UNIVERSITY OF NOTRE DAME

Non-Thermal Plasmas for Revolutionizing Goods Production

David B. Go

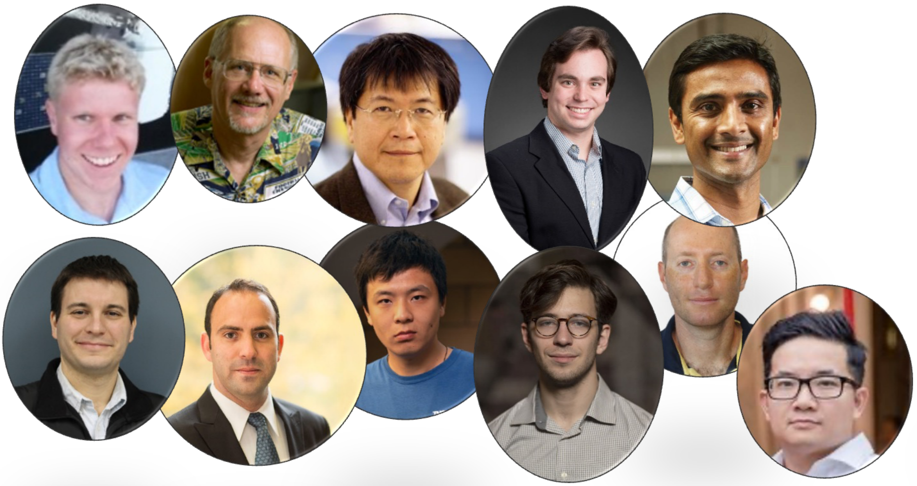
gogroup.nd.edu

Aerospace and Mechanical Engineering
Chemical and Biomolecular Engineering
University of Notre Dame

September 10, 2025

Plasma Electrochemistry

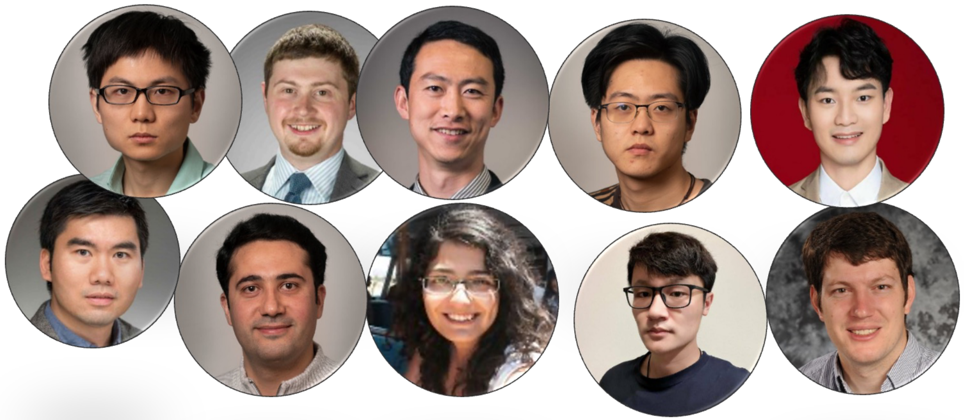
Prof. Paul Rumbach, Dr. David Bartels, **Prof. Mohan Sankaran (Illinois)**, Prof. Chia Chang, **Prof. Daniel Elg** (Southern Indiana), Prof. Felipe Veloso (UC|Chile) **Dr. Hernan Delgado**, Dr. Jinyu Yang, Dr. Oles Dubrovski, **Dr. Daniel Martin, Dr. Hoang Nguyen**



ARO W911NF-17-1-0119
ARO W911NF-23-1-0010
DOE Rickover Fellowship

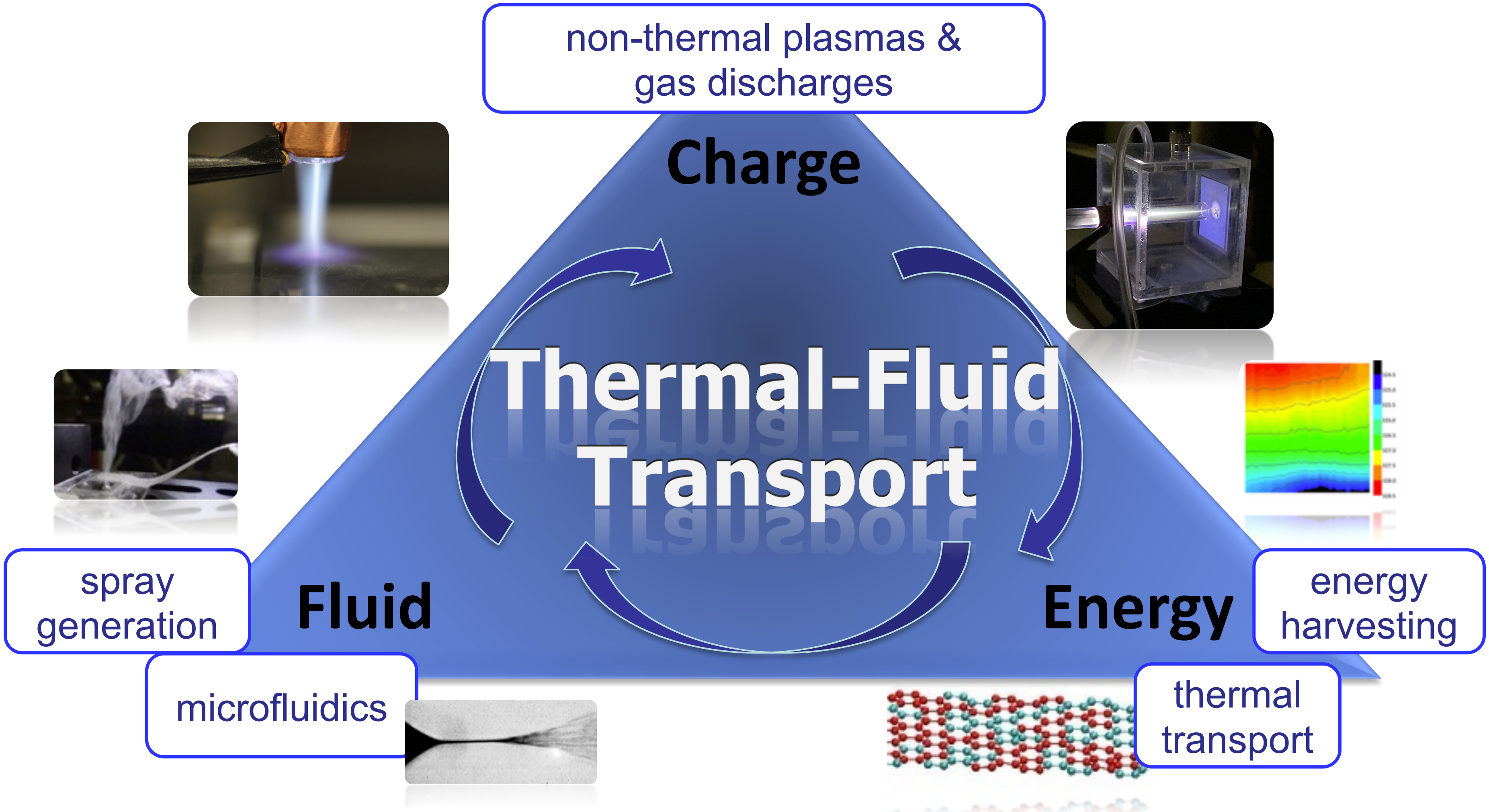
Plasma-Driven Material Processing

Prof. Yanliang Zhang, Prof. Alex Dowling, Prof. Tengfei Luo, Dr. Mike McMurtry (INL), **Dr. Nazli Turan**, **Dr. Mortaza Saeidi-Javash**, **Dr. Jinyu Yang**, **Dr. Yipu Du**, Dr. Ke Wang, Zhongyu Cheng



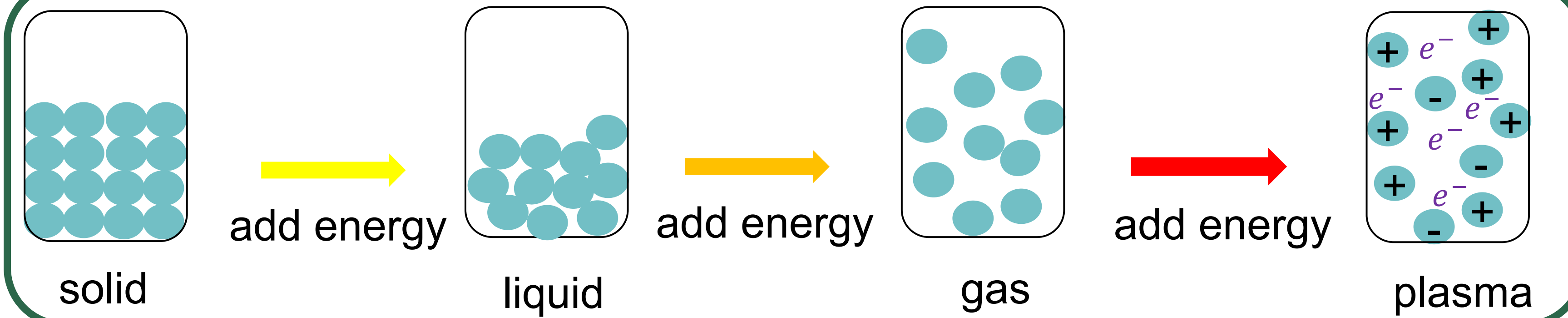
AFOSR FA9550-18-1-0157
DOE DE-EE0009103

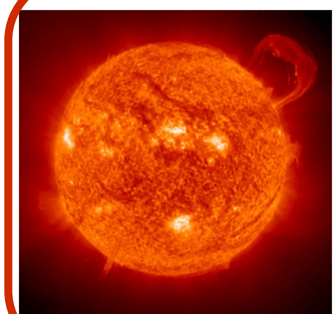
NATIONAL ENERGY TECHNOLOGY LABORATORY



theory **simulations** **experiments** **technology development**

What is Plasma?





Thermal (equilibrium) Plasmas

Average T > 10,000 K

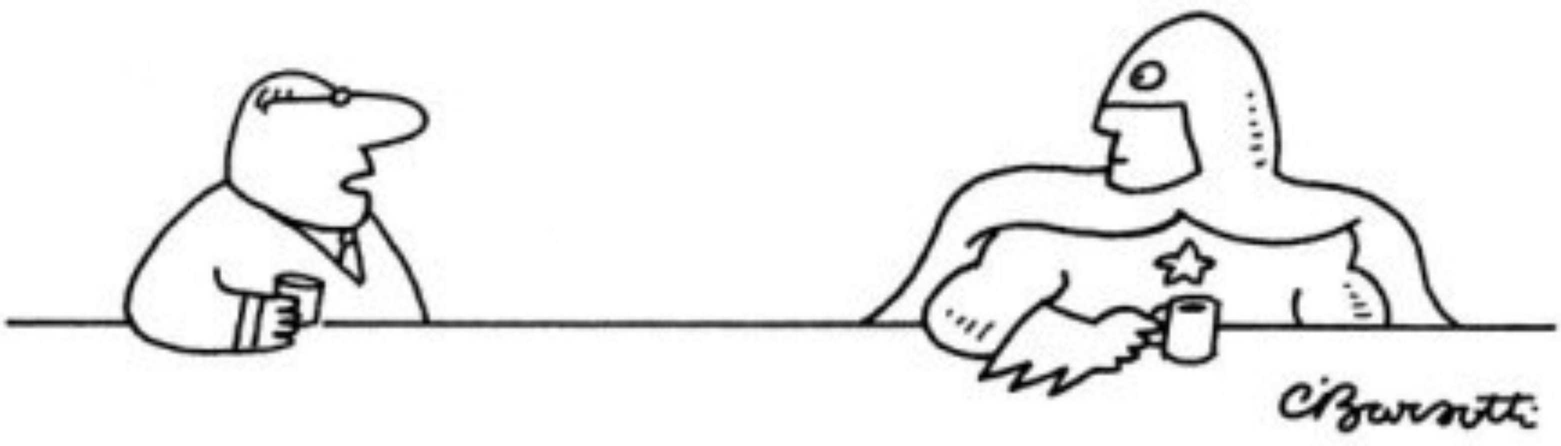
$T_e \approx T_i \approx T_n$

Non-thermal (non-equilibrium) Plasmas

Average T ~ 300 K

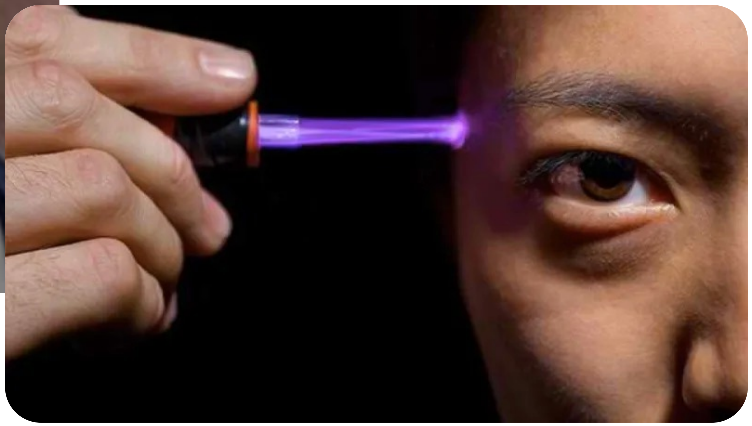
$T_e > T_i \approx T_n$

Non-Thermal Plasmas Revolutionizing Applications



"Some of us are unsung heroes."

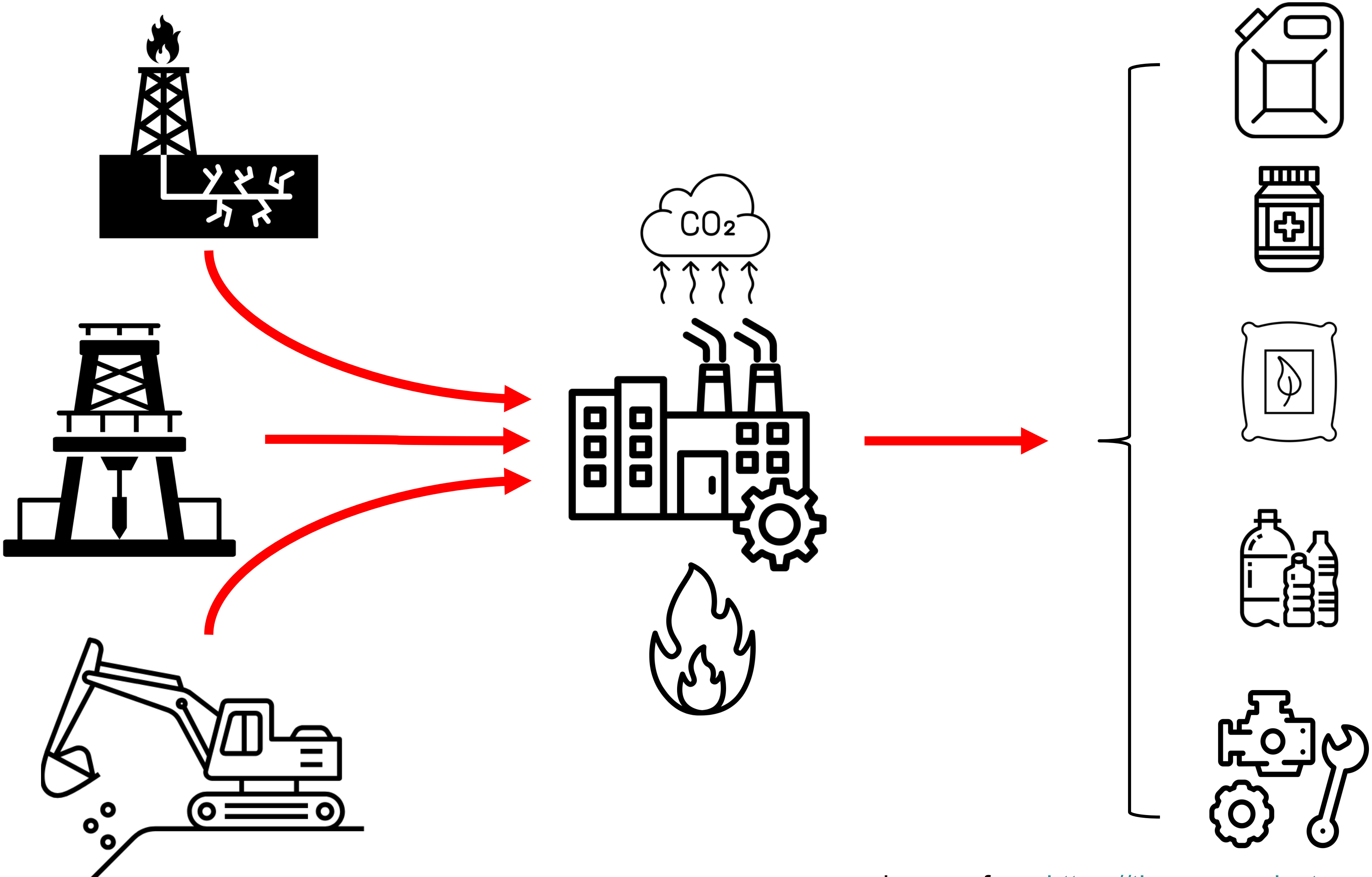
https://www.dcu.ie/ncpst/precision/plasmainmedicine.shtml



https://io9.gizmodo.com/now-you-can-replace-your-antibacterial-soap-with-a-plas-5899149

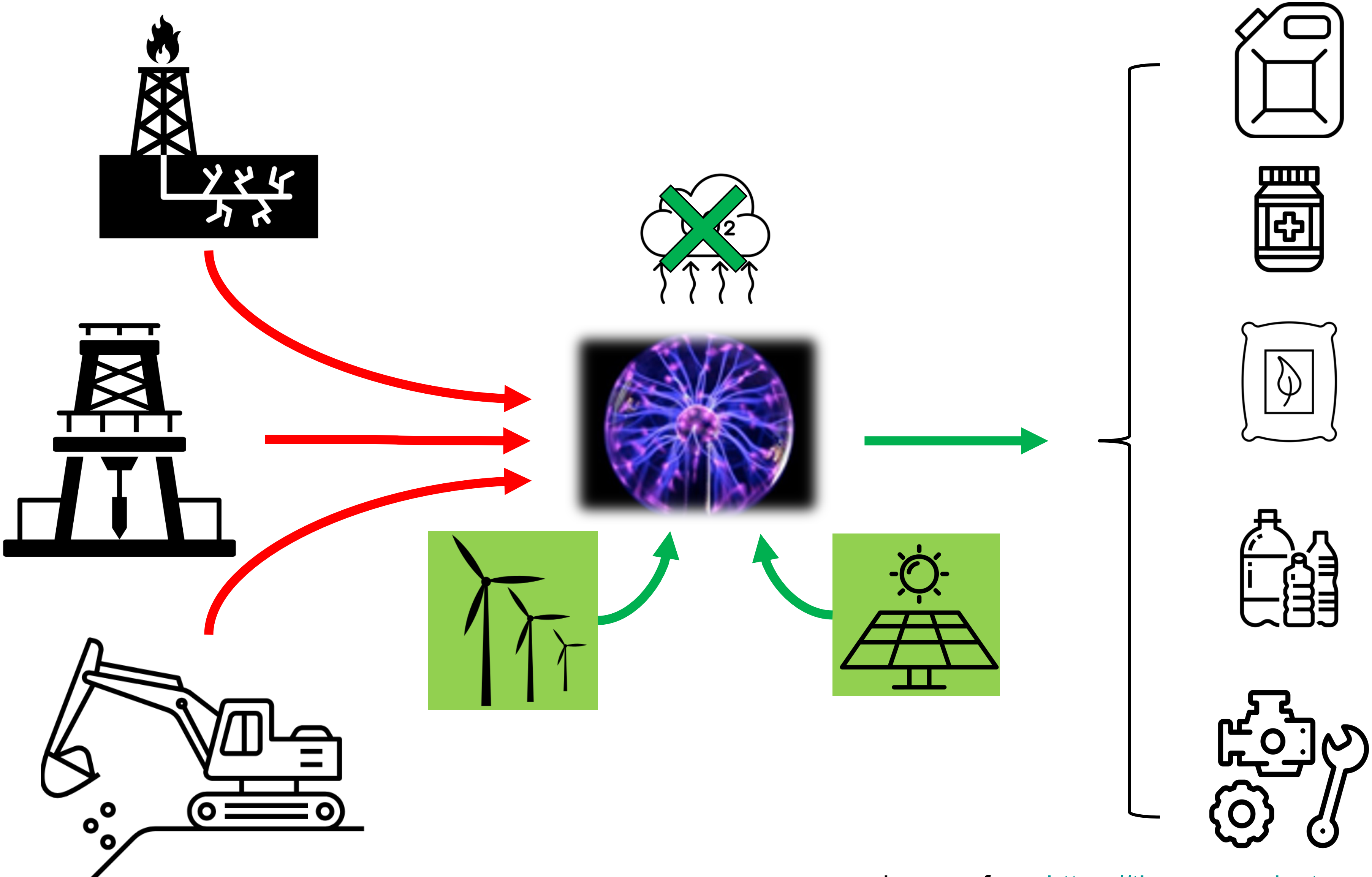
https://www.atb-potsdam.de/en/research-programs/quality-and-safety-of-food-and-feed/plasma.html

Plasmas for More Resilient Goods Production



images from https://thenounproject.com/

Plasmas for More Resilient Goods Production



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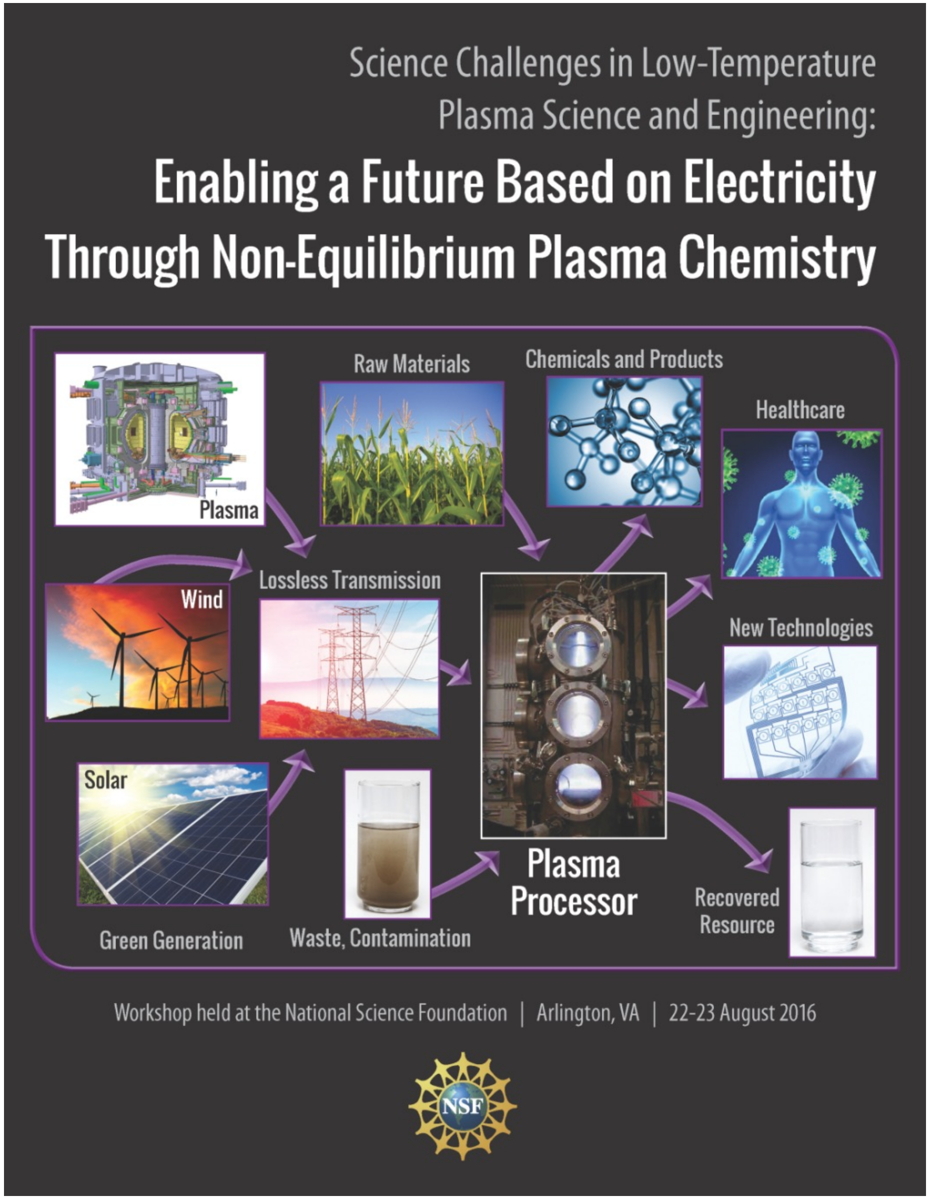
NSF WORKSHOP



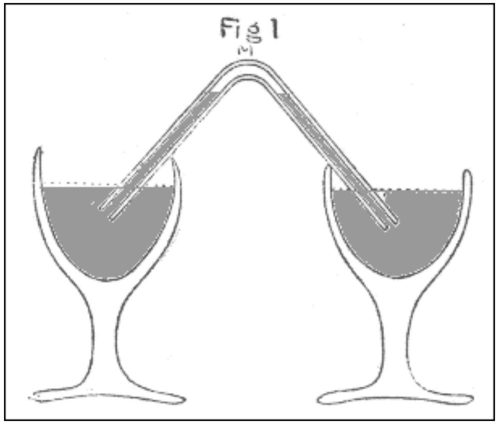
Courtesy: Mark Kushner, U. Michigan

Science Challenges in Low Temperature Plasma Science and Engineering: ENABLING A FUTURE BASED ON ELECTRICITY THROUGH NON-EQUILIBRIUM PLASMA CHEMISTRY

- **Workshop report: arxiv.org/abs/1911.07076**

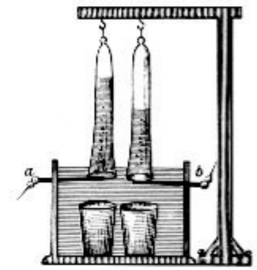
Plasma-Liquid Systems As A Basis for Goods Production

Cavendish uses an arc to convert air to nitrous acid (1784)



H. Cavendish, *Experiments on Air*, 1785.

Schönbein uses an arc to discover ozone (1840)



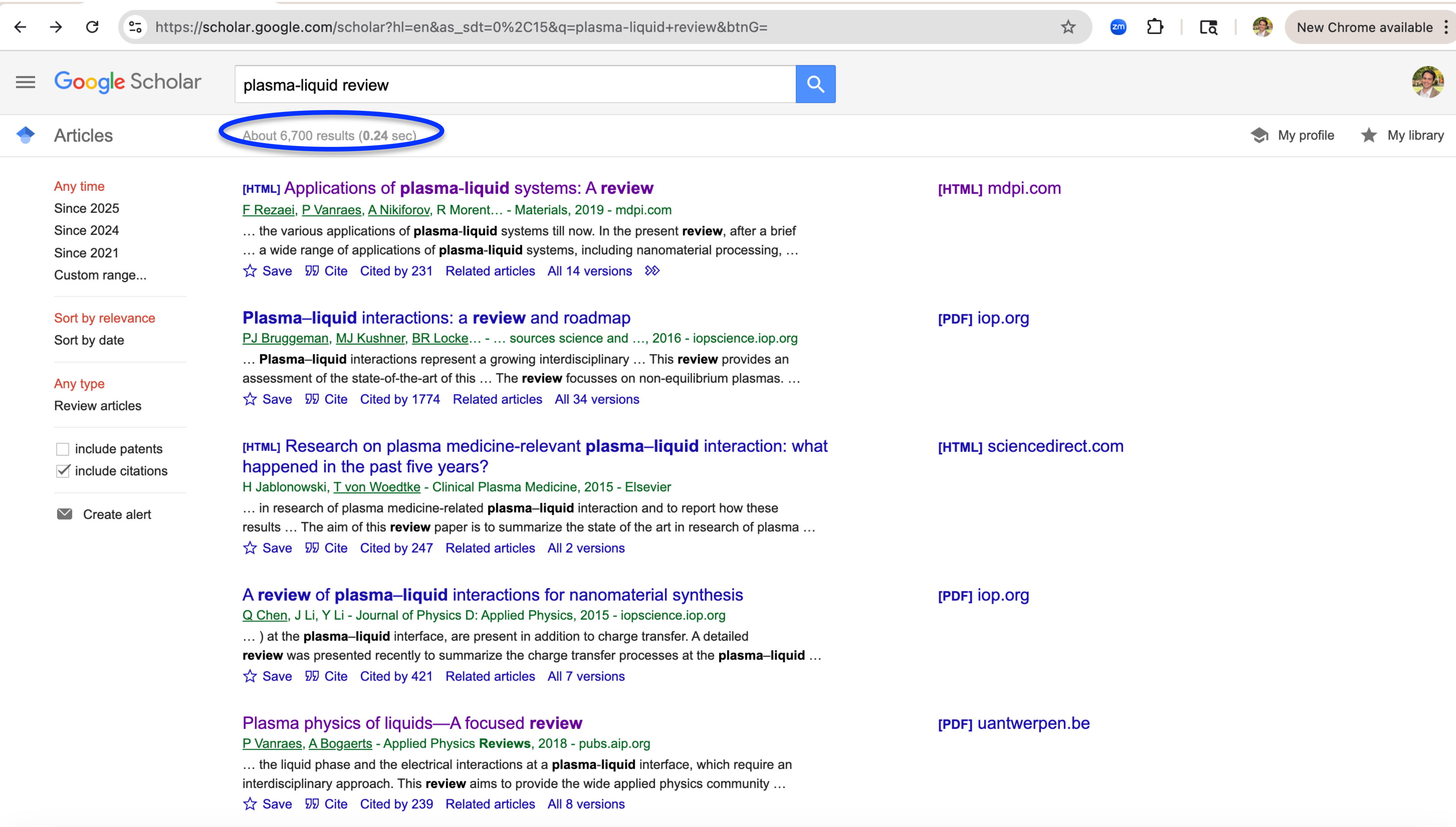
courtesy J. Lopez, Seton Hall University

Rayleigh and Ramsay use an arc to discover argon (1895)

escola.britannica.com.br

Birkeland-Eyde process to produce fertilizer patented (1903)

www.hydro.com/en/About-Hydro/Our-history/1900---1917/Explosive-winter-days-in-1903/



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plasma-liquid review

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[HTML] Applications of **plasma-liquid** systems: A **review** — [HTML] mdpi.com
F Rezaei, P Vanraes, A Nikiforov, R Morent… - Materials, 2019 - mdpi.com
… the various applications of **plasma-liquid** systems till now. In the present **review**, after a brief … a wide range of applications of **plasma-liquid** systems, including nanomaterial processing, …
Save Cite Cited by 231 Related articles All 14 versions

Plasma–liquid interactions: a **review** and roadmap — [PDF] iop.org
PJ Bruggeman, MJ Kushner, BR Locke… - … sources science and …, 2016 - iopscience.iop.org
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H Jablonowski, T von Woedtke - Clinical Plasma Medicine, 2015 - Elsevier
… in research of plasma medicine-related **plasma–liquid** interaction and to report how these results … The aim of this **review** paper is to summarize the state of the art in research of plasma …
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A **review** of **plasma–liquid** interactions for nanomaterial synthesis — [PDF] iop.org
Q Chen, J Li, Y Li - Journal of Physics D: Applied Physics, 2015 - iopscience.iop.org
…) at the **plasma–liquid** interface, are present in addition to charge transfer. A detailed **review** was presented recently to summarize the charge transfer processes at the **plasma–liquid** …
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Plasma physics of liquids—A focused **review** — [PDF] uantwerpen.be
P Vanraes, A Bogaerts - Applied Physics **Reviews**, 2018 - pubs.aip.org
… the liquid phase and the electrical interactions at a **plasma-liquid** interface, which require an interdisciplinary approach. This **review** aims to provide the wide applied physics community …
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Journal of Applied Physics EDITORIAL scitation.org/journal/jap

Plasma–liquid interactions

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View Online

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Note: This paper is part of the Special Topic on Plasma-Liquid Interactions.

Journal of Applied Physics PERSPECTIVE scitation.org/journal/jap

The essential role of the plasma sheath in plasma–liquid interaction and its applications—A perspective

Cite as: J. Appl. Phys. **129**, 220901 (2021); doi: 10.1063/5.0044905
Submitted: 20 January 2021 · Accepted: 19 May 2021 ·
Published Online: 10 June 2021

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Note: This paper is part of the Special Topic on Plasma-Liquid Interactions.

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The Journal of Chemical Physics REVIEW pubs.aip.org/aip/jcp

Advances in plasma-driven solution electrochemistry

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Published Online: 19 February 2025

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Peter J. Bruggeman,[1,a)] Renee R. Frontiera,[2] Uwe Kortshagen,[1] Mark J. Kushner,[3] Suljo Linic,[4] George C. Schatz,[5] Himashi Andaraarachchi,[1] Subhajyoti Chaudhuri,[5] Han-Ting Chen,[4] Collin D. Clay,[2] Tiago C. Dias,[3] Scott Doyle,[3] Leighton O. Jones,[5] Mackenzie Meyer,[3] Chelsea M. Mueller,[5] Jae Hyun Nam,[1] Astrid Raisanen,[3] Christopher C. Rich,[2] Tanubhav Srivastava,[1] Chi Xu,[1] Dongxuan Xu,[1] and Yi Zhang[4]

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APPLIED PHYSICS REVIEWS **5**, 031103 (2018)

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APPLIED PHYSICS REVIEWS—FOCUSED REVIEW

Plasma physics of liquids—A focused review

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(Received 22 December 2017; accepted 23 May 2018; published online 25 July 2018)

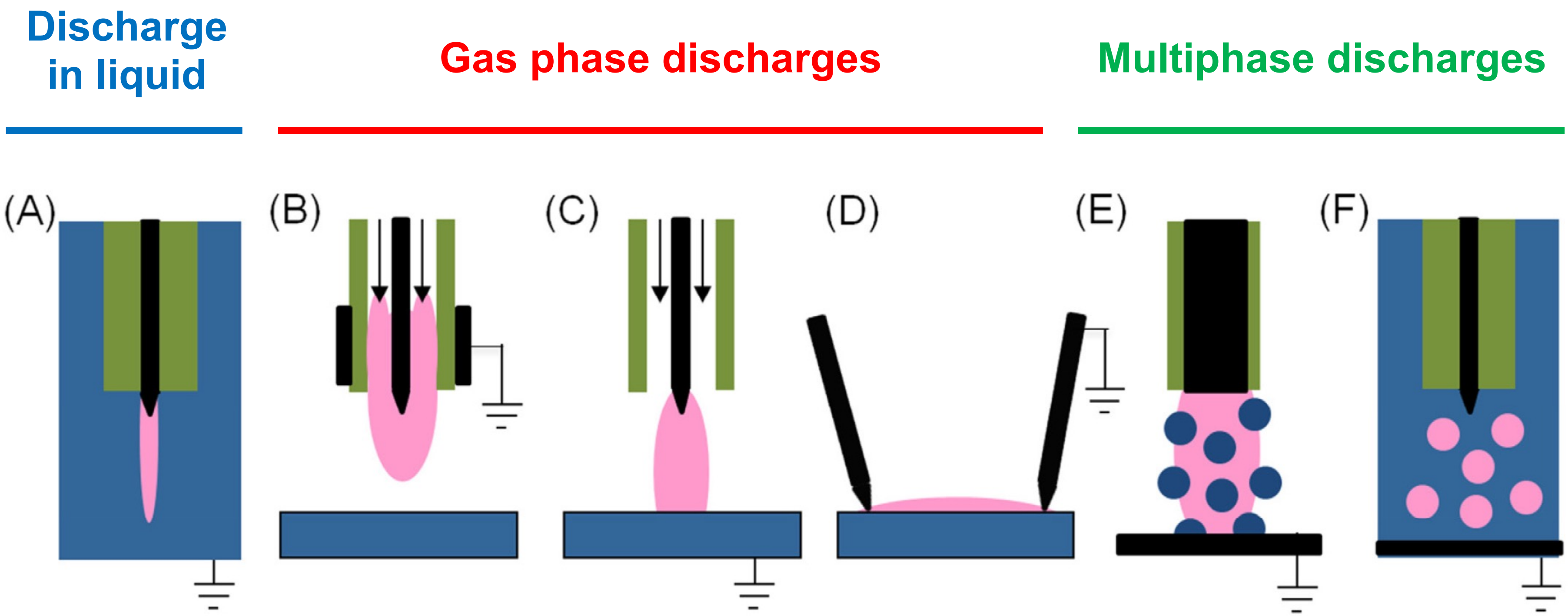
REVIEW ARTICLE

Charge transfer processes at the interface between plasmas and liquids

Rohan Akolkar[a)] and R. Mohan Sankaran[a)]
Department of Chemical Engineering, Case Western Reserve University, 10900 Euclid Ave., Cleveland, Ohio 44106-7217

(Received 14 March 2013; accepted 28 May 2013; published 19 June 2013)

A Diverse Landscape of Interfaces



A) Direct discharge in liquid

B) Plasma jet

C) Gas phase plasma with liquid electrode

D) Surface discharge

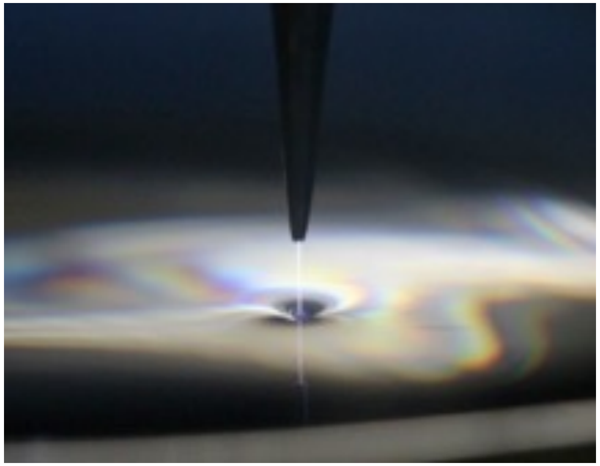
E) Gas discharge in aerosols

F) Gas discharge in bubbles

Bruggeman et al. *Plasma Sources Sci. Technol.*, **25**, 053002 (2016).

Revolutionizing Goods Production: Two Stories

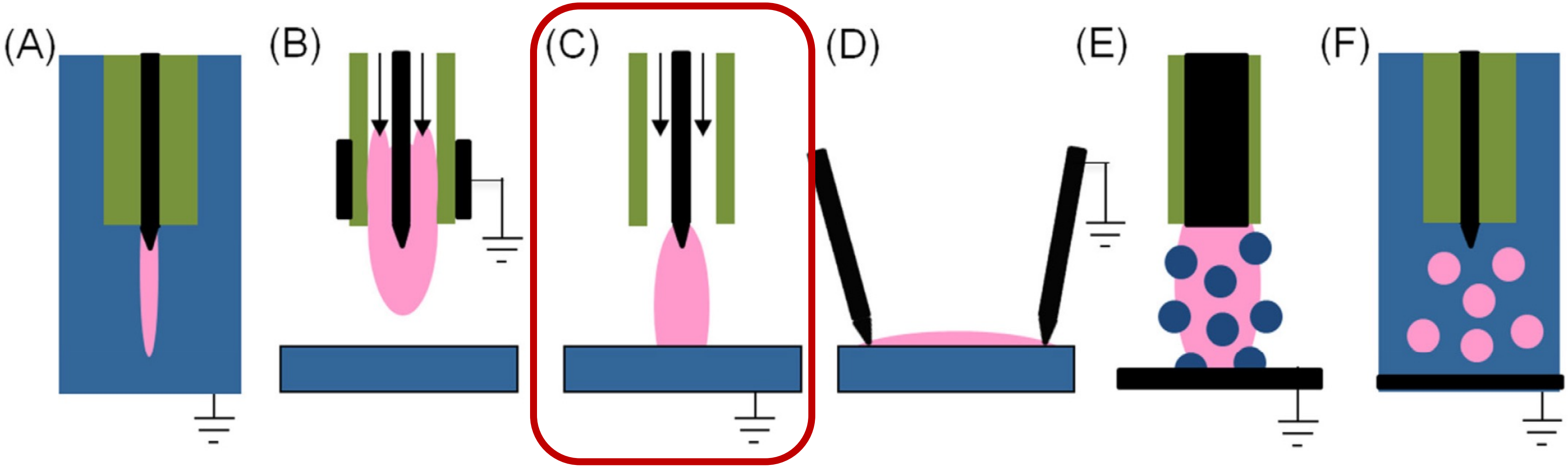
Plasma Electrochemistry



Plasma-Driven Material Processing

A Diverse Landscape of Interfaces

Discharge in liquid | **Gas phase discharges** | **Multiphase discharges**



A) Direct discharge in liquid

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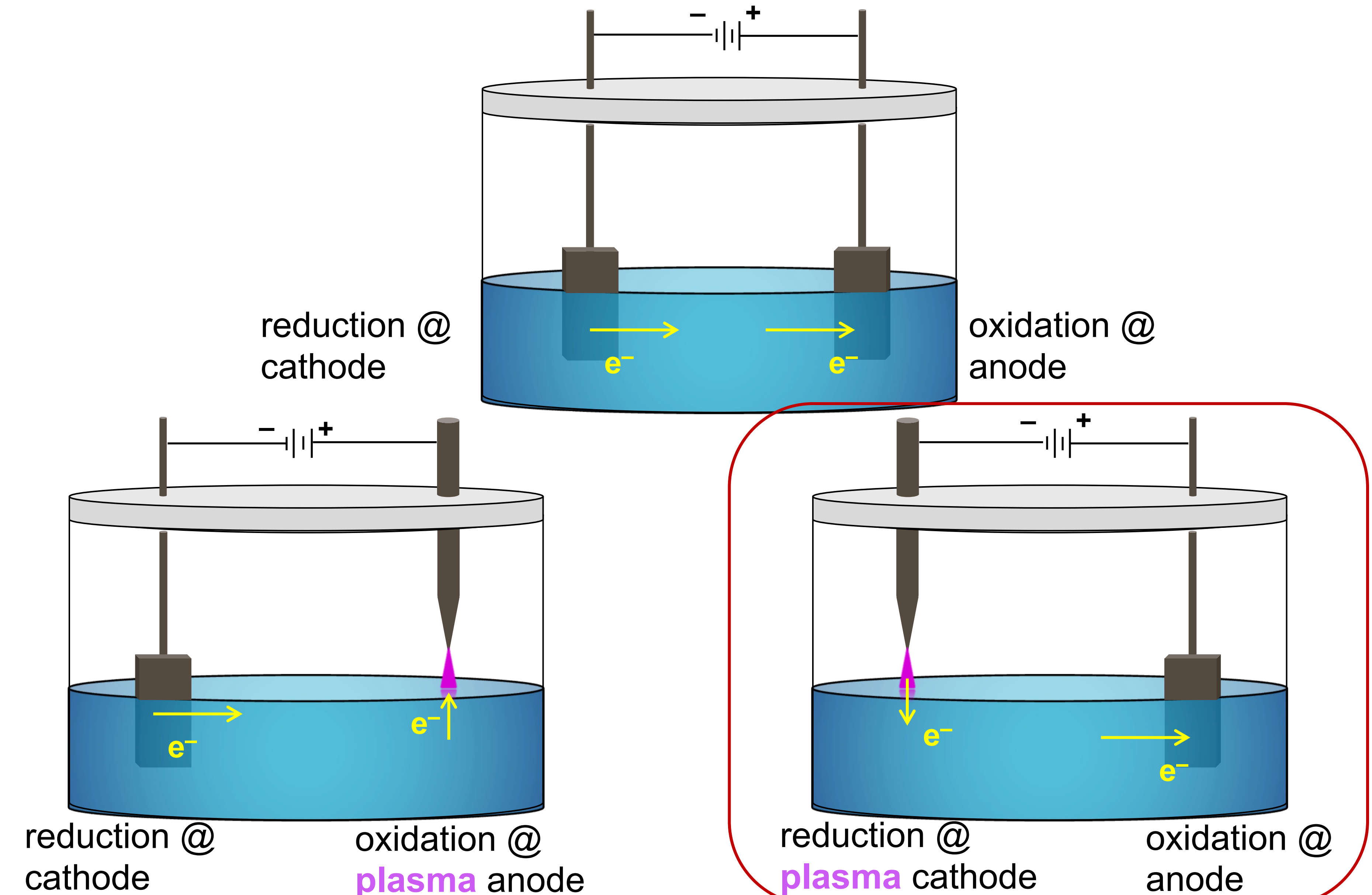
F) Gas discharge in bubbles

Bruggeman et al. *Plasma Sources Sci. Technol.*, **25**, 053002 (2016).

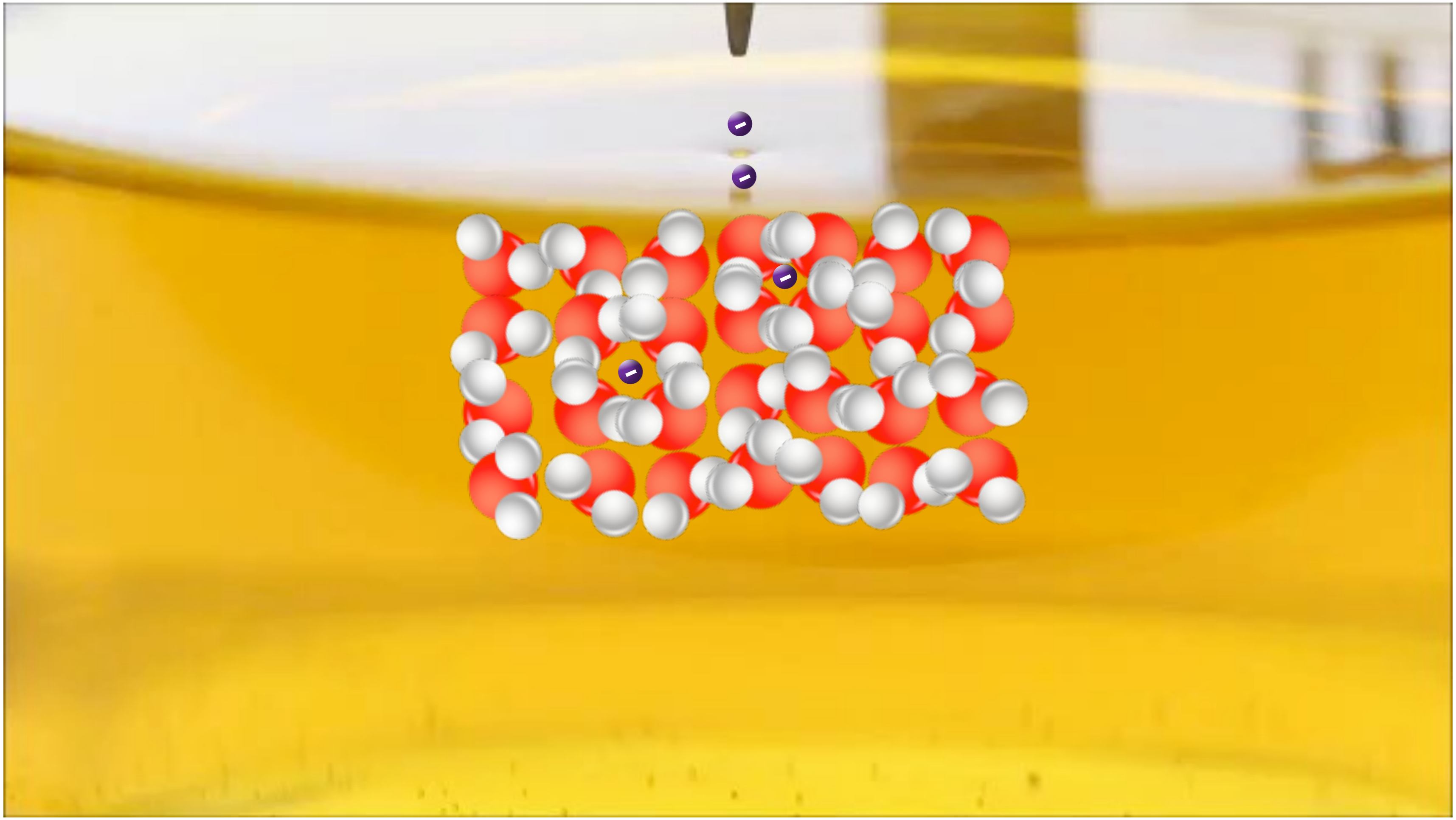
Direct Plasma/Liquid Coupling



Plasma-Induced Water Electrolysis

Rumbach, Griggs, Sankaran, & Go
IEEE Trans. Plasma Sci. **42**, 2610-11 (2014).

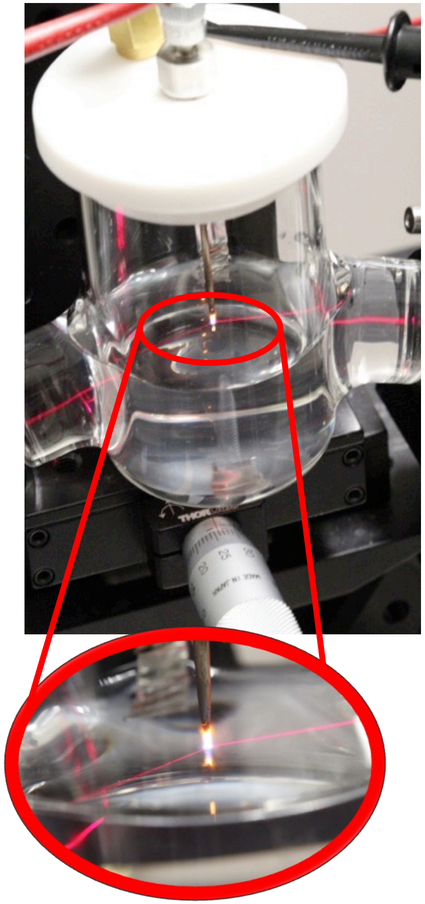
Plasma-Injected Solvated Electrons

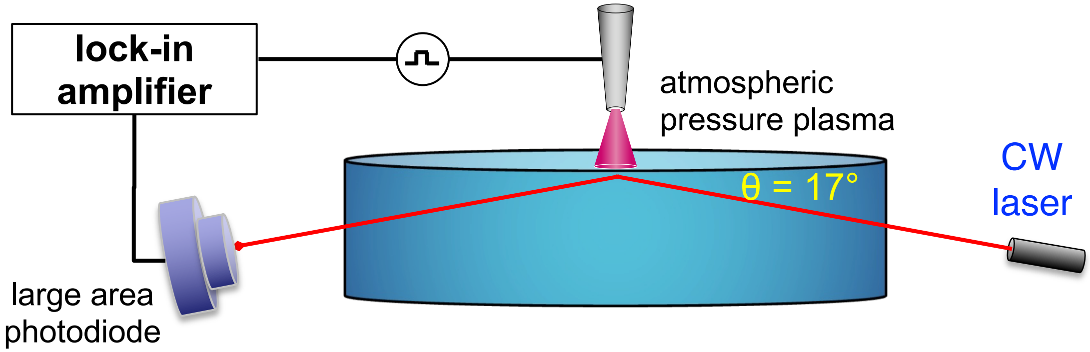


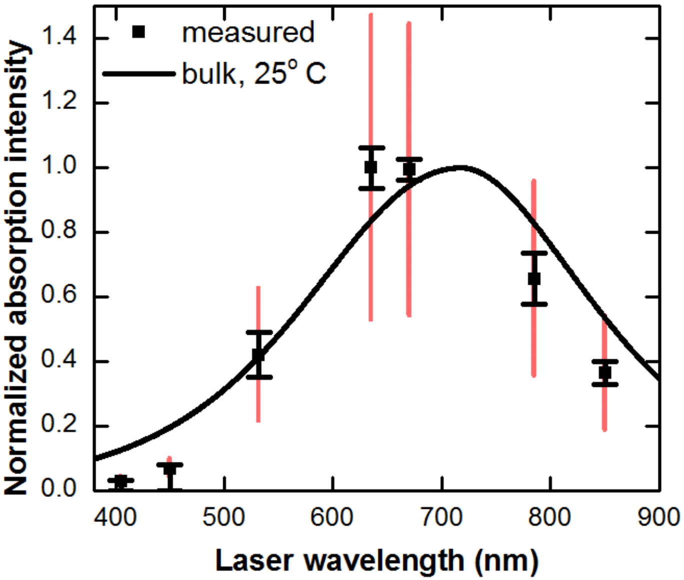
Rumbach, Bartels, Sankaran, & Go, *Nature Comm.* **6**, 7248 (2015)

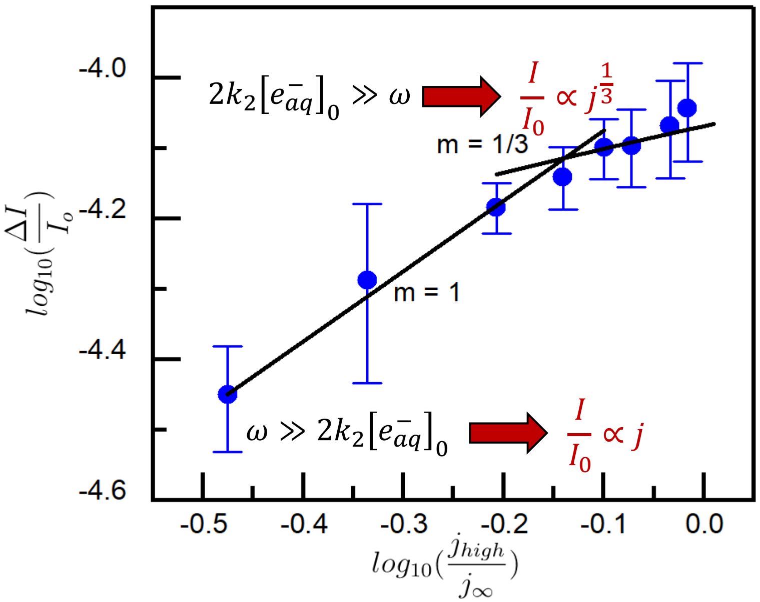
Measuring Plasma-Solvated Electrons

Total internal reflection absorption spectroscopy (TIRAS) measures the time-average, local $e^-_{(aq)}$ concentration at the plasma-liquid interface





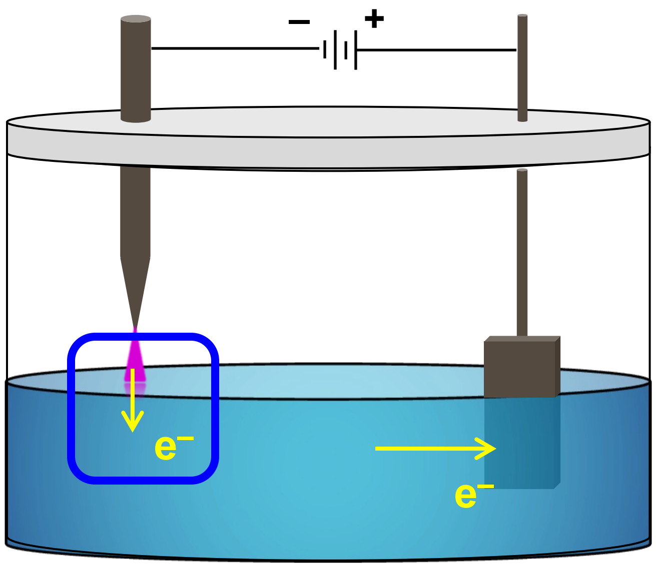


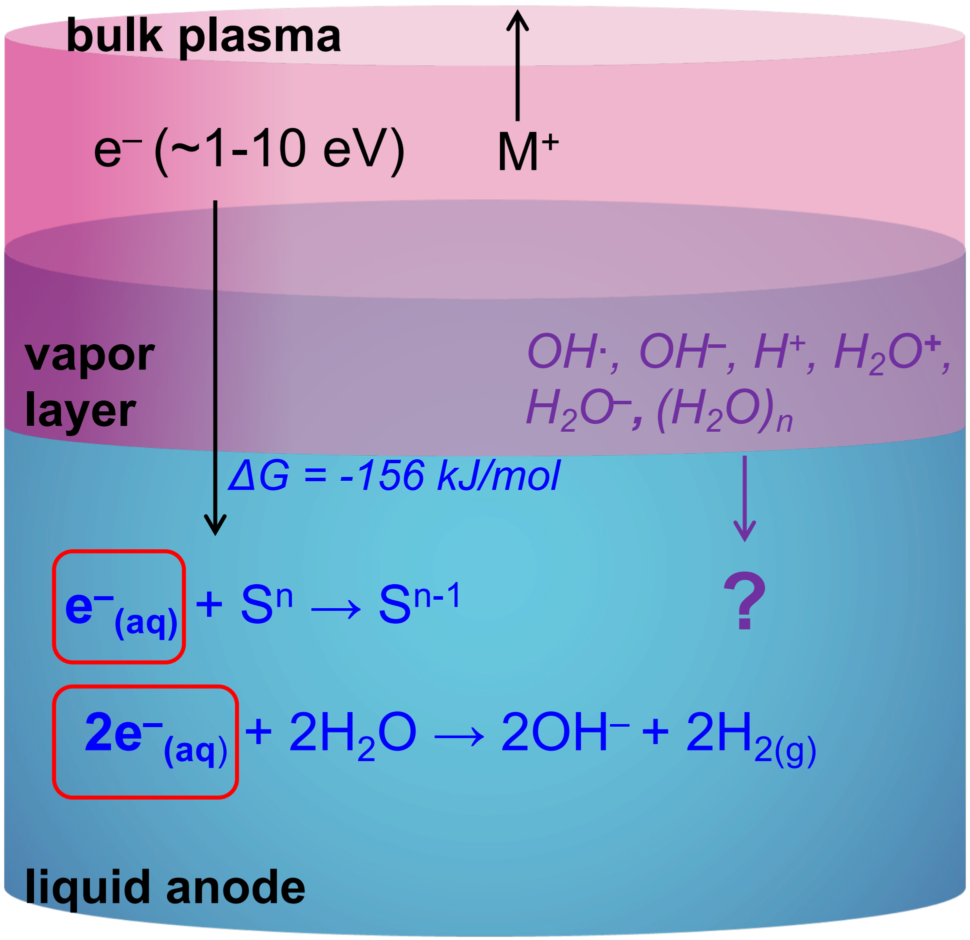


Rumbach, Bartels, Sankaran, & Go, *Nature Comm.* **6**, 7248 (2015)
Martin et al. *Plasma Sources Sci. Technol* **30**, 03LT01 (2021)

Solvated Electrons and the Plasma Cathode

plasma cathode configuration





Key Questions

- What chemistry can/do solvated electrons drive?
- What is the role of other plasma-produced reactive species in the chemistry?
- How are the plasma and liquid coupled?

Spectrochimica Acta Part B: Atomic Spectroscopy 186 (2021) 106307

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Spectrochimica Acta Part B: Atomic Spectroscopy

journal homepage: www.elsevier.com/locate/sab

Review Article

Recent advances in understanding the role of solvated electrons at the plasma-liquid interface of solution-based gas discharges

Daniel T. Elg[a,*], Hernan E. Delgado[b], Daniel C. Martin[c], R. Mohan Sankaran[d], Paul Rumbach[c], David M. Bartels[e], David B. Go[b,c,**]

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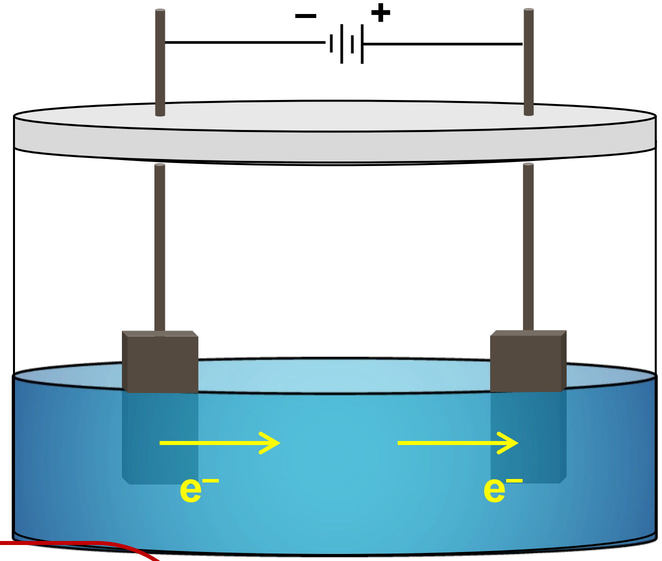
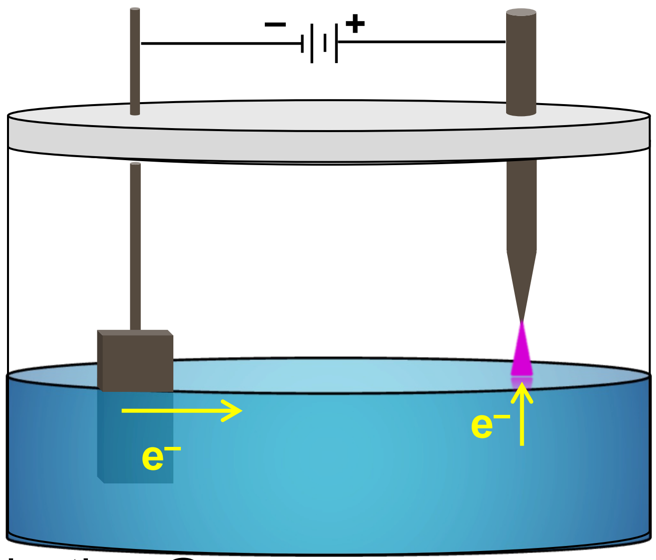
[b] *Department of Chemical and Biomolecular Engineering, University of Notre Dame, Notre Dame, IN 46556, United States*
[c] *Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, IN 46556, United States*
[d] *Department of Nuclear, Plasma, and Radiological Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, United States*
[e] *Notre Dame Radiation Laboratory and Department of Chemistry and Biochemistry, University of Notre Dame, Notre Dame, IN 46556, United States*

Direct Plasma/Liquid Coupling



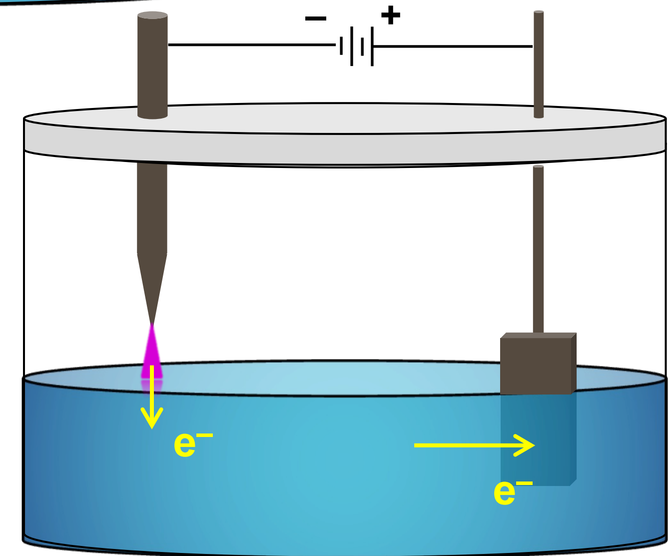
reduction @ cathode

oxidation @ anode



reduction @ cathode

oxidation @ **plasma** anode

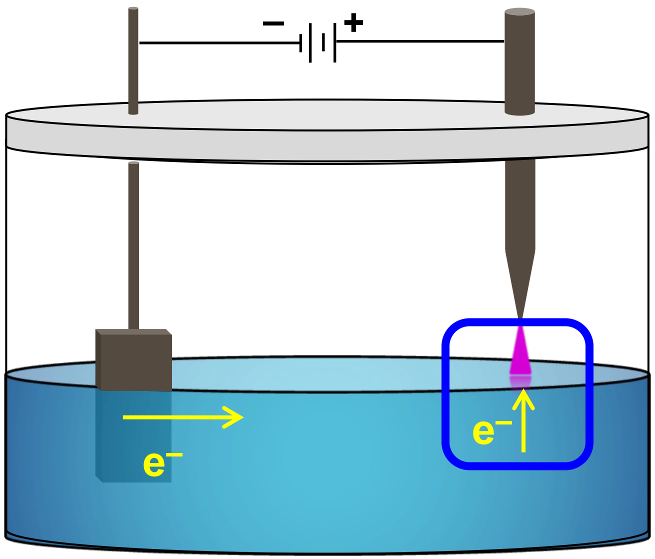


reduction @ **plasma** cathode

oxidation @ anode

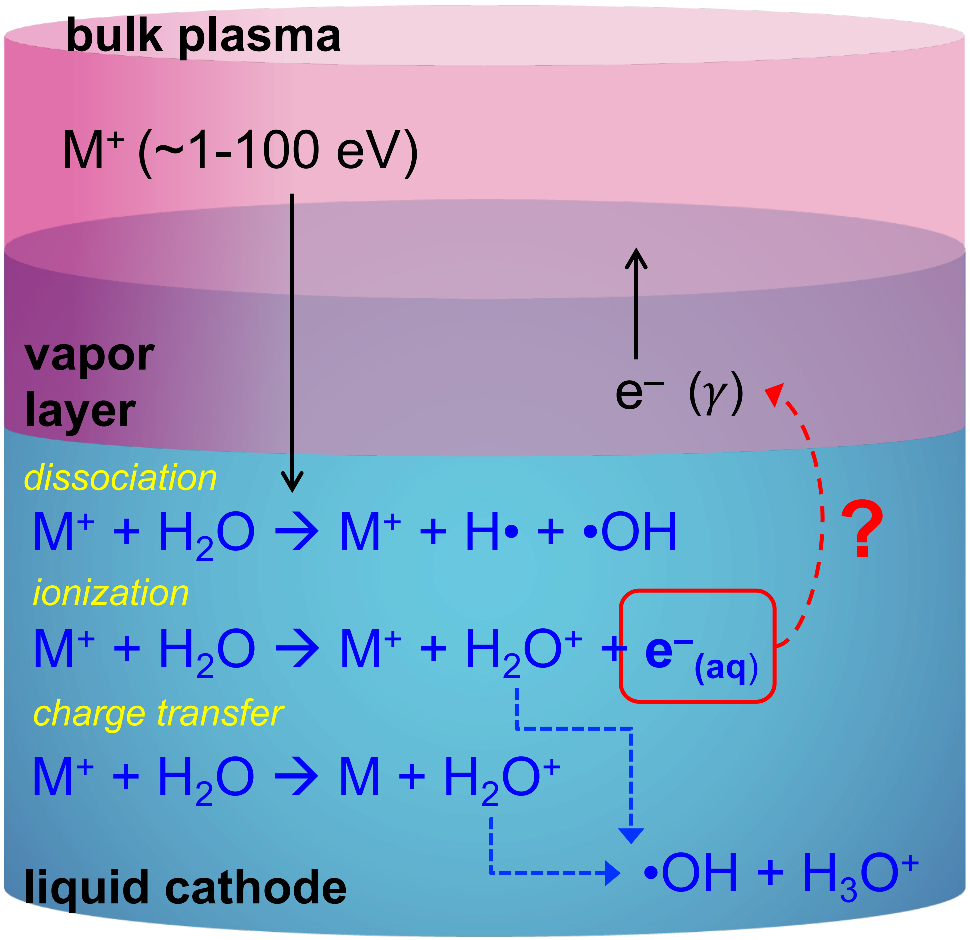
Solvated Electrons and the Plasma Anode

plasma anode configuration



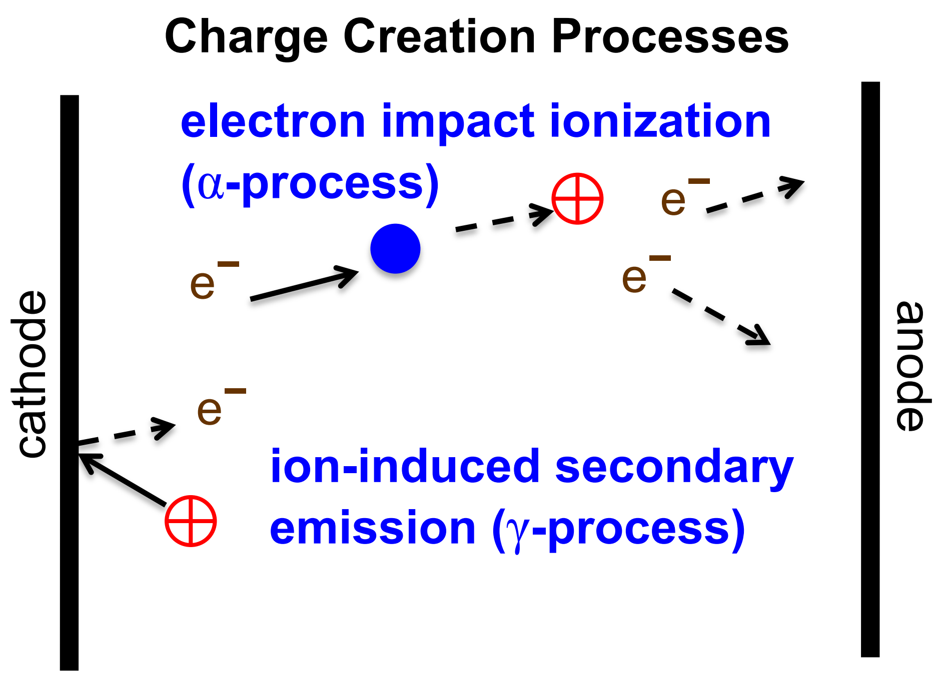
Key Questions

- What is the mechanism of secondary emission from a liquid and do solvated electrons play any role in this mechanism?
- What is the role of solvated electrons in this configuration?
- Can we detect solvated electrons?



Basics of Secondary Emission

In a plasma, **secondary emission** refers to the emission of electrons from the cathode from incoming positive ions



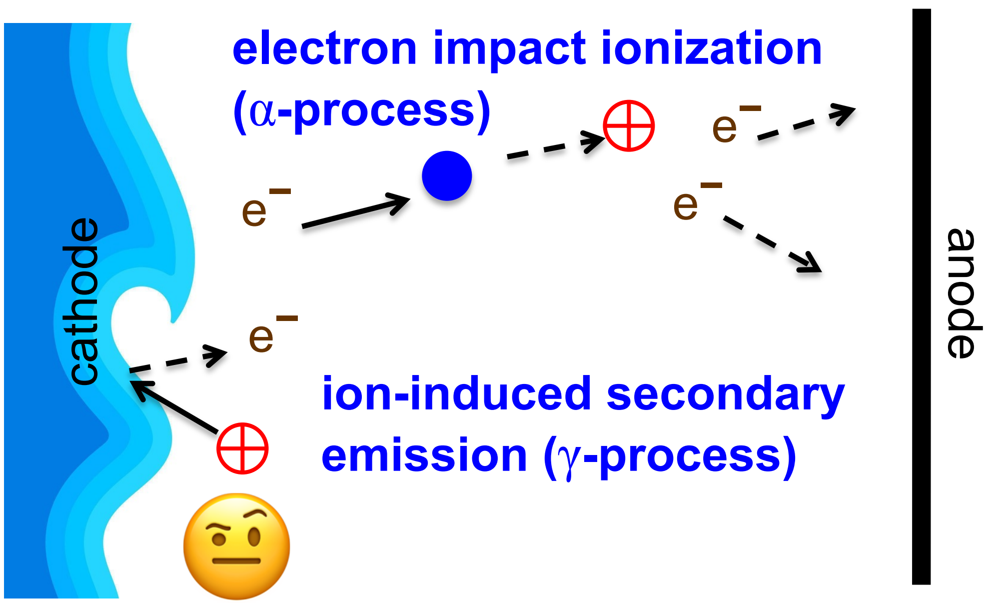
secondary emission coefficient

$$\gamma = \frac{N_{e,emit}}{N_{p,incident}}$$

Basics of Secondary Emission

In a plasma, **secondary emission** refers to the emission of electrons from the cathode from incoming positive ions

Charge Creation Processes



secondary emission coefficient

$$\gamma = \frac{N_{e,emit}}{N_{p,incident}}$$

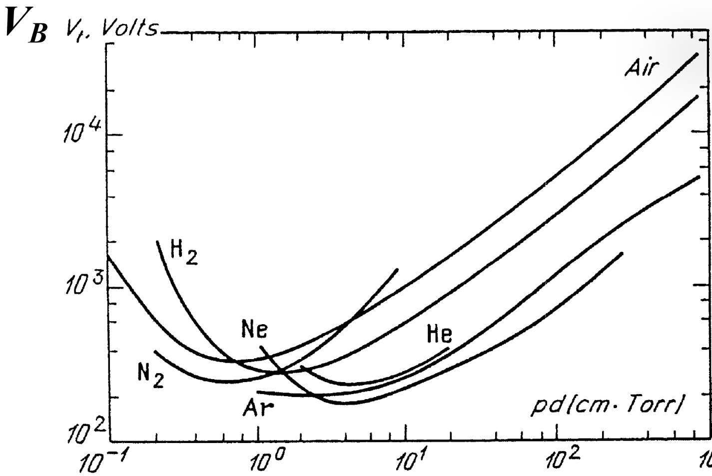
Measuring Secondary Emission Coefficient

Paschen curve

$$V_B = \frac{Bpd}{\ln(Apd) - \ln\left[\ln\left(1 + \frac{1}{\gamma_{se}}\right)\right]}$$

function of gas composition (A and B) and electrode material (γ)

$$\gamma = \frac{N_{e,emit}}{N_{p,incident}}$$



Raizer (Gas Discharge Physics)

Modified expression for the Paschen curve (Spyrou et al. *J. Phys. D.* (1994))

$$\boxed{V_B' \exp\left(-B\,\frac{R}{2d}\,\frac{pd}{V_B'}\right)\left[1 - \exp\left(-B\,\frac{pd}{V_B'}\right)\right] = \frac{B}{A}\ln\left(1 + \frac{1}{\gamma}\right)}$$

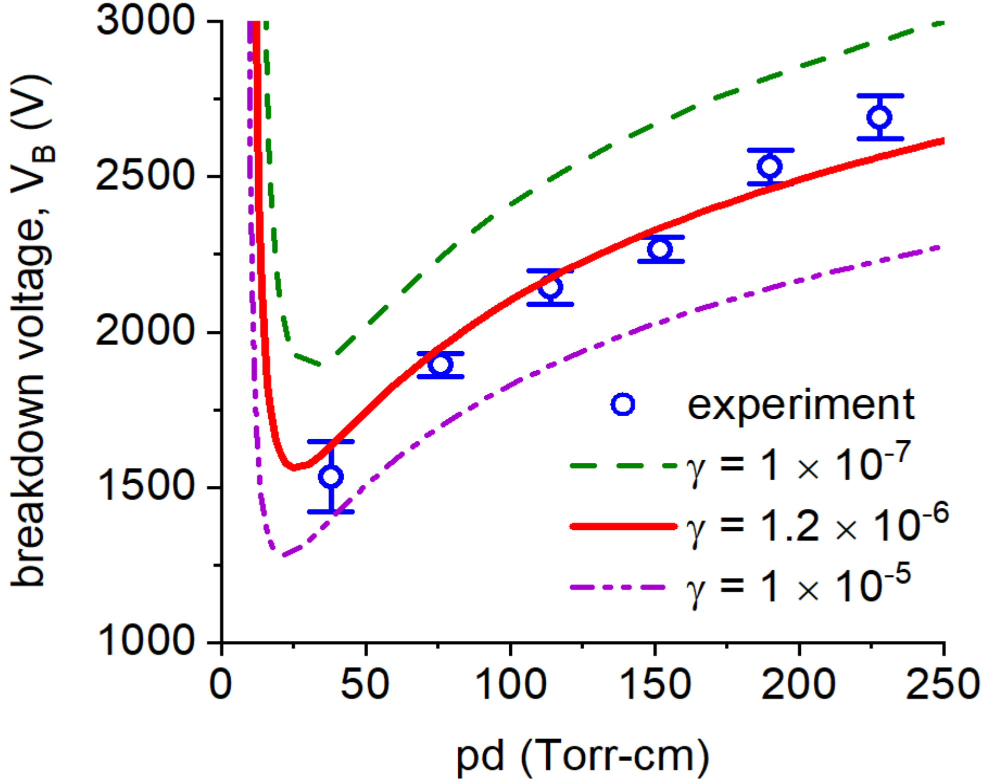
where,

$$V_B' = \frac{V_B}{\ln\left(1 + 2d/R\right)}$$

Estimate γ by measuring V_B at different *pd* values

Small Fraction of Bombarding Ions Result in an Electron Being Emitted

Breakdown voltage as a function of *pd*



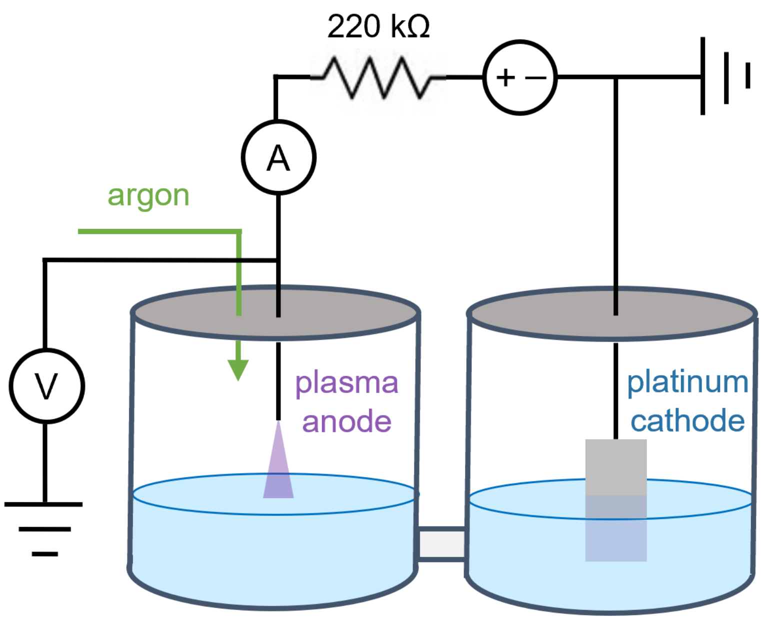
Best fit → $\gamma = 1 \times 10^{-6}$

- maximum γ of ~ 10^{-5}
- secondary emission mechanism is very inefficient

Delgado, Elg, Bartels, Rumbach, & Go, *Langmuir*, **36**, 1156 (2020)

Plasma Voltage Indicator of the Secondary Emission

split cell reaction system



system characteristicss

- argon headspace
- 10 mA current
- 1 mm capillary-liquid separation

$$V_{system} = V_{liquid} + V_{plasma}$$

~ 0 at high ionic strengths

If a critical variable for secondary emission is removed, the gas might not transition into a plasma

Chemical Scavengers Remove Potential Contributors to Secondary Emission

Nitrite (NO_2^-)

$$e_{aq}^- + NO_2^- \rightarrow NO_2^{2-}$$

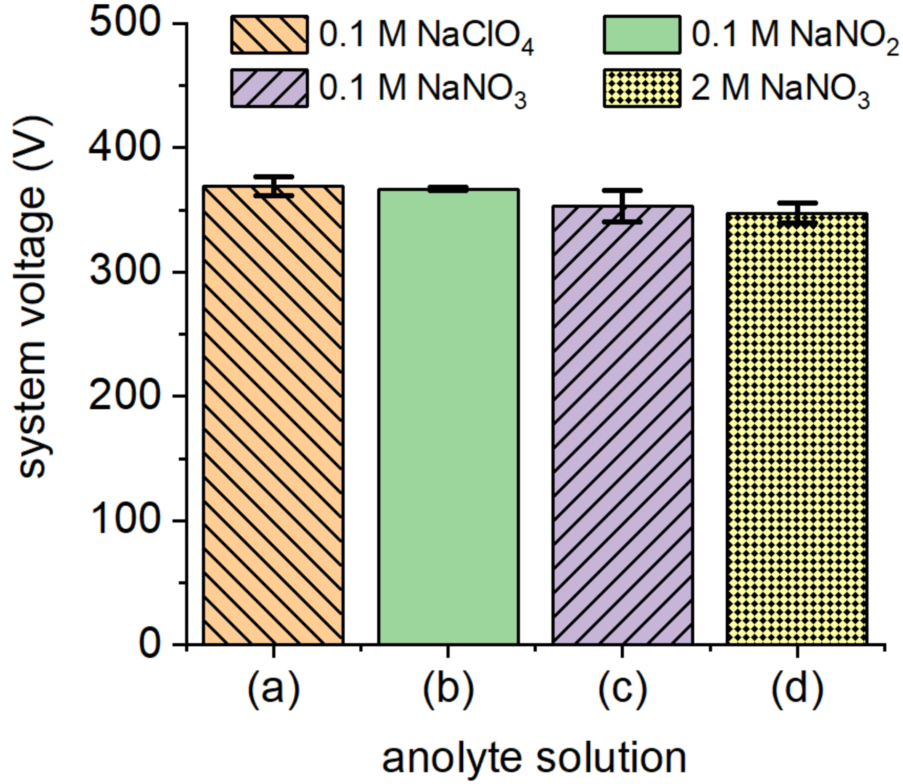
$$H\cdot + NO_2^- \rightarrow OH^- + NO$$

$$\cdot OH + NO_2^- \rightarrow OH^- + \cdot NO_2$$

Nitrate (NO_3^-)

$$e_{aq}^- + NO_3^- \rightarrow NO_3^{2-}$$

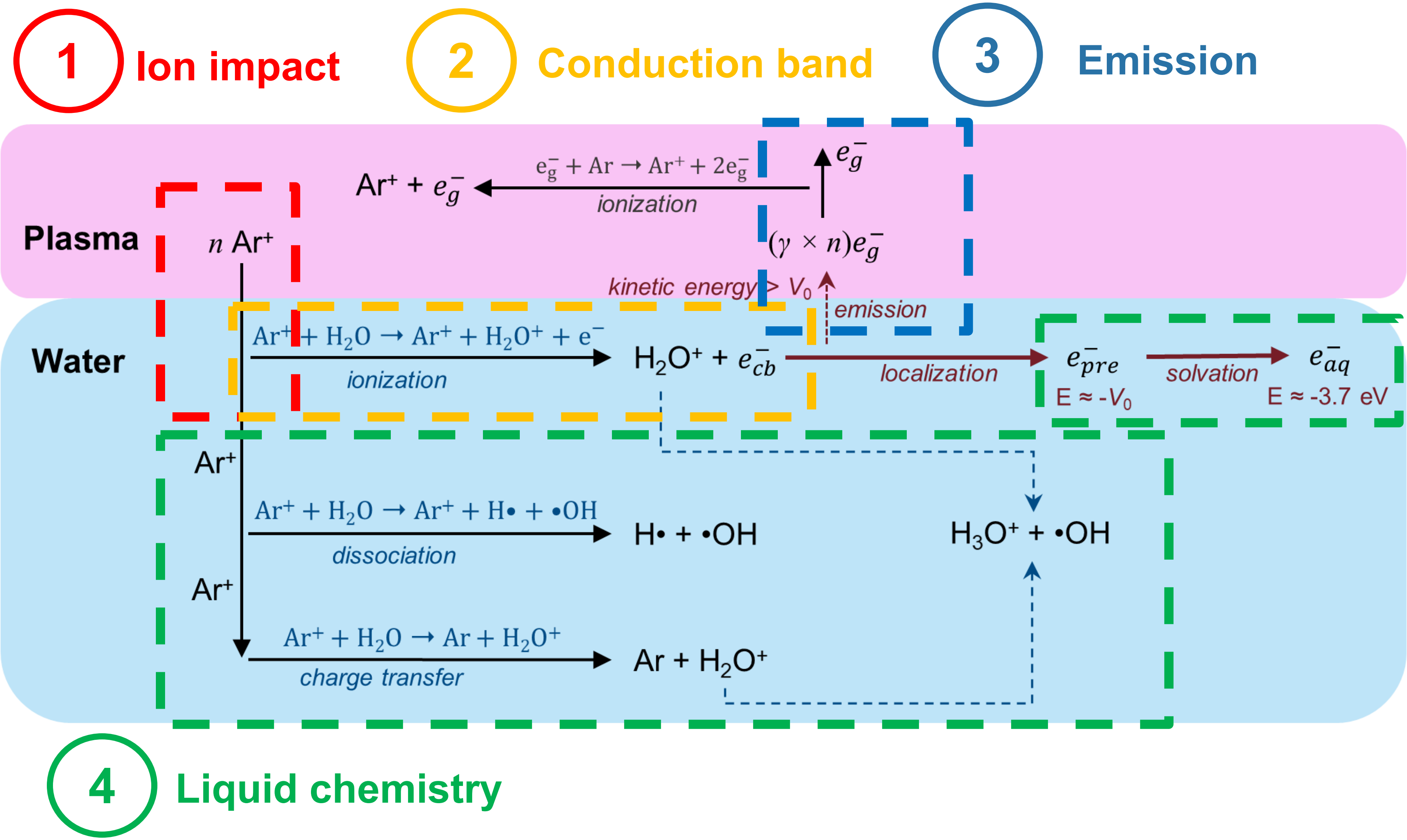
$$e_{pre}^- + NO_3^- \rightarrow NO_3^{2-}$$



- **plasma-liquid chemistry has no effect on system voltage**
- **emitted electron is never solvated or pre-solvated**

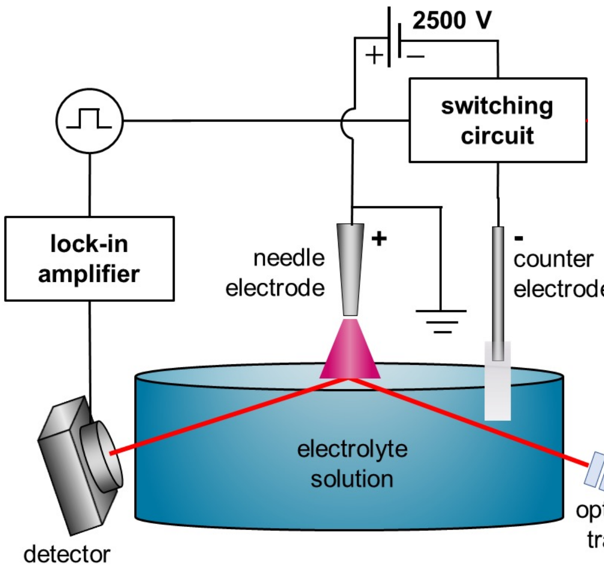
Delgado, Elg, Bartels, Rumbach, & Go, *Langmuir*, **36**, 1156 (2020)

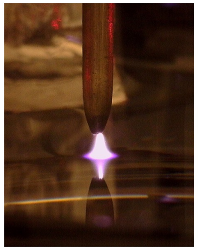
Possible Process for Secondary Emission

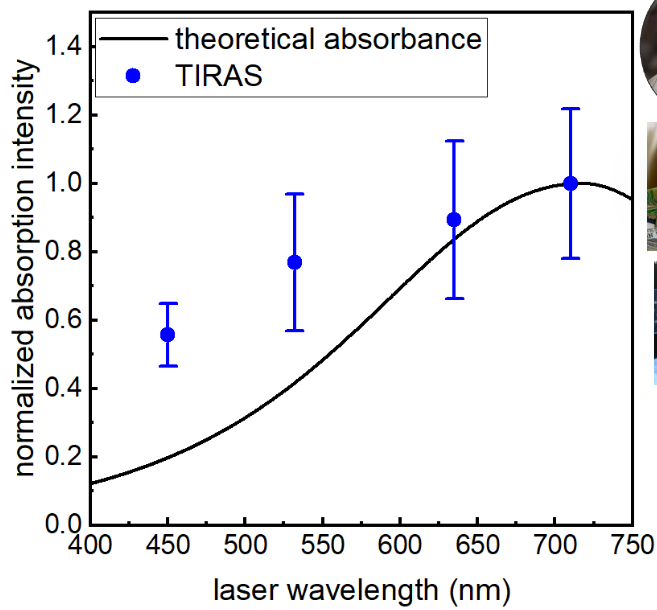


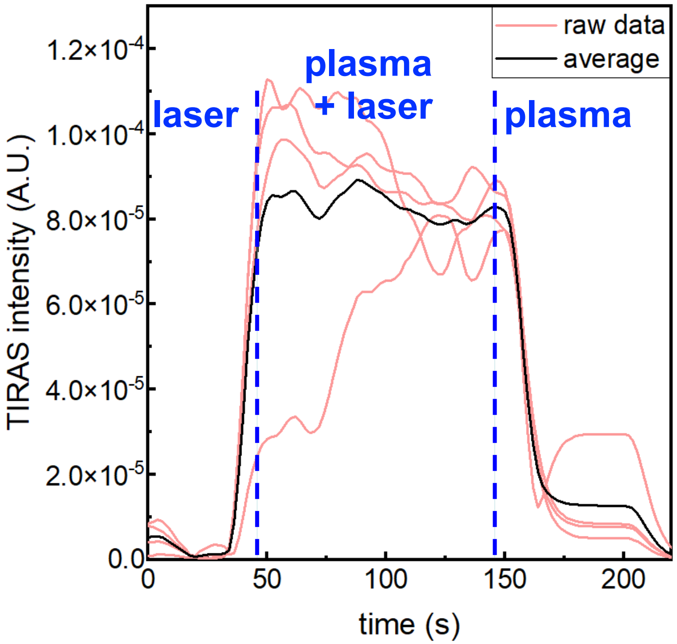
Delgado, Elg, Bartels, Rumbach, & Go, *Langmuir*, **36**, 1156 (2020)

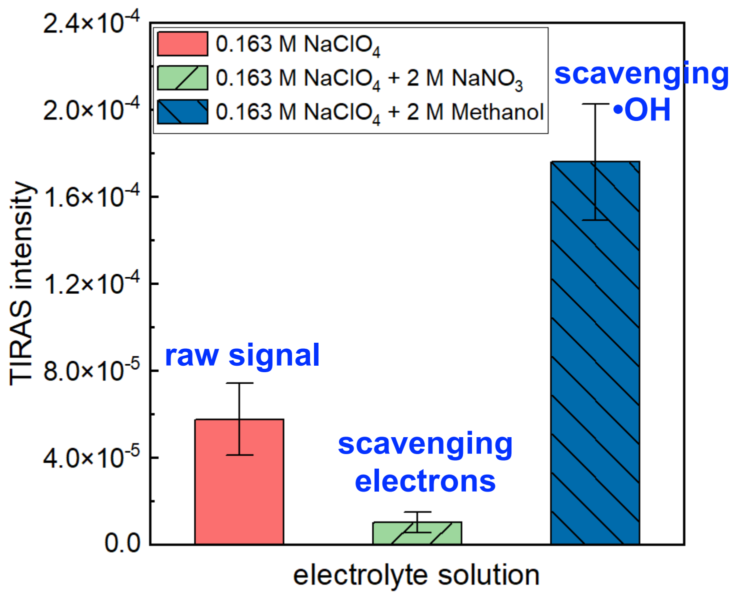
Do We Even Know There Are Solvated Electrons?











Martin et al., *Langmuir*, **40**, 14224 (2024)

How Many Ions Produce a Solvated Electron?

$$e_{aq}^- + ClCH_2COOH \rightarrow Cl^-CH_2COOH, \qquad k_3 = 6.5\times10^9\ mol^{-1}s^{-1}$$

$$e_{aq}^- + e_{aq}^- + 2H_2O \rightarrow H_2 + 2OH^-, \qquad k_4 = 5\times10^9\ mol^{-1}s^{-1}$$

$$e_{aq}^- + H_3O^+ \rightarrow H + H_2O, \qquad k_5 = 3\times10^{10}\ mol^{-1}s^{-1}$$

$$\frac{1}{\eta_{Cl^-}} = \cancel{\frac{1}{\eta_{e_{aq}^-}} \frac{k_4[e_{aq}^-] + k_5[H_3O^+]}{k_3[ClCH_2COOH]}} + \frac{1}{\eta_{e_{aq}^-}}$$

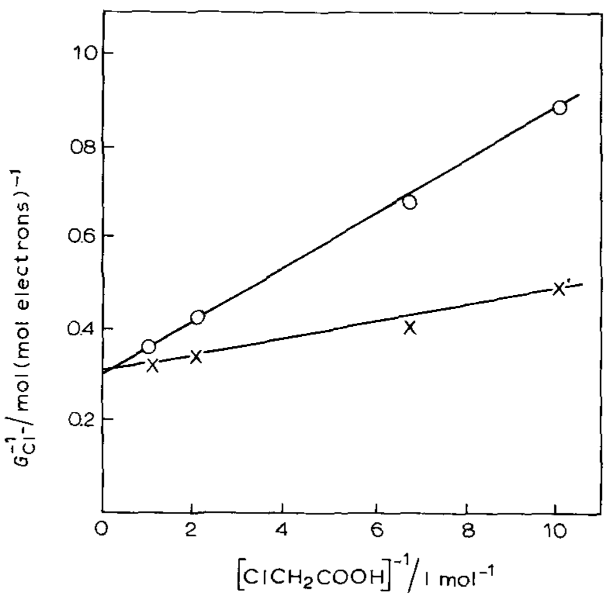
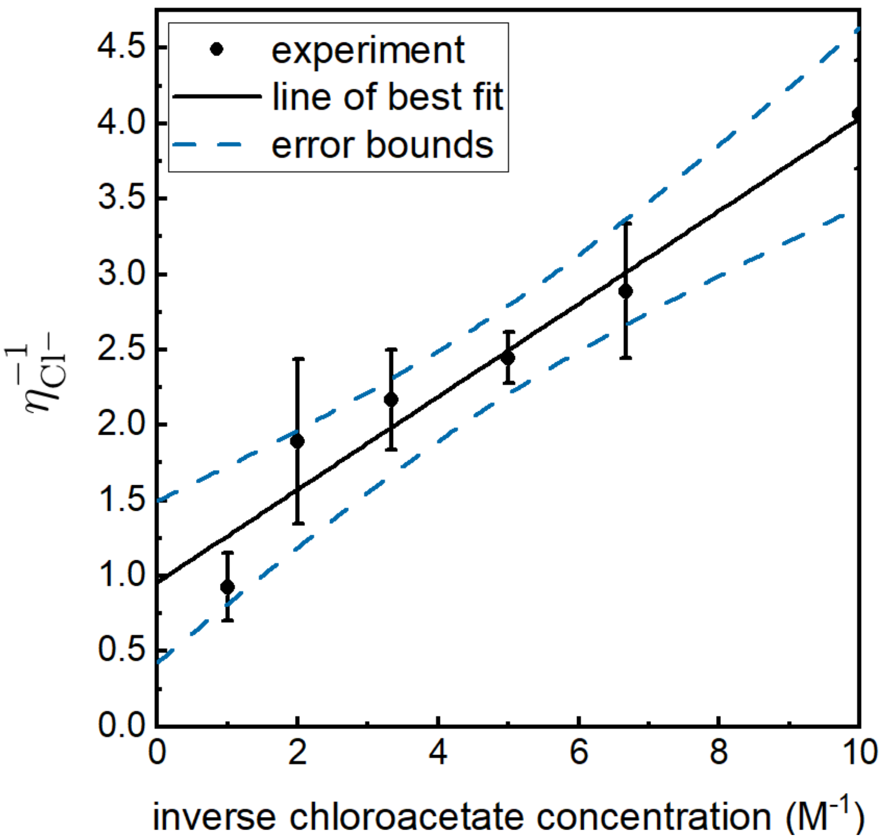


Fig. 1. Plot of G_{Cl}^{-1} *versus* $[ClCH_2COOH]^{-1}$, in (○), 0.5 *M* H_2SO_4; (×), H_2O.

in an H_2 atmosphere
~3.3 electrons per ion
~2.2 •OH via water dissociation per ion

Goodman et al., 1973, Electroanal. Chem. Interf. Electrochem.

Faradaic Efficiency of the Plasma Anode



in an Ar atmosphere
~1 electron per ion
~ 2 •OH per ion

$$\eta^{-1} = (0.308 \pm 0.098)\boldsymbol{x} + (0.958 \pm 0.543) \rightarrow \boxed{\eta = 1.04 \pm 0.59 \left[\frac{e^-}{\text{incident ion}}\right]}$$

Plasma Electrochemistry for Uranium Extraction

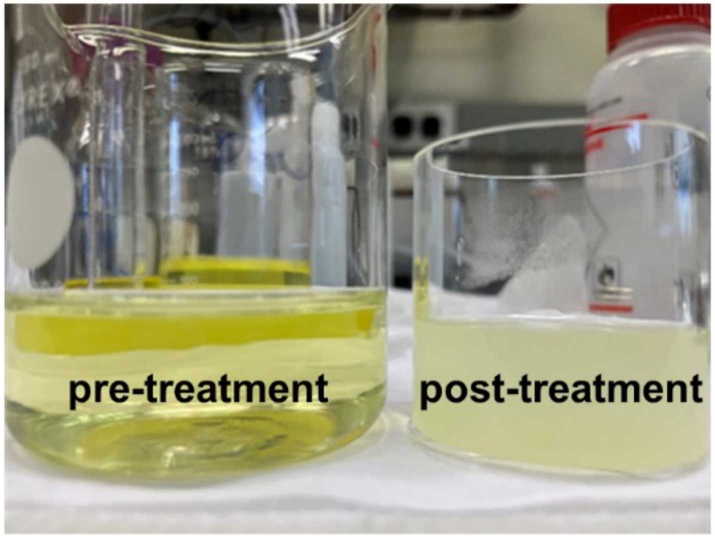
Broad need to recover uranium from water

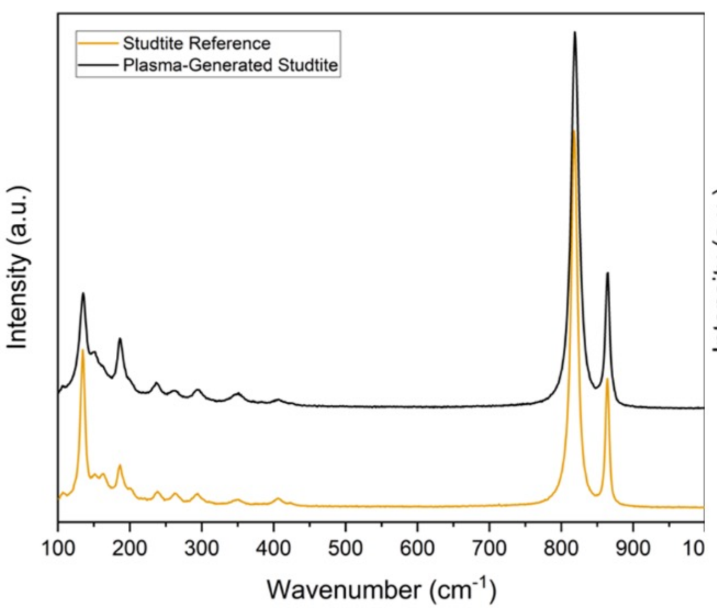
- in situ leach (ISL) mining (56% of world's uranium mining)
- environmental decontamination (mining & weapons programs)
- extraction from seawater

Typically achieved by reacting uranyl with hydrogen peroxide

$$UO_2^{2+} + 4H_2O + H_2O_2 \rightarrow [(UO_2)(O_2)(H_2O_2)_2](H_2O_2)_2 + H_2$$

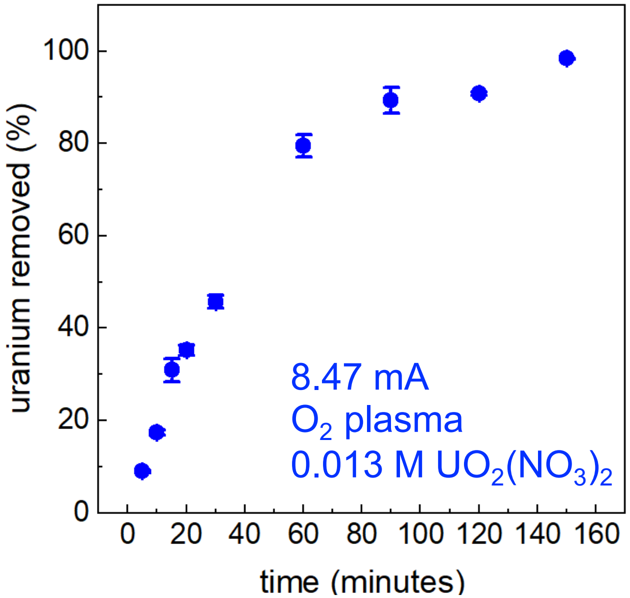
uranyl (sulfate or carbonate) | uranyl peroxide (studtite)





patent pending

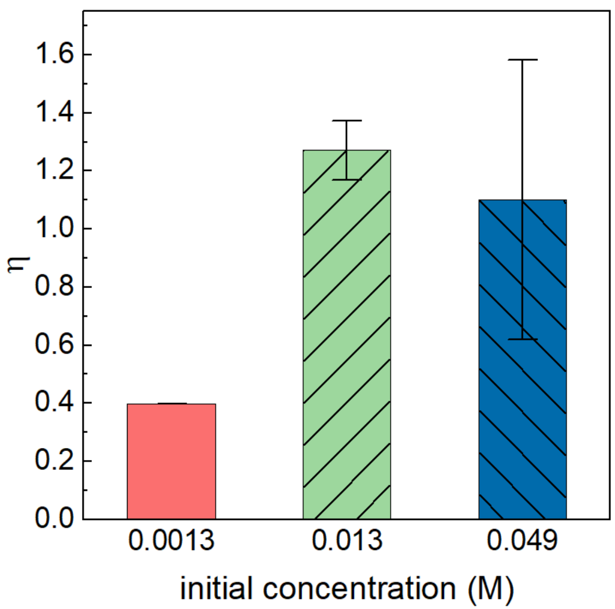
Extraction Can Achieve 100% Faradaic Efficiency

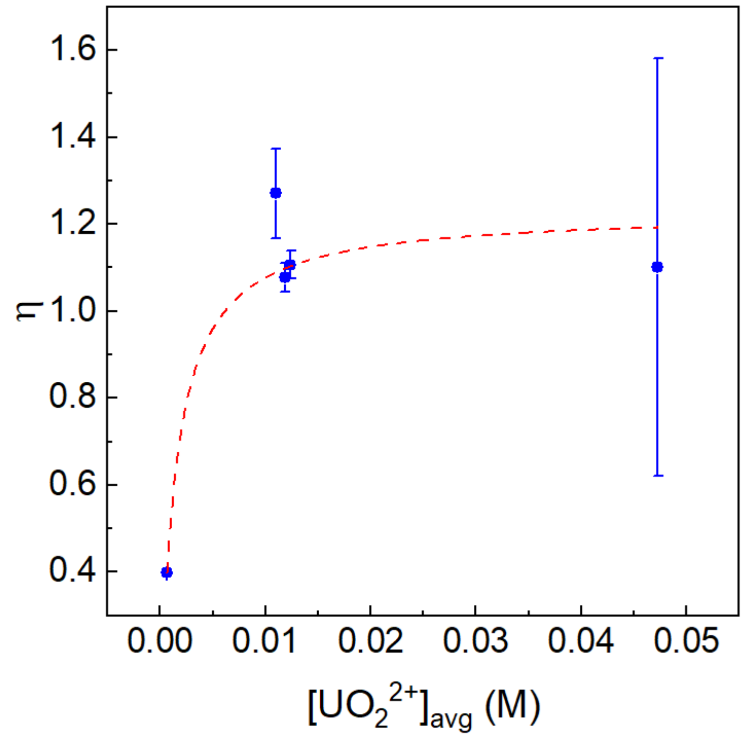


$$UO_2^{2+} + 4H_2O + H_2O_2 \rightarrow [(UO_2)(O_2)(H_2O_2)_2](H_2O_2)_2 + H_2$$

$$\cdot OH + H_2O_2 \rightarrow O_2^- + H_2O$$

$$\eta = \eta_0 \frac{k_{UO_2}[UO_2^{2+}]}{k_{UO_2}[UO_2^{2+}] + k_{OH}\underline{[\cdot OH]}}$$ ~ 2 •OH per ion

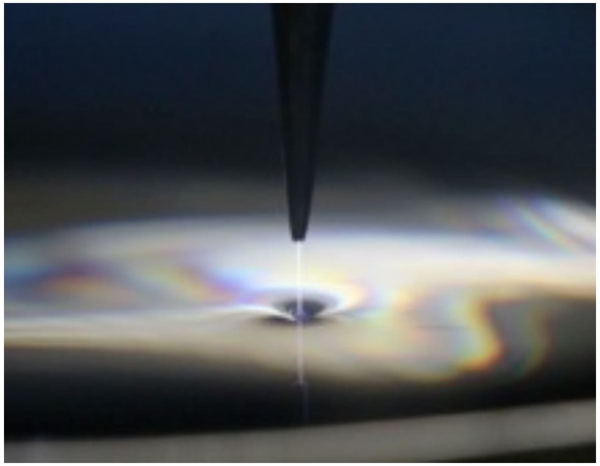




Benjamin, Martin et al., *Inorg. Chem.*, **63**, 21092 (2024)

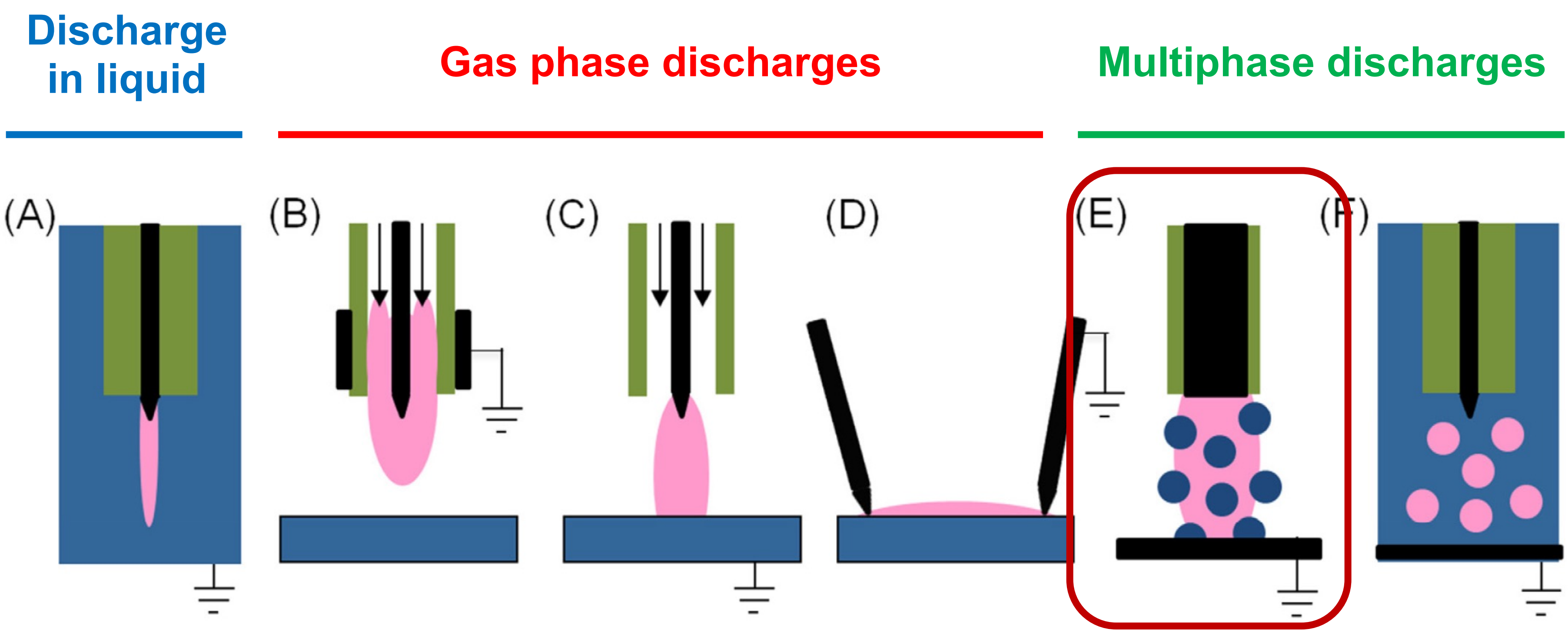
Revolutionizing Goods Production: Two Stories

Plasma Electrochemistry



Plasma-Driven Material Processing

A Diverse Landscape of Interfaces



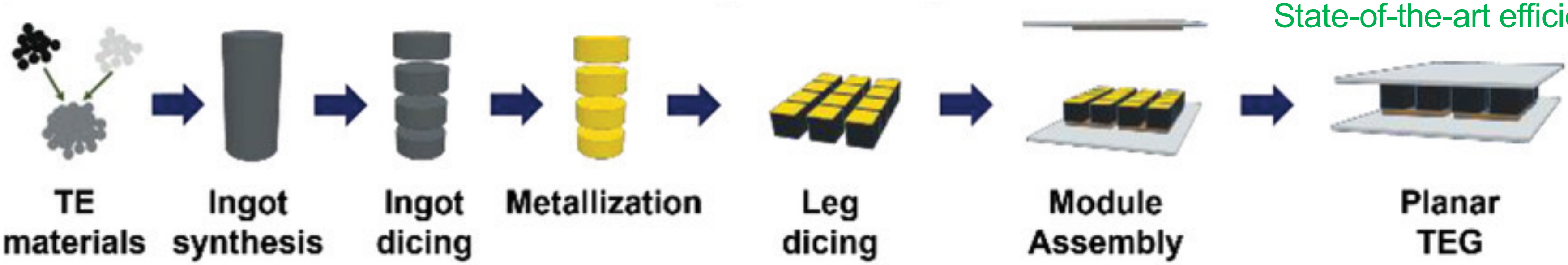
A) Direct discharge in liquid
B) Plasma jet
C) Gas phase plasma with liquid electrode
D) Surface discharge
E) Gas discharge in aerosols
F) Gas discharge in bubbles

Bruggeman et al. *Plasma Sources Sci. Technol.*, **25**, 053002 (2016).

Advanced Manufacturing of Thermoelectrics

Time consuming
Uses more material
Large material waste
Assembling challenges
State-of-the-art efficiency

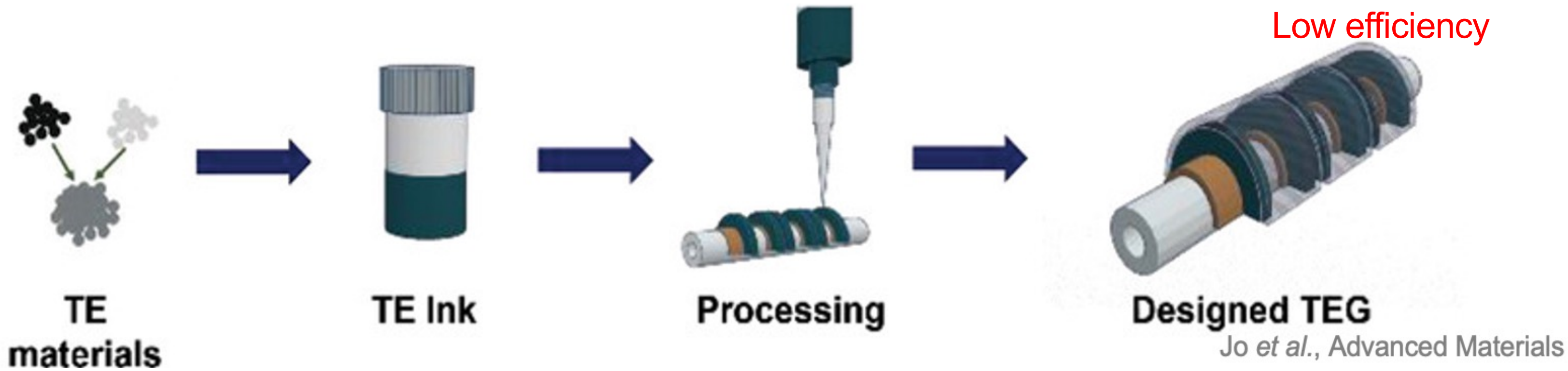
Bulk material-based manufacturing of thermoelectric modules



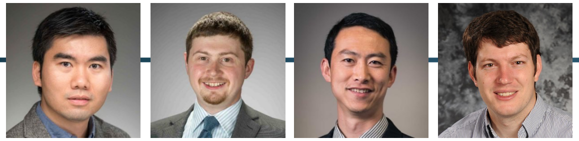
semanticscholar.org

Needs less material
Little material waste
No assembling needed
10× larger power density
90% cost reduction
Low efficiency

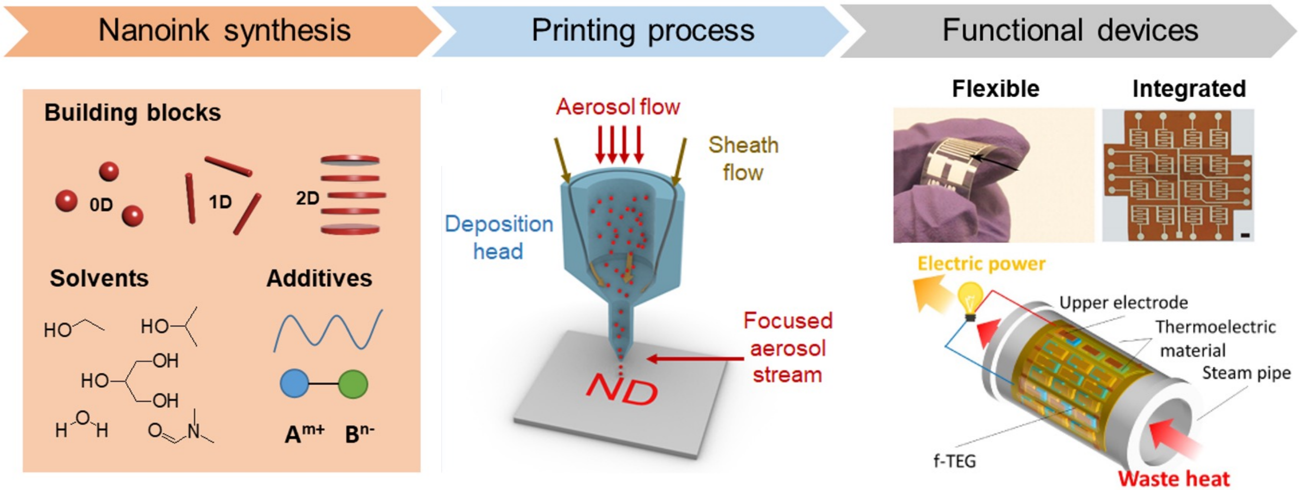
Ink-based additive manufacturing for thermoelectric modules

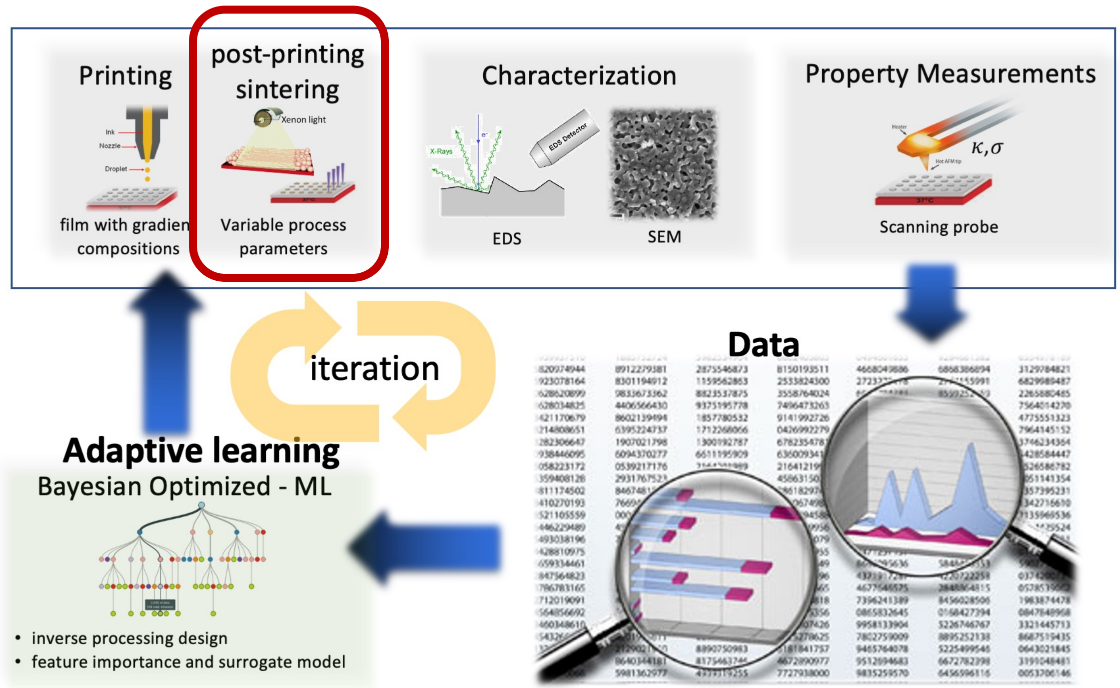


Jo *et al.*, Advanced Materials



Data-Driven Manufacturing Optimization

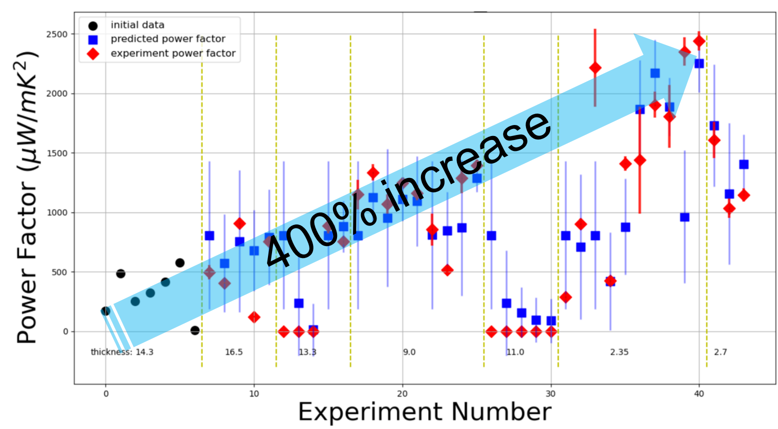




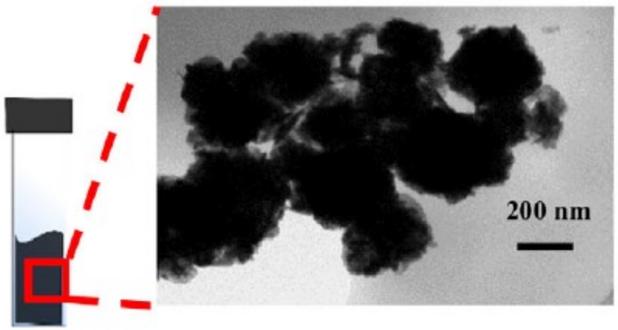
Ink formulation:
composition
solvent
additives
concentration
particle size
….

printing:
printing speed
flow rate
thickness
substrate temperature
substrate material
….

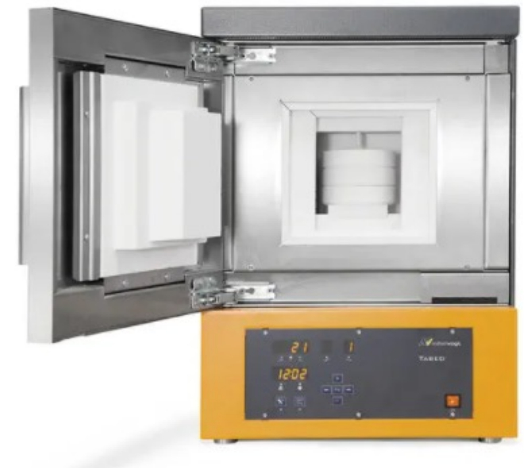
sintering:
sintering temperature
environment
duration
plasma carrier gas
voltage
….



Can Non-Thermal Plasmas Tackle Sintering?



Danaei, R. *et al. Advanced Engineering Materials* 21, 1800800 (2019)



https://www.medicalexpo.com/

nanoink preparation → print thin film → oven sintering

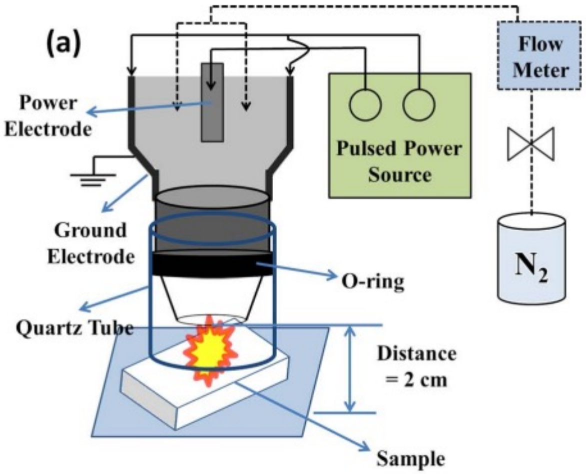
high temperature-activation for several hours

- **> 400 °C**
- **45 min – 3 h**

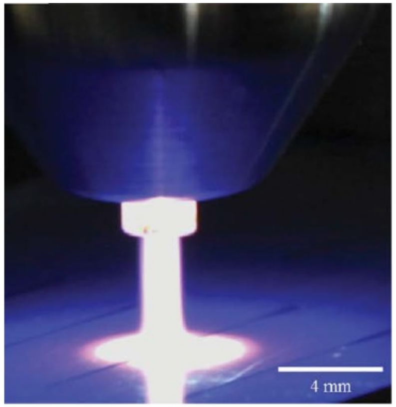
Kamyshny et al., *Small* , **10**, 3515–3535, 2014

Can Non-Thermal Plasmas Tackle Sintering?

N_2 plasma sintering of AlN/CNT
Substrate temperature = 700 ℃



N_2 plasma sintering of TiO_2
Substrate temperature = 500 ℃



Ar plasma sintering of Ag
Substrate temperature < 70 ℃

700 °C | 500 °C | 400 °C | 50 °C

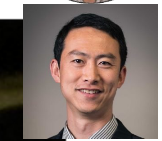
Substrate Temperature

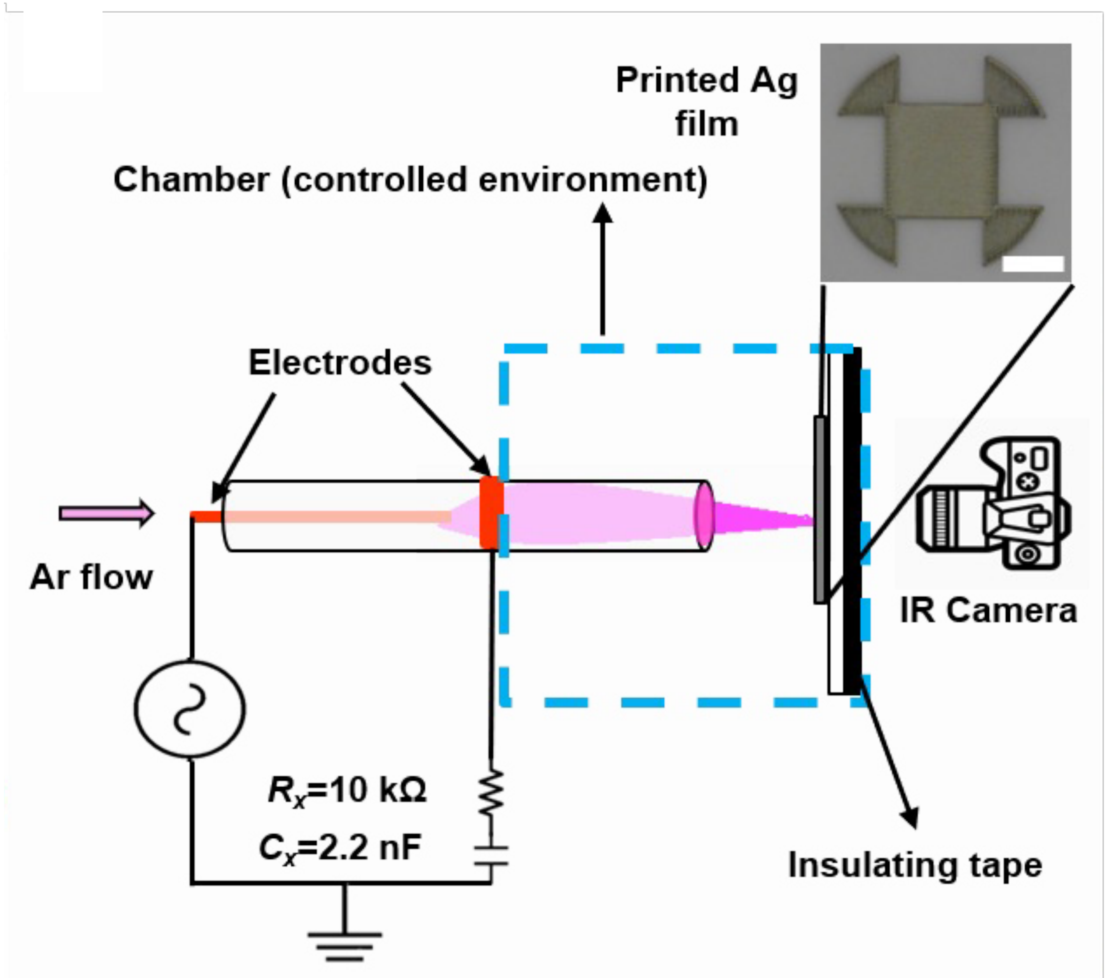
Chiu, Y.-F. *et al. Applied Surface Science* 377, 75–80 (2016)

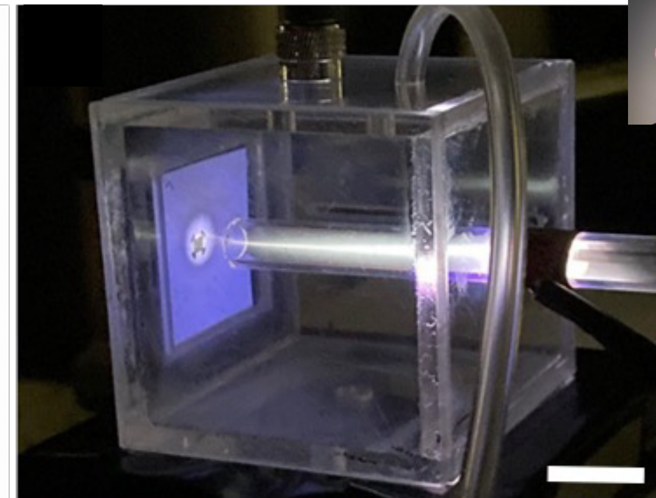
Wang, C. *et al. ECS Journal of Solid State Science and Technology* 4, P3020–P3025 (2015)

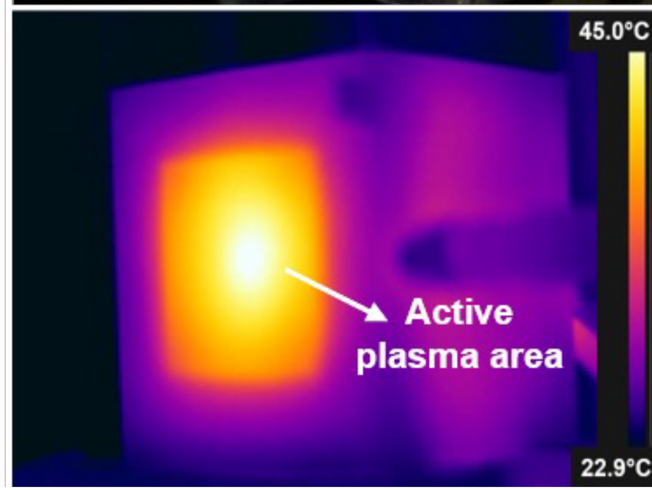
Wünscher, S. *et al. Journal of Materials Chemistry* 22, 24569 (2012)

Plasma Jets for Low-Temperature Sintering







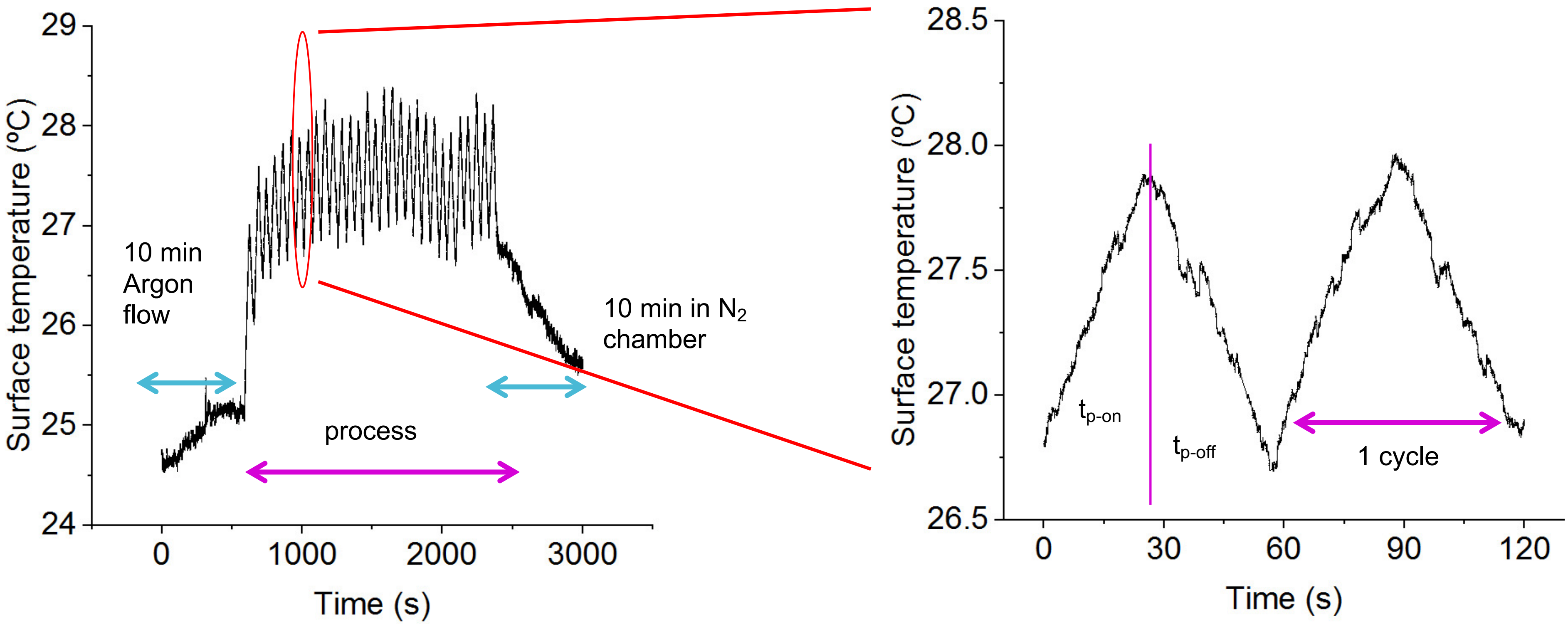


Substrates:
- Glass
- PEL paper

Gas composition:
- Flowing: 1500 sccm Ar
- Chamber: 10 sccm N_2

Thin films: 1-layer printed with Clariant's PRELECT® TPS Nano Silver Conductive Ink (30-50 nm particles)

Modulation for Near Room Temperature Conditions



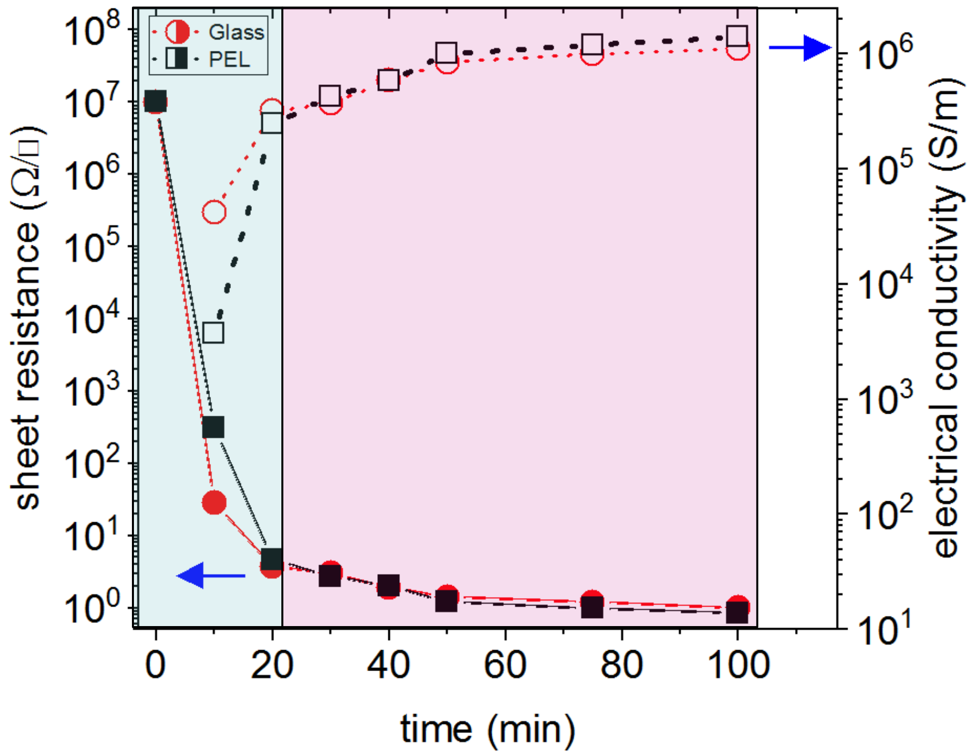
- ➢ **Trade-off:** The cooling down time during the plasma-off portion of the cycle does not affect sintering or the conductivity considerably
- ➢ **Advantage:** Sintering on temperature-sensitive components

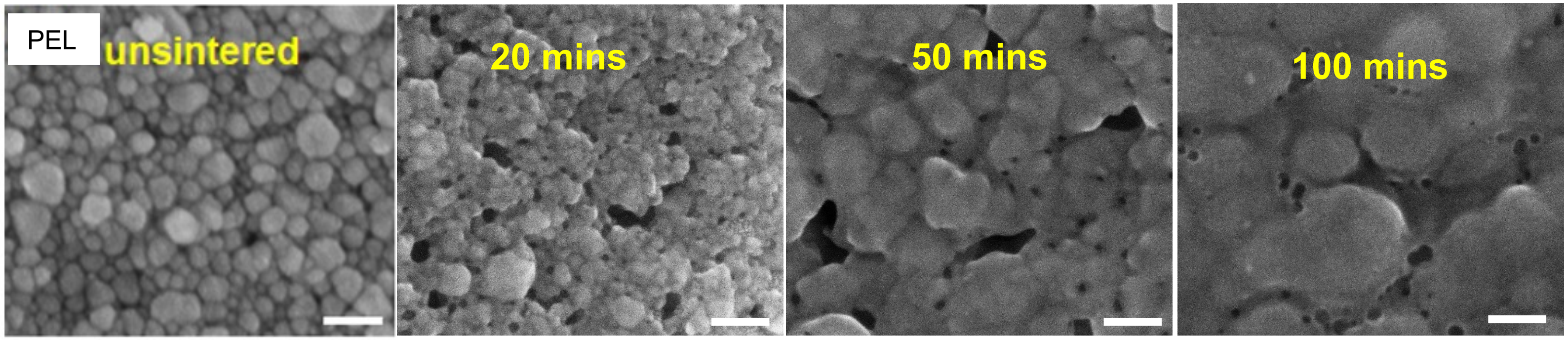
Turan, Saeidi-Javash, et al., *ACS Appl. Mater. Interfaces.* **13**, 47251 (2021)

Plasma Jet Sintering Achieved

<u>First Phase (first 20 min)</u>:
removal of surfactants in the ink by energetic plasma ions and electrons that dissociate chemical stabilizers

<u>Second Phase (20-100 min)</u>:
densification driven by diffusion processes

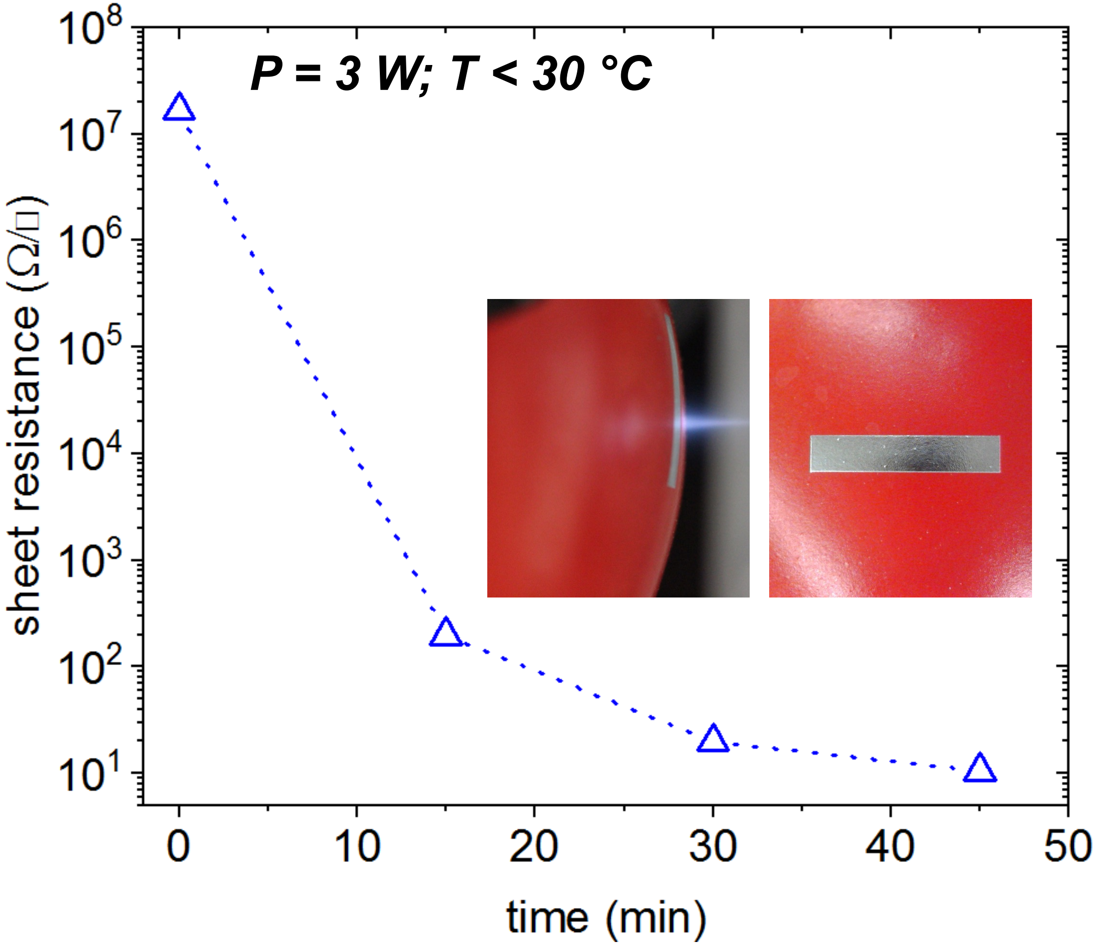


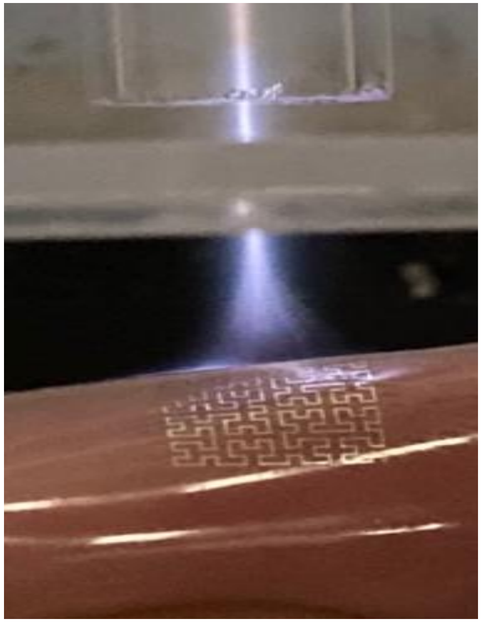


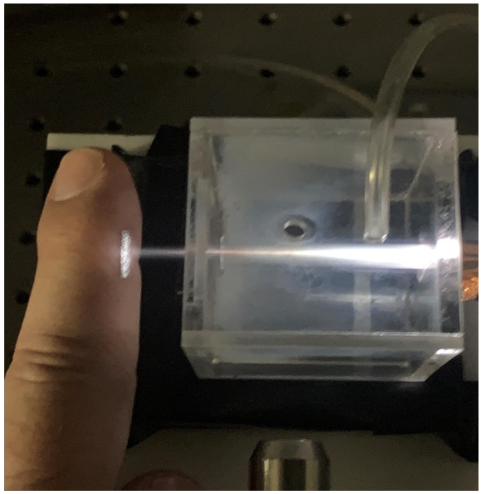
Scale bar:50 nm

Plasma Jet Sintering on 'Delicate' Substrates

sintering on the flesh of a ripe tomato

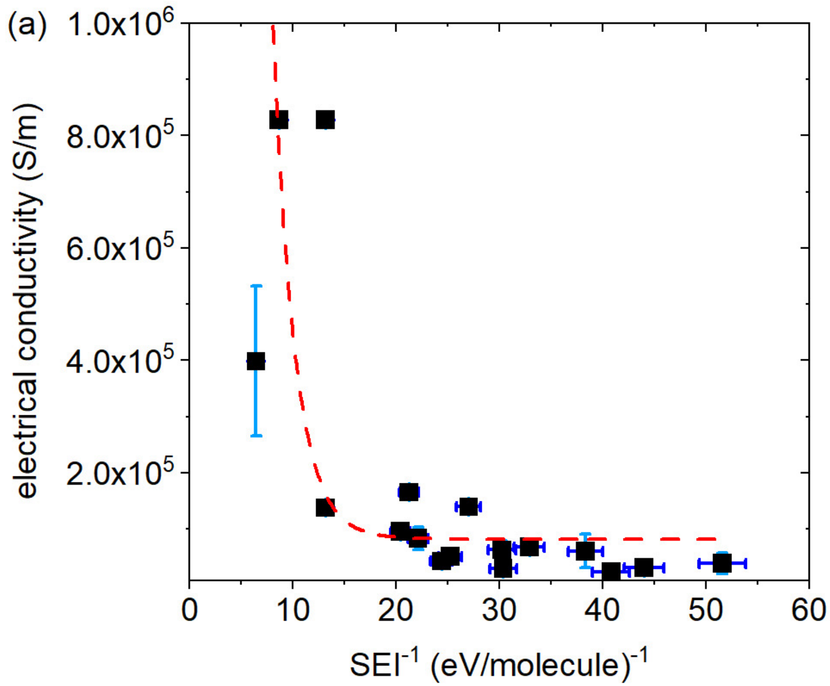


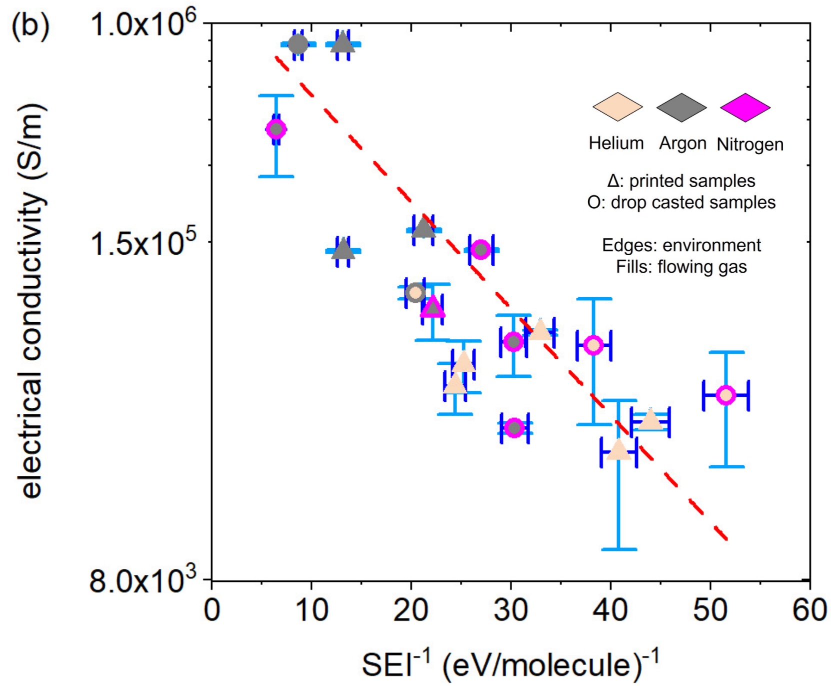




Evidence for Arrhenius-Like Relationship

the electrical conductivity of the film after 2 min of plasma exposure for 17 different SEI conditions





- The most effective conditions occur **at high SEI**
- Linear fit of the data shows that the electrical conductivity (after 2 min of sintering) follows **an Arrhenius-like** $\exp(-\frac{E_c}{SEI})$ **relationship**

Plasma-Integrated Aerosol Jet Printer?

ACS APPLIED MATERIALS & INTERFACES

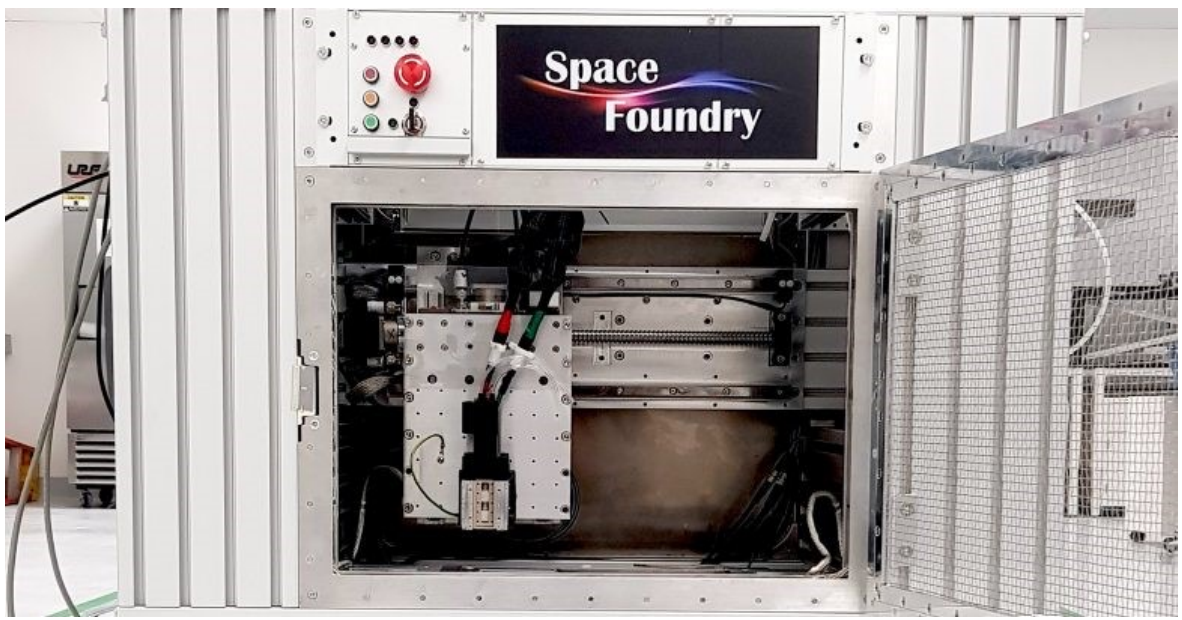
Research Article

www.acsami.org

Plasma Jet Printing of Electronic Materials on Flexible and Nonconformal Objects

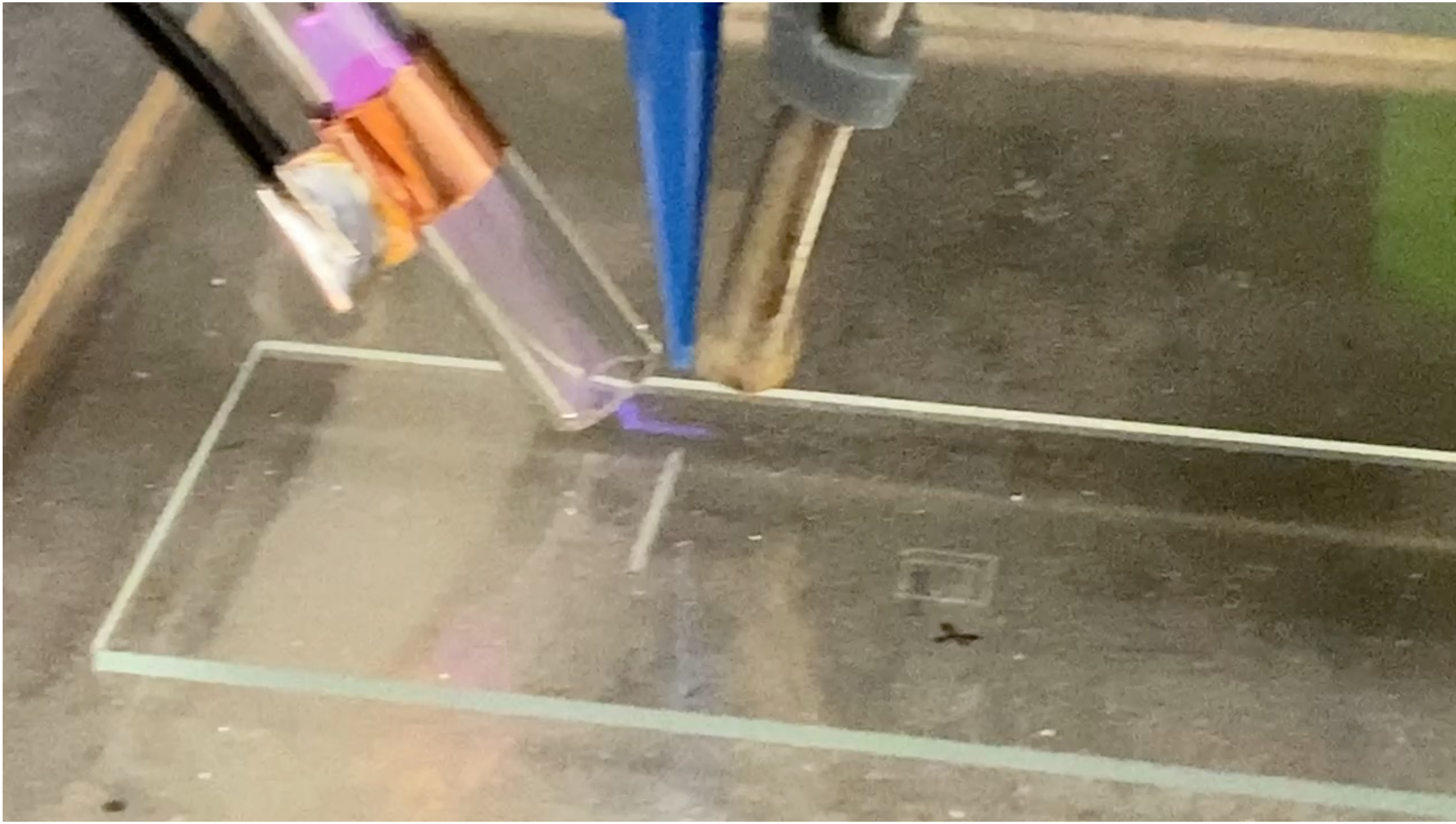
Ram P. Gandhiraman,* Vivek Jayan, Jin-Woo Han, Bin Chen, Jessica E. Koehne, and M. Meyyappan

NASA Ames Research Center, Moffett Field, California 94035, United States



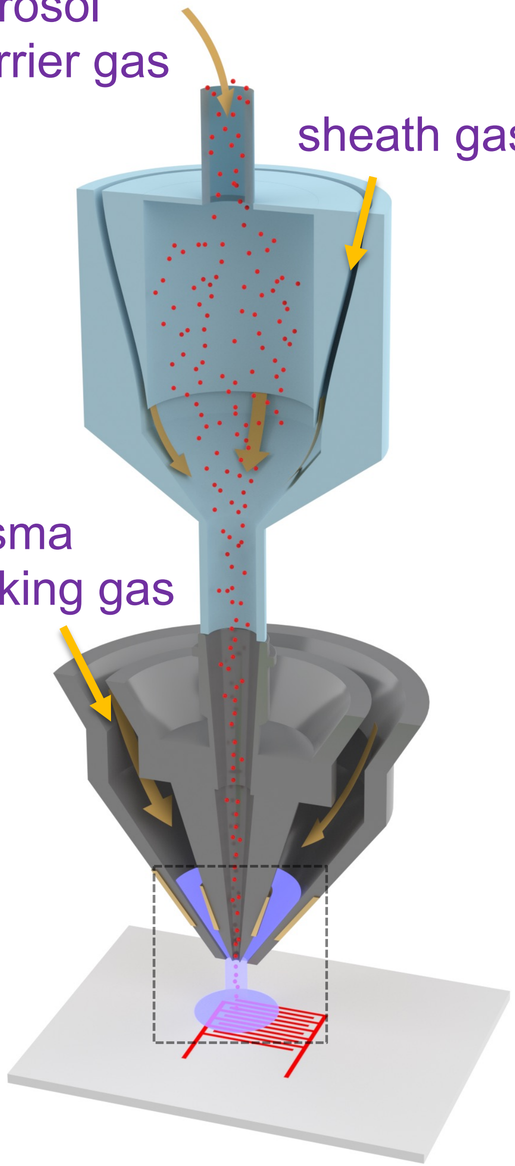
www.spacefoundry.us

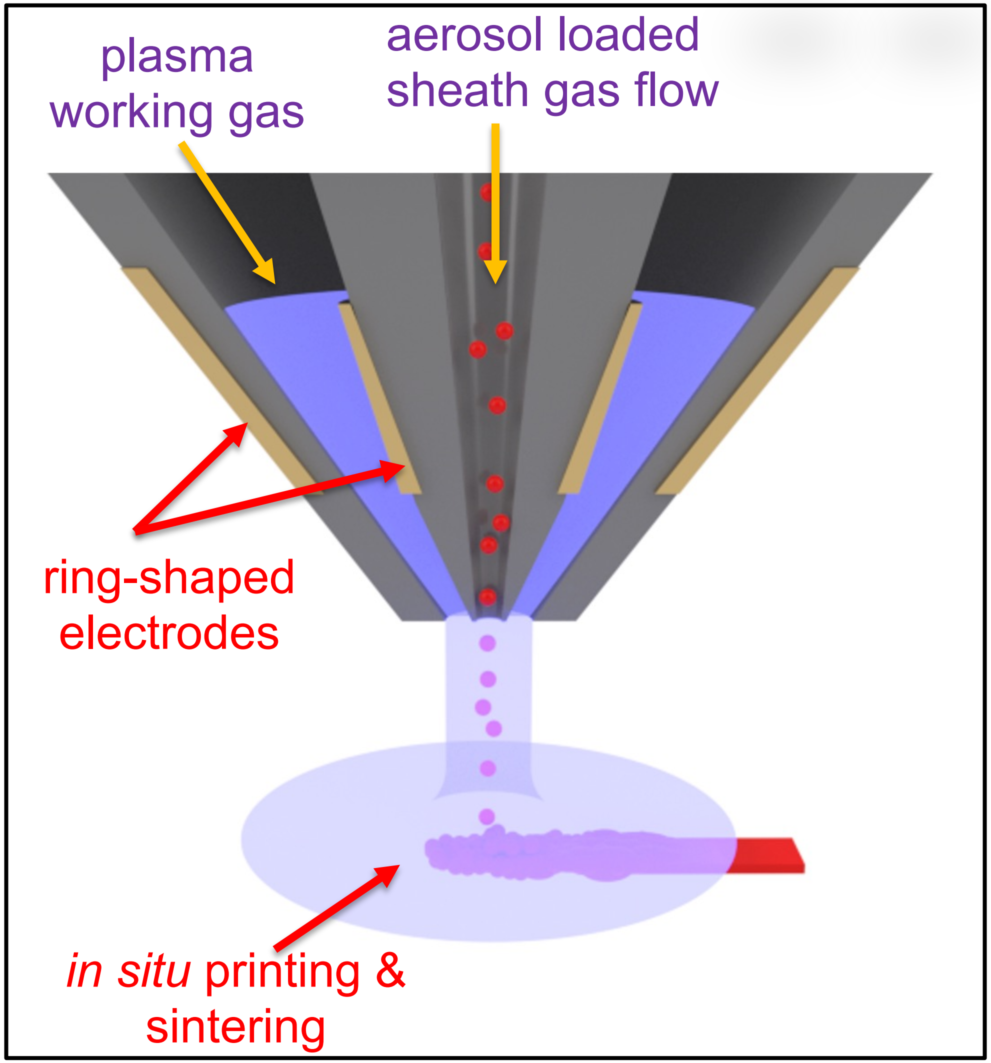
First Generation: Parallel Jets



Second Generation: Co-Axial Jets



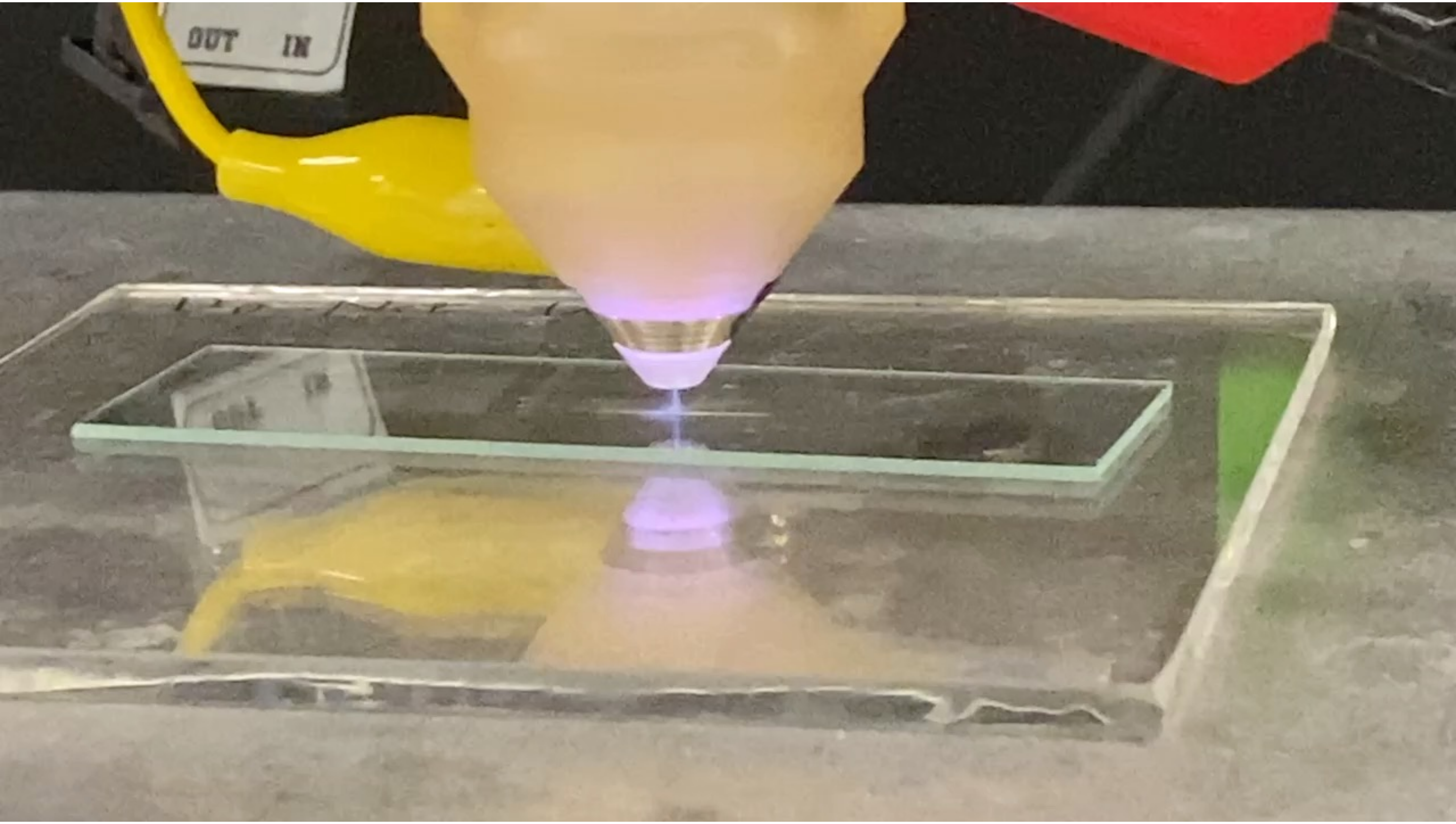




patent pending

Du, Yang et al., *Small*, **21**, 2409751 (2025)

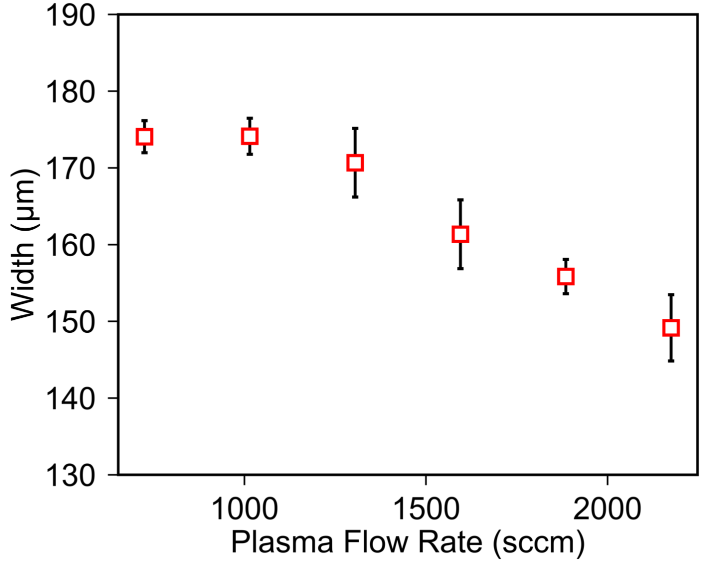
Second Generation: Co-Axial Jets

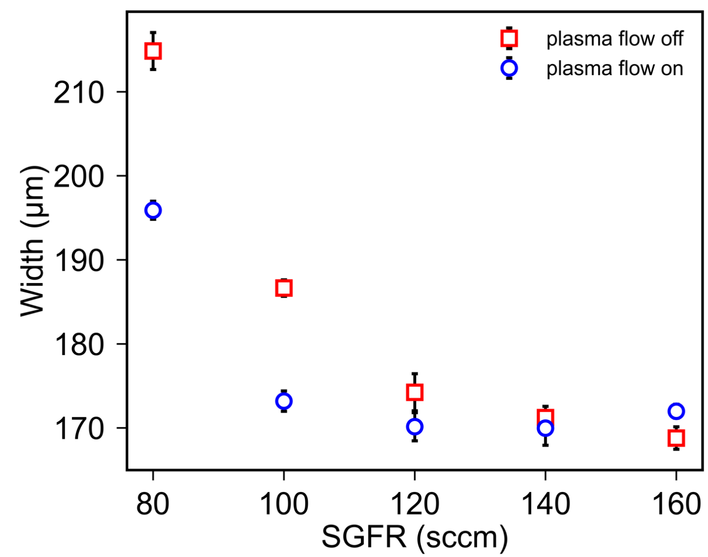


Du, Yang et al., *Small*, **21**, 2409751 (2025)

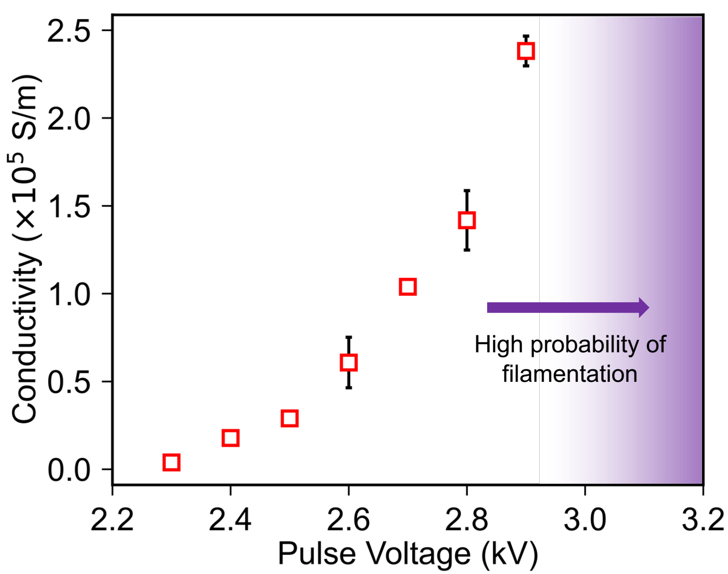
Parameter Variation: Resolution & Performance

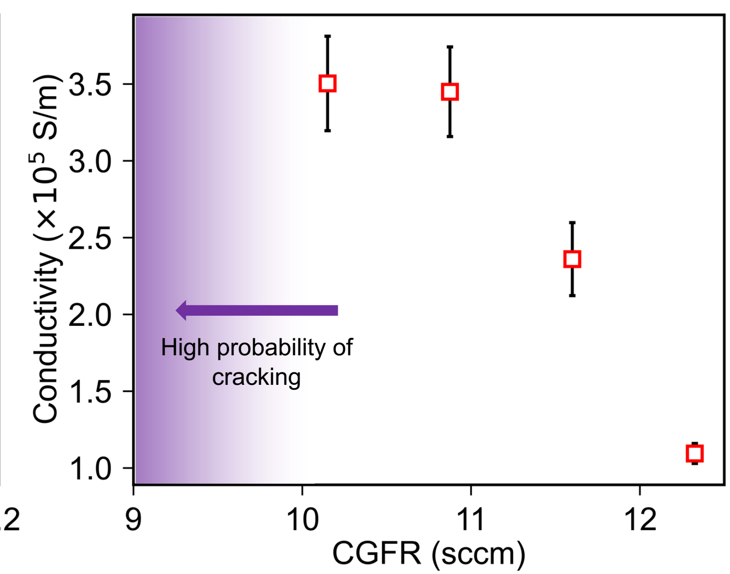
- Both plasma gas and sheath gas affect print resolution





- Challenge to inhibit cracking of the film as it leads to low conductivity and plasma-driven damage





Du, Yang et al., *Small*, **21**, 2409751 (2025)

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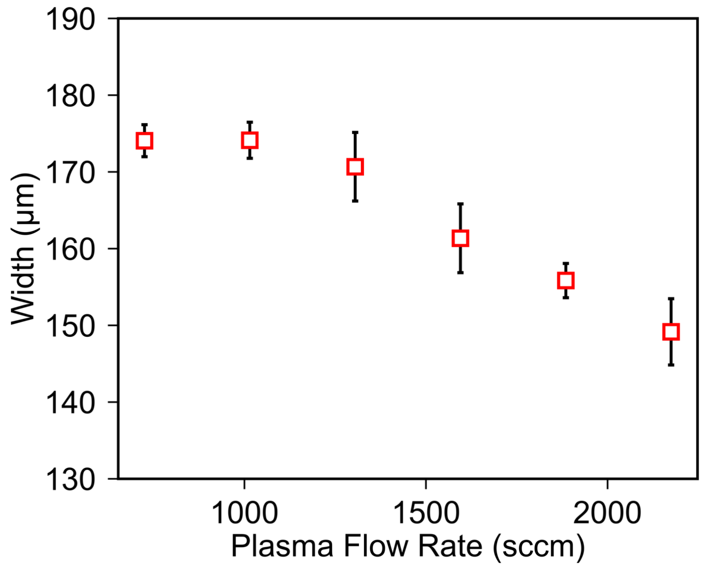
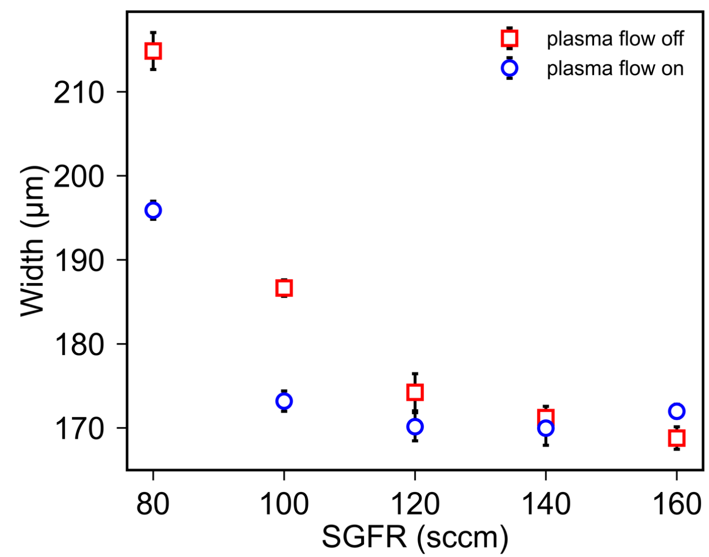
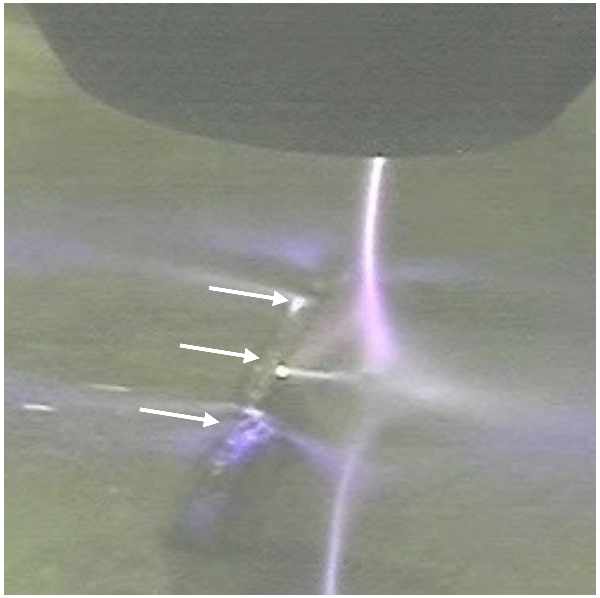


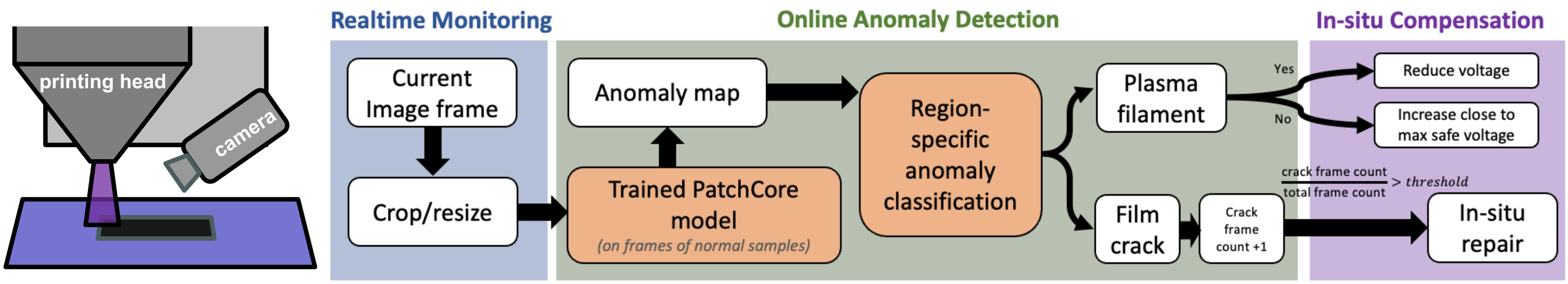


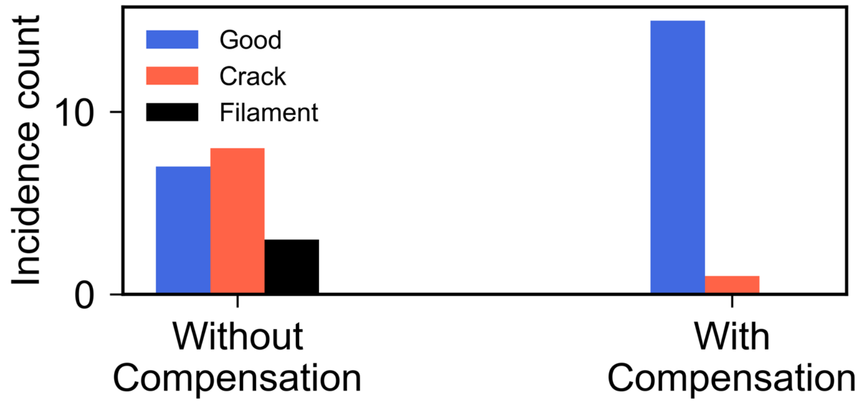
- **Challenge to inhibit cracking of the film as it leads to low conductivity and plasma-driven damage**

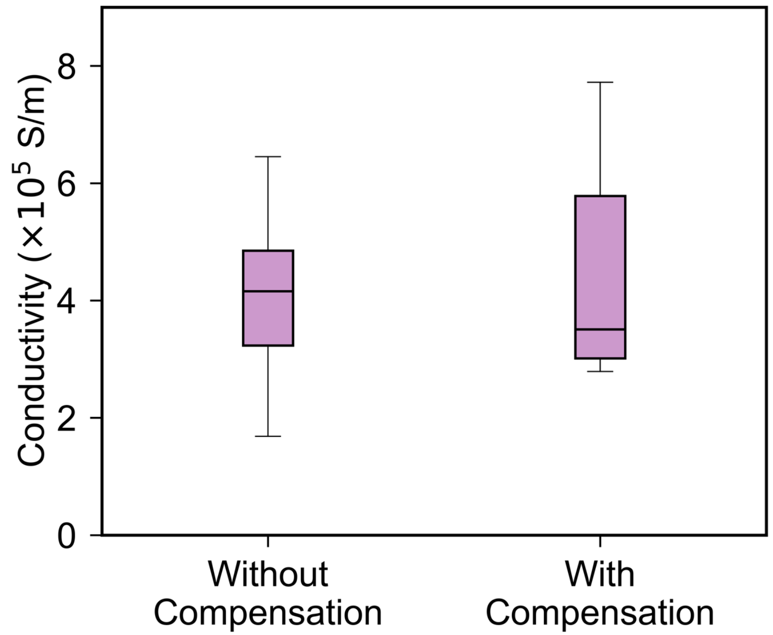


Du, Yang et al., *Small*, **21**, 2409751 (2025)

ML-Based Real Time Control

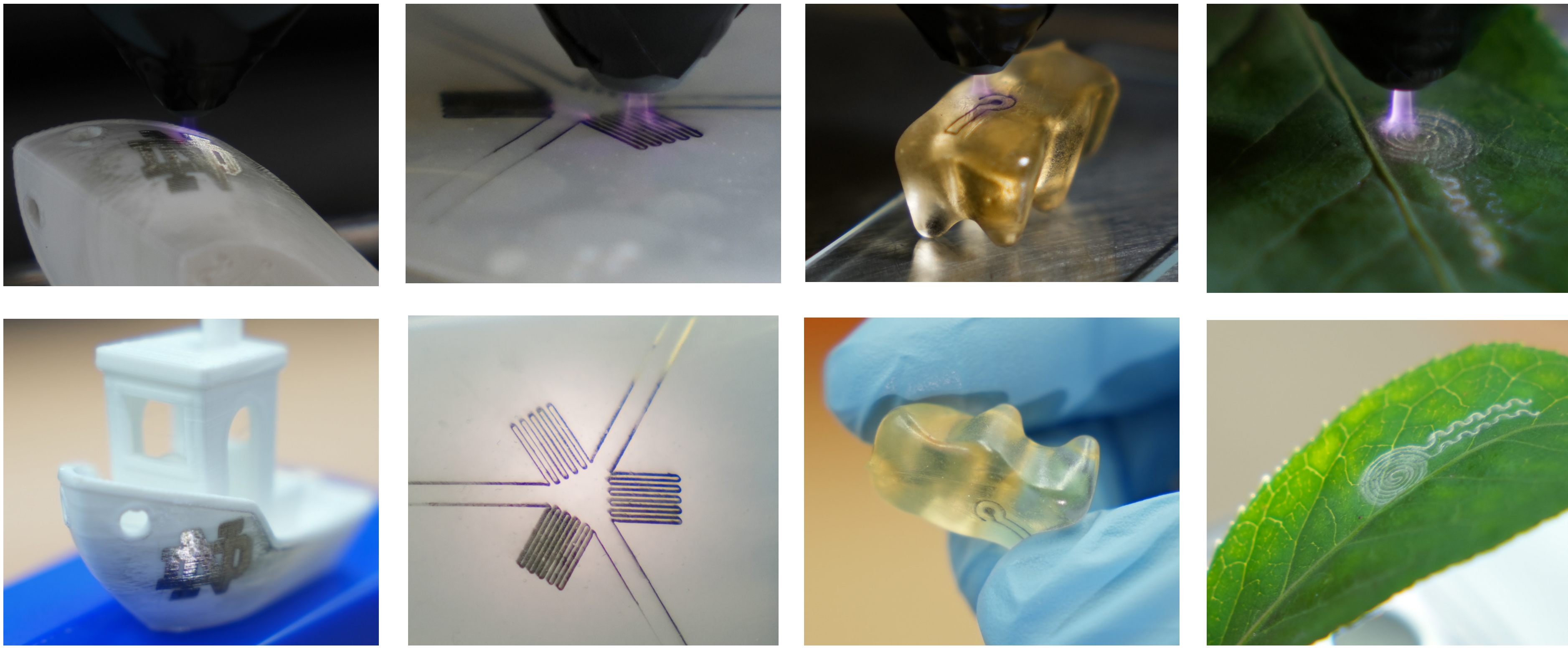






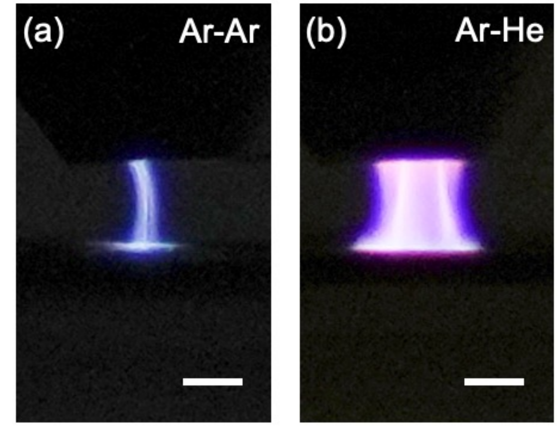
- ML-enabled monitoring allows for higher yield with no impact on performance

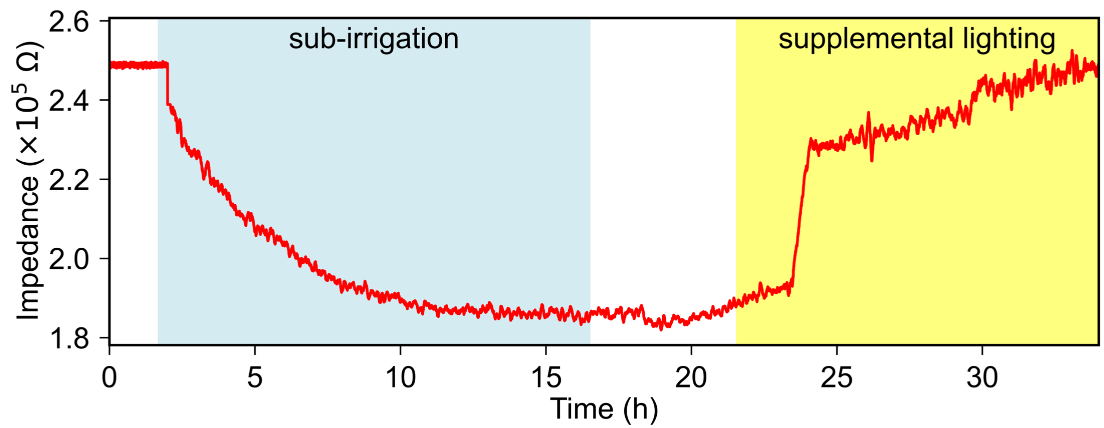
Co-Jet Printing: Rapid, Conformal, Versatile



PLA | Ecoflex | gelatin | leaf

The Potential for Functional Devices

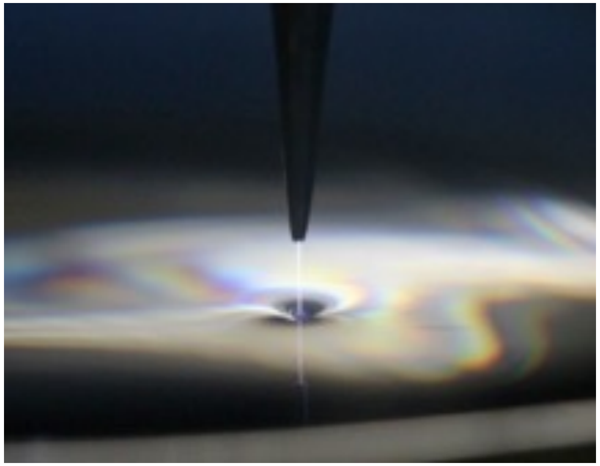




Du, Yang et al., *Small*, **21**, 2409751 (2025)

Revolutionizing Goods Production: Two Stories

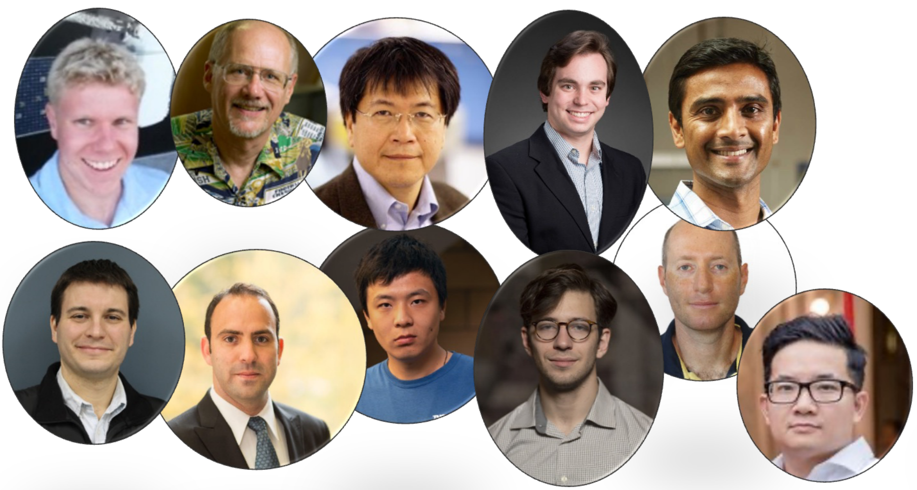
[Plasma Electrochemistry]()



[Plasma-Driven Material Processing]()

Plasma Electrochemistry

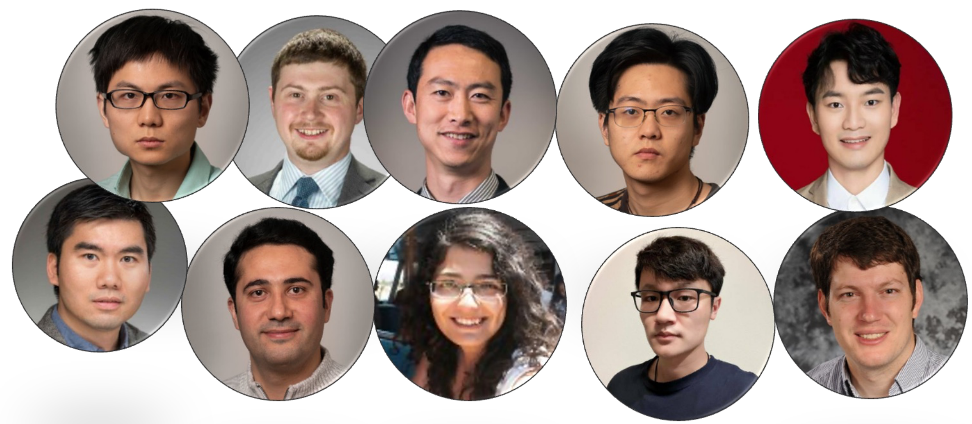
Prof. Paul Rumbach, Dr. David Bartels, **Prof. Mohan Sankaran (Illinois)**, Prof. Chia Chang, **Prof. Daniel Elg** (Southern Indiana), Prof. Felipe Veloso (UC|Chile) **Dr. Hernan Delgado**, Dr. Jinyu Yang, Dr. Oles Dubrovski, **Dr. Daniel Martin, Dr. Hoang Nguyen**



ARO W911NF-17-1-0119
ARO W911NF-23-1-0010
DOE Rickover Fellowship

Plasma-Driven Material Processing

Prof. Yanliang Zhang, Prof. Alex Dowling, Prof. Tengfei Luo, Dr. Mike McMurtry (INL), **Dr. Nazli Turan**, **Dr. Mortaza Saeidi-Javash**, **Dr. Jinyu Yang**, **Dr. Yipu Du**, Dr. Ke Wang, Zhongyu Cheng



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