New Jersey – Plasma State

Plasma State

A HOME FOR THE MIND, THE HEART AND THE SPIRIT
DEPARTMENT OF PHYSICS
LABORATORY OF ELECTROPHYSICS & ATMOSPHERIC PLASMAS (LEAP)
Irving Langmuir was one of the first scientists to work on plasmas and the first to refer to this 4th state of matter as **plasmas**, because their similarity to blood plasma.
Plasma Lighting Technology

Birthplace of the Fluorescent Light Bulb: Edison (Menlo Park) / West Orange, NJ
Plasma Enhanced Technology

A small section of a memory chip.

Straight holes like these can be etched with plasmas.

Birthplace of solid-state microelectronics:
Bell Laboratories, Murray Hill, NJ
The U.S. Department of Energy’s Princeton Plasma Physics Laboratory (PPPL) is a collaborative national center for plasma and fusion science. Its primary mission is to develop the scientific understanding and the key innovations which will lead to an attractive fusion energy source. Associated missions include conducting world-class research along the broad frontier of plasma science and technology, and providing the highest quality of scientific education.

National Spherical Torus Experiment (NSTX)
An Atmospheric Pressure Plasma Generated with a Capillary-Plasma-Electrode Discharge
What is a Plasma?

The *Plasma* state is ‘The Fourth State of Matter’ (99%)  

A *Plasma* is a collection of neutrals, ions, and electrons characterized by a *collective behavior*.

Two Types of plasmas

High-temperature plasmas or Hot (Thermal) plasmas

\[ T_i \approx T_e \geq 10^7 \text{ K} \]

e.g., fusion plasmas

\[ T_i \approx T_e \approx T_g \leq 2 \times 10^4 \text{ K} \]

e.g. arc plasma at normal pressure

Low-temperature plasmas or Cold (Non-thermal Plasmas)

\[ T_i \approx T_g \approx 300 \text{ K} \]

\[ T_i \ll T_e \leq 10^5 \text{ K} \]

e.g. low-pressure glow discharge

high-pressure cold plasma
Plasmas in Nature

The Sun

Aurora

The Comet

Supernova

Lightning
Plasmas are everywhere!!!

- Sun
- Aurora Borealis (Northern Lights)
- Lightning
- Fluorescent Lamps
- Plasma Display Televisions
Low-Temperature ("Cold") Plasmas
[Non-equilibrium, Non-Thermal]

$T_e >> T_i, T_n$ with $T_i \approx T_n$

- **High “electron temperature”** (10,000 – 100,000 K)
  - $T_e$ from 0.5 eV to 10 eV
  - Often highly non-Maxwellian EEDF; “bulk” and “beam” electrons

- **Low gas temperature** (350 – 2,500 K)

- **“High-temperature chemistry”** at low ambient temperatures
  - Electron-driven ionization and dissociation (in molecular plasmas) create reactive radicals
  - Electron interactions (in molecular plasmas) create a vibrational non-equilibrium
Plasmas in the kitchen. Plasmas and the technologies they enable are pervasive in our everyday life. Each one of us touches or is touched by plasma-enabled technologies every day.

Jean (Félix) Picard (July 21, 1620 –July 12, 1682) was a French astronomer and Catholic priest. The first person to accurately measure the circumference of the earth. Around 1670!

Observed in his barometer tube glowing light that were produced when mercury atoms rubbed against the barometer’s glass wall. i.e. first documented observation a low temperature plasma.
Vacuum glows and discharges

Irving Langmuir
How do we make plasmas?

Supply Energy!!!
e.g. Heat transfer, radiation, electric power…

For many plasma applications, an Electric Field is applied to a gaseous environment

Plasma or Gaseous Discharge

- Molecules
- Excited molecules
- Ions
- Electrons
PPPL’s Remote Glow Discharge Experiment (RGDX)

https://www.pppl.gov/RGDX
DC Glow Plasma

DC

Cathode

A - neutrals

A⁺ - ions

e⁻ - electrons

Anode

\( \overrightarrow{E} \)

\[ \text{Accelerating force} \]

\[ \text{Reaction path} \]

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DEPARTMENT OF PHYSICS
Low-Pressure Glow Discharge Plasmas
Low-Temperature Plasma enabled Microchip Fabrication
Low-Pressure, Low-Temperature Plasma Processing

Plasma processing of silicon for semiconductor manufacturing.

Plasma processing to harden or coat materials.
Lawmakers Propose Multibillion Dollar Semiconductor R&D Push

A bipartisan group of lawmakers recently introduced legislation that would channel billions of dollars into manufacturing incentives and new R&D streams to bolster U.S. semiconductor manufacturing in the face of increasing international competition.
Low-Temperature Plasmas

Electron temperatures ($T_e$) and gas temperatures ($T_g$) versus pressure for a glow discharge.

Low temperature plasmas will limit the gas (heavy particles i.e. ions, atoms, molecules, dust, etc.) temperature to room temperature.
Plasmas are easier to be generated at low pressures

Low pressure plasmas
(1 mTorr ~ a few Torr)

- are well understood
- are used extensively nowadays (e.g. in semiconductor industry for computer chips manufacturing)

However, to generate low pressure plasmas:

- vacuum chambers
- expensive vacuum pumps
- pressure monitoring and pressure control devices

Generate Plasmas at Atmospheric Pressure!!
What happens at air pressure?

- No vacuum is involved
- Difficult to generate and sustain
- Run into some challenges such as glow to arc transition – Non controllable

Arc Discharge: thermal plasma
- It’s hot and detrimental
- Gas temperature can reach as high as $2 \times 10^4 \text{ K}$
- Low voltage drop at cathode
- High cathode current density
High Pressure Microplasmas

Stabilization of high-pressure plasmas: “pd scaling”: “p” ↑, so “d” ↓ to keep breakdown voltage low and minimize instabilities after breakdown -

Microplasmas
Dimension: a few millimeter down to and below 100 μm

Paschen Breakdown Curve

Human Hair: 60 – 100 μm
Micro-confinement: Gas heating occurs in the plasma volume, and the energy is carried away by thermal diffusion/convection to the outside. If the plasma has a small volume and a relatively large surface, gas heating is limited.

Dielectric Barrier Discharges: These plasmas are typically created between metal plates, which are covered by a thin layer of dielectric or highly resistive material. The dielectric layer plays an important role in suppressing the current: the cathode/anode layer is charged by incoming positive ions/electrons, which reduces the electric field and hinders charge transport towards the electrode. DBD also has a large surface-to-volume ratio, which promotes diffusion losses and maintains a low gas temperature.

Transient (pulsed) plasmas: In atmospheric plasmas, for efficient gas heating at least 100-1000 collisions are necessary. Thus, if the plasma duration is shorter than $10^{-6} - 10^{-5}$ s, gas heating is limited. Of course, for practical purposes such plasma has to be operated in a repetitive mode, e.g., in trains of microsecond pulses with millisecond intervals.
Advantages of Microplasmas

- Low-cost of implementation
- System flexibility
- Atmospheric pressure operation
- High densities and high reaction rates
- Fast and efficient processes
- Easy to generate and sustain for a variety of gas mixtures
- Glow-like and diffuse
- Non-equilibrium \((T_e > T_g)\) to thermal
- Unique chemistry

... a new realm of plasma science
What can we do with it?

Material Synthesis

Plasma display

Surface Treatment

Lighting

Material processing

Ozone generation for water cleaning

**Bio-application**

**Dental application**

and Many more…
Corona Discharges

- Point Source
- Wire in Cylinder
- Wire Array Between Parallel Plates

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Electrophotography is used in most electronic printers including laser printers.

The electrophotography process generally consists of six steps:

- Charging
- Exposure
- Development
- Transfer
- Fusing
- Cleaning

Electrostatic Precipitator

ESP is a physical process in which particles suspended in a gas flow are ionized in a corona discharge, separated from the gas stream under the influence of an electric field and transported to collecting plates, from which they can be removed periodically and mechanically (dry ESP) or continuously by washing (wet ESP).
Dielectric Barrier Discharge (DBD)

- High Voltage AC Generator
- High Voltage Electrode
- Dielectric Barrier
- Microplasmas
- Ground Electrode
Role of the Dielectric (Insulator)

The dielectric is the key for the proper functioning of the discharge.

Serves two functions:

1. Limits the amount of charge transported by a single microplasma
2. Distributes the microplasmas over the entire electrode surface area
Principals of DBD Microplasmas

\[ \begin{align*}
\{ & C_G \\
\{ & C_D \}
\end{align*} \quad \begin{align*}
\{ & C_G \\
\{ & C_D \}
\end{align*} \]
Principals of DBD Microplasmas

Four Different Gap Widths

Dielectric Barrier Discharge

Ozone Generator

Dielectric Barrier Discharge

$3 \text{O}_2 \leftrightarrow 2 \text{O}_3$

O$_2$ O$_2$ O$_2$ O$^-$ e$^-$ O$_2$ O$^-$ O$_2$ O$_3$ O$_3$ O$_2$ O$_2$ O$_3$ O$_3$ O$_2$ O$_2$

Heat Heat

O$_3$ + O$_2$

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Properties of Ozone ($O_3$)

- Tri-atomic form of oxygen.
- Most powerful commercial oxidizing agent
- Unstable - must be generated and used onsite
- Limited solubility in water, but more so than oxygen
- Leaves a dissolved residual which ultimately converts back to oxygen
Ozonia Advanced Technology
Ozone Generator
Ozone Water Treatment

- Easy to use
- Low energy usage
- Mass transfer efficiencies to > 90%

Bubble Diffusion
Reference (Traditional) Arrangement

![Diagram of Reference (Traditional) Arrangement](image)
Optimized Arrangement

Inlet Outlet

Gas flow direction
Intelligent Gap System (IGS)

Molecular Oxygen (O$_2$)  Ozone (O$_3$)

Molecular Oxygen (O$_2$)  Ozone (O$_3$)

Capillary Dielectric Barrier Discharge
3-D Expansion

Plasma Capillary

Electrode

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Cylindrical Arrangement
Pulsed DC Homogeneous DBD

The Dielectric Barrier Discharge (DBD) cell.

A typical plasma in pure nitrogen environment.

Side view of the DBD cell experiment with the fast high voltage transistor switch connected to the bottom electrode.
Capillary Plasma Electrode (CPE)

(pulsed) dc, ac, or rf voltage

Capillary Plasma Electrode (CPE) Realizations

Solid Pin Electrodes (Cross Flow)

Hollow Pin Electrodes (Flow-Through)

Cylindrical Electrodes (Longitudinal Flow)
For instance, if we want to modify the surface of a material (e.g. a silicon wafer).
Plasma surface treatment for films, glass, paper or plastic sheets, and 3D materials

Reference: www.3dtlc.com
Plasma Discharges in Water

Gas phase discharge

\[ O_3(g) \rightarrow \text{e}^- \rightarrow \text{H}_2\text{O}(g) \]

Liquid phase discharge

\[ \text{O}_3(aq) + \text{H}_2\text{O}_2 \rightarrow \text{OH}^- \rightarrow \text{H}_2\text{O}(aq) \]

Images:
- Pulsed Corona in Water
- Spark Discharge in Water
- Plasma Arrays in Water
- Spark Discharge in Water
- Gliding Arc Discharge with Water Spray
- Pinhole Discharge in Water
Plasma Application in Medicine

Direct Plasma – Charges on Tissue, Produced In Air or Oxygen

Indirect Plasma – Jet, Often NOT in OXYGEN

Drexel Plasma Institute
Drexel University, Camden, NJ
Plasma Micro Jet Inside Water
Inactivation of Bacteria

Experimental Set-up

Experimental Procedure

Total path length: 120 mm
Moving speed: 4 mm/s
Time per path: 30 s
Total treatment time: 30s / 60s / 90 s
Area exposure/path: < 1 s (visible plasma), ~10 s (radical exposure)

List of bacteria cultures studied

<table>
<thead>
<tr>
<th>Bacteria</th>
<th>Gram stain</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Escherichia coli</td>
<td>Negative</td>
</tr>
<tr>
<td>B Staphylococcus aureus</td>
<td>Positive</td>
</tr>
<tr>
<td>C Micrococcus luteus</td>
<td>Positive</td>
</tr>
<tr>
<td>D Bacillus megaterium</td>
<td>Positive</td>
</tr>
<tr>
<td>E Bacillus subtilis</td>
<td>Positive</td>
</tr>
<tr>
<td>F Bacillus natto</td>
<td>Positive</td>
</tr>
</tbody>
</table>
Plasma Dose Effect

E. coli M. luteus

Control 30 seconds 60 seconds 90 seconds

radially decreasing survival rate

uniform decreasing survival rate

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SEM of PMJ treated S. aureus show clear poration on cell membrane as well as the change of the cell morphology.
Living tissue sterilization without harm:
Recent pig experiments

Courtesy: Drexel Plasma Institute
Saphenous vein cut: without plasma animal continues to bleed for 10-20 minutes.

15 seconds of FE-DBD clots the blood and seals the vessel without damaging tissue, preventing additional bleeding.

Courtesy: Drexel Plasma Institute
Biological Mechanisms: Plasma Interference into Natural Intracellular Biochemistry

Core plasma

- metastables
- neutrals
- radicals
- ions
- electrons

Plume

- energy
- neutrals
- radicals
- metastables

Liquid

Biological sample

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Dental Application

Cleaning of Dental Cavities

Other Applications

• Bio Decontamination
• Sterilization of Medical Instruments and Wounds
Teeth Whitening with non-thermal plasma

- The plasma jet did not heat tooth surface over 37 degrees.
- Heating the tooth over 42 degrees can cause severe damages to the nerves inside a tooth.

“No thermal-damages”
Teeth Whitening with non-thermal plasma

\[ \text{H}_2\text{O}_2 \quad \text{before} \quad 20\text{min} \quad \text{H}_2\text{O}_2 \quad \text{after} \]

\[ \text{Plasma}+\text{H}_2\text{O}_2 \quad \text{before} \quad 20\text{min} \quad \text{Plasma}+\text{H}_2\text{O}_2 \quad \text{after} \]
A Brief Collection of Atmospheric Pressure Plasma Jets (APPJ)

Gases used: Helium, Argon… or mixed with reactive gases (O₂, CH₄…)
AC, pulsed DC, rf or microwave
New Jersey – Garden State

New Jersey

SETON HALL

Garden State

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Our Version of the Atmospheric Pressure Plasma Jet

Gerald J. Buonopane, Cosimo Antonacci, & Jose L. Lopez. 
Plasma Processing: Experimental Plan

- Harvest
- Distillation
- Plasma Treatment
- Antioxidant Testing GC-MS
- Measure Plants
Plasma Seed Treatments

(a) Side-view of basil seedlings grown from plasma treated seeds (left) and untreated seeds (right). (b) Top-view of basil seedlings grown from plasma treated seeds (left) and untreated seeds (right).
Untreated (Control) Basil
Plasma Treated Basil
Basil: Plasma Treated vs. Untreated
Graph demonstrating average final height of twelve treated and non-treated sweet basil plants after a month of growth from seeds.
<table>
<thead>
<tr>
<th>Antioxidant / Concentration</th>
<th>15 μg/mL</th>
<th>25 μg/mL</th>
<th>50 μg/mL</th>
<th>125 μg/mL</th>
<th>250 μg/mL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma-Treated Basil</td>
<td>48.00%</td>
<td>62.55%</td>
<td>81.55%</td>
<td>90.55%</td>
<td>94.82%</td>
</tr>
<tr>
<td>Non-Treated Basil</td>
<td>19.55%</td>
<td>26.91%</td>
<td>46.36%</td>
<td>78.27%</td>
<td>90.64%</td>
</tr>
</tbody>
</table>
Gas Chromatogram: Overlay of Commercial Oil and Extracted (T + NT)

Shimadzu GC-MS; Column: RTX-5 MS: 15m X 0.25mm X 0.25μm

Estragole (Commercial Basil)

Eugenol (Extracted Basil)
Biosynthesis of Phenylpropanoids and Phenolic Compounds
(Valgimigli, 2012)
Aeroponic & Aquaponic Investigations

Kidney Bean Research
Create plasma jets in multiple directions

3-D Arrays!

Plasma Jet Array

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Irrigation: Water & Plasma

Water irrigation in fields and greenhouses

Plasma irrigation for agriculture
Microplasma interaction with biological materials???

Many unanswered questions as to the role of plasma in the biological interactions with biological materials.

- What are the microplasmas doing to the live biological materials?
- Can microplasma sources be tailored to better control interactions with biological materials?
Plasma – Spark of Life?

Urey-Miller Experiment – Origin of Life
Many, many Innovative Technologies...

- Plasma Surface Treatment
- Gas Laser
- Spark Gap
- Ozone generator
- High Intensity Plasma Arc Lamp
- Fluorescent Lamp
- Plasma Display (150 inch Panasonic)
The dangerous plasmas...
The ST:TNG future is all about plasma technologies...
The Star Trek: TNG future

Plasma Torpedoes vs. Plasma shields
The Star Trek: TNG future

Warp Drive core

Plasma injector

Nacelle Warp Drive Engines
Star Trek’s Dermal Regenerator

On *Star Trek*, the dermal regenerator is a hand-held device that instantly heals cuts and burns without leaving a scar. It’s used not just for injuries, but also for quick healing after surgery, making for a very speedy recovery.
Star Trek’s Dermal Regenerator
What LTP technologies will the future bring?

Jean Felix Piccard

Mercury barometer

Jean Luc Piccard

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The future ain’t what it used to be...

….Yogi Berra
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DEPARTMENT OF PHYSICS
Jose L. Lopez – Seton Hall University
Senior Editor of Industrial, Commercial, and Medical Applications of Plasmas
Masters of Science (M.S.) in Physics

Two M.S. in Physics Degree Tracks:
1. Course track (33 credits) for educators / doctoral degree (Ed.D.) and business tracks (M.B.A)
2. Master’s Thesis (30 credits) for R&D research or scientific research doctoral degree (Ph.D.)

Research Areas:
1. Plasma Physics - Science & Technology
2. Condensed Matter / Complex Matter Physics
3. Biophysics & Environmental Physics
4. Environmental Systems & Technologies

www.shu.edu/physics
Questions???
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