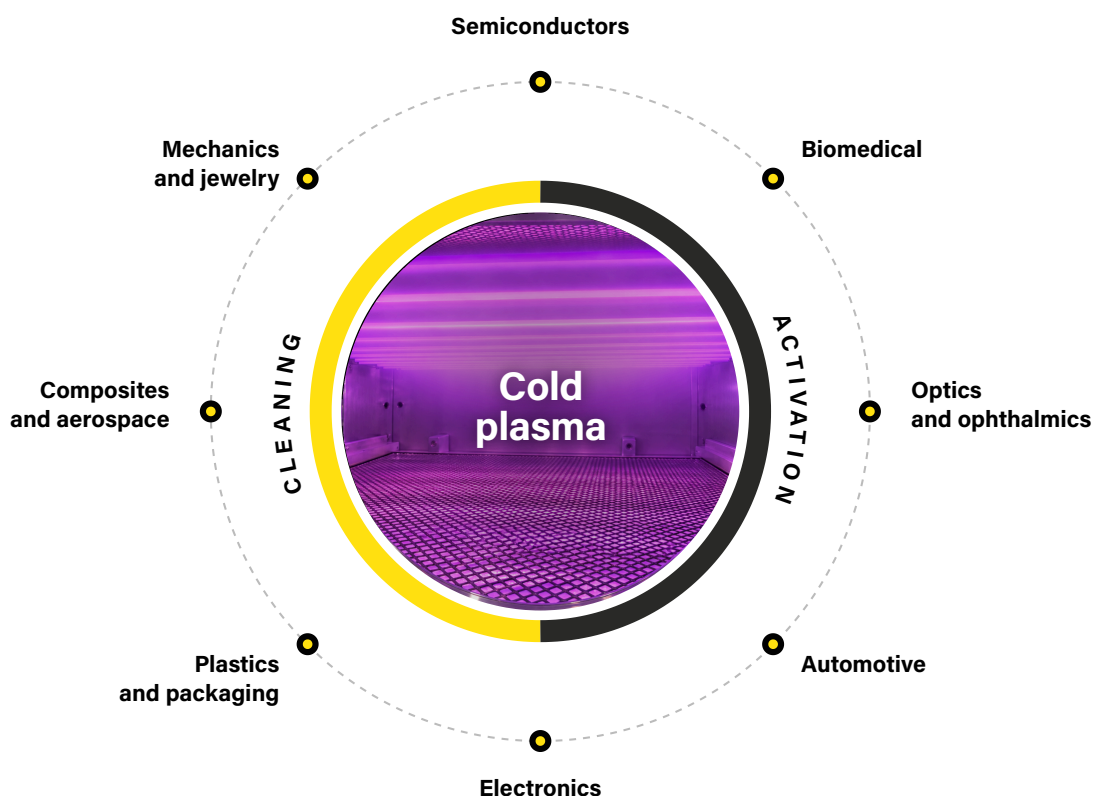


Cold plasma

Clean surfaces, ready surfaces.

Precision cleaning and surface activation: how it works, how it is measured, where it is used.



Cleaning. Plasma reacts chemically with organic contaminants, and the vacuum pump carries them away.

Activation. Plasma changes the chemistry of the outermost layers of the material, increasing its wettability and adhesion.

WHY READ THIS NOTE

Clean is not enough

Every surface carries its own history. A copper sheet keeps the thin film of oil from machining, a prosthesis the residues of its production process, a polypropylene bumper its stubbornly hydrophobic nature. To the naked eye they are clean. To an adhesive, a paint or a coating they are anything but.

This is where the most insidious defects begin: paint that lifts, bonds that fail, coatings that do not cover, colors that shift. The cause is almost always invisible: a few nanometers of contaminant, or a chemically "closed" surface that refuses to be wetted.

Cold plasma solves both problems in a single process, at low temperature and without solvents. It removes what cannot be seen and prepares the surface for whatever comes next.

This note explains what plasma is, how it works, how its effect is measured, and the results obtained in our laboratory on metals, polymers and medical devices.

Two effects, one technology.

Cleaning: plasma reacts chemically with organic contaminants, turning their carbon into gas, and the vacuum pump carries them away.

Activation: plasma changes the chemistry of the outermost layers of the material, creating polar groups that increase wettability and adhesion without altering its bulk properties.

THE INVISIBLE PROBLEM

Two enemies of adhesion

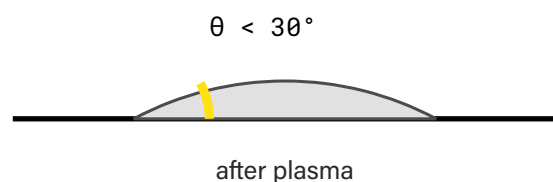
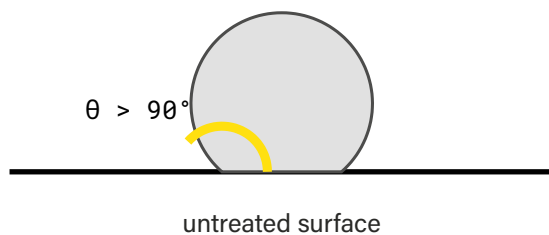
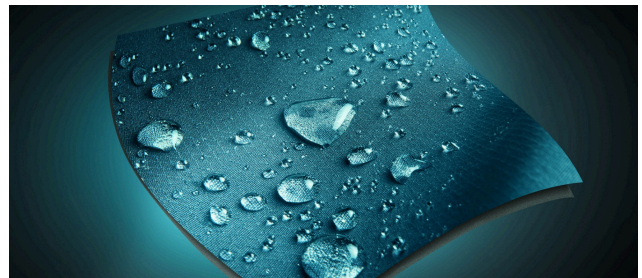
1. Contamination

Oils, greases, waxes, silicones, mold release agents, fluorinated residues, fingerprints, dust and fibers. Even after thorough industrial washing a thin layer remains, often only molecules thick. That is enough to change the wettability of a surface and compromise painting, bonding or thin-film deposition.

When even invisible impurities must be removed, we speak of ultra-cleaning.

2. Low surface energy

Many polymers, such as polypropylene, polyethylene, PTFE and silicone, naturally have low surface energy. In practice the surface "repels" liquids: a drop of water stays round, as on a lotus leaf, and in the same way adhesives, inks and paints do not spread or adhere.



The contact angle θ measures how far the drop spreads: the lower it is, the more wettable the surface.

Traditional solutions and their limits

Chemical primers, flame treatment, corona treatment, mechanical abrasion. They work, but at a price: solvents and volatile organic compounds, thermal risk for delicate materials, uneven results on complex geometries, possible damage to the substrate.

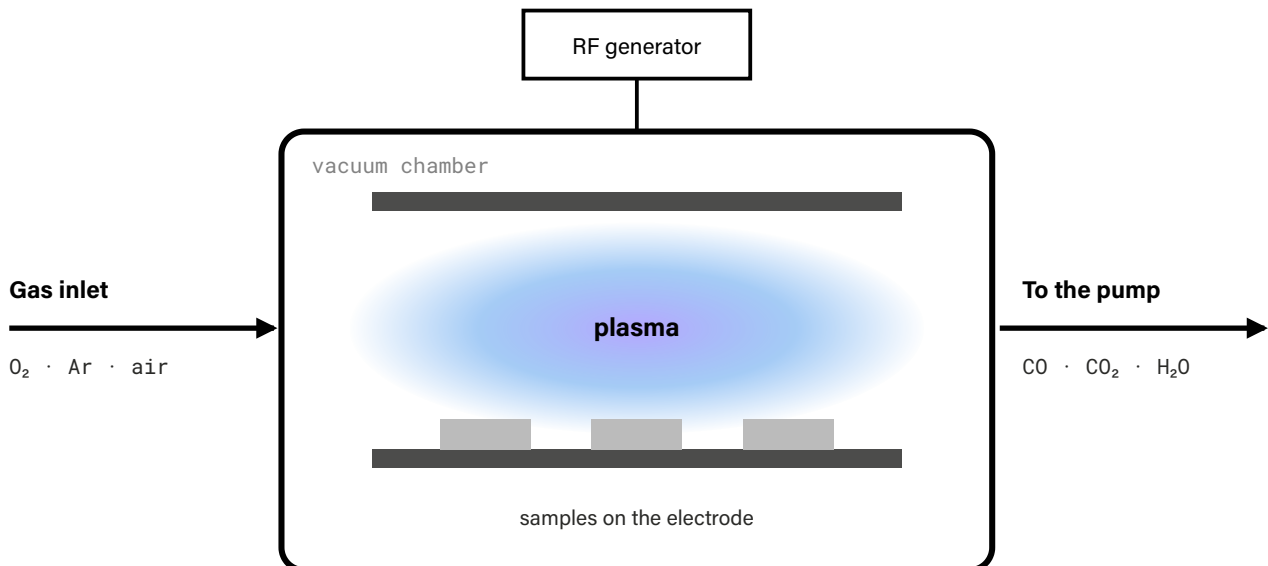
HOW IT WORKS

The fourth state of matter

A gas is fed into a low-pressure chamber and a sufficiently strong electric field is applied. The gas partially ionizes: alongside intact molecules appear positive ions, free electrons, radicals and ultraviolet photons. This is plasma, the fourth state of matter, the same as in the northern lights and neon signs.

"Cold" plasma works at close to room temperature. This makes it possible to treat heat-sensitive materials too, such as plastics, medical devices, bonded assemblies or electronic components. Ion bombardment of the sample does, however, transfer energy and therefore heat: the temperature stays low and does not alter the material.

Think of it as a reactive gas that acts on the outermost layers of the material, on the scale of nanometers, without altering its bulk properties.



Simplified cross-section of a plasma reactor: the gas enters the chamber, ionizes between the electrodes, and the volatile by-products are drawn off by the vacuum pump.

How it cleans

Four mechanisms act simultaneously during treatment:

Physical effect. Heavy argon ions strike the surface and dislodge contaminants, like hammering on an atomic scale.

UV radiation. The plasma emits ultraviolet light that breaks the chemical bonds of contaminants and makes them easier to remove.

Chemical effect. Ionized oxygen and its radicals react with the carbon in organic contaminants and convert it into CO and CO₂, volatile molecules that the vacuum pump draws off.

Low pressure and mild heating. These promote natural evaporation of residual substances.

The result: the contaminant is broken down, turned into gas and removed by the pumping system. Nothing is left on the surface.

Plasma does not replace industrial washing; it completes it. It is the final stage of a cleaning cycle, the one that takes a surface from "clean" to "ultra-clean".

How it activates

On polymers plasma does more: it changes the chemistry of the surface layers.

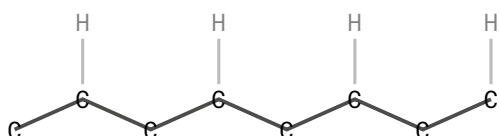
Bond scission. Ions and radicals break the C-C and C-H bonds at the surface.

Functionalization. Polar groups such as hydroxyl (-OH), carbonyl (C=O) and carboxyl (-COOH) attach to the open bonds and increase surface energy.

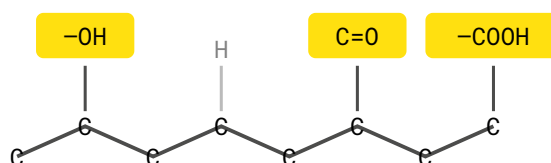
Micro- and nano-roughness. Roughness changes by only a few nanometers: a minor contribution compared with chemical functionalization and surface cleaning.

Surface cross-linking. A more cohesive, mechanically more stable outer layer forms.

BEFORE



AFTER PLASMA



Stylized polymer chain: after treatment, polar groups attach to the surface and increase surface energy.

THE PROCESS RECIPE

The right gas for every surface

Gas	Main effect	Typical use
Air / Oxygen (O ₂)	Chemical: oxidation of organic contaminants, maximum polar functionalization	Organic cleaning, activation of most polymers
Argon (Ar)	Physical: ion bombardment	Cleaning of metals and oxidation-sensitive surfaces
Argon/Oxygen	Combined physical and chemical	General cleaning, adjustable to the substrate
Nitrogen (N ₂)	Introduction of nitrogen groups	Specific biomedical applications
Hydrogen and H ₂ mixtures	Reducing	Removal of surface oxides from metals

The parameters that matter

Gas is only one of the variables. The result depends on the balance between:

Working pressure	0.1–1.0 mbar
Generator power	5–200 W (from 10 W with oxygen)
Frequency	kHz or 13.56 MHz (RF), depending on the system
Treatment time	from a few seconds to a few minutes
Gas flow and mixture	in sccm, depending on the substrate
Sample position	distance and orientation relative to the electrodes

Every combination of substrate and contaminant has its own recipe. Defining it is the work we do with each customer, on their own samples.

HOW IT IS MEASURED

Seeing the invisible

The effectiveness of a plasma treatment is verified with different methods, chosen according to the level of detail required.

Method	What it reveals	When it is used
Contact angle	Wettability: the more the drop spreads, the higher the surface energy	Quick check, in the lab and in production
Dyne inks	Surface energy in mN/m, with a pen test	Immediate in-line check
SEM + EDX	High-magnification image of the surface and its elemental composition	Cleanliness check, residue analysis
XPS (ESCA)	The chemistry of the first few nanometers: which functional groups are present	Process study and optimization
Adhesion tests	The real strength of the joint: pull-off, peel test, cross-cut	Final product validation

Contact angle in one line. On an untreated polymer a water drop often forms an angle above 90°. After plasma the angle can drop below 30°: the surface has become "welcoming".

Four tests, four surfaces

Real cases treated in our reactors, with process parameters and measured results.

01	A copper sheet contaminated with oil	p. 9
02	An orthopedic prosthesis	p. 10
03	Polypropylene learns to wet	p. 11
04	An LDPE cap that no longer comes off	p. 12



FROM OUR LABORATORY

Test 1. A copper sheet contaminated with oil

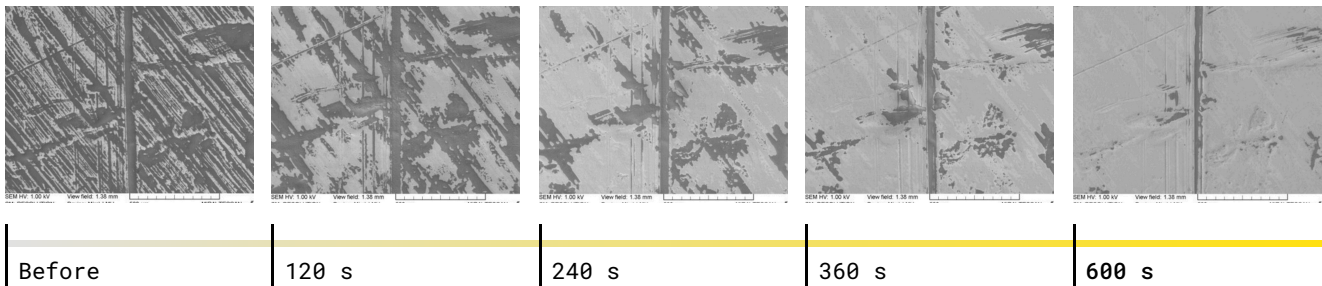
A copper sheet was polished and degreased with acetone, then deliberately contaminated with vacuum pump oil and wiped with a clean cloth until only a thin film remained: the typical situation of an "apparently clean" part.

The sample was then treated in successive cycles in the **Colibrì**.

TEST CONDITIONS

Reactor	Colibrì
Power	80 W
Frequency	50 kHz
Gas	Ar/O ₂ 50:50
Analysis	SEM, 200x

The dark spots are residual oil. They shrink with every cycle until they almost disappear.



Oil-contaminated copper sheet under the SEM at 200x, before and after successive plasma cycles. The images are representative of the whole surface.

600 s

of cumulative Ar/O₂ plasma cycles to take copper from "clean" to "ultra-clean"

FROM OUR LABORATORY

Test 2. An orthopedic prosthesis

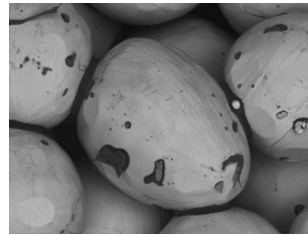
Components of an orthopedic prosthesis with organic contamination were treated in a **Tucano** reactor with an argon-rich plasma.

TEST CONDITIONS

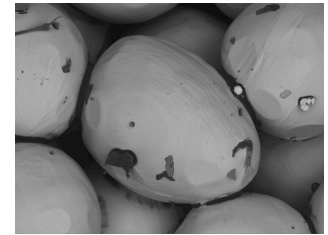
Reactor	Tucano
Power	80 W
Frequency	13.56 MHz
Gas	Ar/O ₂ 98:2
Time	120 s
Analysis	SEM (backscattered electrons) + EDX

In the SEM images the dark areas correspond to the organic component. After treatment the surface appears lighter and more uniform.

BEFORE

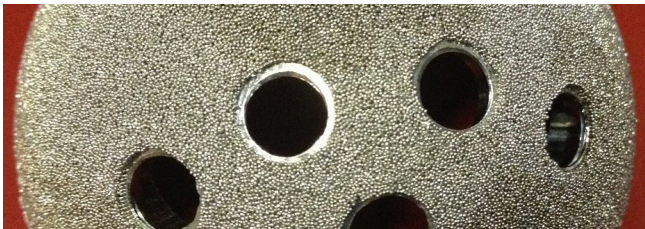


AFTER 120 s

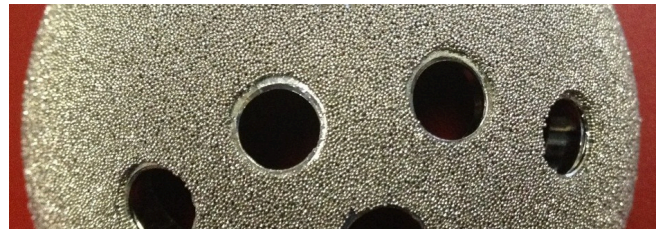


Top, sample A; bottom, sample B: before treatment and after 120 s of plasma.

BEFORE

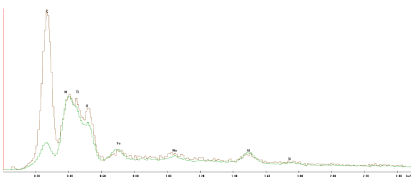


AFTER TREATMENT



The prosthesis acetabular cup before and after plasma treatment.

EDX analysis confirms what the images suggest: the carbon peak, the signature of organic contaminants, drops sharply. The substrate peaks (titanium, nitrogen, aluminum) remain unchanged: plasma removed the dirt without affecting the material. Longer times or higher power would have reduced residual carbon further: the recipe is tuned to the required cleanliness level.



EDX spectrum of the prosthesis before (dark curve) and after treatment (light curve). The carbon peak at about 0.28 keV drops markedly.

FROM OUR LABORATORY

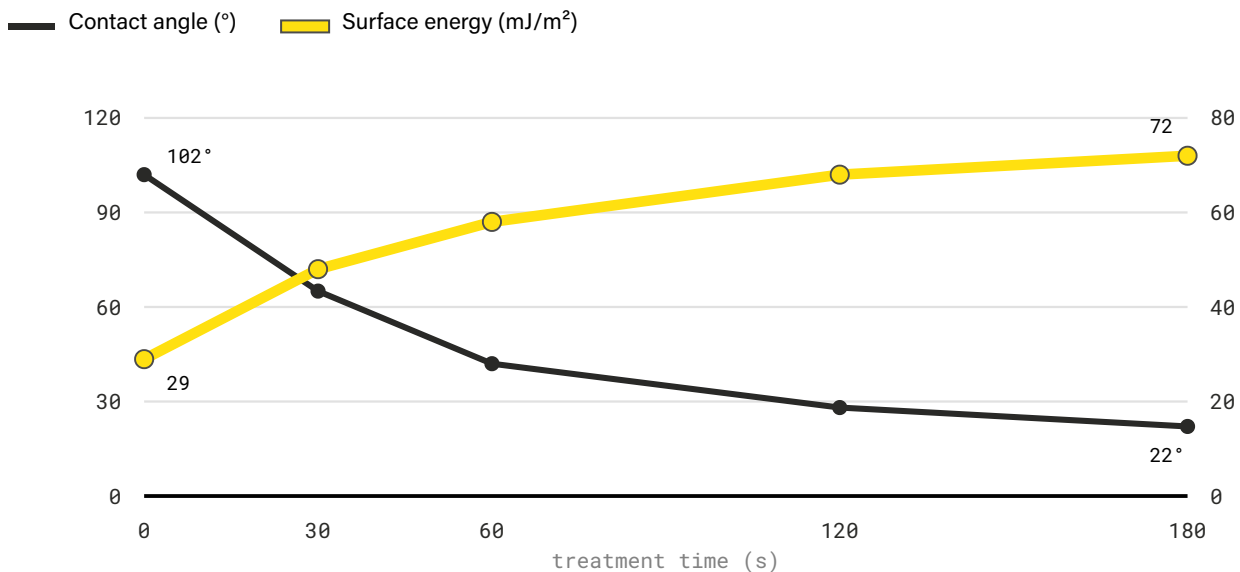
Test 3. Polypropylene learns to wet

Polypropylene samples treated in air, with increasing times.

Treatment time	Contact angle (H ₂ O)	Surface energy
0 s (untreated)	102° ± 2°	29 mJ/m ²
30 s	65° ± 3°	48 mJ/m ²
60 s	42° ± 2°	58 mJ/m ²
120 s	28° ± 2°	68 mJ/m ²
180 s	22° ± 3°	72 mJ/m ²

TEST CONDITIONS

Gas	Air
Power	100 W
Pressure	0.3 mbar
Time	0-180 s



Polypropylene treated in air: the contact angle falls while surface energy rises with treatment time.

from 102° to 22°

contact angle in three minutes

A REAL CASE

Test 4. An LDPE cap that no longer comes off

A customer was bonding a low-density polyethylene (LDPE) cap onto a glass-epoxy (FR4) circuit board, using the UV adhesive **Loxeal UV30-12**. A large number of parts failed the tensile test even before going into storage.

Today the caps are first treated in a **Tucano** reactor, then fed into the automatic bonding machine, where the adhesive is dispensed, the cap placed on the board and the adhesive cured under UV light.

TEST CONDITIONS

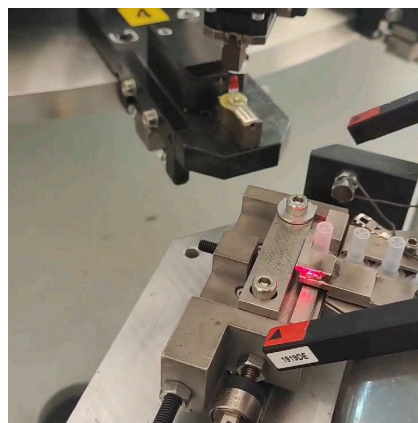
Reactor	Tucano
Gas	Air
Flow	40 sccm
Power	100 W
Time	300 s
DC bias	160 V
Pressure	0.99 mbar
Batch	250 parts



The LDPE cap and the glass-epoxy board to be bonded.



1 The LDPE caps, on their tray, go into the Tucano chamber.



2 Automatic bonding onto the glass-epoxy board and UV curing.



3 Pull test: not even pliers can detach the cap.

BEFORE PLASMA

0.8 kg

tensile strength. Not all parts passed the test before storage; others lost their bond after a few days.

AFTER PLASMA

The cap breaks first

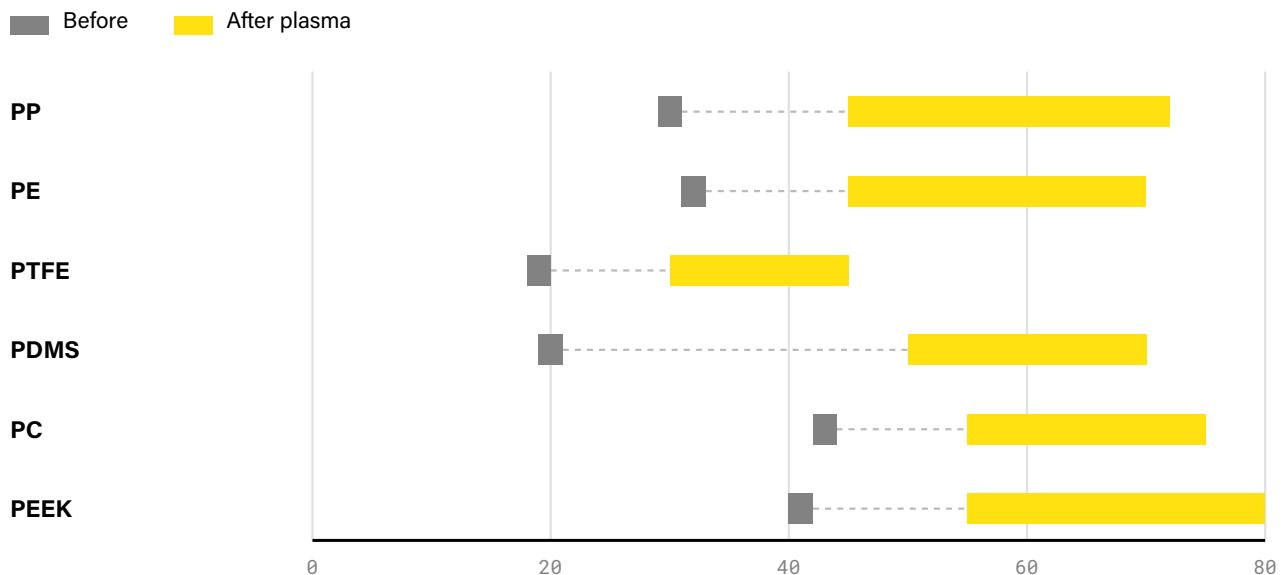
The LDPE cap fails before the bond does.

MATERIALS

How much surface energy changes

Typical values before and after plasma treatment.

Polymer	Before (mJ/m ²)	After (mJ/m ²)	Typical applications
PP, polypropylene	29–31	45–72	Automotive, packaging
PE, polyethylene	31–33	45–70	Containers, films
PTFE, polytetrafluoroethylene	18–20	30–45	Medical, electronics
PDMS, silicone	19–21	50–70	Microfluidics, medical
PC, polycarbonate	42–44	55–75	Optics, automotive
PEEK	40–42	55–80	Aerospace, medical



Typical surface energy ranges, in mJ/m², before and after plasma treatment.

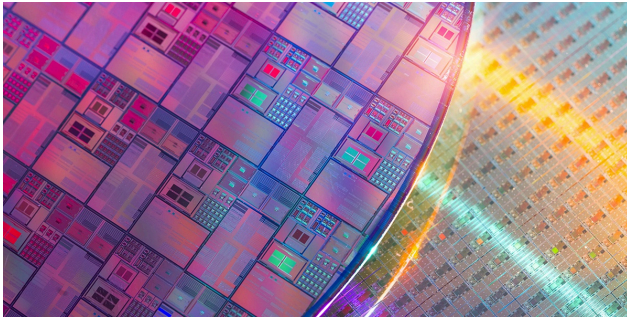
up to +250%

increase in surface energy (PDMS)

Plasma also cleans metals, glass and ceramics: the technique suits almost any material and assemblies made of different materials.

WHERE IT IS USED

One process, many industries



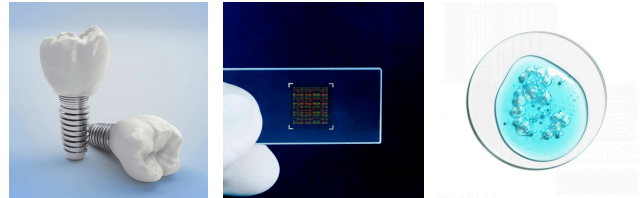
Semiconductors

- Photoresist removal (ashing) and residue removal (descumming)
- Removal of organic polymers
- Cleaning before wire bonding



Optics and ophthalmics

- Cleaning and pretreatment before anti-reflective and anti-scratch coatings
- Wettability of contact and intraocular lenses



Biomedical

- Bonding dissimilar materials, including heat-sensitive ones: needles on syringes, catheters
- Silicone catheters and tubing: adhesion of antimicrobial coatings
- Dental implants, prostheses and implantable PEEK: better wettability, improved osseointegration
- Filters for biological fluids: cleaning and wettability
- PDMS microfluidics: permanent bonding without adhesives
- Final cleaning of vials, beakers and slides



Automotive

- PP/TPO bumpers: primer-free painting
- EPDM seals: stronger, longer-lasting bonds
- Interior components: multi-material bonding without aggressive adhesives



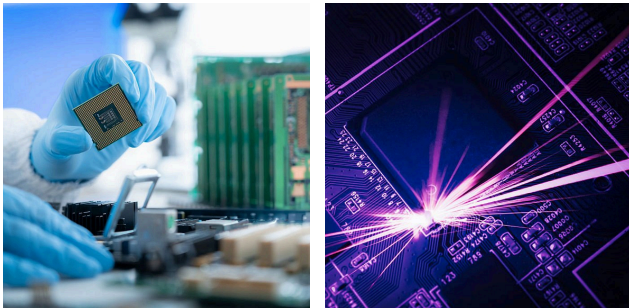
Plastics and packaging industry

- Removal of release agents and residues after molding
- Activation before printing, painting and labeling, without primer
- Multilayer lamination of dissimilar films, ink anchoring on barrier films



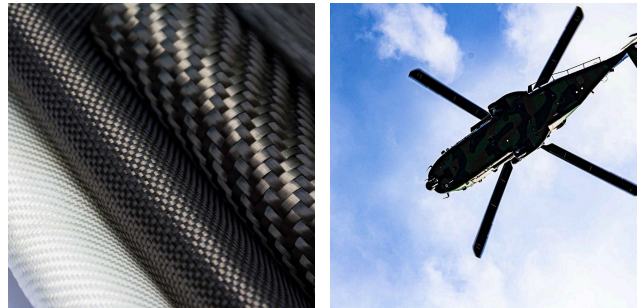
Precision mechanics and jewelry

- Cleaning metals, glass and ceramics before bonding, painting and PVD coating
- Bonding gemstones onto precious metals



Electronics and optoelectronics

- LED encapsulation: adhesion of epoxy resins to plastic
- Flexible circuits: adhesion of copper to polyimide
- Touch displays: optical bonding of protective films



Composites and aerospace

- Carbon fibers: stronger fiber-matrix interface
- Surface preparation for structural bonding

WHY PLASMA

Compared with traditional methods

Compared with	Plasma offers
Chemical primers	No solvents or volatile organic compounds. Seconds of treatment instead of hours of drying. No risk of contaminating the substrate. Lower cost per part.
Corona treatment	Uniform results even on complex 3D geometries. Longer-lasting activation. Conductive materials can be treated. Finer process control.
Flame treatment	No thermal risk. Suitable for heat-sensitive materials. Repeatable, controllable process. More selective and stable activation.
Washing and chemical baths	No residues: by-products are gases drawn off by the pump. No liquid waste to dispose of. Lower costs for consumables, safety equipment and training.

Clean for operators too. Plasma does not expose operators to hazardous substances and produces no wastewater. An environmental advantage that is also an economic one.

GOOD TO KNOW

Activation has a shelf life

Activation does not last forever. Over time the surface tends to return to its initial state, a phenomenon known as aging or hydrophobic recovery: polymer chains rearrange and polar groups migrate inward.

The rate depends on:

type of polymer: PP and PE age faster than PC and PEEK;

storage conditions: temperature, humidity, airborne contaminants;

treatment intensity: more intense treatments tend to be more stable.

Our recommendations

1. Bond, paint or coat within 24–48 hours of treatment.
2. Store parts in a clean, low-humidity environment.
3. If needed, a short re-treatment restores the surface to its active state.

Glossary

Contact angle: the angle a liquid drop forms with the surface; the lower it is, the more wettable the surface.

Ashing / descumming: complete removal of photoresist / of its residues in microfabrication processes.

Wettability: the ability of a liquid to spread over a surface.

EDX (o EDS): X-ray microanalysis coupled with SEM; identifies the chemical elements present.

Surface energy: a measure of how "willing" a surface is to bond with a liquid; expressed in mJ/m^2 .

mbar: unit of pressure; atmospheric pressure is about 1,013 mbar.

sccm: standard cubic centimeters per minute, a unit of gas flow.

SEM: scanning electron microscope.

XPS (o ESCA): X-ray photoelectron spectroscopy; analyzes the chemistry of the first few nanometers of a surface.

OUR SOLUTIONS

Designed and built in Binasco

G. Gambetti Kenologia designs and manufactures plasma systems in Italy for research and industry, from the lab bench to production.



Colibrì

MULTIPURPOSE PLASMA SYSTEM

The essential benchtop plasma for cleaning, activation and surface modification. Cylindrical aluminum chamber with Dark-Shield electrode, microcontroller control with display and keypad. Ideal for R&D and small-batch production.

Power	200 W
Frequency	50 kHz (LF)
Chamber	2 liters, Ø102 × L256 mm
Gas	1 line, stainless steel micro-regulator
Recipes	9, editable
Weight	16 kg



Tucano

LOW PRESSURE TABLE TOP PLASMA

Benchtop reactor in capacitive configuration, RF powered. Seamless aluminum chamber, Dark-Shield parallel-plate electrodes, PLC with color touch screen and bias voltage readout.

RF power	5-200 W, 1 W steps
Frequency	13.56 MHz
Chamber	5.9 liters, Ø153 × L324 mm
Pressure	0.1-1 mbar
Gas	2 MFC lines, 2-50 sccm
Recipes	10, 2-step



Falcon RIE+

ETCHING PLASMA · RIE & CLEANING

Two machines in one: plasma cleaning with a biased upper electrode and Reactive Ion Etching with a biased lower electrode, selectable by recipe with no mechanical changes. For microfabrication, 2D materials and cutting-edge research.

Mode	RIE + Cleaning
RF power	200 W, 13.56 MHz, 1 W steps
Chamber	≥ 14 liters
Wafer	5-8"
Gas	O ₂ , Ar, N ₂ , SF ₆ , CF ₄ , forming gas
Vacuum	from atmosphere to 10 ⁻⁶ mbar

SCIENTIFIC LITERATURE

Research with our reactors

A selection of papers published between 2017 and 2025 in which universities and research centers used Gambetti Kenologia reactors. The system used is shown next to each title.

Adhesion and bonding

C. Mandolino et al., "Polypropylene surface modification by low pressure plasma to increase adhesive bonding: effect of process parameters", *Surface and Coatings Technology*, 2019. Tucano

C. Mandolino et al., "Functionalization of neutral polypropylene by using low pressure plasma treatment: effects on surface characteristics and adhesion properties", *Polymers*, 2019. Gambetti Kenologia

C. Mandolino et al., "Influence of cold plasma treatment parameters on the mechanical properties of polyamide homogeneous bonded joints", *Surface and Coatings Technology*, 2017. Gambetti Kenologia

Coatings and functional surfaces

S. Ferraris et al., "Coupling of keratin with titanium: a physico-chemical characterization of functionalized or coated surfaces", *Surface and Coatings Technology*, 2020. Tucano

R. Sesia et al., "Exploitation of tannic acid as additive for the adhesion enhancement of UV-curable bio-based coating", *Progress in Organic Coatings*, 2024. Tucano

R. Sesia et al., "Natural tannin layers for the corrosion protection of steel in contact with water-based media", *Coatings*, 2024. Tucano

V. Marturano et al., "Light-responsive nanocapsule-coated polymer films for antimicrobial active packaging", *Polymers*, 2019. Tucano

Catalysis and environment

L. Pastor-Pérez et al., "Effect of cold Ar plasma treatment on the catalytic performance of Pt/CeO₂ in water-gas shift reaction (WGS)", *Applied Catalysis B: Environmental*, 2018. Tucano

M. J. García-Fernández et al., "Proposed mechanisms for the removal of nitrate from water by platinum catalysts supported on polyaniline and polypyrrole", *Applied Catalysis B: Environmental*, 2018. Tucano

J. J. Villora-Picó et al., "Conducting polymer-TiO₂ hybrid materials: application in the removal of nitrates from water", *Langmuir*, 2019. Tucano

Biomedical and life sciences

V. Benedetti et al., "Engineered kidney tubules for modeling patient-specific diseases and drug discovery", *EBioMedicine*, 2018. Tucano

I. Tonazzini et al., "Neuregulin 1 functionalization of organic fibers for Schwann cell guidance", *Nanotechnology*, 2017. Tucano

A. R. Salgarella et al., "Optimal ultrasound exposure conditions for maximizing C2C12 muscle cell proliferation and differentiation", *Ultrasound in Medicine & Biology*, 2017. Colibrì

S. Jadavi et al., "Fluorescence labeling methods influence the aggregation process of α -syn in vitro differently", *Nanoscale*, 2023. Tucano

Microfluidics and sensors

F. Lopresti et al., "Green and integrated wearable electrochemical sensor for chloride detection in sweat", *Sensors*, 2022. Tucano

D. Pezzuoli et al., "Increased flexibility in lab-on-chip design with a polymer patchwork approach", *Nanomaterials*, 2019. Tucano

D. Pezzuoli et al., "Nanofluidic-based accumulation of antigens for miniaturized immunoassay", *Sensors*, 2020. Tucano

L. D. Garma et al., "Inkjet-printed PEDOT:PSS multi-electrode arrays for low-cost in vitro electrophysiology", *Lab on a Chip*, 2019. Colibrì

M. C. Ceccarelli et al., "Real-time monitoring of a 3D blood-brain barrier model maturation and integrity with a sensorized microfluidic device", *Lab on a Chip*, 2024. Colibrì

Robotics and advanced materials

I. Fiorello et al., "Climbing plant-inspired micropatterned devices for reversible attachment", *Advanced Functional Materials*, 2020. Colibrì

M. Martusciello et al., "Stretchable distributed Bragg reflectors as strain-responsive mechanochromic sensors", *ACS Applied Materials & Interfaces*, 2024. Colibrì

M. Meiser et al., "Tribological studies of carbon fiber reinforced zirconium diboride based UHTCMC-material paired with carbon disk material", *Journal of the European Ceramic Society*, 2025. Colibrì

In short

Effective.

Surface energy up to +250%, bonds stronger than the material itself.

Versatile.

Metals, glass, ceramics, almost all polymers, complex assemblies.

Clean.

No solvents, no residues, no wastewater.

Economical.

Low operating costs, cycles of a few minutes.

Repeatable.

Controlled parameters, uniform results even on 3D geometries.

Do you have an adhesion or cleaning problem?

Send us your samples: together we will define the process recipe and verify the result.

Further reading

E. M. Liston, L. Martinu, M. R. Wertheimer, "Plasma surface modification of polymers for improved adhesion: a critical review", *Journal of Adhesion Science and Technology*, 7 (1993) 1091-1127.

C.-M. Chan, T.-M. Ko, H. Hiraoka, "Polymer surface modification by plasmas and photons", *Surface Science Reports*, 24 (1996) 1-54.

S. Bhattacharya, A. Datta, J. M. Berg, S. Gangopadhyay, "Studies on surface wettability of poly(dimethyl) siloxane (PDMS) and glass under oxygen-plasma treatment and correlation with bond strength", *Journal of Microelectromechanical Systems*, 14 (2005) 590-597.

D. K. Owens, R. C. Wendt, "Estimation of the surface free energy of polymers", *Journal of Applied Polymer Science*, 13 (1969) 1741-1747.

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