DGPT Deutsche Gesellschaft für Plasmatechnologie e.V.

C|A|U Christian-Albrechts-Universität zu Kiel

KIEL NANO SURFACE & INTERFACE SCIENCE

cauinnovation

21. Fachtagung für Plasmatechnologie
21. Plasma Technology Conference

September, 23 – 25, 2025

Kiel University
Faculty of Engineering
Lecture Building D

www.pt21-kiel.de

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1 General Information

1.1 PT21 in Kiel

In the established series of specialist conferences for plasma technology, PT21 is the leading platform for the latest developments in the broad field of plasma technology. It serves the scientific and technical exchange of ideas and experiences. The spectrum of topics ranges from the urgent questions of sustainable energy supply and techniques for improving materials to the innovative field of plasma technology applications in medicine.

1.2 Organizing Institution and Partners

Kiel University
Faculty of Engineering
Theoretical Electrical Engineering (TET)
Kaiserstraße 2
24143 Kiel, Germany

CAU Innovation GmbH
Fraunhoferstraße 13
24118 Kiel, Germany

Deutsche Gesellschaft für Plasmatechnologie e.V. (DGPT)
c/o Ruhr University Bochum
P.O. Box 10 21 48
44780 Bochum, Germany

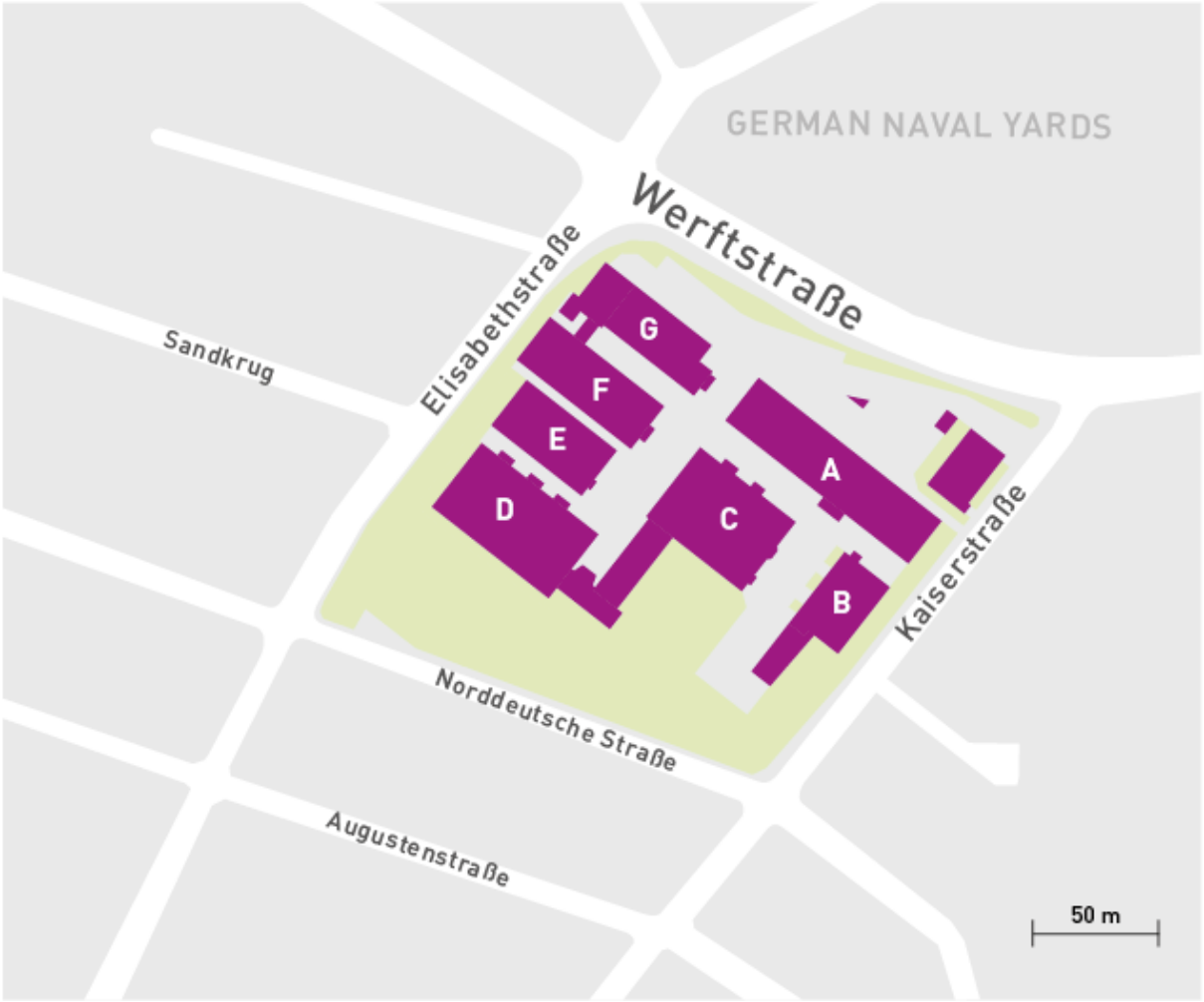
Acknowledgment Financial support from Kiel University's research priority area Kiel Nano, Surface and Interface Science (KiNSIS) is acknowledged.

1.3 Conference Office

Mrs. Heike Thodt
Kiel University
Faculty of Engineering
Theoretical Electrical Engineering (TET)
Kaiserstraße 2
24143 Kiel, Germany
Phone: +49 (0)431 880-6251
Email: info@pt21-kiel.de

1.4 Venue and Arrival

The venue of PT21 is the **Faculty of Engineering on Kiel University's east campus**. It will take place in **Lecture hall building D / HSG** (Kaiserstraße 2 / Elisabethstraße 21).

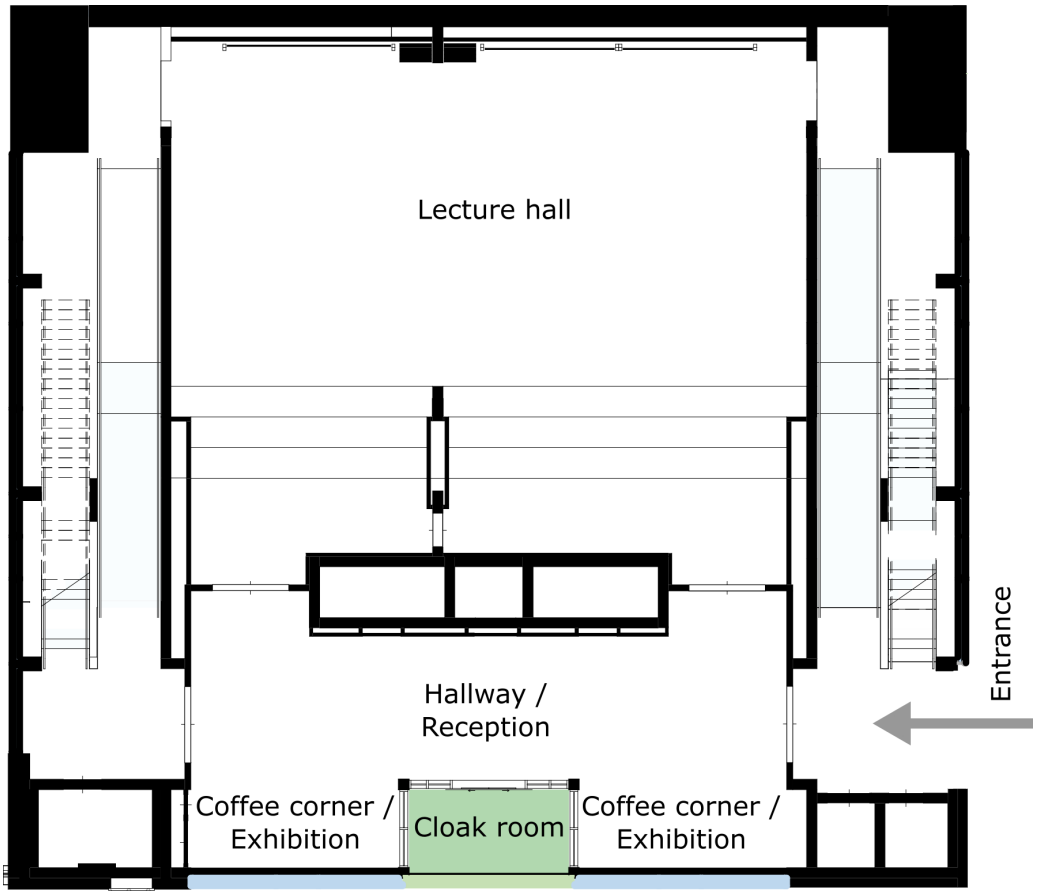


Directions by bus (from Hauptbahnhof / main train station):
11 (Direction Dietrichsdorf, Pillauer Straße)
100 (Direction Laboe, Hafen)
60S (Direction Fachhochschule) only during the lecture periods

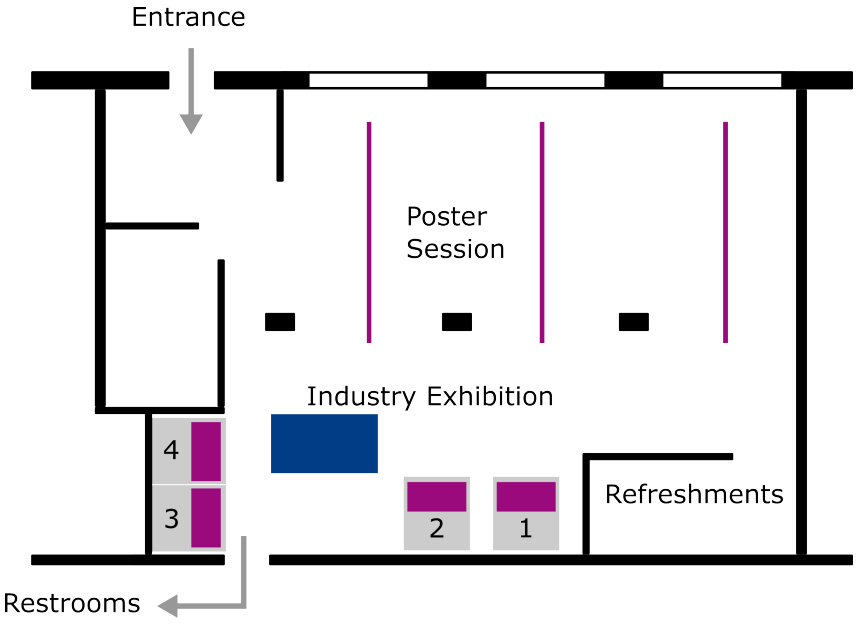
Take the bus to the HDW stop

1.5 Floorplan

Faculty of Engineering, Lecture hall building D



Faculty of Engineering, Building A



1.6 Conference Dinner

The conference dinner will take place on Tuesday, September 23, 2025 from 19:00 in the LAGOM restaurant at the Kiellinie.

1.7 DGPT Rudolf Seeliger Award and Lecture

Since 2001, the Deutsche Gesellschaft für Plasmatechnologie e.V. (DGPT) has awarded the Rudolf Seeliger Award to distinguished scientists in the field of plasma technology. The award is named after Rudolf Seeliger, founder of the "Institut für Gasentladungsphysik" in Greifswald, the predecessor of the "Leibniz Institute for Plasma Science and Technology". In 2025 the award will be given to **Prof. Dr. Peter Awakowicz**, Ruhr University Bochum. The award ceremony and the associated lecture entitled "Recent developments in die field of gas conversion with surface-DBD plasmas" will take place on Tuesday, September 23, 2025 at 17:00 in the lecture hall of building D.

Previous Awardees:
2001: Prof. Dr. Alfred Rutscher, Greifswald
2003: Prof. Dr. Rolf Wilhelm, Garching
2005: Prof. Dr. Dr. h.c. Günter Ecker, Bochum
2007: Prof. Dr. Dr. h.c. Jürgen Engemann, Wuppertal
2009: Prof. Dr. Uwe Schumacher, Stuttgart
2011: Dr. Ulrich Kogelschatz, Baden/Schweiz
2013: Prof. Dr. Jürgen Mentel, Bochum
2015: Priv.-Doz. Dr. Hans-Erich Wagner, Greifswald
2017: Prof. Dr. Jörg Winter, Bochum
2019: Prof. Dr. Claus-Peter Klages, Braunschweig
2023: Prof. Dr. Jürgen Röpcke, Greifswald

1.8 KiNSIS Diels-Planck-Lecture and Get-together

Since 2014, the members of Kiel University's research priority area KiNSIS have been awarding the Diels-Planck-Medal to outstanding international scientists in the field of nano and surface sciences. The award is named after Nobel Prize winners Max Planck and Otto Diels, the founders of the Kiel nanosciences. The winner of the Diels-Planck Medal 2025 is **Prof. Dr. Annemie Bogaerts**, University of Antwerp, Belgium. As part of the Diels-Planck Award ceremony, she will give the Diels-Planck Lecture entitled "Plasma catalysis: How to unravel the complex chemical and physical mechanisms?" on Wednesday, September 24, 2025 at 17:30 in the lecture hall of building D.

Following the Diels-Planck-Lecture, a get-together and complementary reception will be offered to registered participants. It will provide the unique opportunity to exchange with conference participants and members of research priority area KiNSIS. Light finger food will be served.

1.9 Poster Session and Poster Awards

The poster session will take place on Tuesday, September 23, 2025 from 15:30 to 17:00 in the old Mensa in building A. However, the posters can already be attached to the poster walls prior to the poster session so that they can be viewed all Tuesday during the conference breaks.

The DGPT once again funds three poster prizes for students and doctoral candidates this year. The selection committee of the PT21 will select the prize winners and announce them in the frame of the conference dinner.

1.10 Kiel Nanolab Guided Tours

As the central institution for nano science and surface research at Kiel University, the Kiel Nano Laboratory offers modern processing facilities including a class 100/1000 cleanroom with a total area of 300 square meters. During the Wednesday and Thursday coffee breaks in the morning, PT21 participants will have the opportunity to attend short guided tours. The possibility to register will be offerered during the conference, as announced during the conference welcome.

1.11 Catering

Hot and water as well as biscuits are available during the coffee and refreshment breaks of the conference. For lunch the Dockside cafeteria is available on campus. Vouchers for the lunch breaks (main dish, dessert, 0.5L water) will be distributed during the on-site registration.

1.12 Wifi-Access

Eduroam is available at the conference venue. You may also retrieve a temporary guest access code to connect to the wireless network of Kiel University during the on-site registration.

1.13 Scientific Committee

The scientific committee of the PT21 is the active board of the Deutsche Gesellschaft für Plasmatechnologie e.V.:

- Dr. Marc Böke, Bochum
- Prof. Dr. Ronny Brandenburg, Greifswald
- Dr.-Ing. Anke Dalke, Freiberg
- Dr. Andreas Pflug, Braunschweig
- Dr. Edmund Schüngel, Haag, Schweiz
- Prof. Dr.-Ing. Jan Trieschmann, Kiel

1.14 Local Organizing Committee

- Heike Thodt (Conference Office)
- Prof. Dr.-Ing. Jan Trieschmann (Chair)
- Prof. Dr. Jan Benedikt (Co-Chair)
- Dr. Luka Hansen

Team Jülf Buschmann, Ihda Chaerony Siffa, Tobias Gergs, Holger Kersten, Richard Kalhöfer, Kushtrim Krasniqi, Mats Olbrich, Thorben Rath, Lennart Saalmann, Tobias Schmidt, Heike Thodt, Sahitya Yarragolla

2 Industry Exhibition

The industrial exhibition will take place during the poster session on Tuesday, September 23, 2025 from 15:30 to 17:00 in building A. It will facilitating a great opportunity for fruitful exchange and discussion.

Participating Industrial Exhibitors:

Aurion Anlagentechnik GmbH Page 9
Hiden Analytical Ltd. Page 10
PlasmaSolve s.r.o. Page 11
Tectero BV Page 12

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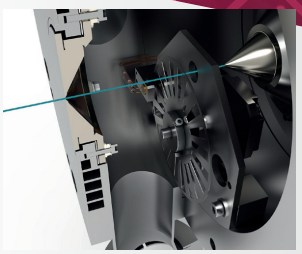

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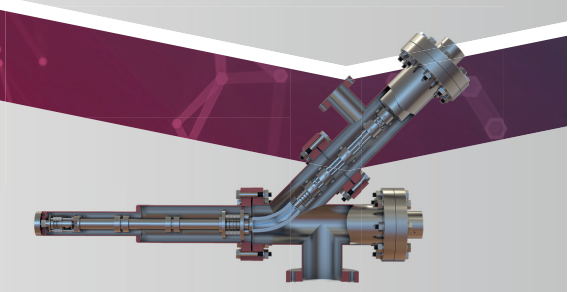

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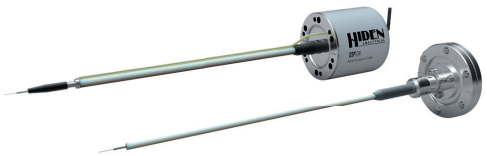

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HaloFreeEtch Project – Sustainable semiconductor manufacturing (EU initiative)

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TBA

3 Scientific Program

3.1 Agenda

Time	**Tuesday, 23-Sep-2025**	**Wednesday, 24-Sep-2025**	**Thursday, 25-Sep-2025**
08:00	Registration		
09:00	**Opening**	Mihailova	Jaritz
09:30	Nizenkov	Busse	Music
10:00	Herdrich	Nishime	Hans
10:30	**Coffee Break**	**Coffee Break**	**Closing & Coffee Break**
11:00	Rudolph	Vahl	DGPT General Assembly
11:30	Thorwarth	Ellis	
12:00	Stamate	Zikán	
12:30	Neidhardt	Flötgen	
13:00	**Lunch Break**	**Lunch Break**	**Lunch Break**
14:00	Held	Krumpolec	
14:30	Sgonina	Knospe	
15:00	Koch	Winzer	
15:30	**Refreshments & Poster Session**	**Coffee Break**	
16:00		Niemann	
16:30		Melzer	
17:00	Awakowicz, Seeliger Prize	**Refreshments**	
17:30		Bogaerts, Diels-Planck Lecture	
18:00	**Break / Transfer**		
18:30			
19:00	**Conference Dinner**		
19:30		**KiNSIS Get-together**	

3.2 Invited Talks and Award Lectures

Tuesday, 23-Sep-2025

9:30 Uhr	Dr. Paul Nizenkov, Stuttgart	Page 15
10:00 Uhr	Prof. Georg Herdrich, Stuttgart	Page 16
11:00 Uhr	Dr. Martin Rudolph, Leipzig	Page 17
11:30 Uhr	Dr. Kerstin Thorwarth, St. Gallen	Page 18
12:00 Uhr	Prof. Eugen Stamate, Lyngby	Page 19
12:30 Uhr	Dr. Jörg Neidhardt, Dresden	Page 20
14:00 Uhr	Prof. Julian Held, Eindhoven	Page 21
14:30 Uhr	Dr. Kerstin Sgonina, Kiel	Page 22
15:00 Uhr	Christian Koch, Leipzig	Page 23
17:30 Uhr	**Prof. Peter Awakowicz, Bochum**	Page 24

Wednesday, 24-Sep-2025

09:00 Uhr	Dr. Diana Mihailova, Eindhoven	Page 25
09:30 Uhr	Dr. Benedikt Busse, Duderstadt	Page 26
10:00 Uhr	Dr. Thalita Nishime, Greifswald	Page 27
11:00 Uhr	Dr. Alexander Vahl, Greifswald	Page 28
11:30 Uhr	Dr. James Ellis, Severn Beach	Page 29
12:00 Uhr	Dr. Petr Zikán, Brno	Page 30
12:30 Uhr	Dr. Christoph Flötgen, St. Florian am Inn	Page 31
14:00 Uhr	Dr. Richard Krumpolec, Brno	Page 32
14:30 Uhr	Dr. Alexander Knospe, Steinhagen	Page 33
15:00 Uhr	Tristan Winzer, Hohenlockstedt	Page 34
16:00 Uhr	Jessica Niemann, Kiel	Page 35
16:30 Uhr	Marcel Melzer, Chemnitz	Page 36
17:30 Uhr	**Prof. Annemie Bogaerts, Antwerp**	Page 37

Thursday, 25-Sep-2025

09:00 Uhr	Dr. Montgomery Jaritz, Aachen	Page 38
09:30 Uhr	Prof. Denis Music, Malmö	Page 40
10:00 Uhr	Dr. Marcus Hans, Aachen	Page 41

OPEN-SOURCE MODELLING OF RAREFIED GAS AND PLASMA DYNAMICS WITH PICLAS: STEP-BY-STEP VERIFICATION AND APPLICATION EXAMPLES

Paul Nizenkov[1], Asim Mirza[1], Stephen Copplestone[1], Julian Beyer[1]
[1] *boltzplatz - numerical plasma dynamics GmbH*
Email: nizenkov@boltzplatz.eu

We introduce PICLas, a freely available open-source software for simulating rarefied gas and plasma dynamics. It provides a powerful framework for Particle-in-Cell (PIC), Direct Simulation Monte Carlo (DSMC) as well as other kinetic/particle-based simulation methods, making it a versatile tool for studying complex flow phenomena in low-pressure environments. This talk will cover the background of PICLas, including its current development by a dedicated team of researchers and contributors.

To demonstrate the capabilities of PICLas and establish trust in its reliability, a step-by-step verification of the Particle-in-Cell with Monte Carlo Collisions (PIC-MCC) module will be presented. The verification process is based on established benchmark cases, allowing for a detailed assessment of the accuracy and robustness of the implemented algorithms [1,2]. Beyond verification, a practical application example will be showcased to illustrate how PICLas can be employed for the simulation of plasma etching [3].

References

[1] P. Parodi and F. Petronio, *Physics of Plasmas*, **32**, 013902 (2025)
[2] M. M. Turner et al., *Physics of Plasmas* **20**, 013507 (2013)
[3] S. Rauf, *Plasma Sources Science and Technology*, **29**, 095019 (2020)

TBA

INTENTIONAL EXCITATION OF SPOKES IN MAGNETRON SPUTTERING DISCHARGES

Martin Rudolph[1], Wahyu Diyatmika[1], Oliver Rattunde[2], Edmund Schuengel[2], Dmitry Kalanov[1], Jörg Patscheider[2], André Anders[1,3]

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[2] *EVATEC AG, Hauptstraße 1A, 9477 Trübbach, Switzerland*

[3] *now at Plasma Engineering LLC, 708 Avila Pl., El Cerrito, CA 94530, USA*

Email: martin.rudolph@iom-leipzig.de

Spokes in magnetron discharges are zones of enhanced excitation and ionization that have been shown to influence the ion ejection from the plasma toward a substrate [1,2] and by that influence a deposited thin film morphology. Spokes are observed under conditions at which the classical electron transport is unable to carry the current toward the anode. For example, spokes are present at low argon working gas pressure of 0.5 Pa on an aluminum cathode in high power impulse magnetron sputtering, while they gradually disappear when increasing the working gas pressure to up to 5.0 Pa while maintaining the peak discharge current [3]. Here, we show that spokes can also be intentionally excited at a desired location by introducing a step in the magnetic field strength along the racetrack. For the experiments we use a magnetron with a 300 mm Al target operated in direct current mode [4]. Two magnetic field strength transitions are obtained when splitting the racetrack into a section with a weak parallel magnetic field strength above the racetrack of ≈ 40 mT, and a strong magnetic field strength section with ≈ 90 mT. Using a gated intensified charge-coupled device (ICCD) camera, we observe the generation of spokes where drifting electrons transit from the strong to the weak magnetic field. The generated spokes move against the electron Hall drift into the strong magnetic field section, thereby creating a region of high spoke activity. The observation can be explained by an accelerating electron drift velocity as the magnetic field strength weakens. At the transition from the weak to the strong magnetic field, we observe a region of enhanced light emission that we attribute to the accumulation of electrons due to a lower drift velocity in a strong magnetic field. The observed effect is similar to a cross-corner effect known from rectangular magnetrons, and we confirm here that this effect is primarily due to the change in the magnetic field strength and not caused by the geometry of the racetrack.

The authors acknowledge funding of this work by the German Federal Ministry of Education and Research (grant number 01QE2116B), by Innosuisse – Swiss Innovation Agency, and the European Union (E!114756).

References

[1] M. Panjan, R. Franz, A. Anders, Plasma Sources Science and Technology, **23**, 025007 (2014)
[2] M. Panjan, A. Anders, Journal of Applied Physics, **121**, 063302 (2017)
[3] M. Rudolph, D. Kalanov, W. Diyatmika, A. Anders, Journal of Applied Physics, **130**, 243301 (2021)
[4] M. Rudolph, W. Diyatmika, O. Rattunde, E. Schuengel, D. Kalanov, J. Patscheider, A. Anders, Plasma Sources Science and Technology, **33**, 045002 (2024)

Role of PVD Coatings in Medical Applications: Implants, Tools and Diagnostics

Kerstin Thorwarth[1], Monalisa Gosh [1] Götz Thorwarth[2], Sebastian Siol[1]
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[2] *IMT Masken und Teilungen AG, im Langacher 46, 8606 Greifensee, Switzerland*
Email: kerstin.thorwarth@empa.ch

Physical Vapor Deposition (PVD) coatings are of paramount significance in the field of medical technology, offering a sophisticated method to enhance the surface properties of medical devices and implants. This thin-film coating technology provides a unique combination of biocompatibility, wear resistance, and corrosion resistance, which is crucial for devices that come into contact with the human body. The application of PVD coatings addresses several critical challenges in modern medicine, leading to improved patient outcomes and device longevity. It is diverse and continually expanding. In the field of orthopaedic, as well as dental implants, cardiovascular devices, surgical instruments, and diagnostic tools [1].

Plasma process monitoring is an essential tool for ensuring process stability and improving coating reliability.

It also supports documentation and traceability of process parameters, aiding in meeting stringent medical device regulations. Therefore, plasma diagnostics are indispensable in the PVD coating processes for medical technology. They provide the data and control necessary to create high-performance, biocompatible, and reliable coatings that meet the demanding standards of medical devices and implants, ultimately improving patient outcomes and advancing medical innovation

Here we present some recent developments in the field of medical applications. A smart drill can detect nerves, improving the safety of the operation and enabling minimally invasive surgery. This can significantly shorten the patient's hospital stay and reduce costs [2]. In a different application, specialized PVD coatings are being used to improve the accuracy and reproducibility of fluorescence microscopy. These coatings create stable, uniform surfaces that facilitate more precise calibration of microscopic imaging systems and enhance the quantifiability of fluorescence-based assays [3].

For both examples, plasma diagnostics serves as a tool for commercialization on industrial machines and a monitoring tool for process stability.

Innosuisse is l acknowledged for funding both, SoFluorCal as well as SmartDrill.

References

[1] Santo D., Castro J-D., Cruz S., Carvalho I., Cavaleiro A., Carvalho S., Customisation of PVD coatings for biomedical devices, Surface and Coatings Technology,**512,**132277(2025)
[2] Ansó J, Scheidegger O, Wimmer W, Gavaghan K, Gerber N, Schneider D, Hermann J, Rathgeb C, Dür C, Rösler KM, Mantokoudis G, Caversaccio M, Weber S. Neuromonitoring During Robotic Cochlear Implantation: Initial Clinical Experience. Ann Biomed Eng.;**46(10)**:1568 (2018)
[3] Thorwarth G. Kalibrierungstarget, Patent EP3926022A1, publication 2022, pending

METAL OXIDE THIN FILMS BY MAGNETRON SPUTTERING: CHALLENGES AND APPLICATIONS

Eugen Stamate[1]
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Email: eust@dtu.dk

Metal oxide thin films exhibit valuable optoelectronic properties making them relevant for solar cells, displays, thin film transistors, sensors, and smart windows, just to mention large area applications. However, reaching the desired parameters is not an easy task due to the various factors influencing thin film growth. In particular, the energetic negative oxygen ions, formed in very close proximity of the target and accelerated towards the substrate in the plasma-sheath, have been demonstrated to induce large variations of resistivity by preferential sputtering [1] when depositing Al doped ZnO, one of the most investigated transparent conductive oxides.

In this work we are presenting a detailed investigation into the nonuniformity of the optoelectronic properties when depositing various metal oxide thin films by magnetron sputtering, including analytical characterization of the deposited films and plasma diagnostics by a dual thermal-electrostatic probe.[1-3] A transition from a glow-like discharge to magnetron mode is demonstrated for a rather narrow range of pressure. Moreover, a new approach to reduce the detrimental role of the negative oxygen ions is introduced and demonstrated for planar and rotatable sputtering targets. It consists of a tuning electrode able to reduce the DC selfbias and consequently the negative oxygen ions energy while also improving the uniformity of the optoelectronic parameters.[4] Additional considerations regarding the best operation mode, among DC, pulse-DC, RF, HiPIMS (with and without kick) are to be presented with respect to reducing the impact of energetic species during thin film growth.

Acknowledgment: This work was partially financed by the project Smart3D (2081-00011B) financed by Innovation Fund Denmark.

References

[1] K. Norrman, P. Norby, E. Stamate, Preferential zinc sputtering during the growth of aluminum doped zinc oxide thin films by radio frequency magnetron sputtering, J. Mater. Chem. C. 10 (2022) 14444.
[2] S. Khan and E. Stamate, Comparative study of aluminium-doped zinc oxide, galium doped zinc oxide and indium doped tin oxide thin films deposited by radio frequency magnetron sputtering, Nanomaterials, 12 (2022) 1593.
[3] M.A. Petrea and E. Stamate, Spatial distribution of plasma parameters by a dual thermal-electrostatic probe in RF and DC magnetron sputtering discharges during deposition of aluminum doped zinc oxide thin films, Plasma Sources. Sci. Technol. 30 (2021) 045002.
[4] E. Stamate, Lowering the resistivity of aluminum doped zinc oxide thin films by controlling the self-bias during RF magnetron sputtering, Surf. Coat. Technol. 402 (2020) 126306.

Double Ring Magnetron sputtering – superior process control for high-rate, stress-controlled, single-phase AlScN piezo layers and polarity controlled AlN epitaxy

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Email: joerg.neidhardt@fep.fraunhofer.de

The virtues of the double ring magnetron configuration have been explored by Fraunhofer FEP over the better part of 25 years. The galvanically separated targets offer numerous advantages compared to standard single target face-to-face, move-mag and/or confocal configurations. Especially the excellent reactive close-loop process control in close vicinity to the substrate enable superior deposition rates (up to 250 nm/min for compounds and 1.5 µm/min for metals) and homogeneity over 200 mm substrate diameter as well as adjustable energy of the film-forming and growth-supporting species [1]. The latter is especially important for stress management as well as the control over stoichiometry, crystallinity, and morphology of the growing films. The so called “hyperthermal” growth enables the stabilization of phases at much lower temperatures and/or the shift of solubility limits (as compared to equilibrium phase diagrams). An increasing push for new materials and functionalities as well as resource efficiency have more recently respiked the interest in this well-established technology. Two mayor examples will, thus, be highlighted during this talk.

1. High-rate, low-stress, single phase AlScN films

Piezoelectric AlScN films are used in a wide range of applications due to their much lower environmental impact (compared to, e.g. PZT), while still retaining a respectable piezoelectric coefficient. The thin film synthesis poses, however, a number of challenges, such as phase-, texture- and stoichiometry control as well as stress- and temperature management for highest performance, rates and lowest cost-of-ownership. This talk gives, thus, an overview of the recent advances regarding AlScN processes developed at FEP for a range of applications, such as MHz ultrasound microscopy and energy harvesting utilizing stress-controlled films exceeding thicknesses of 10µm, THz filter designs beyond 5G [2] and tunable optical waveguides at lowest damping [3]. All these applications are putting highest demands on crystalline quality as will be demonstrated by single phase films with FWHM of <1.5° at Sc contents of up to 45at%.

2. Polarity-controlled AlN epitaxy

Advancing III-nitride epitaxy is key to low-cost and energy-efficient power electronics. Further, a simplified polarity control of this wurtzite semiconductor family will unlock novel high-performance devices. Magnetron sputter epitaxy (MSE) is an emerging technology for III-nitride growth and a promising candidate for high-throughput, low-cost, and more environmentally friendly technology as compared to state-of-the-art Metal-Organic-Chemical-Vapor-Deposition (MOCVD) [4,5]. Also, MSE enables reduced temperature processes (<1000°C), simplifying stress management and paving the way for improved material quality and device reliability, while potentially allowing monolithic integration with the Si-CMOS process chain. This talk presents our latest achievements of high-rate AlN MSE on 200 mm Si(111) at reduced temperatures (<800°C) with an in-situ control of the polarity of the AlN epitaxial layers, so far not possible with competing technologies.

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METAL OXIDE REDUCTION WITH HYDROGEN PLASMAS

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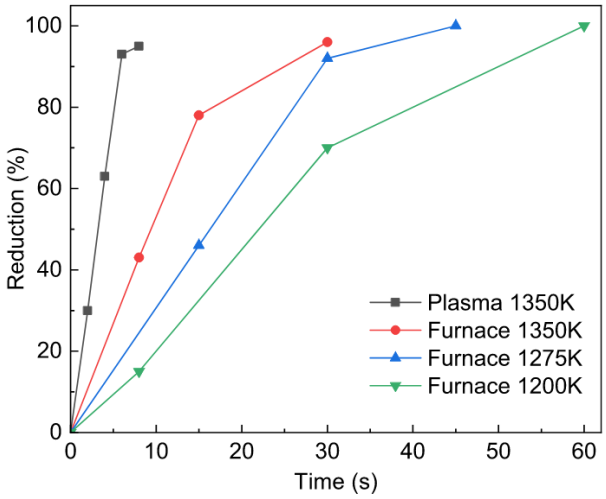
Metals are indispensable to modern society, playing a critical role in infrastructure, transportation, and virtually all manufacturing sectors. Currently, 3.2 billion tons of minerals are mined annually to meet the increasing global demand of currently 2 billion tons of metals and alloys per year [1].
Most metals are mined as oxides and need to be reduced to the pure metal for further processing. This reduction step is often very energy intensive and can range from simple single-step reactions with carbon-based reduction agents (e.g. in the case of iron) to complex processes including multiple steps and chemicals as in the case of titanium. For the less stable oxides, like iron and nickel, the reduction with carbon may be replaced with hydrogen, forming H_2O as the byproduct instead of CO_2.
Molecular hydrogen alone is able to reduce iron oxide to metallic iron ($Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$) at similar temperatures as used for the direct reduction using carbon monoxide ($Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$) and often even at a higher reduction rate [2].



Reduction progress over time for small (< 5 µm) particles placed in the spatial afterglow of a Ar-H_2 (90-10%) microwave plasma torch or in a furnace under otherwise similar conditions. At the same temperature, the reduction is considerably faster for particles exposed to the plasma species [3].

However, studies have consistently shown that the use of a hydrogen plasmas can further increase the reduction rate (see figure) or lower the required temperature compared to heated gas alone [3,4].
This is because, atomic hydrogen, ions or vibrationally excited hydrogen molecules are much more reactive and readily produced by low-temperature plasmas. Thus, there has recently been an renewed interest in the metal oxide reduction with hydrogen plasmas, allowing us to replace carbon-based processes and potentially enabling new and simpler reduction pathways for more stable oxides.
The presentation aims to give an overview over the current and past research on metal reduction using hydrogen containing plasmas, from fundamental processes to practical implementations.

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CONCEPT OF AN AUTOMATED REACTOR FOR PLASMA-ASSISTED CATALYSIS

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The transition to a climate-neutral chemical industry depends on the use of renewable wind and solar energy. Non-thermal plasmas combined with catalysts offer an energy-efficient, decentralized route to chemical synthesis: plasmas can be switched on as needed, drive reactions at ambient temperature, and generate excited and dissociated species that interact synergistically with catalyst surfaces to increase conversion rates.

Despite the already long existing experimental evidence for plasma-catalyst synergy, the inherent complexity and vast parameter space have hindered detailed mechanistic insights and transformative advances. To overcome this, a systematic framework is needed that jointly analyzes plasma characteristics, catalyst properties, and surface processes.

A dielectric barrier discharge reactor designed for operation at up to 650°C is presented, featuring rapid product extraction and compatibility with powder and porous catalysts. A transparent electrode provides optical access, while integration into an automated analysis platform – equipped with absolutely calibrated mass spectrometry and precise electrical diagnostics – will enable quantitative evaluation of conversion and energy efficiency. Using N_2-H_2 and CO_2-H_2 mixtures with hydrogenation as the initial model reaction, this high-throughput system will create a comprehensive database of plasma-catalyst interactions, thereby laying the foundation for targeted optimization of plasma-assisted chemical processes.

Obtaining CO-rich gas streams from CO_2 point-sources

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Motivation: The conversion of CO_2 is of significant interest due to its impact on climate change. However, the high stability of the C=O bond makes thermal activation highly energy-intensive. While catalysis can reduce the required energy input, plasma catalysis offers further advantages, making CO_2 conversion potentially viable at a commercial scale. Non-thermal plasma can dissociate CO_2 into CO and highly reactive oxygen radicals (O*) [1]. However, at a certain specific energy input (SEI), the process reaches a steady-state conversion limit due to back-reaction of O* with CO, leading to energy losses. Strategies to overcome this limitation are needed [2] with regard to further industrial application.

Experimental and Results: A systematic catalyst screening was conducted in a tubular dielectric barrier discharge (DBD) reactor to evaluate the influence of different catalyst properties. The results showed that oxygen vacancies suppress the back-reaction to CO_2, while nanosized metal oxides (e.g., NiO) enhance it. However, also for CO_2 splitting over adjusted catalysts a steady-state CO_2 conversion was observed, hence conversion never reached commercially viable levels (e.g., >50%). Introducing CH_4 into the plasma system significantly improved the overall performance by quenching O*, thereby preventing O_2 formation and increasing overall conversion efficiency. The resulting product gas primarily consisted of CO and H_2 (syngas). Despite these improvements, the dry reforming of methane (CO_2 + CH_4) in a DBD reactor also exhibited a steady-state conversion limit.

Industrial Outlook: Overcoming this limitation requires not only an optimized catalyst but also an intelligent reactor design. The up-scaling of volume DBD reactors is constrained by Paschen's law posing challenges for industrial applications such as minimizing pressure drop. In contrast, surface DBD reactors are not subjected to these constraints and enable industrially relevant flow geometries and volume streams. The key challenge in surface DBD systems is maximizing gas interaction with the plasma and the catalyst, which requires precise control of flow dynamics. Additionally, the electrodes must be chemically and mechanically stable to withstand prolonged operation under high-energy input conditions. To operate a stacked S-DBD reactor design, custom made plasma generators are needed supplying the required power and pulse characteristic. Here, enaDyne is working on a full concept for industrial DBD application.

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RECENT DEVELOPMENTS IN DIE FIELD OF GAS CONVERSION WITH SURFACE-DBD PLASMAS

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Surface discharges based on so-called Surface Dielectric Barrier Discharges (SDBD) have proven very successful for the removal of trace substances in gases [1]. Typical trace substances include volatile hydrocarbons (VOCs), but unusual cases such as oxygen in coke oven gases can also play a role [2], [3]. Recently, so-called PFCs, per- and polyfluorinated chemicals, have also been addressed, as these are typical waste gases from semiconductor processes.
In all these cases, SDBD reactors are suitable for oxidizing and thus enriching the trace substances mentioned. However, on closer consideration, the question arises as to why this type of plasma reactor can work at all with very low power requirements, as the plasma expansion is extremely low and the majority of the gas flow is directed past the plasma.
The secret lies in linking plasma effects with gas dynamics, which are stimulated in these reactors in a similar way to plasma actuators.
In this lecture, the essential aspects of plasma generation and its coupling with gas dynamics will be presented and quantified using the example of various trace substances. A correlation to the fundamental plasma properties will be established in order to better scale up the process.

Acknowledgement

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PLASMA MATTERS FOR SEMICON INDUSTRY

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Plasma Matters B.V. [1] is a spin-off company from the *Elementary Processes in Gas Discharges* (EPG) group within the Department of Applied Physics and Science Education at Eindhoven University of Technology (TU/e). Established in 2015, the company operates with a dual focus: providing consultancy services primarily to industrial partners engaged in plasma technology and offering licenses for the plasma simulation framework **PLASIMO** [1]. The development of PLASIMO is now a joint effort between Plasma Matters and the EPG group. This public-private collaboration model is emblematic of the *Brainport Region Eindhoven* [2], a high-tech ecosystem characterized by intensive cooperation among academia, industry, and government. In this contribution, we present illustrative examples of the company's role in advancing plasma science and technology, with a focus on recent projects in the domain of semiconductor manufacturing—specifically, extreme ultraviolet (EUV) lithography.

EUV lithography uses 13.5 nm photons to pattern silicon wafers for high-end semiconductor devices. The sole manufacturer of EUV lithography systems is ASML, located in the Eindhoven region. These systems rely on laser-produced plasma to generate EUV photons. As the photons propagate through low-pressure hydrogen gas inside the scanner, they create a complex environment in which multiple secondary plasmas are induced. One major challenge in this environment is the formation and transport of dust particles. If a particle lands on the reticle, it will result in repeating image defects across the wafer with significant yield implications. Several years ago, Plasma Matters B.V. was engaged in the development of a simulation tool for tracking charged dust particles in the reticle environment under plasma conditions. We will demonstrate the model and present its initial results.

More recently, a more comprehensive treatment of dust-particle physics, including plasma-particle interactions, charging, and forces acting on particles in the scanner environment, has been incorporated into PLASIMO within the framework of the "10Ace" project [3]. We will present recent simulation results obtained with this extended model, demonstrating its capabilities for analyzing dusty plasma dynamics in technologically relevant conditions.

Through these activities, Plasma Matters B.V. is helping companies to understand plasma sources and foster innovations in plasma technology. At the same time, these projects allow, even necessitate, Plasma Matters to realize innovations in plasma science and simulation technology. These efforts highlight the synergistic potential of academia–industry collaborations in driving both fundamental and applied research in plasma science. In this presentation, we aim to provide insight into the dynamic and mutually beneficial nature of such public–private partnerships.

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Cold Atmospheric Plasma (CAP) for treatment of badly healing wounds – Lessons from 15 years on the road to clinical routine

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The treatment of badly healing wounds caused by chronic diseases of different etiologies is currently the main indication for application of CAP in human medicine followed by treatment of different dermatological conditions, surgical site care and inflammation/infection control of transdermal conduits and implants. Current research covers in addition the potential future role of CAP in the treatment of solid tumors.

Different CAP technologies have gained regulatory market approval within the European Union (MDD and MDR) for the indication of chronic wound care and national health care and reimbursement providers evaluate the potential of the methodology in the ambulant sector. The technologies and characteristics of currently applied CAP sources for the treatment of badly healing wounds differ significantly as well as the suggested application routines and intervals. While the comparison of clinical outcomes in relation to the different technologies used is still limited, available data is mainly covering single technologies within individual trials.

In this presentation data from a prospective, open-label multicenter trial of 116 patients with chronic and badly healing wounds of different etiologies in a realistic patient care scenario will be presented. The observation of routine application of a direct CAP system (single electrode DBD system with the human body used for potential equilibration) is summarized. Direct CAP was integrated into the regular wound care activities for a period of 16 weeks including application in the home care environment. Additionally, a follow-up after 6 months was performed. Wound healing rates, wound size reduction, wound related quality of life, severe adverse events and device related events were analyzed. Furthermore, the user and patient acceptance for integration of the technology in the regular wound care activities was evaluated.

The importance of the data is to enable a patient and user centric view in a real-world application scenario for CAP in chronic and badly healing wounds as part of medical routines.

Plasma Technologies for Vertical Farming

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Leafy greens, various crops, and fruits cultivated through vertical farming systems are playing an increasingly important role in food supply, particularly in densely populated urban areas. This approach enables rapid and repeated crop cycles that are not dependent on external environmental conditions. Nevertheless, the highly intensive nature of vertical farming brings its own set of challenges. The most pressing issue is maintaining a clean system that prevents the entry of pathogens, which could potentially compromise an entire harvest. At the same time, there is a goal to reduce or eliminate the use of synthetic agrochemicals such as plant protection agents and fertilizers. Another concern involves efficiently using resources like water by recirculating it, although this can inadvertently encourage the growth and spread of pathogens.

Plasma technologies have been extensively studied and are already used for disinfecting and decontaminating surfaces and liquids. Because they require only electrical power and no additional chemicals, these methods are emerging as environmentally friendly and sustainable treatments. Plasma-treated water can also deliver nitrogen for fertilization, while plasma application to seeds can sanitize them and even encourage better germination and plant growth.[1,2]

Given these advantages, we explored the potential benefits of plasma technology in a fourth-generation vertical farming system designed to fully control environmental conditions for economically significant crops—in this case, basil, with 600 plants per tray grown at once. This larger, practical setup stands in contrast to previous laboratory-based research. A water recirculation system was implemented, allowing us to test different plasma treatment strategies for preserving system hygiene and reducing the need for nitrogen fertilizers. We also compared the growth of plasma-treated seeds to untreated controls. Results over a 3-4 week period showed that plasma treatments effectively replaced nitrogen fertilizers and reduced microbial contamination, with positive effects on plant health. Various treatment approaches were assessed for their economic and resource-saving benefits, such as conserving water.

The project is funded by the German Federal Ministry of Research and Education under contract number 03WIR2817.

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Low temperature plasmas for sustainable material synthesis and surface modification - From plasma-printing to bio-inspired electronics

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Plasma technology applying low temperature plasmas offers a wide range of approaches for (nano-)material synthesis and tailored surface modification, both at low pressure and atmospheric pressure conditions. Plasma-based material synthesis offers pathways to create tailored nanomaterials and composites using surfactant-free, green synthesis conditions. Furthermore, low temperature plasmas attract research interest as they open up versatile pathways for sustainable surface engineering, either by modifying existing properties or by equipping surfaces with additional properties. Here, plasma technology enables diverse modification pathways, via the controlled cleaning, activation and functionalization, via the application of thin film coatings, and via material removal and etching.

Plasma technology is commonly is considered as sustainable technological approach. However, sustainability aspects arise at different stages of the material and surface life cycle, ranging from the processing (i.e. limiting the use of toxic chemicals, minimizing material usage and processing energy), over the usage (i.e. extending lifetime, minimizing energy consumption) towards the post-usage (i.e. recyclability, reuseability, disposal).

This contribution showcases three plasma-based approaches for nanomaterial synthesis and surface modification, namely (I) plasma electrolytic processing for fine cleaning, polishing and deburring of metallic work pieces in mild, water-based electrolyte solutions; (II) plasma-printing and microfabrication using locally confined atmospheric pressure plasmas for on-demand thin film deposition and etching with spatial resolution down to 35 µm [1], and (III) nanoparticle beam deposition from gas aggregation with optimized conversion efficiency for self-organized nanoparticle arrangements with applications in bio-inspired electronics [2,3]. For each approach, the contribution outlines key sustainability aspects and comments on open questions regarding the ecological impact alongside different stages of the life cycle.

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Tacit Translation: From empirical art to predictive science in plasma processing

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Plasma processing is the unsung hero that has enabled modernity through the nanofabrication of materials into a plethora of devices. Its versatility has resulted in widespread adoption of the technique in both etching and deposition including the atomic scale precision demanded by multiple markets [1]. Despite the sophistication of these applications, a peculiar dichotomy exists within the industry. Process and applications departments possess an immense, world-class repository of empirical, recipe-based knowledge. However, this expertise often operates independently of a deep, fundamental understanding of the plasma physics underpinning these processes. This gap represents a significant barrier to efficient process development, hardware development, and troubleshooting in the face of ever-tighter customer requirements.

There are multiple approaches to bridge this knowledge gap. Firstly, the inclusion of industrially relevant plasma modelling and simulation expertise to augment the hardware development process that enables the next generation of plasma reactors. This enables substantial cost-reduction and a level of optimisation unparalleled by empirical iteration. The expansion of these models to include industrially relevant chemistry enables the acceleration of both process optimisation in the lab and fault finding for production customers.

Establishing credibility in timely model solutions is critical if they are to carry any value in the commercial world. For this, a conscious effort must be placed on the validation of any simulation endeavour. Here, plasma diagnostics, sensors, and on-wafer metrology play a crucial role in establishing the credibility of the models. Unfortunately, a credible solution is not sufficient to be useful if this cannot be delivered in a timely manner. Therefore, efforts to accelerate the convergence of plasma simulations are critical for industrial uptake [2].

Finally, we will look to the future, examining the transformative potential of machine learning (ML). By integrating data from a suite of plasma sensors, ML algorithms can identify subtle signatures and correlations that precede process drift or tool failure [3]. This enables a paradigm shift from reactive troubleshooting to proactive, intelligent process control, enhancing yield and tool uptime. By synergistically combining deep process expertise with advanced simulation, validated by diagnostics, and augmented by machine learning, we can unlock new frontiers in semiconductor manufacturing, ensuring that plasmas continue to define modernity into the second half of the 21st century.

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MatSight: Turning Plasma Simulations into Engineering Tools

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While plasma simulations have long been a focus of academic research, far less attention has been given to making them practical tools for everyday industrial use. In this talk, we share our multi-year journey transforming research-grade plasma solvers into a production-ready software platform tailored for coating engineers—no numerical methods or DevOps expertise required.

For decades, predicting 3D coating uniformity on complex geometries or computing target erosion profiles remained out of reach for most engineers: coupled field-and-particle simulations often took days or weeks to complete. We developed proprietary acceleration techniques that cut runtimes by orders of magnitude, unlocking fast, iterative design capabilities.

Our evolving platform MatSight, now entering its third generation and currently in beta testing, has been validated in real-world industrial environments and is built around five core principles:

- **Declarative input layer**: Engineers describe equipment, materials, gas chemistry, power settings, and process sequences through a high-level, unit-aware interface—no scripting needed.
- **Automated preprocessing**: CAD model import, boundary extraction, and mesh generation are fully automated. Integrated visualization ensures shared understanding across teams.
- **Reproducible workflows**: Simulations capture every input, output, and parameter in a single project file. Runs are idempotent, version-controlled, and chainable—enabling fully automated design-of-experiments.
- **Self-contained reporting**: Interactive HTML reports combine live code, plots, and commentary, replacing manually crafted slides and screenshots with transparent, reviewable outputs.
- **Turnkey deployment**: Delivered as sealed containers and virtual appliances, the platform fits seamlessly into existing IT policies with simple commands for login, reset, and updates.

A graphical user interface is also under active development to further broaden accessibility. We'll demonstrate these ideas using examples from the 3D Uniformity App and reflect on the practical challenges of building industry-grade simulation tools that are robust, scalable, and easy to operate.

This presentation focuses not on physics models or numerical algorithms—those are treated as prerequisites and published elsewhere, but on the engineering, design, and operational choices required to make simulation technology truly usable in a production context.

PLASMA ACTIVATED WAFER BONDING – STATE OF THE ART, OPPORTUNITIES AND CHALLENGES

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Wafer-to-wafer fusion bonding has evolved into a mature and widely adopted process in the semiconductor industry over the past few decades. It plays a critical role in enabling technologies such as 3D IC stacking, hybrid integration of memory on logic, and the fabrication of backside-illuminated image sensors. First introduced in 1986 [1], one of the most influential early studies was conducted by Stengl et al. in 1989 [2], demonstrating that thermal annealing above 800 °C was required to achieve sufficient bonding strength for subsequent device processing.

However, such high temperatures exceed the thermal budget of CMOS fabrication, which is typically limited to below 400 °C. This challenge was addressed through the introduction of plasma-based surface activation, giving rise to Plasma-Activated Wafer Bonding (PAWB, e.g. [3]). PAWB has since become the state-of-the-art technique for achieving strong bonds at low annealing temperatures.

Despite its industrial relevance, the plasma activation process remains insufficiently characterized and poorly understood at a fundamental level. As emerging device technologies impose increasingly stringent requirements on process control and reliability, the need for deeper insight into plasma–surface interactions and improved plasma process control has become more critical than ever. Key questions about the nature of plasma–surface interactions, surface chemistry modifications, and their correlation with bonding strength are still open, in particular in the light of varying bonding layer materials. At the same time, tight control over subsurface point defect generation, stress introduction across bonded layers, and defect hydrolysis during annealing is required to meet the stringent demands of modern device fabrication. These challenges make the implementation of robust plasma diagnostics in industrial environments not only beneficial but increasingly indispensable to ensure process stability, uniformity and reproducibility.

In this work, we first provide an overview of the fundamental bonding mechanisms in wafer-to-wafer fusion processes, followed by a primer on the specific challenges posed by advanced device manufacturing requirements. Building on this foundation, we present experimental results that explore the correlation between plasma diagnostic data and final bonding outcomes, highlighting the potential of plasma diagnostics as a powerful tool for process optimization and control in industrial PAWB applications.

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ATMOSPHERIC PLASMA FUNCTIONALIZATION OF MATERIALS: NITROGENATION AND AMINATION OF rGO FOR ADVANCED WATER FILTRATION MEMBRANES

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Atmospheric pressure plasma is versatile technology for surface activation, modification and functionalization of various materials. Diffuse Coplanar Surface Barrier Discharge [1] is known as a powerful tool for plasma surface modification of flat and 2D flexible substrates. We present a novel DCSBD linear atmospheric pressure plasma jet (DCSBD linear APPJ) [2] generating an exceptional cold linear plasma plume (Fig. 1) optimized for plasma surface modification of temperature sensitive rough, porous and complex 3D materials and surfaces. The results of remote plasma treatment of thick, porous materials, in particular thick SMS polypropylene nonwoven fabrics and glass fiber fabrics are shown, including an example of utilization for enhancement of composite materials properties. Nitrogen DCSBD linear APPJ is capable of simple low temperature nitrogenating and amination. We have studied the plasma nitrogen incorporation and amination of plasma-reduced graphene oxide (rGO) papers. These rGO papers [3,4] were incorporated into rGO-based composited membranes, fabricated and tested for water filtration. We show the result of water filtration experiments for separation of selected organic dyes, pharmaceuticals (analgesics, antibiotics, and pesticides) as well as heavy metal elements often present in tap and utility water. As presented, utilizing the atmospheric low temperature non isothermal plasma generated by DCSBD technology it is possible to effectively plasma functionalize the rGO and other nanomaterials and fabricate advanced rGO-based nanocomposite-based membranes for effective water filtration.

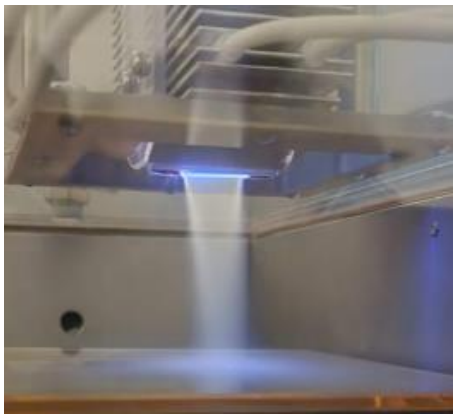

Figure 1: Nitrogen DCSBD linear APPJ in closed chamber.

This research has been supported by the project LM2023039 funded by the Ministry of Education, Youth and Sports of the Czech Republic.

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Atmospheric Pressure Plasma in Surface Technology: Industrial Applications and Perspectives

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Nozzle-based atmospheric pressure plasma has established as a versatile and efficient tool in surface technology, enabling a broad range of applications. It also allows environmentally friendly, inline treatment of a wide variety of materials – especially for applications requiring high treatment speeds, site-selective modifications, and robust processes. Its industrial relevance has increased significantly over the past two decades, particularly in the activation of low-energy surfaces and the deposition of plasma polymer coatings. These processes improve adhesion, corrosion resistance, and wettability, thus contributing to cost reduction and quality improvement.

The lecture will present current applications, including the activation of complex 3D components and the reduction of oxide layers in the electronics industry. A special application example is the coating of battery housings for electric vehicles: Here, extremely thin plasma polymer adhesion promoter and corrosion protection layers are used in the flange area to ensure long-term sealing.

Another focus is on process-related monitoring of both the plasma parameters and the modified surface to ensure reproducible results in series production. Finally, an outlook on new application areas is provided that further illuminate the potential of the technology in functional surface modification.

COLD ATMOSPHERIC PLASMAS FOR MATERIAL SYNTHESIS: PARTICLE-FREE THIN FILM DEPOSITION INITIATED BY VUV PHOTOCHEMISTRY

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Deposition of high-quality, homogeneous thin films with controllable chemical structure and properties under ambient conditions is a topic of current research due to the possibility to integrate such processes in production lines without the challenge of transferring substrates into vacuum. Atmospheric plasmas are promising tools for this application [1]. The high collision frequency at this pressure increases reaction rates but also leads to low kinetic energy of depositing species, source degradation by internal deposition, fast gas phase polymerization and ultimately to film defects like nanoparticle incorporation [2]. This work addresses these issues by utilizing vacuum ultraviolet (VUV) radiation from a pure noble gas plasma for initiating (ionic) gas phase chemistry with deposition from different common precursors.
Organosilicon precursors are often used for film deposition not only by plasma. This is due to the diverse obtainable film structures and their stability under normal conditions, while still being easily dissociated if energy is supplied. We present here first a study on ionic photochemistry with deposition from hexamethyldisilane (HMDS) diluted in helium or argon and initiated by photons from helium or argon plasma [3]. A deposition source was built, which provides windowless separation of plasma, photons and precursor. Influence of photon energy could be studied as photons from helium plasma have higher energies compared to photons from argon plasma. We found increasing carbon and decreasing oxygen content of the films with higher precursor admixture, which we assigned mainly to more photons being absorbed in the gas phase instead of interacting with the growing film. Precursor fragment ions from dissociative ionization have been identified via positive ion mass spectrometry and gas phase polymerization mainly proceeded via reactions of precursor fragment ions with neutral precursor molecules. Probably plasma-related ions were found, due to the plasma effluent flowing in direction of the substrate. This was overcome by a redesign of the deposition source with an inverted plasma gas flow, while gas phase polymerization was reduced by bringing photochemistry closer to the surface. Film oxidation due to omnipresent water impurities was found to be advantageous in case of SiO_x deposition from hexamethyldisiloxane (HMDSO) in the new source geometry [4]. In addition, all detected ions could be unambiguously assigned to the precursor or impurities. Energetic photons removed again the organic fraction from the film by photodesorption, enhanced cross-linking and reduced porosity. To demonstrate the capabilities of the developed source and the general concept, a worst case scenario for deposition at atmospheric pressure was studied by admixing acetylene (C_2H_2) and silane (SiH_4) as precursors, which very effectively form nanoparticles from negative ions in plasma [5]. In contrast to direct plasma-based deposition, homogeneous, particle-free films could be deposited over a wide admixture range following dissociative photoionization by helium plasma radiation. With acetylene, a small fraction of the solvent acetone showed a strong contribution to ion chemistry and deposition at the studied admixtures. Diluting silane in argon proved to increase deposition efficiency, as photons above the excitation or ionization threshold of argon were absorbed by the large number of argon atoms, which subsequently transferred their energy to the precursor molecules in frequent collisions.

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PROBING ION DRAG AND ELECTRIC FIELD FORCES IN CCRF PLASMAS WITH OPTICAL TWEEZERS

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Many different diagnostics can be used to measure the spatial distribution and temporal evolution of plasma parameters. Over the past decade, the concept of utilizing externally injected microparticles as non-invasive probes, influenced by various forces and energy fluxes in plasmas, has been implemented. Information about local electric fields [1], energy fluxes towards the particles [2], and momentum transfer by ions to the particles [3] can be obtained based on their behavior in the surrounding plasma. Especially, the manipulation of microparticles by an optical tweezer is of great interest, as it enables the microprobe to be positioned in areas of the plasma that are typically inaccessible by conventional diagnostic methods, such as the plasma sheath.

In this study, optically trapped microparticles in a highly focused laser beam are used to investigate both the electrostatic field force [4] in the sheath and the ion drag force in the pre-sheath of a capacitively coupled radio-frequency (CCRF) discharge. These forces differ by roughly one order of magnitude, requiring adjustments of the trapping laser power to control the sensitivity of the optical trap accordingly (Fig. 1). By observing the displacement of the trapped particle under varying gas pressure and phase angle in single- and dual-frequency [5,6] discharges, the spatial structure and parameter dependence of both forces are resolved. These measurements allow the experimental reconstruction of the fundamental plasma structure comprising bulk, pre-sheath, and sheath.

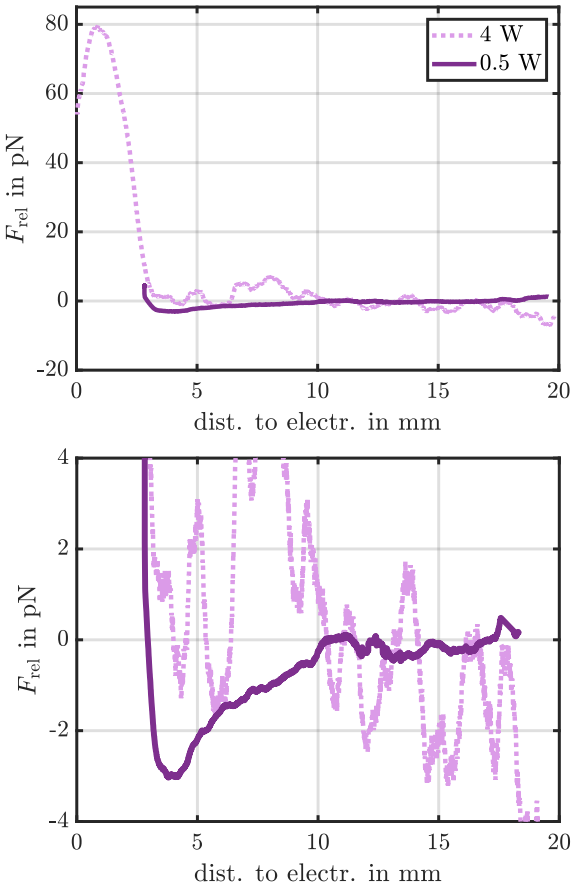

***Figure 1**: The top figure illustrates the force measured in the sheath and pre-sheath using an optically trapped particle at two different trapping laser powers. The bottom figure shows a zoomed-in view for low laser power (0.5 W). At this reduced laser power, a noticeable dip in the force profile can be observed, which corresponds to the ion drag force. The measurements were conducted in a 27.12 MHz discharge at 20 Pa with a peak-to-peak voltage of U_{pp} = 228 V and a dc self-bias of U_{dc} = −112 V.*

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MINIATURIZED PLASMA SYSTEMS AS ENABLER FOR NOVEL SENSOR GENERATIONS

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Since 2003, split-ring resonators (SRR) have been investigated as compact plasma sources [1]. SRRs exploit an electromagnetic resonance in the frequency range of 0.4 – 10 GHz. At the characteristic gap, the resonant field concentration produces sufficiently high electric field strengths to ignite a plasma. When properly designed, such sources can be operated with input powers in the milliwatt range [2], offering significant advantages for portable and energy-efficient applications.

In this work, SRR-based plasma sources are proposed as a key element in gas analysis systems through their integration with micro-opto-electromechanical systems (MOEMS). The combination of these miniaturized plasma generators with MOEMS-based optical components enables the realization of compact spectrometers for on-site gas sensing. Two MOEMS designs will be presented, employing distinct concepts: one utilizing movable elements for tunability [3], and the other based on a static, fixed-geometry configuration. Special emphasis will be placed on the engineering challenges associated with the design and cleanroom fabrication of the MOEMS, as well as the control and tuning of the split-ring resonators.

The results contribute to the development of next-generation sensor platforms, potentially enabling precise, low-power, and field-deployable spectroscopic gas analysis tools. This research is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - 496343159.

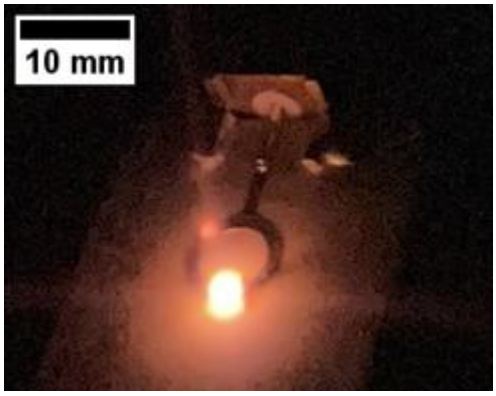

Fig. 1: Split-ring resonator based on silicon at 2.5 GHz including Ar plasma at a pressure of 500 Pa.

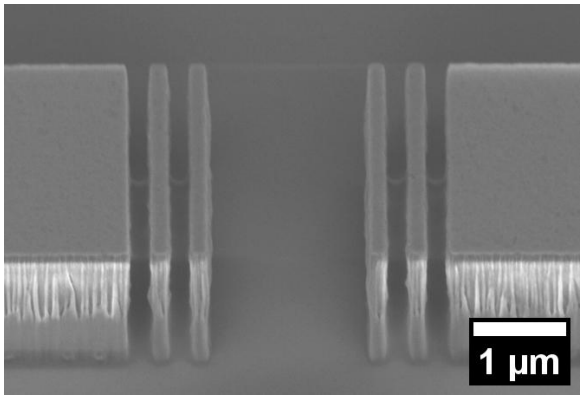

Fig. 2: Bragg reflectors for visible light in a Si_3N_4 waveguide for integration into a MOEMS.

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KiNSIS Diels-Planck Lecture

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Plasma catalysis is gaining increasing interest for various applications, such as for air pollution control (i.e., removing low concentrations of harmful components, like volatile organic compounds (VOCs), particulate matter and NOx, from the air), and for sustainable chemistry (such as CO_2 and CH_4 conversion, including CO_2 hydrogenation, partial oxidation or dry reforming of CH_4 (DRM) to produce syngas, higher hydrocarbons or oxygenates, as well as NH_3 and NO_x synthesis from N_2 and H_2 or air, respectively). The first application field is already at high technology readiness level (TRL), with commercial devices available for many years, especially for VOC removal. In contrast, the second application field is at much lower TRL, and still faces several challenges, such as limited energy efficiency, limited product yield, and limited product selectivity. The main reason is that the underlying mechanisms are far from understood. Indeed, while plasma-catalyst synergy is often reported, in other cases it is not observed. Hence, there is a need for better insights into the current limitations, and especially how to overcome them, in order to make significant progress in this emerging research field.

This talk will discuss some of the critical limitations. First, we will discuss the lack of insight in the optimal catalyst material tailored to the plasma environment, leading to trial-and-error experiments often based on insights from thermal catalysis. For instance, metal catalysts are most often used, e.g., in DRM, but chemical kinetics modelling of plasma and catalyst surface reveals that metals act as radical scavengers, where the radicals react back into the reactants, rather than into targeted products. So, they could be seen as “anti-catalysts”, and the question arises whether other catalysts, like metal oxides, could be more suitable. Second, the problem could also be solved by promoting other plasma species for plasma catalysis, rather than radicals, which are mostly formed at typical plasma catalysis conditions (i.e., DBD plasmas). By tuning the plasma conditions to the catalyst needs, for instance by promoting the formation of (vibrationally or electronically) excited molecules, plasma-catalyst synergy could also be enhanced. Last but not least, we believe there is a need for improved plasma reactor design with better contact between plasma and catalyst, so that the catalyst surface chemistry becomes more important than the plasma chemistry, which is now often dominant. Insights obtained from experiments and modelling can help to unravel the complex chemical and physical mechanisms, in order to better understand the above limitations, and make progress in this promising research field.

IonKraft – In 4 Years from Science to Industrial Application

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Only about 6% of the 150 million tons of plastic packaging produced globally each year is currently recycled. The remainder is either incinerated or accumulates in landfills, contributing to environmental degradation and the loss of valuable material resources. One of the main barriers to increasing recycling rates lies in the prevalence of complex, non-recyclable high-barrier packaging systems. Packaging for products such as household cleaners, industrial solvents, pharmaceuticals, cosmetics, and perishable foods must ensure reliable protection against oxygen, carbon dioxide, moisture, and aggressive chemicals to preserve quality and ensure safety. These stringent barrier requirements are often met through multi-layer plastic laminates or surface treatments that incorporate fluorinated polymers, both of which hinder recyclability or involve the use of environmentally persistent substances such as per- and polyfluoroalkyl substances (PFAS).

Regulatory developments in the European Union, such as the proposed ban on PFAS and the forthcoming Packaging and Packaging Waste Regulation (PPWR), are increasingly pushing packaging developers toward safer, more circular solutions. However, existing mono-material alternatives often fail to meet the demanding performance criteria of modern packaging applications. Addressing this technological gap is essential to enable both environmental sustainability and industrial viability.

IonKraft GmbH, a deep-tech startup founded in late 2021 in Aachen, Germany, has developed a novel solution to this challenge. Our proprietary plasma coating technology allows the deposition of ultrathin, chemically stable barrier layers onto rigid mono-material plastic containers, effectively replacing traditional multilayer or fluorinated systems. The coatings are generated using a low-pressure microwave plasma polymerization process that operates within a tightly controlled window of energy input, process gas composition, pressure, and substrate temperature. The result is a composite film composed of alternating silicon-organic and silicon-oxide phases, each tuned for maximum barrier performance, chemical robustness, and long-term stability.

Unlike conventional silicon oxide (SiOx) coatings, which are prone to cracking, hydrolysis, or chemical attack, IonKraft's coating structure ensures high durability and resistance to both polar and non-polar permeants. It provides excellent barrier performance against oxygen, carbon dioxide, aromatic solvents, acidic and alkaline substances, and various toxic or corrosive liquids. Moreover, the coating chemistry is entirely PFAS-free and compliant with food-contact regulations, making it suitable for a broad spectrum of sensitive and regulated applications.

A central innovation in our technology lies in the design of the plasma reactor system. Developed in close collaboration with RWTH Aachen University and leading automation partners, the reactor enables uniform and reproducible coatings across containers of any shape or size, from 250 milliliters up to 20 liters. The modular architecture of the system allows for flexible scaling of production capacity, supporting seamless integration into standard blow-molding production lines. This enables packaging manufacturers to adopt the technology without major disruptions to their existing operations.

Our pre-production prototypes and pilot-scale systems have demonstrated commercial viability in real-world production settings. The coating process is compatible with high-throughput manufacturing and meets the performance demands of sectors such as household and industrial chemicals, cosmetics, food and beverage, and pharmaceuticals. Importantly, the technology is not limited to virgin plastics: it can be applied to containers made from recycled, bio-based, or even biodegradable polymers. This expands the options available for manufacturers aiming to reduce their carbon footprint and increase circularity.

In addition to enabling full recyclability, the coatings developed by IonKraft support reuse systems by retaining barrier functionality through multiple packaging life cycles. The lightweight nature of mono-material plastics, combined with the functional enhancement provided by our coatings, leads to lower material use, reduced transport emissions, and better overall resource efficiency compared to traditional solutions.

Crucially, the development of this technology represents the successful transfer of scientific research into industrial application. IonKraft's origins lie in fundamental research in plasma polymerization and thin-film coatings conducted at RWTH Aachen University and the Institute for Plastics Processing (IKV). Recognizing the potential of these findings to address pressing global challenges in packaging sustainability, the founding team initiated the transition from academia to entrepreneurship. In its early stages, the company focused on tackling critical technical barriers, such as coating adhesion, uniformity, and chemical stability, across a variety of container geometries and substrate materials.

The transition from lab-scale demonstration to market-ready production involved iterative engineering, material testing, and collaborative validation with stakeholders across the packaging value chain. Today, IonKraft's industrialized reactor systems reflect a convergence of material science, mechanical design, and manufacturing innovation. This journey exemplifies the power of translational research and interdisciplinary collaboration in addressing systemic sustainability challenges. It also demonstrates how science-based startups can function as catalysts for the industrial adoption of environmentally responsible technologies.

In summary, IonKraft's plasma coating system offers a unique and scalable solution to the longstanding conflict between barrier performance and recyclability in rigid plastic packaging. By enabling mono-material containers to meet high barrier requirements without reliance on PFAS or multilayer structures, the technology enables circular plastic applications.

PRIMARY AND SECONDARY PROPERTIES OF THERMOELECTRIC HEUSLER ALLOYS – FROM PLASMA TO MACHINE LEARNING

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Thermoelectrics can convert heat to electricity without greenhouse gas emissions and hold significant potential as energy sources for wearable devices [1]. Current research focuses on designing compounds that combine high conversion efficiency and stability with mechanical flexibility. Half-Heusler phases, such as TiNiSn, demonstrate promising thermoelectric efficiency, but they are brittle and tend to oxidize which limits their application in flexible devices [1]. To address these shortcomings, amorphous TiNiSn thin films were synthesized by sputtering on various substrates, such as Kapton, silk, and paper, to evaluate their bending response [2]. We show that plasma does not damage these sensitive substrates [2]. TiNiSn thin films show good adhesion to the substrates, as predicted by density functional theory, and do not delaminate under mechanical loading [2]. To further enhance the thermoelectric efficiency of these devices, density functional theory and Boltzmann transport theory were employed to tune the electronic structure and identify suitable doping elements among 3d and 4d transition metals [3]. Experiments were carried out to validate these predictions, yielding an order of magnitude increase in performance at room temperature [3]. Considering oxidation of TiNiSn, experiments render Ni relatively inert, which is counterintuitive [4]. Oxygen molecules dissociate and chemisorb onto TiNiSn surfaces, which is followed by ingress of O [4]. Both Ti and Sn egress, while Ni is less mobile [4]. Such diffusion processes give rise to Ti and Sn binary oxides, while Ni is inert [4]. A general challenge for thermoelectric devices is oxidation, which can affect performance. To mitigate this, Sn-rich TiNiSn and consequent Sn-O oxide formation were explored [5]. Sn-O nanostructures are observed on the surfaces of amorphous Sn-rich TiNiSn thin films [5]. Describing the evolution of these nanostructures at the density functional theory level requires substantial computational resources. By employing artificial neural networks based on small-cluster interactions with Sn-O surfaces, significant computational speed-ups are achieved [5]. Ignoring secondary features, such as thermal fatigue and oxidation, in design efforts of novel thermoelectric devices for green energy generation may lead to failure.

This work was financially supported by the Olle Engkvist Foundation (project number 217-0023). The computations were enabled by resources provided by the National Academic Infrastructure for Supercomputing in Sweden (NAISS) at National Supercomputer Centre (NSC) in Linköping partially funded by the Swedish Research Council through grant agreement no. 2022-06725.

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PERSPECTIVE ON PATHWAYS TOWARDS RESPONSIBLE SURFACE ENGINEERING

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In this perspective [1] sustainability-relevant aspects of modern surface engineering technologies, which enable improved structural and functional surface properties, are critically evaluated. Although plasma-assisted physical vapour deposition (PVD) is increasingly employed to address global challenges, such as energy efficiency and reduction of CO_2 emissions, their inherently resource-intensive nature is often not considered.

Surface engineering research should thus embrace sustainability-relevant aspects from a processes and materials design point of view (***Figure 1***). While we are convinced that sustainability-relevant surface engineering has to be based on synchronised process and materials solutions, we will discuss processes and materials separately.

In terms of processes, we are going to describe the challenges of state-of-the-art technology, including energy and mass balances as well as product cycles. With respect to materials, the coating and process purity as well as chemical and microstructural complexity are discussed. Such approaches are fully in line with the United Nations Sustainable Development Goal 12 *Responsible Consumption and Production*.

We expect that the here discussed urgently needed pathways towards responsible surface engineering will become important for the surface engineering community and adopted within the near future. Responsible surface engineering includes the human behaviour and necessitates a change in mindset of materials scientists and process engineers. Hence, two main questions are critically evaluated in this perspective:

1) What are sustainability-relevant aspects of PVD processes and materials?

2) Which pathways are available to move towards responsible surface engineering?

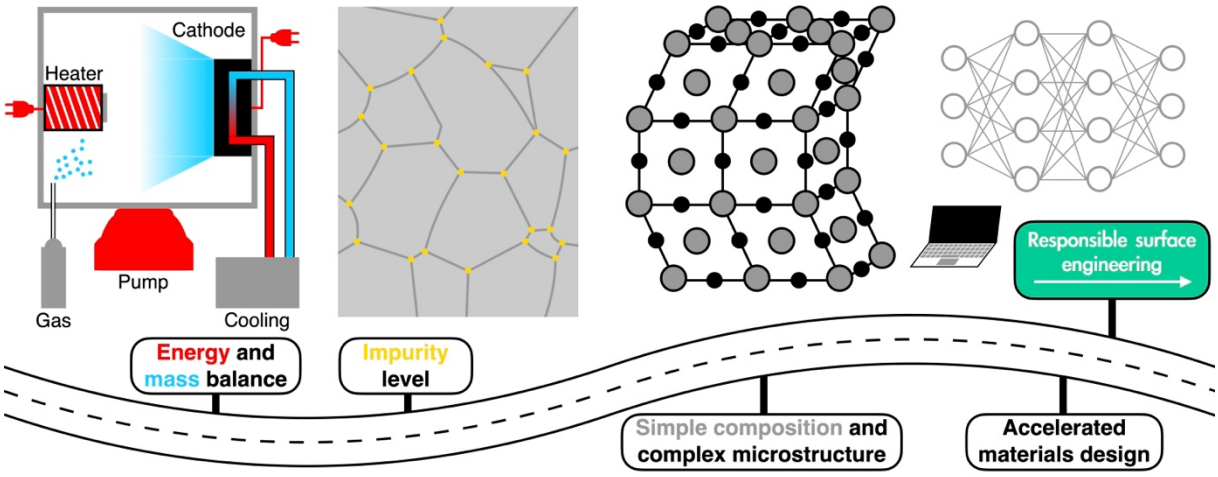

***Figure 1**. Sustainability-related aspects of surface engineering.*

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3.3 Poster Contributions

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A NEW FACILITY DEDICATED TO PLASMA-BASED GAS CONVERSION RESEARCH AT IRS

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The advancing climate change, caused by anthropogenic greenhouse gas emissions, necessitates a drastic shift in our carbon economy. As a promising solution, plasma-based conversion of carbon dioxide has gained significant international interest. This technology enables the transformation of greenhouse gases into valuable products, offering the potential to create a carbon-neutral cycle. [1]

One challenge in plasma-based CO_2 conversion is that currently, no mature technology exists to separate its reaction products, e.g., CO and O_2 [2]. Thus, two approaches are investigated at the Institute of Space Systems (IRS) to separate the products of the CO_2-plasma and prevent their recombination. In the first approach, hydrogen is injected into the plasma jet to create water and carbon monoxide, which are then separated by condensing the water vapor. To understand this chemical quenching process and determine the expected efficiencies, an investigation of the reaction kinetics is planned.
The second approach addresses In-Situ Resource Utilization (ISRU) on Mars by producing oxygen and carbon directly from the CO_2-rich atmosphere, which can save on the costly mass of rocket launches from Earth. The oxygen could then be used as an oxidizer in return ships or as breathable air for astronauts, while the carbon could be used as a building material. This approach aims to directly deposit atomic carbon onto a collector plate, leaving oxygen as the only gaseous product.

Previous research at the IRS has already investigated the CO_2 splitting performance of the Inductive Plasma Generator IPG4 [3]. Building on this knowledge, a new dedicated facility is being constructed based on IPG6-S, which is a miniaturized version of IPG4, to test the two novel concepts described above. IPG6-S has already been extensively characterized for air and has demonstrated operation with CO_2 [4]. In Fig. 1, the experimental setup of IPG6-S is shown, which is being refurbished to demonstrate the separation of plasma-based gas conversion products. Future additions to the test bed include a Fourier Transform Infrared Spectrometer (FTIR) for exhaust gas analysis, a carbon separator to resublimate atomic carbon, and a hydrogen injector for chemical quenching. This poster presents the experimental facility and the planned projects.

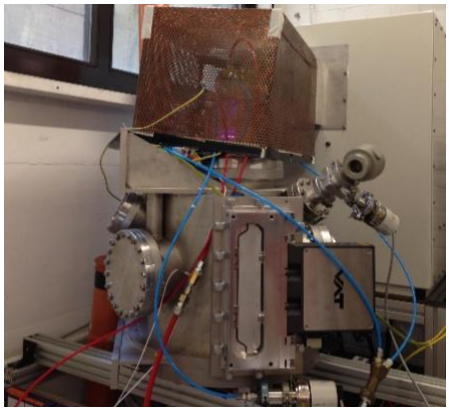

Figure 1: Testing facility of IPG6-S with an ignited air plasma.

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Electrostatic and calorimetric diagnostics of a gas aggregation source

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Gas Aggregation cluster Sources (GAS) have been emerging as a key technology for the production of metal and metal oxide clusters and nanoparticles (NPs) of precisely controlled size and composition [1]. They can be used in many applications such as catalysis, optoelectronics, neuromorphic computing, biomedicine and functional coatings, where efficiency and reproducibility are crucial [2-4]. A deeper understanding of the physical processes within GAS is, therefore, essential – particularly, regarding plasma conditions and energy fluxes that influence particle growth and deposition.

In this study, Langmuir probe measurements and calorimetric diagnostics were conducted to investigate the plasma characteristics and energy fluxes within a GAS based on a post (cylindrical) magnetron with a rotating magnetic circuit [5] and fed with Ar and/or N2. Langmuir probes enable a detailed analysis of plasma properties, including electron temperature, plasma density, plasma and floating potential, respectively. These parameters are critical for understanding correlations between the sputtering events, working gas conditions, nucleation and growth of NPs.
Furthermore, a key finding is that the energy flux in the aggregation zone significantly affects NP growth kinetics, with higher fluxes promoting rapid nucleation and increased particle densities [6]. Calorimetric measurements i.e., a passive thermal probe (PTP) [7,8], on the other hand, allow for the determination of the energy balance of the NPs within the aggregation chamber and should quantify the total energy influx to the particle as a function of gas pressure, magnetron power and target material.

The combination of these methods provides a comprehensive view of the physical conditions in a GAS and enables optimization of (external) process parameters (current, voltage, continuous or pulsing, Ar or N2 gas pressure and flow) and the (internal) plasma parameters and their correlation with the NP nucleation, growth, and transport to enhance nanoparticle throughput. Future studies should further investigate the effects of reactive gases and alternative experimental configurations to improve control over particle size and morphology.

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A combination sensor for the diagnostic of particle and energy fluxes in process plasmas

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Particle and energy fluxes play an important role for the growth of thin films on substrates and the modification and activation of surfaces [1]. Specifically, different ion fluxes and energies and by extension the resulting substrate temperature can have a significant impact on film hardness, adhesion and especially density [2, 3, 4]. Here, we present an in-house built combination diagnostic for the study of ion fluxes and energy distributions as well as the determination of energy flux contributions of ions and neutrals to the substrate [5]. This combination sensor consists of a Retarding-Field-Analyzer (RFA) grid system and a Passive-Thermal-Probe (PTP) as a collector [6, 7]. The RFA grid system enables energy filtering of ions, while the PTP allows for an almost simultaneous measurement of the energy flux density onto the substrate. The operational area includes applications such as DC-Magnetron sputtering, HiPIMS, CCRF discharges as well as ion beam sources at working pressures of up to 10 Pa. A unique challenge is presented by the energy flux density transmission of the grid system, currently constraining the application of the probe to moderate discharge powers.

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CO generation in an atmospheric microwave plasma torch

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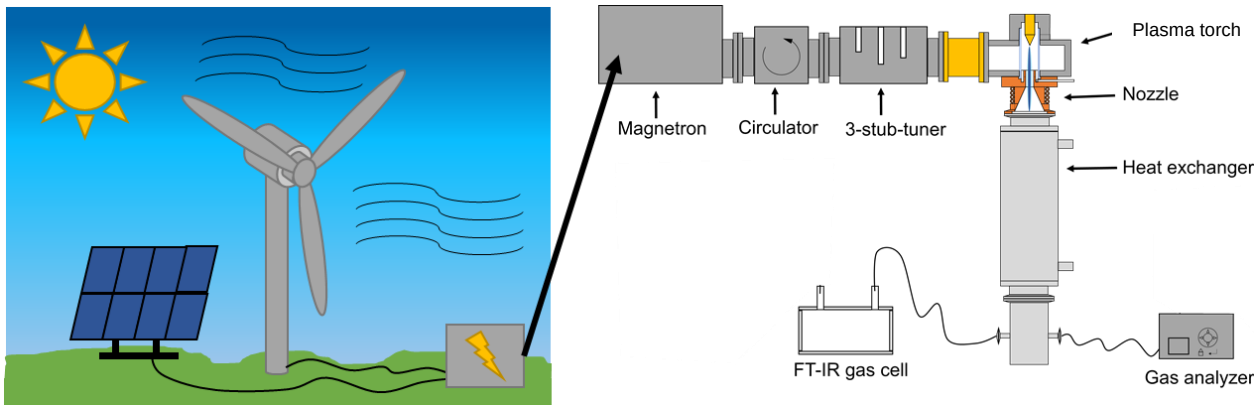
The emissions caused by mankind increase the concentration of climate-active gases in the atmosphere. This leads to a rise of the earth's surface temperature. The gas with the greatest impact is carbon dioxide (CO_2), which is produced, for example, through the use of fossil fuels. CO_2 emissions from industrial processes must be reduced and ideally used as a feedstock for other products. Renewable processes to utilize CO_2 must be developed. One possible way is an on-demand plasma process that activates CO_2 and converts it into the valuable product carbon monoxide (CO) using renewable, intermittent energy [1,2]. CO can be converted together with green hydrogen as synthesis gas into many different chemicals. The use of renewable CO from CO_2 closes the carbon cycle by utilizing emissions form industrial processes or CO_2 from direct air capture.
In this work, an atmospheric microwave plasma torch for CO_2 conversion is investigated, with focus on high microwave power and high energy efficiency [3]. The plasma splits CO_2 into CO and oxygen (O_2). The torch is operated in reverse vortex configuration. This means that the vortex stabilizes the plasma inside the quartz glass tube. A nozzle behind the resonator prevents the product to react back to CO_2 by quenching [4]. The fully mixed product gas, cooled to room temperature, is analyzed with a Fourier Transform Infrared absorption spectrometer (FT-IR) and an Emerson X-Stream gas analyzer. The impact of the microwave power and the CO_2 gas flow was studied. The energy efficiency was calculated based on the conversion values. Maximum conversions of up to 21 % and an energy efficiency of more than 40 % were achieved with our microwave plasma process.



Schematic illustration of CO_2 microwave plasma process using renewable energy.

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PKat4Chem – Non-Thermal Plasma Catalysis for CO_2 Valorization

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Power-to-X processes are essential to sustainable chemical production. However, they face challenges due to their elevated energy demand. Unlike conventional high-temperature catalytic routes, Non-Thermal Plasma Catalysis (NTPC) enables CO_2 activation using electrically generated cold plasma. This allows for the direct synthesis of valuable chemicals under mild conditions, with high energy efficiency and operational flexibility [1].

Building on this potential, *PKat4Chem* — a consortium of research institutions and industrial partners — focuses on integrating NTPC directly into biogas plants. It aims to develop mobile, containerized reactor units for decentralized, on-site valorization of CO_2 and CH_4. These modular systems employ dielectric barrier discharge (DBD) plasma in synergy with tailor-made catalysts, enabling efficient and selective single-step conversion to value-added chemicals at ambient temperature, with a focus on methanol [2].

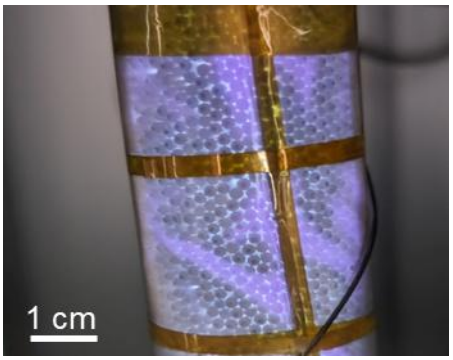

Fig.1: *Catalyst pellets packed in a dielectric barrier discharge (DBD) plasma reactor.*

Within the project, Leipzig University is responsible for the design, synthesis, and characterization of catalysts for NTPC. In a first stage, studies focus on the role of chemical and textural properties of metal-loaded porous oxide supports (e.g., Ni, Cu / Al_2O_3 or ZrO_2). Acid-base and textural properties are systematically tuned to direct product selectivity toward desired liquid products. This is achieved by methods such as introducing alkaline metals with varying loadings to adjust the strength and density of the basic sites, or tailoring pore widths to enhance the interaction of plasma-activated species with the catalyst's active sites.

The development of these catalysts represents a core contribution in *PKat4Chem*, enabling efficient and selective plasma-catalytic CO_2 conversion, supporting the overarching goal of advancing sustainable chemical production. In this presentation, we will show the tools used to study structure-activity relationships of prepared catalysts applied in plasma-driven dry reforming of methane under ambient pressure and temperature conditions (Fig. 1).

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Impact of the HiPIMS and RF superposition on a single magnetron on plasma dynamics and energy flux

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High power impulse magnetron sputtering (HiPIMS) has shown significant potential for thin film deposition by providing high ionized flux fractions [1] and ion energies [2]. To optimize the deposition process, HiPIMS can be operated in superposition with an additional discharge on the same magnetron, such as DC [3, 4] or MF (mid-frequency pulses) [5]. This leads to an increase of the deposition rate and facilitates low-pressure operation by utilizing the pre-ionization of the continuously running discharge during the off-time between HiPIMS pulses.

In this study, a novel combination of HiPIMS and RF (radio-frequency, 13.56 MHz) is investigated in continuous superposition on the same magnetron, using a planar copper target in argon atmosphere. The discharge is characterized at varied power ratios of HiPIMS and RF with plasma diagnostics employed to analyze the system. This includes measuring the combined HiPIMS/RF voltage signal and conducting optical emission spectroscopy (OES) to gain insights into the plasma composition. Two key factors influencing the microstructure of deposited films are the kinetic energy of particles bombarding the growing film and the substrate temperature [6]. Substrate heating from the plasma is evaluated using a passive thermal probe (PTP) [7], a “non-conventional” calorimetric diagnostic that measures the total energy flux to the substrate surface. The kinetic energy is assessed through energy-selective mass spectrometry [8], including time-resolved operation. The results regarding the plasma parameters are compared with the morphology of the deposited copper films, analyzed using scanning electron microscopy (SEM).

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Continuous Technical Scale Polymer Grafting onto Carbon Fibres by Atmospheric Plasma using CASING and Preirradiation Method

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The grafting of polymers to surfaces is an uprising technology since it gives the possibility combine unique features of substrate and coating. A high potential application is reinforcing fibres, where fibre coating enables crucial features: processability and load transfer in composite. Grafting a matrix polymer onto the surface will result in ideal adhesion as well as better recyclability due to a better recycling resistance. Still, the grafting of polymers to a solid substrate surface is challenging since most industrial processes are continuous with high speed and low purity. Low-pressure plasmas have shown in literature that they do initiate grafting. [1,2] This work transfers these techniques to an easier operable atmospheric pressure plasma. We compared different grafting initiating techniques regarding their grafting efficiency in technical-plant scale. In a prestudy, the generated radiacls by preirradiation method have been measured and the efficiency of CASING tested. [1,2] The general process parameters power, distance and contact time have been investigated to find suitable grafting conditions. In a second step, a pilot process is established, and fibres are coated. The adhesion between fibre and a matrix polymer and the stability in a solvolytic recycling have been validated

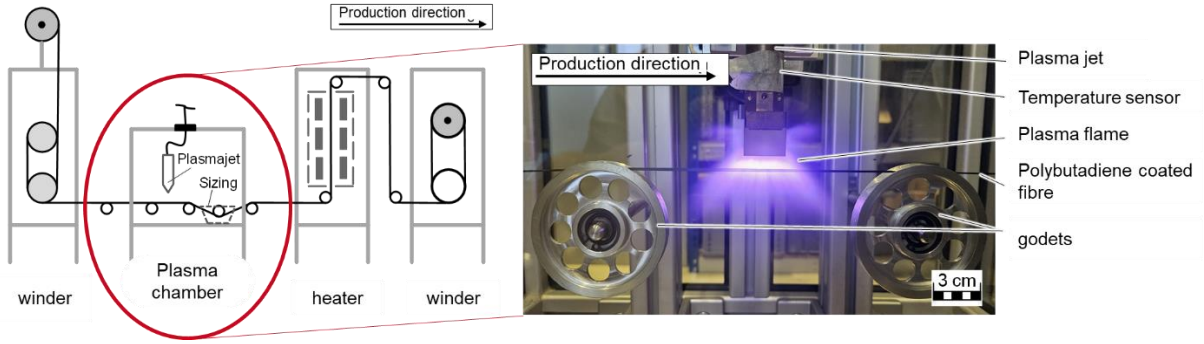

Figure 1: Set up of the Plasma Grafting module on contious, technical scale.

While radical generation by preirradiaton was not successful, CASING induced grafting. A parameter window where crosslinking is feasible has been determined. We found that coating thickness and solvent is crucible to a successful immobilization. By comparing the results with UV and electron-beam-treated polybutadiene, we identify that in contrary to low pressure plasmas UV-irradiation is not responsible for the crosslinking in the polymer.[3] Comparing the results of plasma-grafted coatings with a conventional sizing, the interactions between fibre and coating are based on covalent bonds.
Plasma Grafted coatings on reinforcing fibres offer a great opportunity to flexibilise the functionalisation. Using this technique has three big features: 1. a technically easier functionalisation in two steps instead of five, 2. easy matrix adaption to new sizing materials and 3. Improved recyclability: using this technique for a first time a continuous carbon fibre can be recycled instead of lower-value short carbon fibres.

We thank the BMFTR for the funding of the Project “GrafCarbon” which enabled this research.

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INFLUENCE OF MAGNETRON SPUTTERING CONDITIONS ON THE EARLY STAGES OF GROWTH OF NOBLE METALS ON DIFFERENT POLYMERS

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The controlled deposition of ultra-thin metal films is critical for advancing applications in flexible electronics, sensors, and optoelectronic devices. In particular, noble metals such as silver (Ag), gold (Au), and copper (Cu) offer unique advantages due to their outstanding electrical conductivity, optical properties, and chemical stability. Therefore, the early-stage growth of Ag, Au, and Cu thin films on five different polymers—polystyrene (PS), poly(methyl methacrylate) (PMMA), polytetrafluoroethylene (PTFE), ethylene glycol dimethacrylate (EGDMA), and tetravinyltetramethylcyclotetrasiloxane (PV4D4)—using both direct current magnetron sputtering (DCMS) and high-power impulse magnetron sputtering (HiPIMS).
Scanning electron microscopy (SEM) and in-situ grazing-incidence small-angle X-ray scattering (GISAXS) are utilized to analyze morphological features such as island formation, cluster density, and surface coverage [1]. Electrical properties are evaluated via sheet resistance measurements. The results demonstrate that HiPIMS significantly improves surface coverage and reduces electrical resistance for Ag and Au films compared to DCMS, while exhibiting a higher density of clusters [2,3]. Among the substrates, PS promotes high surface coverage, whereas PTFE consistently yields the lowest, underscoring the influence of polymer surface energy on nucleation and growth dynamics.By comparing deposition techniques and material combinations, it is revealed that film morphology and functional properties can be finely tuned through process parameters alone—without the need for additional layers or surface modifications.

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EXAMPLE MASS BALANCE OF DRM VIA PLASMA CATALYSIS

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The utilization of greenhouse gases such as CO_2 and CH_4 for syngas (CO + H_2) production is crucial for industrial applications and climate mitigation. Conventional thermal catalytic dry reforming of methane (DRM) is highly energy-intensive, leaving room for improvement through non-thermal plasma catalysis (NTPC) to mitigate its energy demands. NTPC enables gas conversion at lower operating temperatures and expands the range of possible reaction products, including oxygenates and higher hydrocarbons. However, for industrial viability, the scalability and mass balance of packed-bed plasma reactors in DRM require further investigation.

An example gas mixture containing CO_2 and CH_4 is processed in a custom-built dielectric barrier discharge (DBD) reactor at ambient temperature and pressure. Plasma is generated using a pulsed voltage supply with peak voltages up to 18 kV and repetition frequencies up to 20 kHz. Pulsed plasma is continuously operated for more than 8 hours. A cold trap after the reactor captures condensable species post plasma. The remaining gas phase is continuously quantitatively analyzed using an on-line Micro Gas-Chromatograph. The usage of a Dilution constant allows for accurate processing of acquired data.

Various example input conditions are analyzed and the dilution constant are determined. Resulting CO_2 and CH_4 conversions as well as gas phase product selectivity are analyzed. Gas phase syngas is determined to be consistently above 80%. Mass balance analysis provides insight into the separation of gaseous and liquid products, as well as monitoring total mass losses, confirming measurement accuracy. This work offers insights into the scalability of packed bed reactors for DRM, particularly under long operation times and with higher volumetric feed conditions.

Bridging Plasma and Chemistry: Data-Driven Acceleration of Sustainable Catalysis

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One of the key challenges in achieving sustainable chemical production is the often excessive energy demand of traditional synthesis processes. Efficient CO_2 conversion requires advanced technologies that operate with high selectivity and minimal energy loss. enaDyne addresses this challenge through non-thermal plasma catalysis, where molecules are excited using electrically generated cold plasma. This approach significantly facilitates chemical reactions and enables the production of green base chemicals—such as ethylene or e-fuels—without the heat losses typically associated with thermal processes.

A critical aspect of optimizing such plasma-assisted reactions lies in the precise coordination of mutually dependent experimental parameters. These include the properties of the catalyst, the characteristics of the plasma species, the electrode configuration, the composition of the feed gas, and the overall reactor conditions. To accelerate the discovery of efficient parameter combinations, enaDyne leverages data-driven models of parameter interdependencies in conjunction with Bayesian optimization algorithms [1]. This enables systematic, guided exploration of the parameter space, reducing the experimental effort required for optimization to approximately 20–40% compared to conventional approaches such as standard Design of Experiments (DOE) or brute-force sampling.

A complementary strategy involves applying data mining techniques to recent scientific literature and publicly available repositories such as the Pioneer database [2]. This broader analysis aims to identify use-case-specific patterns and key performance factors in plasma catalysis using machine learning methods. Constructing a consistent and generalizable dataset from these heterogeneous sources posed a challenge—balancing the model's inherent capacity to generalize with the dataset's internal coherence. To improve model quality, selective filtering strategies were implemented to systematically exclude noisy or unreliable data points, thereby enhancing the robustness and predictive power of the resulting models.

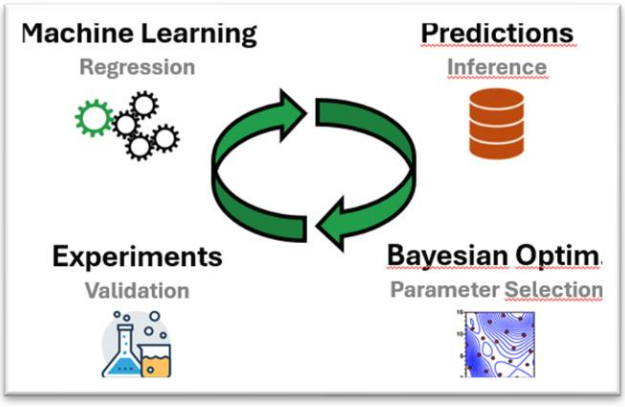

Figure 1. Concept of sequential experimental design with integration of a machine learning method.

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SILICON NITRIDE MEMBRANE AS ENTRANCE WINDOW FOR PLASMA-INDUCED VACUUM ULTRAVIOLET RADIATION

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Vacuum ultraviolet (VUV) radiation corresponds to the wavelength range between 10 nm and 200 nm (124 eV to 6.2 eV) and plays a crucial role in biomedicine, lithography, material modification, and photocatalysis [1]. However, the diagnostic of VUV photons generated by non-thermal atmospheric pressure plasmas is complicated by the strong absorption of VUV photons in air and common window materials like lithium fluoride or magnesium fluoride as these window materials have a cutoff wavelength of around 110 nm [2]. Various windowless techniques have been developed in the past to transfer the VUV radiation into a vacuum, including differential pumping systems [3,4] or an aerodynamic window [1], though each method has its drawbacks.

This contribution presents a novel method to measure VUV photons using an evacuated monochromator equipped with an ultra-thin silicon nitride (Si_3N_4) membrane as an entrance window, originally designed for applications in transmission electron microscopy. Measurements have demonstrated that the Si_3N_4 membranes are capable of withstanding the forces generated by the pressure gradient between atmospheric pressure and vacuum while being significantly thinner (20 nm membrane thickness) than conventional vacuum windows. Further, the Si_3N_4 membranes have proven to be resistant to plasma and plasma-generated species [5], making them suitable as either an entrance or exit window for plasma-induced VUV radiation.

Two non-thermal atmospheric pressure plasma sources, one based on the RF-driven capillary plasma jet [6], the other based on a DC microplasma source [7], were developed to generate VUV excimer radiation.

Emission spectra were measured and analyzed for different monochromator pressures, membrane thicknesses, and working gas mixtures. Measurements of the emission spectra, taken at different pressures inside the monochromator revealed interesting self-absorption effects in noble gases. The transmittance of Si_3N_4 was indirectly measured and confirmed literature data [8]. Analysis of the Si_3N_4 membranes after plasma exposure revealed modifications in their elemental composition, potentially opening new pathways to the production of ultra-thin oxide films from nitrides.

Additionally, first results from the DC microplasma source, including electrical and optical measurements, are presented.

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MEASUREMENT OF ATOMIC OXYGEN DENSITIES AND THEIR TRANSPORT USING TALIF AND SEA IN A MICRO CAVITY ARRAY REACTOR FOR CATALYSIS

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1. Introduction

Micro-structured plasma discharge cavity devices show great potential for applications requiring large-area treatment, catalytic conversion, or decomposition of volatile organic compounds. Therefore, arrays of dielectric barrier micro discharges in well-defined cavities are of high relevance from a scientific and technical point of view. To understand the underlying processes, fundamental knowledge about the discharge dynamics and generation and transport of reactive species (here: atomic oxygen) is necessary. Additionally, the impact of fluxes of (charged) particles driven by electric fields and plasma-induced surface charges on catalysis are of high interest.

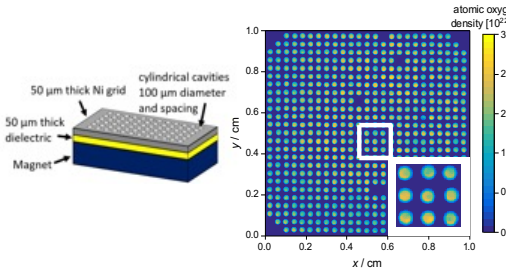

Fig. 1. MGA & O density inside

2. Methods

In this work, we investigate modular constructed metal-grid micro cavity [1] plasma arrays (MGA) which allow for stable operation and the incorporation of catalysts (Fig. 1 left). MGAs consist of hundreds to thousands of discharge cavities with ~100µm dimensions and are operated in helium with admixtures of reactive gases, typically in the percentage range (excitation: kHz triangular voltages of 400-800V). However, diagnostics in these cavities are challenging due to their small dimensions. The basic discharge behavior like discharge mode and expansion, electrical characteristics and dynamics will be discussed and accompanied by optical emission-based methods to determine electric fields (Stark shift) [2] and 2D resolved atomic oxygen densities inside (by helium state enhanced actinometry (SEA)) and two-photon absorption laser induced fluorescence (TALIF) outside the MGA [3,4].

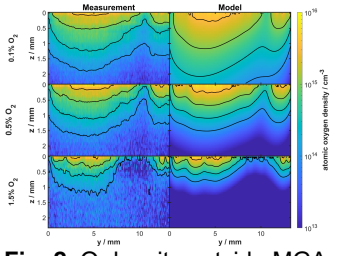

Fig. 2. O density outside MGA

3. Results and Discussion

Atomic oxygen densities in the volume inside and above a micro cavity plasma array are successfully determined spatially and time-resolved using SEA and TALIF measurements and explained by a basic model. Fig. 1 (right) shows spatially resolved atomic oxygen densities measured by SEA of a whole MGA. Inside the cavities nearly complete dissociation of O_2 is achieved. Fig. 2 shows TALIF measurements and results of a basic diffusion model outside the MGAs. Slightly outside an equilibrium density is reached after 3ms. Regions further away are dominated by diffusion and ozone formation. SEA findings can be linked to the TALIF measurements outside via the model. An optimal dissociation is found at 0.4% oxygen admixture, where there is a balance between production inside the cavity and losses outside.

This work is supported by the DFG within SFB1316.

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FROM PLASMA FABRICATION TO DEVICE PERFORMANCE: INSIGHTS FROM SPUTTERED RESISTIVE SWITCHING DEVICES

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Plasma-based fabrication is crucial for tailoring material properties at the nanoscale and remains central to the manufacturing of advanced electronic devices. A recently emergent class of components that shows promise in this regard is that of memristive devices, which offer a potential solution toward energy-efficient, brain-like information processing. The behavior of these materials is highly sensitive to the material structure formed during plasma-assisted deposition. In this study, SiO_x/Cu devices as introduced in [1] are fabricated using reactive sputtering in Ar/O_2 and Ar plasmas. A data-driven classification approach, based on self-organizing maps [2], is applied to over 50,000 devices to identify how fabrication conditions influence performance behavior. The analysis reveals distinct types linked to deposition environments. To interpret these trends, a compact model based on a cloud-in-a-cell approach inspired by the particle-in-cell approach (commonly used in plasma simulations) is used [3]. The model successfully captures the transport of particles, the evolution of internal fields, and current mechanisms, thereby providing a mechanistic understanding of the observed variability in the switching phenomenon. This combined experimental and modeling approach highlights the importance of plasma process control in determining functional outcomes in nanoscale electronic devices. The overall workflow is illustrated in Fig. 1.

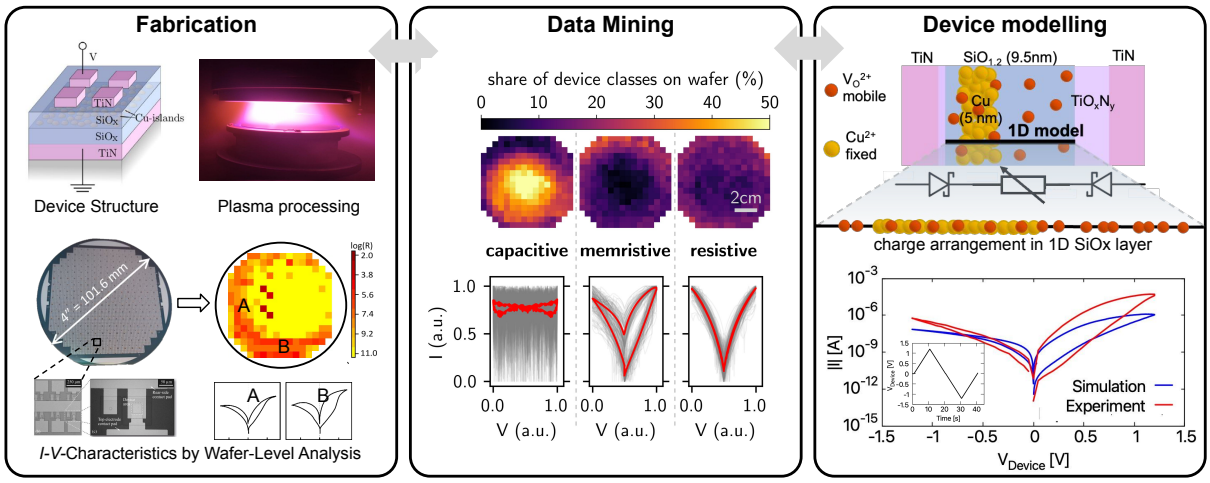

Figure 1. Overview of the interdisciplinary workflow: plasma-based fabrication of SiO_x/Cu memristive devices (left), data-driven classification of switching behavior (center), and compact physical modeling inspired by plasma simulation techniques (right).

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – Project-ID 434434223 (SFB 1461).

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3D EM-SIMULATION OF THE INFLUENCE OF GAPS AND LATTICE STRUCTURES IN CAVITIES ON THEIR RESONANCE BEHAVIOR TO BE APPLIED IN MICROWAVE CAVITY RESONANCE SPECTROSCOPY

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Extracting relevant plasma parameters, such as the plasma electron frequency ω_{pe} or electron temperature T_e from a plasma reactor remains a challenge to this day, since external parameters such as input power do not correspond to the behaviour of the plasma directly. To facilitate said extraction, techniques such as active plasma resonance spectroscopy (APRS) were developed, which subjects a plasma to an electromagnetic (EM), wide-band radio frequency signal. The frequency response of the system is then measured and analysed, and utilising a model yields ω_{pe} and T_e, which in turn are used to determine the plasma electron density n_{pe}. Several different methods of APRS have been developed, one of which is called microwave cavity resonance spectroscopy (MCRS). It operates in the electromagnetic domain where wave propagations inside the plasma are possible, which is the case for $\omega > \omega_{pe}$. In MCRS, standing waves are excited inside a vacuum cavity. The frequencies of these standing waves, representing oscillating modes, is entirely dependent on the dimensions and material of the cavity, as well as any deviations from the ideal case, such as antennas. Introducing a plasma to the cavity causes a shift of the observed modes towards higher frequencies, as the plasma acts as a frequency-dependent dielectric, which shows a spatial dependency as well. This shift changes in size depending on ω_{pe}, and allows for the extraction of n_{pe} using models. Compared to other procedure of determining plasma densities, this method is non-invasive, and due to its low perturbation potential a good candidate to be applied to nanodusty plasmas. Due to the limits of other diagnostic methods, such as Mie polarimetry, or dust density waves, namely a lower bound of the size of the dust particles and a limit for the type of species that can be observed as well as a lower density boundary, respectively, the development of a robust method for determining plasma parameters for low densities inside dusty plasmas is needed.

Building on previous results achieved for an ideal cylindrical cavity, a special emphasis will be put on analysing the influence of transparent elements in the form of gaps or lattice structures for optical verification measurements. If the assumption of small disturbances holds for several modes, a model may be introduced that combines the analysis of the shift of several modes to allow for a spatial picture of the densities inside a reactor. For that purpose, precise knowledge of which modes are excited, their mode profile, as well as their frequency shift when introduced to a plasma is needed. Simulation data from a commercial software will be used to show how the different spectra react to the introduction of non-ideal elements.

This project was funded by Deutsche Forschungsgesellschaft (DFG), Project No. 531667910, which is gratefully acknowledged.

3D NANOPATTERNING USING ION BEAM ETCHING

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Nanodevice manufacturing will be faced with new challenges in future applications like quantum computing and/or integrated electro-optical devices like:

- Processing and patterning of materials that are not used in standard microelectronics applications so far;
- Requirements in device or property homogeneity that require localized correction technologies and
- Generation of localized 3D structures.

Ion beam etching is a versatile tool that covers the requirements for 3D nanodevice production. Based on its high kinetic energy, ion beam milling can pattern all materials without the need for a specific process chemistry. Nevertheless, reactive ion beam milling might address additional benefits.

Furthermore, due to the directional anisotropic removal effect at simultaneously low divergence, ion beam technologies can be applied to generate 3-dimensional nanostructures.

The presentation covers exemplary specific applications of ion beam technologies in nanodevice manufacturing.

Ion beam patterning of multilayer-based devices: Nanodevices often apply multilayer structures with quantum-mechanical effects appearing in between these films. However, standard etching technologies may not be suitable for magnetic, magneto-resistive, or piezoelectric materials. Ion beam milling is mostly the technology of choice for patterning multilayers. Besides accessing any arbitrary material with this technology, an additional advantage is gained from the directed ion flux; for example, sidewall redeposition can be avoided. The patterning of magneto-resistive and piezoelectrical devices is a new field of application that will be shown in this presentation.

Generation of 3-dimensional structures in micro-optical devices: Sidewall angles of optical devices often need to be adjusted to a defined slope. Even more difficult 3D structures are applied in micro-optical devices such as diffraction structures or coupling grids. Because of the directional removal of an ion beam, the exact angular orientations of structures can be easily adjusted. Furthermore, a scanning ion beam can adjust different orientations and structural depths across a single substrate. For example, a localized ion beam process will be applied to produce slanted grating structures used as coupling grids in data projection. This will also be shown in the presentation.

STRUCTURING AND UNIFORMITY IMPROVEMENT OF THIN-FILM LITHIUM NIOBAT AND OTHER WAVEGUIDE MATERIALS

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The demand for photonic integrated systems (PICs) is growing rapidly in telecommunications and data centers due to their wide bandwidth, low transmission loss, and numerous other advantages over traditional electronic integrated circuits.

Thin-film waveguides, widely acclaimed for their electro-optic and piezoelectric properties, are used frequently in PICs. They demand precise fabrication techniques to ensure consistent device performance. Integrating new materials, material stacks, and designs is pivotal in advancing photonics and optoelectronics, but it requires new etching solutions. scia Systems' advanced ion beam etching and trimming processes enable the manufacturing of three-dimensional optoelectronic microstructures for PICs.

Furthermore, due to the directional anisotropic removal effect at simultaneously low divergence, ion beam technologies can be applied to generate 3-dimensional nanostructures. The presentation will cover specific applications of ion beam technologies in nanodevice manufacturing, such as ion beam trimming of piezoelectric films.

SURFACE ANALYSIS OF THE REACTIVITY OF PLASMA-ACTIVATED POLYLACTIDE FILMS UNDER AMBIENT CONDITIONS

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Polylactide (PLA) is a biobased and biodegradable polymer that can be synthesized using renewable resources such as corn and other crops. Due to its positive carbon footprint and the absence of petroleum-based chemicals in its production process, PLA is considered an environmentally friendly material. Its applications span from packaging to medical implants, each requiring tailored surface properties.
Surface chemistry modifications are often necessary to meet specific application needs and can be achieved using various plasma modification techniques, including low-pressure discharges and atmospheric plasma jets. In our previous work, we investigated the effects of nitrogen low-pressure plasma treatment on PLA surfaces using in-situ Polarization Modulated Infrared Reflection Absorption Spectroscopy (PM-IRRAS), and in-vacuo X-ray Photoelectron Spectroscopy (XPS). [1] The findings were supported by contact angle measurements, confirming changes in the surface free energy.
In our current research, we investigate how freshly plasma-treated PLA surfaces interact with ambient environmental conditions, particularly varying humidity levels. To better understand the interactions and the stability of these surfaces, we incorporate additional analytical techniques, including Quartz Crystal Microbalance (QCM), and electrochemical methods such as Kelvin Probe analysis of surface dipoles and electrochemical impedance spectroscopy for the analysis of polymer hydrolysis.

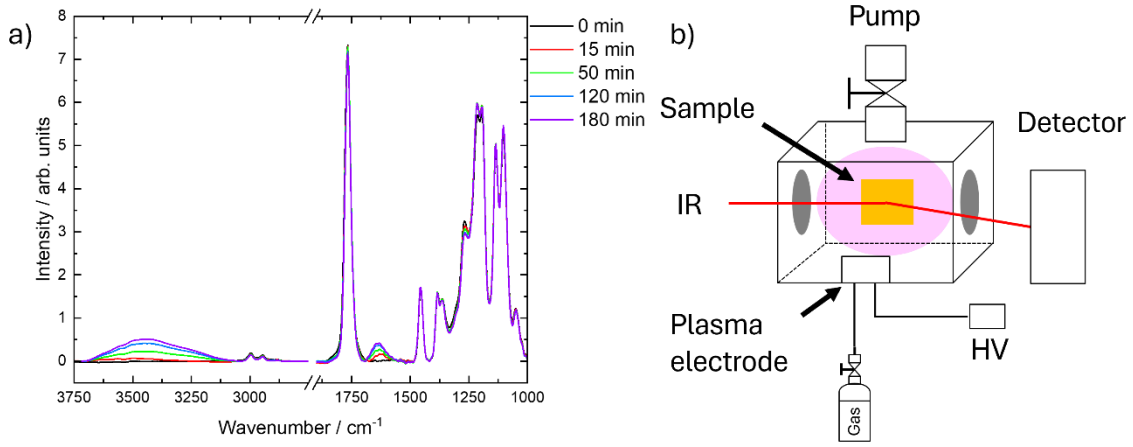

Figure 1.
a) In-situ PM-IRRAS spectra of plasma-treated PLA recorded before (0 min) and after 15, 50, 120 and 180 min of exposure to 99% relative humidity. The spectra show the emergence and growth of bands associated with adsorbed water on the activated PLA surface. Additionally, changes in the polymer crystallinity are evident in the spectral region between 1215 and 1192 cm^{-1}. [1]
b) Schematic representation of the in-situ PM-IRRAS setup. [1]

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NOVEL TECHNIQUES FOR PLASMA SPECTROSCOPY

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Low-temperature non-equilibrium reactive molecular plasmas play a crucial role in numerous industrial processes, most noteworthy in the microelectronics industry, and hold significant potential for driving essential chemical transformations. Precise information on the molecular composition of the plasma, on the absolute concentrations and temperatures of the reactive species in the plasma, their population distribution among the quantum states and their reaction kinetics is essential for understanding, optimizing, and controlling plasma processes. We present our recent progress in plasma spectroscopy in the infrared and terahertz spectral region. We develop and apply state-of-the-art optical frequency comb-based spectroscopy techniques, offering a unique combination of broad bandwidth and high spectral resolution [1,2]. This enables the simultaneous detection of multiple species in the plasma. Furthermore, terahertz absorption spectroscopy using quantum cascade lasers has recently been developed and implemented as a new diagnostic technique for investigating ground state atomic oxygen densities in plasmas [3]. This method could be a compact and easy-to-use alternative for the industry for measuring atomic densities.

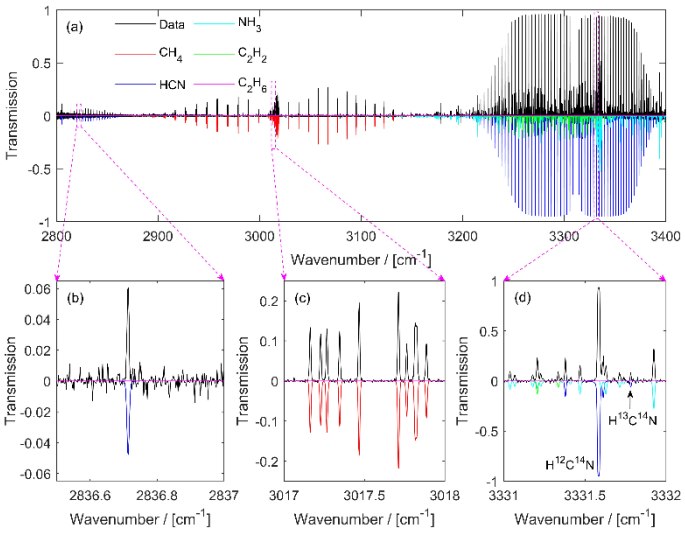

Figure 1: (a) High-resolution spectrum measured (black) and simulated (colours) in a pulsed DC discharge at 3 mbar, and a plasma power of 26 W. (b)–(d) are zoomed-in portions of the spectrum, highlighting the state-resolved absorptions achieved for multiple molecular species in the plasma [1].

This work is funded by the DFG - project number 499280974 and the Federal Ministry of Research, Technology and Space (13N14947).

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INFLUENCE OF FREQUENCY ON OZONE PRODUCTION USING HIGH-IMPEDANCE TRANSFORMERS IN AIR

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Plasma-assisted air purification utilizes reactive oxygen and nitrogen species to inactivate microorganisms and degrade gaseous pollutants. Besides atomic oxygen, singulett oxygen and hydroxyl radicals, its effectiveness is largely determined by the amount of ozone generated in situ. In this work, a volume dielectric barrier discharge was investigated, consisting of two electrode arrays with a total of 136 individual electrodes with 0.3 mm glass dielectric (Ø 2 mm, gap 2 mm) and powered by a high-impedance high-voltage transformer in the low-frequency range up to a few hundred hertz. The transformer was operated via an H-bridge with rectified mains voltage (325 VDC). The frequency and modulation depth (MD) of the primary voltage can be controlled independently of each other, resulting in separate control of the output frequency and voltage, allowing the role of the excitation frequency to be evaluated at four constant power levels (60–90 W). The resonance frequency of the transformer-plasma electrode system was 75 Hz with 100.14 ± 0.96 W. [1]
The ozone production rate was determined in a 3 m³ stainless steel chamber at a volume flow of 898 ± 170 $\frac{m^3}{h}$ [2]. At constant power input, the ozone production rate scales with frequency. The maximum was reached at 81 Hz and MD = 71% and amounted to 4.07 $\frac{\mathrm{g}}{h}$ at 69.9 ± 2.56 W. This corresponds to a yield of 58 $\frac{\mathrm{g}}{kWh}$. [1]
The results prove that frequency-adaptive control can significantly increase ozone yield without additional power consumption. For practical applications – such as in agricultural stable air cleaners – operation above the resonance frequency is therefore recommended to ensure high efficiency with moderate energy consumption. [1]

Acknowledgements
I would like to express my sincere thanks to Roland Damm for the informative and fruitful discussions, and to Tom Götting for soldering the numerous circuit boards. The work was carried out as part of the EIP project PlaLuST (grant no.: EIP: 14 35 10). The authors would like to thank the project management organization, the Lower Saxony Chamber of Agriculture and the funding body, the European Union.

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MACHINE LEARNING APPLICATIONS IN LOW-TEMPERATURE PLASMA RESEARCH BEYOND SUPERVISED LEARNING

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Machine learning (ML) has proven to be an indispensable set of tools in many industries and scientific fields, and low-temperature plasma (LTP) science and technology is not an exception. LTP research has enabled various technologies of high societal significance [1], and here, ML can be of use to improve the modeling and analysis of complex LTP systems. Applications of ML in LTP research have mostly focused on supervised learning [2], which depends on a large amount of labeled data. In this contribution, we bring forth examples of ML applications across various learning paradigms. First, we demonstrate a supervised learning approach to construct surrogate models for LTP simulations [3]. Second, we introduce physics-informed neural networks (PINNs) [4,5] utilized to solve complex physical equations in LTP physics, such as the electron Boltzmann equation, in a self-supervised manner. Furthermore, the same PINN approach is used to tackle inverse problems, which are ill-posed for conventional numerical methods. Lastly, we present a preliminary result of reinforcement learning for optimizing equivalent circuits of gas discharges based on electrical measurement data. All in all, the examples demonstrate various ML methods beyond the typical supervised learning approach, which we see as valuable tools to advance LTP research.

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INVESTIGATIONS OF HYDROGEN PLASMAS FROM A MICROWAVE PLASMA SOURCE FOR METAL FOIL PUMPS FOR FUSION TECHNOLOGY

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The efficient separation and recycling of hydrogen isotopes, especially tritium, are essential for the fuel cycle in future fusion power plants. Metal foil pumps (MFPs) offer a promising solution based on the superpermeation mechanism, where hydrogen isotopes selectively permeate through metal membranes under plasma exposure [1, 2]. The focus of this study is the numerical and experimental investigation of hydrogen plasmas generated by the Duo-Plasmaline, a linearly extended microwave plasma source, intended for integration into MFP systems for hydrogen isotope separation and recycling.

Self-consistent simulations of hydrogen plasma were performed to analyze plasma parameters such as electron density, electron temperature, reaction pathways and composition of heavy species under various operational conditions. Since the MFP will be in close proximity to the torus, the influence of strong magnetic fields up to 1 T on the plasma properties and microwave heating mechanism is modelled as well. The results are compared with studies in the FLIPS experiment, where the influence of magnetic fields on the Duo-Plasmaline with up to 250 mT can be investigated. The focus of the experiments was on plasma behavior, stability and ignitability under various magnetic field configurations. The numerical and experimental results show, that the Duo-Plasmaline can be ignited and operated in strong magnetic fields depending on gas pressure and microwave power [3].

The results of this study contribute to ongoing research within a subtopic of the recently launched SyrVBreTT joint project, which, among other objectives, explores the development and optimization of metal foil pumps (MFPs) in a flexible experimental setup. The project emphasizes detailed experimental studies of plasma properties and the complex interactions between the plasma source, metal foil, and reactor wall. Diagnostic techniques such as Langmuir probe measurements, optical emission spectroscopy, and energy-dispersive mass spectrometry are employed to characterize these interactions. The primary objectives are to optimize hydrogen isotope permeation through the metal foil and to ensure the long-term operational stability of MFPs by identifying and mitigating degradation mechanisms that have, until now, limited their practical application.

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DEPOSITION OF THIN CORROSION-RESISTANT PLASMA FILMS ON AA 2024 USING AN ATMOSPHERIC PRESSURE PLASMA JET

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Aluminum and its alloys are widely used in industrial applications such as construction and the transport sector due to their advantageous properties, which can be tailored through processing and treatment. Aluminum alloy AA2024 combines low density and high strength, yet it suffers from corrosion due to the presence of copper-rich intermetallic phases, particularly in chloride-containing environments. Conventionally, wet-chemical silanization methods are used to improve corrosion resistance of aluminum alloys [1]. However, also plasma deposition of ultra-thin SiOx-like films led to effective corrosion protection [2].

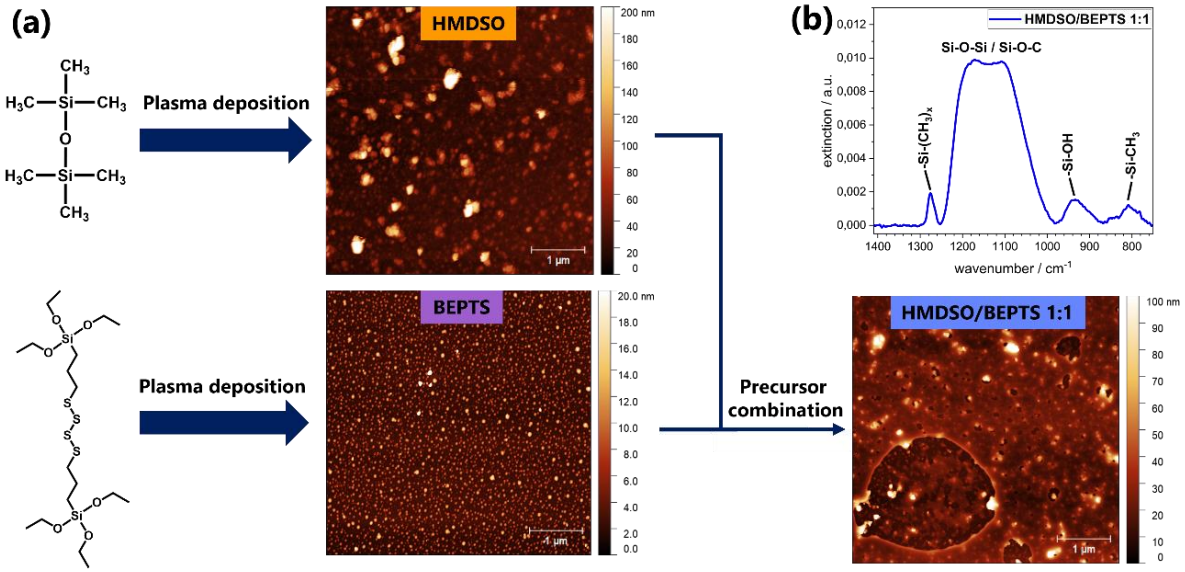

Figure 1: (a) Schematic overview of the different surface textures observed by AFM after plasma deposition of different precursors on polished Si-Wafers. (b) FT-IRRAS extinction spectrum of a plasma coated AA2024 sample coated with a 1:1 HMDSO/BEPTS mixture.

Atmospheric-pressure plasma jets (APPJs) can offer a solvent-free route to clean and functionalize metallic surfaces using a single experimental setup, without the need for additional solvents or thermal treatments. For this, an APPJ operating at up to 400 W was used to deposit hexamethyldisiloxane (HMDSO) and bis(triethoxysilylpropyl)tetrasulfide (BEPTS) and mixtures of both from the aerosol phase on the aluminum alloy AA2024, using nitrogen as the process gas. The deposited layers were investigated using Fourier-transform infrared reflection-absorption spectroscopy (FT-IRRAS), atomic force microscopy (AFM), X-ray photoelectron spectroscopy (XPS), contact angle (CA), and electrochemical impedance spectroscopy (EIS). The results show that the plasma-based approach produces homogenous, crosslinked thin films with thicknesses in the low nanometer range, consisting of Si-O-Si and Si-O-C species exhibiting hydrophobic properties. AFM imaging revealed significant differences in surface texture depending on the precursor and mixing ratios of both. Increasing the ratio of BEPTS/HMDSO leads to dewetting phenomena on the surface of the deposited layers and apparent densification of the deposited films leading to improved corrosion resistance as shown by EIS studies.

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Streamer dynamics of a µs/ns-pulsed surface dielectric barrier discharge

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Surface dielectric barrier discharges (SDBDs) are widely studied for their potential in applications ranging from plasma-assisted gas conversion to surface treatment [1-3]. In this work, SDBDs driven by microsecond (µs) and nanosecond (ns) voltage pulses are investigated in various gas mixtures and at different pressures. A combination of experimental diagnostics and two-dimensional fluid simulations is used to gain insights into the spatial evolution of streamers, specifically their length and width, as key discharge parameters are systematically varied.

Phase-resolved optical emission spectroscopy (PROES) reveals streamer dynamics that show good qualitative agreement with simulations results. It is consistently observed that under ns-pulse operation, a positive streamer is initiated at the powered electrode of the twin-SDBD configuration, while, under most conditions, a simultaneous negative streamer emerges from the grounded electrode. Notably, the discharge exhibits less stochastic behavior under ns-pulse excitation compared to µs-pulse excitation, enabling spatio-temporally resolved observation of streamer propagation and, in combination with optical filters, the tracing of highly energetic electron dynamics.

Finally, the mutual influence between the positive streamer at the powered electrode and the negative streamer at the grounded electrode is investigated, with evidence indicating that the positive streamer partially affects the development of the negative streamer.

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ANALYSIS AND COMPARISON OF SWARM PARAMETERS IN EUV INDUCED PLASMAS

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State-of-the-art semiconductor manufacturing intrinsically relies on extreme ultraviolet (EUV) radiation used in the lithography step. EUV light is reflected of the mask onto the wafer with photoresist coating to create nanometer-scale circuit patterns. The chamber volume of the scanner holding the optics is filled with hydrogen gas at low-pressure. The EUV radiation is subject to strong absorption at the walls and in the gas phase, and initiates a highly transient plasma discharge. This entails a complex chemical reaction set and associated discharge kinetics. Consequently, a model description is desired to accurately predict the gas-phase kinetics and the plasma-surface interactions.
To gain deeper understanding on the involved physicochemical mechanisms, spatially resolved particle-in-cell (PIC) simulations are accurate but computationally very expensive [1]. In contrast, global model approaches like a 0D kinetic Monte Carlo (kMC) simulation aim to reduce the order of complexity while still depicting the plasma chemistry precisely [2]. To compare the influence of the different approaches, so-called swarm analyses are studied in which a gas-filled tube subject to a DC bias is represented. From a statistical analysis of the microscopic dynamics macroscopic parameters like the Townsend ionization coefficient and the reduced mobility can be obtained. In this work, the results from kMC plasma simulations using the LoKI-MC code are evaluated and compared with 3D PIC simulation results using the same cross-section reaction set [3,4]. Furthermore, the influence of scattering mechanisms and their impact on the electron energy distribution function is analyzed. Lastly, an analysis on the sensitivity of reactions is presented, in which different cross sections of the same reaction type but from different databases are evaluated and compared.

Funding from ASML B.V. is gratefully acknowledged.

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PLASMA-KG: A SEMANTIC PLATFORM LINKING CONCEPTS, DATA, AND KNOWLEDGE FOR PLASMA TECHNOLOGY

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Knowledge graphs (KG) offer the possibility of semantic linking data and information from different sources, which allows various knowledge sources to be accessed more easily, thus, accelerating research and development. A KG implementation in plasma technology addresses many challenges in how information is managed, such as, non-standardized uses of terminologies, inconsistent metadata, and the lack of important relationships between studies, devices, processes, materials, diagnostics, etc. To this end, the development of Plasma-KG, a knowledge graph for low-temperature plasma science and technology was initiated. Plasma-KG is based on the domain ontology Plasma-O and uses explicit plasma concepts to semantically interlink research data, scientific literature, patents, and further information [1]. By turning dispersed information into machine-actionable knowledge, Plasma-KG enables cross-resource discovery, and reuse of results across the breadth of low-temperature plasma applications.

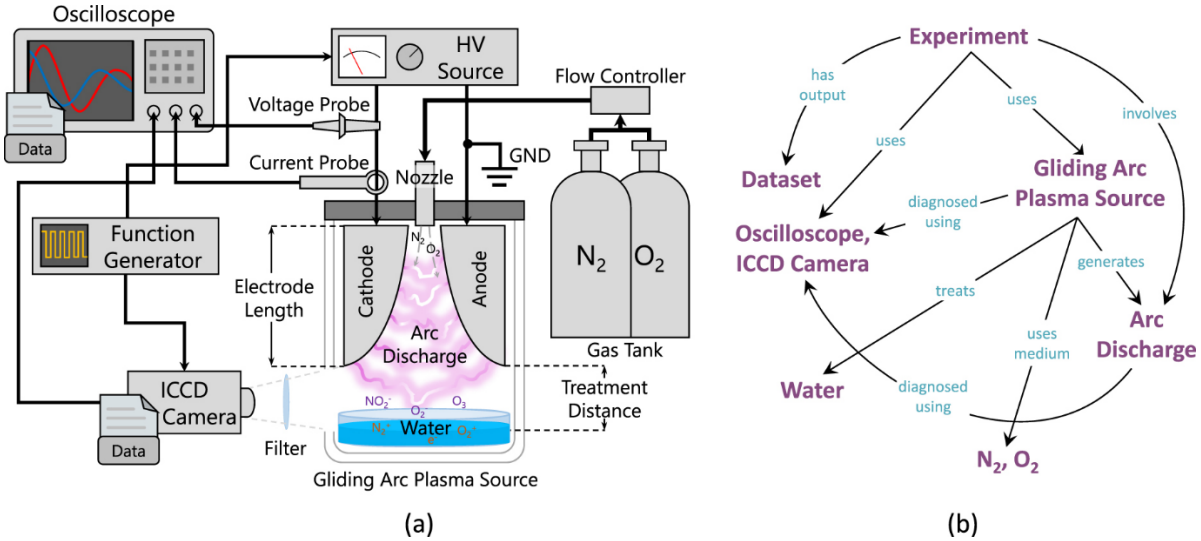

***Figure 1**: Typical experiment setup in low-temperature plasma research (a) represented as semantically interlinked concepts within the framework of Plasma-KG (b), taken from [1].*

As illustrated by Fig. 1, Plasma-KG uses key entities and relations central to low-temperature plasma science and technology, such as (examples in brackets) plasma source (gliding arc) and generated plasma (arc discharge), used medium (N_2/O_2 gas mixture), treated target (water), used diagnostics (Oscilloscope, ICCD camera) and links these entities to the conducted experiment and resulting dataset. Plasma-KG is designed as a living, community-driven platform. It will grow through curated vocabularies, data ingestion pipelines from various information sources and richer process semantics to address uses cases such as knowledge discovery and data-driven meta-analyses.

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ON CARBON DIOXIDE SPLITTING IN NONTHERMAL PLASMAS AT ELEVATED PRESSURS

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Nonthermal plasmas are one option for a plasma-based conversion of carbon dioxide (CO_2) by using intermittent renewable energy for new power-to-X approaches [1]. This contribution will compare the CO_2 splitting in barrier discharges and glidings arc. In particular it will be evaluated how the energy yield of carbon monoxide (CO), a component of the chemical feedstock syngas, can be improved by the parameters of barrier discharge and gliding arc reactors. Planar and coaxial volume barrier discharges as well as packed bed reactors and a linear gliding arc are studied. Special attention is given to the electrical characterization of the discharges and the role of the specific input energy as a microscopically and macroscopically defined scaling parameter governing the energy transfer by the electric field to the molecules via inelastic collisions [2].

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In-situ determination of molecule concentrations in real time - key process indicators for the active control of plasma processes

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The technologically use of molecular plasmas as efficient and sustainable tool for materials and surface processing is continuously gaining in economic and ecological importance. Nowadays plasma technological processes play a key role in branches of industry like semiconductor industry, automotive industry, mechanical engineering, light sources, and biomedical technology to name a few. The intense use of plasma processes demands proper diagnostic techniques for monitoring, controlling and optimization purposes in industrial environments. When addressing efficiency aspects of such production processes, in-situ trace gas detection with online capabilities is a favorable diagnostic tool. Mid infrared absorption spectroscopy using tunable laser sources providing high spectral resolution has progressed considerably as a powerful diagnostic technique for in-situ monitoring applications of the fundamental physics and chemistry. In this context, its ability to determine absolute ground state concentration of stable and transient molecular species in molecular plasmas is of great importance [1-3].
The aim of the present contribution is to review recent achievements using QCLAS for plasma diagnostics and to emphasize its potential for plasma technological applications. Latest developments achieved in the cooperation project SappCU (Self-Adjusting Plasma Process Control Unit) are introduced. One project goal is the implementation of a compact and robust spectroscopic instrument (Figure 1) with high sensitivity and time resolution to allow the online investigation of reaction kinetics. Together with the correlation of the measurements with ex-situ determined processing performance, this shapes the way for KPI driven online control of plasma technological processes.

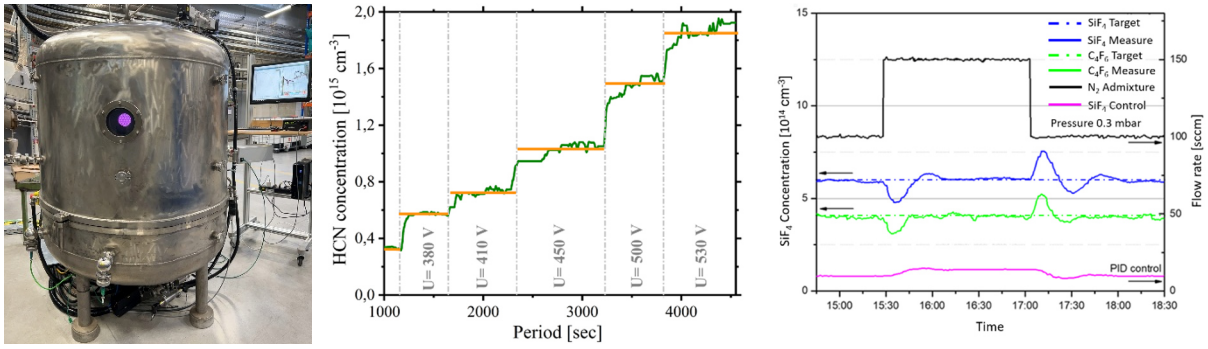

Figure 1: left - Q-MACS sensor installed at a Plasma nitriding chamber, center - production rate of reactive species in correlation to bias voltage, right - performance in active process control

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STEPPED HIGH-VOLTAGE WAVEFORMS FOR CONTROLLING PULSED-DRIVEN DIELECTRIC BARRIER DISCHARGES

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Dielectric barrier discharges (DBDs) are widely used for generating low-temperature, non-thermal plasmas at atmospheric pressure, enabling many different plasma applications ranging from surface modification and sterilisation to gas conversion and plasma medicine. Tailoring the discharge properties for specific applications by adaption of the applied high-voltage (HV) waveform is a promising approach, since the HV waveform directly influences the ignition and evolution of the gas discharge [1, 2]. This contribution explores how precisely shaped HV pulses—with controlled rise times, steps, and plateaus—affect the breakdown dynamics and discharge development in a single-filament DBD configuration.

The used setup consists of two pin electrodes covered by hemispherical dielectrics. These are separated by a 1 mm gas gap and operated in a binary N_2-O_2 gas mixture at atmospheric pressure, which is highly relevant to practical plasma processing environments. The HV waveform shaping is enabled by a custom-built, impedance-matched solid-state Marx generator [3], allowing to systematically study the role of voltage pulse features in optimising plasma characteristics for application-driven outcomes.

The impact of waveform shaping on plasma generation is determined using synchronised fast electrical and optical diagnostics. Electrical measurements yield discharge current, charge transfer, and energy/power data, while a combination of iCCD and streak camera systems delivers sub-mm, sub-ns insights into streamer propagation and discharge morphology [1]. Complementary plasma simulations further elucidate how tailored waveform parameters steer breakdown physics—such as manipulating the Townsend pre-phase and streamer dynamics—enabling targeted plasma properties that serve the needs of emerging plasma technologies.

The results show that the discharge properties are strongly influenced by prescribed step-profiles of the HV signal, indicating that this work opens pathways toward highly controllable and application-optimised atmospheric pressure plasmas.

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First Insights into the Characterization of Millimeter-Sized, Low-Pressure Argon Plasmas in Multiscale Aeromaterials

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Laboratory plasmas are confined by solid boundaries, and interacting with these surfaces can significantly alter their behaviour. However, quantum-level modifications at the plasma-solid interface and their effects on plasma properties remain understudied. The universal law of electron penetration depth into solids indicates values exceeding 100 nm for low-energy electrons (< 3 eV). This implies that nanoscale structures, such as the 10–20 nm thick pore walls of multiscale aeromaterials, can be transparent to electrons, which strongly influences sheath formation and plasma characteristics.
To study these effects, we generated low-pressure argon plasmas within 1 mm diameter bores of 8 mm high aeroglass cylinders. These structures have a high surface-to-volume ratio, which amplifies potential plasma-material interactions. Using electrostatic double probes, we observed plasma states that were not observed with conventional solid boundaries, highlighting the significant impact of multi scale porous surface architectures on plasma behaviour.

NH AND OH KINETICS IN NANOSECOND PULSED N_2:H_2O DISCHARGE AT ATMOSPHERIC PRESSURE

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Nitrogen oxidation (NO_x formation) has been extensively studied in the contexts of combustion and atmospheric chemistry. In contrast, nitrogen reduction (NH_x formation) for ammonia synthesis in electrical discharges has received far less attention, and the underlying kinetics remain largely unexplored [1]. This work employs laser-induced fluorescence (LIF) spectroscopy to investigate the two-dimensional distribution of NH and OH radical kinetics in a nanosecond-pulsed plasma sustained in an N_2:H_2O gas mixture.

The discharge was generated using 10 ns full-width at half-maximum pulses at a 10 Hz repetition rate in a dielectric barrier discharge (DBD) configuration. Experiments were performed at atmospheric pressure in humidified nitrogen with an absolute humidity of 0.22%. OH radicals were measured using a previously described LIF arrangement [2]. NH radicals were detected via the NH($X^3\Sigma^- – A^3\Pi$, $v'' – v' = 0 – 1$) transition by exciting the $P_1(5)$ rotational level with a 306.58 nm laser. Fluorescence was captured with an ICCD camera equipped with a 337 ± 10 nm band-pass filter. To minimize overlap from N_2 second positive system (SPS) emission, measurements were delayed by 1 µs after plasma initiation, and background subtraction was performed using a detuned laser at fixed energy. Absolute radical densities were calibrated via Rayleigh scattering in air, implemented in a 4-level kinetic model. The gas temperature required for calibration was measured by Rayleigh scattering spectroscopy.

LIF measurements revealed peak NH and OH densities of 10^{23} and 10^{24} m^{-3}, respectively. Two-dimensional maps of NH show a ring-shaped profile, with reduced intensity at the center of the discharge gap, coinciding with regions of maximum OH density and elevated gas temperature. Reaction pathway analysis indicates that the OH + N → NH + O reaction is the primary formation mechanism for NH. The central depletion of NH is attributed to thermally driven loss channels, including reactions leading to HNO, H_2O, and NH_2.

These findings underscore the critical role of OH radicals in both the formation and depletion of NH, with gas temperature acting as a key parameter that controls the balance between hydrogenation (NH → NH_2 → NH_3) and NH loss. This insight contributes to a deeper understanding of nitrogen reduction chemistry via non-equilibrium plasmas.

An optional acknowledgment may be inserted here.

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Time	**Tuesday, 23-Sep-2025**	**Wednesday, 24-Sep-2025**	**Thursday, 25-Sep-2025**
08:00	Registration		
09:00	**Opening**	Mihailova	Jaritz
09:30	Nizenkov	Busse	Music
10:00	Herdrich	Nishime	Hans
10:30	**Coffee Break**	**Coffee Break**	**Closing & Coffee Break**
11:00	Rudolph	Vahl	DGPT General Assembly
11:30	Thorwarth	Ellis	
12:00	Stamate	Zikán	
12:30	Neidhardt	Flötgen	
13:00	**Lunch Break**	**Lunch Break**	**Lunch Break**
14:00	Held	Krumpolec	
14:30	Sgonina	Knospe	
15:00	Koch	Winzer	
15:30	**Refreshments & Poster Session**	**Coffee Break**	
16:00		Niemann	
16:30		Melzer	
17:00	Awakowicz, Seeliger Prize	**Refreshments**	
17:30		Bogaerts, Diels-Planck Lecture	
18:00	**Break / Transfer**		
18:30			
19:00	**Conference Dinner**		
19:30		**KiNSIS Get-together**	

Imprint

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