An Incomplete Summary of the Applied Plasma Session

Yi-Kang Pu
Department of Engineering Physics
Tsinghua University
November 8, 2019
Five Plenary Talks

• Rod Boswell: Innovations, cheeses, business ethics, startups

• Young-Hoon Song: Application of plasma technologies for air pollution control

• Hirotaka Toyoda: High-energy negative ions in processing plasma

• Kazuhiko Endo: Atomic Layer Etching, Deposition and Modification Processes for Novel Nano-matetials and Nano-devices

• Jin-Xiu Ma: Basic experiments on ion waves excitation and propagation
Rod Boswell’s talk

• Using the story of cheese, an important source of food (a non spoiling protein source). He claims that this is the first major innovation of mankind. Cheese has a huge impact on the development of our society and the world, since it increases the ranges for herding, migration and war

• He discussed the history of the semiconductor industry and his personal involvement in this sector. One of his main messages is that invention in science and engineering can precede successful innovation by many years if not decades. (it took 22 years for the semiconductor equipment people to believe what he found in the lab in 1983)
• Necessity is the mother of invention

• Conflict is the mother of innovation

• Technical or scientific innovation can be considered the practical implementation of an invention that can make a meaningful impact on society.

• Disruptive innovation will typically attack a traditional business model with a lower-cost solution and overtake incumbent firms quickly.

• Foundational innovation is slower, and typically has the potential to create new foundations for global technology systems over the longer term.
Large companies and small start-ups

Parents do not worry whether their children will usurp them and will do everything possible to help them succeed, even with adopted children.
Application of Plasma Technologies for Air Pollution Control
- AAPPS-DPP 2019 -

Song, Young-Hoon

Korea Institute of Machinery & Materials
Dept. of Environment System
DPF + plasma burner (rotating arc plasma) for vehicles with a diesel engine
An effective way of emission reduction from these vehicles!
PFCs treatment with arc torch & product
• Both technologies have been successfully commercialized in Korea!
High-energy negative ions in processing plasma

Hirotaka Toyoda

Department of Electronics,
Center for Low-temperature Plasma Sciences,

Nagoya University
Major findings

• O- is the major negative ion in DC magnetron sputtering process
• O- with high kinetic energy, can affect the quality of the deposited film on the substrate
• Using heat flux to detect the O- flux
• Spatially resolved heat flux was obtained and the location of the peak of its profile is consistent with the location of plasma ring
High-energy Negative Ions in Oxide Sputter Plasma

Production mechanism of high-energy negative ion

Production of O⁻ on the Surface

O⁻ Acceleration

Impingement on film surface
Induces damage

Localized impingement of high-energy negative ion

O⁻ beam induces localized damage.

Production mechanism of high-energy negative ion:

1. Oxide Target
2. Cathode Fall
3. Plasma
4. Substrate

Potential \( \varphi \)

Localized impingement of high-energy negative ion:

O⁻ beam induces localized damage.
O⁻ Ion Flux Evaluation from Heat Flux

Thermocouple

With Shield

Shield Plate

Ceramic Adhesive

Thermocouple

SS Pipe

Rotatable

Shielding angle: ±10°

Target (ITO)

Magnet

10 cm

Plasma

Scanned

Rotatable

Thermocouple

Without Shield

Anisotropic Heat Flux

Isotropic Heat Flux

Heat flux from plasma

\[ J_{with} = J_{Iso}. \]

\[ J_{without} = J_{Iso} + J_{Aniso}. \]

O⁻ heat flux is evaluated from the difference

\[ J_{Aniso.} = J_{total} - J_{Iso}. \]
Localized heat flux is observed at plasma ring radius.

**Spatial Profile of Heat Flux**

- **Thermocouple is scanned**
  - Target-TC distance: 10 cm
  - Radial position: 0 ~ 30 mm

Heat Flux Density (W/m²) vs. Radial Position (mm)

- **Without shield**
  - Heat flux density increases with radial position.

- **With shield**
  - Heat flux density is reduced compared to without shield.

Components:
- e⁻ (electrons)
- Ar⁺ (argon ions)

Diagram showing the spatial profile of heat flux with and without a shield.
RF Magnetron with Insulating Target
Experimental setup

- **Target**: MgO (120 mm in diameter and 3 mm in thickness)
- **Distance between target surface and QMA orifice**: $L = 138$ mm
- **Pressure**: $p = 1$ mTorr

**Experimental condition**

- RF frequency: 13.56 MHz
- RF Power $P_{RF} < 50$ W
- Gas: Ar
- Radial position $r = 0 \sim 38$ mm

- Target: MgO (120 mm in diameter and 3 mm in thickness)
- Distance between target surface and QMA orifice $L : 138$ mm
- Pressure $p = 1$ mTorr
Spatial Measurement of O⁻ Energy Distribution

- Plasma emission -

$P_{RF}=40 \, W, \, p=1 \, \text{mTorr}$

- Relative position between target and magnet -

$\Rightarrow$ Spatial profile is measured

$\text{Magnet}$

$\text{Target}$

$\text{Plasma}$

$r$ : radial position from magnet center

$\Rightarrow$ Strong emission along ring magnet

Projected QMS orifice position

Rotation of magnet $\Rightarrow$ Spatial profile is measured
Example of O⁻ Energy Distribution

**O⁻ energy distribution**

\[ P_{RF} = 40 \text{ W, } p = 1 \text{ mTorr, } r = 38 \text{ mm} \]

\[ V_{ts} \sim V_H + V_P \]

\[ eV_H : \text{Maximum O⁻ energy} \]

\[ V_P : \text{Plasma potential} \]

**Schematic of O⁻ energy distribution**

Time variation of MgO surface potential

\[ \text{(Time variation of sheath voltage)} \]

\[ V_P \]

\[ V_{ts} \]

MgO surface potential \((V_I)\)

\[ eV_P \]

\[ eV_H \]

**Example of O⁻ Energy Distribution**

\[ RF = 40 \text{ W, } p = 1 \text{ mTorr, } r = 38 \text{ mm} \]

\[ O⁻ \text{ intensity (arb. units)} \]

\[ \text{Kinetic Energy (eV)} \]

\[ 0 50 100 150 200 250 300 \]

\[ O⁻ \text{ energy distribution} \]

\[ V_{ts} \sim V_H + V_P \]

\[ eV_H : \text{Maximum O⁻ energy} \]

\[ V_P : \text{Plasma potential} \]
O⁻ Energy Distribution
- Radial position dependence-

Interesting features

1) Radial variation of maximum O⁻ energy
2) Fine structure in O⁻ EDF
Radial variation of maximum O\(^{-}\) energy
Comparison of DC-conductive/RF-insulative magnetron plasmas

Plasma density and sheath thickness

- Plasma density
- Sheath: Thick, Thin, Thick
- Target: N, S

Radial potential profiles

- Insulative RF
  - Surface potential uniform
- Conductive DC
  - Surface potential potential uniform

MgO: insulator
Surface variation induced

ITO: conductive
Surface potential uniform

Difference in O⁺ energy
Radial Profile of O⁻ EDF

$P_{RF}=350 \text{ W}, p=5 \text{ mTorr}, L=13.8 \text{ cm}$

Appearance of fine structure

Peaks of fine structure

Peak energies are the same irrespective of radial position.
Simulation almost explains energy fine structure

Oscillation of E field in the sheath \(\Rightarrow\) Modulation of O\(^{-}\) Energy
Kazuhiko Endo’s Talk

- **Title:** Atomic Layer Etching, Deposition and Modification Processes for Novel Nano-materials and Nano-devices
- The main message: for etching, deposition and other processes in semiconductor industry, neutral beams have a significant advantage over processes involved with energetic ion beams.
Newly Developed Neutral Beam Source for Etching

- High Density Neutral Beam (mA/cm²)
- Lower Energy Beam (10eV ~)
- High Neutralization Efficiency (≈100%)

Neutral Beam Source

Ion acceleration
Negative ion
\( \text{Cl}^- \)
Electron
\( e \)
UV photon
\( P \)

Aperture

Neutral beam
(1eV ~ more than 100eV)

Carbon Plate

Process Chamber

High Density Plasma

13.56MHz

UV Intensity (a.u.)

Wavelength (nm)

10mm

1mm

Negative ion

Electron

UV photon

Ion acceleration

Cl⁻

Neutral beam

Process Chamber

High Density Plasma

13.56MHz

Carbon Plate

UV Intensity (a.u.)

Wavelength (nm)
High-Performance Si-Fin-MOS Transistor by Defect-free Etching

Sub-6nm Ge Fin MOSFET

NBO of Transition Metal for ReRAM

Oxygen neutral beam at RT
Gas: O₂, ICP plasma power: 500W, Time: 2 min

2.5-nm-thick Ta
2.5 nm

Before oxidation

Ta
Pt

Cu

Oxygen Neutral Beam

After oxidation

Ta-O
Pt

3.8-nm-thick TaOx

2.5 nm

NBO of Transition Metal for ReRAM

Oxygen neutral beam at RT
Gas: O₂, ICP plasma power: 500W, Time: 2 min

2.5-nm-thick Ta
2.5 nm

Before oxidation

Ta
Pt

Cu

Oxygen Neutral Beam

After oxidation

Ta-O
Pt

3.8-nm-thick TaOx

2.5 nm
Electrical Characteristics of Cu/Ta$_2$O$_5$/Pt

Our Ta$_2$O$_5$ film can work as an ionic transport layer for resistive switching.

- 0.5 μA operation current
- $R_{OFF}/R_{ON} > 500$
- 100 times endurance

Surface Reaction in NBECVD

## Film properties comparison

<table>
<thead>
<tr>
<th>Metric</th>
<th>Porous SiCO by PECVD</th>
<th>Non-porous SiCO by NBECVD</th>
</tr>
</thead>
<tbody>
<tr>
<td>k-value</td>
<td>Hg-probe</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.2</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>Nano-indenter</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.7</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>XRR</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.54</td>
</tr>
<tr>
<td>Pore size (nm)</td>
<td>SAXS</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No detected</td>
</tr>
</tbody>
</table>

- NBECVD SiOCH has Higher modulus
- NBECVD SiOCH has Higher density
- NBECVD SiOCH has no pores

By using NBECVD method and controlling reaction, NBE SiOCH film is achieved as NON-Porous SiOCH with ultra low-k.

Next, discuss about molecular structure of NP-SiOCH
Pseudo-waves in an ion-beam-plasma system

Jin-Xiu Ma, Kai-yang Yi, Zi-an Wei, Fei Wu, Qi Liu, and Zheng-yuan Li

School of Physical Sciences,
University of Science and Technology of China,
Hefei, Anhui, China

*Work supported by NSFC (Grant No. 11575183)
wave excitation and detection circuitry

excitation voltage:

\[ V_{EG} = V_{dc} + V_{pp}\tanh(t/\tau) \]

\[ V_{dc} = -52 \text{ V} \]

\[ V_{pp} \rightarrow \text{peak to peak amplitude, } \tau \rightarrow \text{ramp rise time} \]
Invited talks on diagnostics

- Wonho Choe: Tomography-based 2-D plasma imaging for low- and high-temperature large-scale plasmas
- Hiroshi AKATSUKA: Optical emission spectroscopic (OES) analysis of electron temperature and density in atmospheric-pressure non-equilibrium argon plasmas
- D. P. Subedi: Optical Characterization of Atmospheric Pressure Dielectric Barrier Discharge (DBD) in Air Using Transparent Electrode
Tomography-based 2-D plasma imaging for low- and high-temperature large-scale plasmas

Wonho CHOE\textsuperscript{1}, J. Jang\textsuperscript{2}, S. Park\textsuperscript{2}, I. Song\textsuperscript{1}, B. Peterson\textsuperscript{3}

\textsuperscript{1}Korea Advanced Institute of Science and Technology (KAIST), Korea
\textsuperscript{2}National Fusion Research Institute (NFRI), Korea
\textsuperscript{3}National Institute of Fusion Science (NIFS), Japan
Plasma radiation after tomographic reconstruction (Kr injection)

- Radiation power increases by Kr gas injection
- Tomographic reconstruction is routinely used for X-ray and VUV diagnostics in KSTAR
Optical emission spectroscopic (OES) analysis of electron temperature and density in atmospheric-pressure non-equilibrium argon plasmas

Hiroshi AKATSUKA, Hiroshi Onishi, Thijs van der Gaag, Atsushi Nezu

Tokyo Institute of Technology, Tokyo, Japan
Ne-dependence in the low Ne-region of Te-Tex relation of atmospheric pressure plasma

• In the low Ne-region, the influence of Ne on Te is small.

• At Tex \sim 0.4 \text{ eV}, the error of Te is about \pm 0.1 \text{ eV} against the change of 10^{10} – 10^{12} \text{ cm}^{-3}.
Experimental Example

• 50Hz DBD

• Atmospheric-pressure non-equilibrium Ar plasma source by DBD

• Pulse voltage up to about 9 kV at secondary voltage

Boltzmann plot

Hakozaki, Akatsuka et al., JSAP-Spring meeting (2018).
Optical Characterization of Atmospheric Pressure Dielectric Barrier Discharge (DBD) in Air Using Transparent Electrode.

D. P. Subedi¹, R. Manandhar¹, R. Guragain¹, H. Baniya¹, G. Panta¹, C.S. Wong²
¹ Dept. of Physics, School of Science, Kathmandu University, Dhulikhel, Kavre, Nepal
² Dept. of Physics, University of Malaya, Kuala Lumpur, Malaysia
e-mail: dsubedi@ku.edu.np

3rd Asia-Pacific Conference on Plasma Physics, 4-8.11.2019, Hefei, China
Improvement of Growth and Yield of Rice Plants with Plasma Treatment

Hiroshi Hashizume\textsuperscript{1}, Hidemi Kitano\textsuperscript{1}, Hiroko Mizuno\textsuperscript{1}, Satoru Kinoshita\textsuperscript{1}, Genki Yuasa\textsuperscript{2}, Satoe Tohno\textsuperscript{2}, Mikiko Kojima\textsuperscript{3}, Yumiko Takebeyashi\textsuperscript{3}, Hiromasa Tanaka\textsuperscript{1}, Kenji Ishikawa\textsuperscript{1}, Shogo Matsumoto\textsuperscript{1}, Hitoshi Sakakibara\textsuperscript{1}, Susumu Nikawa\textsuperscript{2}, Masayoshi Maeshima\textsuperscript{1}, Masaaki Mizuno\textsuperscript{1}, and Masaru Hori\textsuperscript{1}

\textsuperscript{1}Nagoya Univ., Japan, \textsuperscript{2}Fujitsu Client Computing Ltd., Japan, \textsuperscript{3}RIKEN, Japan

3\textsuperscript{rd} Asia-Pacific Conference on Plasma Physics (AAPPSS-DPP2019), Crowne Plaza Hefei, China, 2019/11/4, 14:30-15:00
Plasma treatment for cultivation of rice plants

Rice cultivation consists of the multi-steps in greenhouse and paddy field. It is necessary to investigate the effect of plasma for each growth stage.

·Process of Rice cultivation

In general, raising the healthy seedlings in early stage can lead to high harvest in rice cultivation.
Rice cultivation consists of the multi-steps in greenhouse and paddy field. It is necessary to investigate the effect of plasma for each growth stage.

- Process of Rice cultivation

Plasma treatment for cultivation of rice plants

A-I2, Hashizume, Nagoya Univ.
According to the climate changes from summer to autumn, the growth shifts from vegetative to reproductive growth, resulting in heading. The cultivation in the paddy field is the important step, because it is directly linked to the harvest through the drastic change of the growth stage.

Rice cultivation consists of the multi-steps in greenhouse and paddy field. It is necessary to investigate the effect of plasma for each growth stage.

Process of Rice cultivation

Germination → Raising seedling → Transplant → Heading → Harvest

Greenhouse

Paddy field

A-I2, Hashizume, Nagoya Univ.

Plasma treatment for cultivation of rice plants
Plasma treatment for cultivation of rice plants

A-I2, Hashizume, Nagoya Univ.

Rice cultivation consists of the multi-steps in greenhouse and paddy field. It is necessary to investigate the effect of plasma for each growth stage.

- Process of Rice cultivation

<table>
<thead>
<tr>
<th>Greenhouse</th>
<th>Paddy field</th>
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<tbody>
<tr>
<td>Germination</td>
<td>Transplant</td>
</tr>
<tr>
<td>Raising seedling</td>
<td>Heading</td>
</tr>
<tr>
<td></td>
<td>Harvest</td>
</tr>
</tbody>
</table>

Plasma treatment in the paddy field

According to the climate changes from summer to autumn, the growth shifts from vegetative to reproductive growth, resulting in heading. The cultivation in the paddy field is directly linked to the harvest through the drastic change of the growth stage.

Yield increase, and quality improvement
Feng Huang’s talk on plasma agriculture

China Agricultural University

Control group

Plasma group
Zilan Xiong’s talk on plasma medicine

Plasma Treatment of Onychomycosis

Toe Treatment Results by SMD

Only **three times** of 45 min SMD treatment **over one week** (not every week) with a proprietary treatment. 9 **toes** of the patient got clear after 7 months. Although 3 toes are re-infected, however, 6 toes are cured by such short time of plasma treatment.
High throughput production of silicon nanorod from powder feedstock by plasma flash evaporation

A. Tanaka¹, R. Chiba¹, and M. Kamatana¹

¹ Dept. of Mater. Eng., The Univ. Tokyo, Tokyo, Japan

Next-G high density Lithium-ion battery

- Si as high density anode
  - Si: 10x higher capacity than C
  - Pulverize due to huge Si dilution → Rapid capacity decay

- Si nanowire/nanotube
  - 1D structure
  - direct contact with current collector
  - spaces to buffer dilution
  - aligned anisotropic dilation direction

Vapor-Liquid-Solid (VLS) mode

VLS mechanism proposed first by Wagner

- VLS requires:
  - catalyst+liquid → catalyst template needs to be prepared in advance
  - Si+vapor

- VLS of SiNW requires “molten catalyst” and “vapor Si”
  - Slow growth. Expensive gas necessary. Not practically feasible for LiB market.

Plasma spraying: Plasma Flash Evaporation (PFE)

Si powders → Raw material → Complete Evaporation → M Nucleation → Metallography grade silicon powders (Mo-Si) → Si-NP + Ni51% purity

1/20
Effect of Process Parameters on the Growth and Field Emission Properties of Graphene -Carbon Nanotube Composite

Suresh C. Sharma, Department of Applied Physics, Delhi Technological University (DTU), Delhi-110 042, India

In order to enhance or control the electron emission characteristics of (graphene-CNT), process parameters such as, gas pressure, input power, and substrate bias on the number density and dimensions of VG sheet grown over CNT surface are investigated. Plasma enhanced chemical vapor deposition (PECVD) is considered as the most viable technique for the growth of graphene-CNT as it exhibits better control over the graphene-CNT structure at relatively low temperatures and also offers the advantage of graphene-CNT structure modification by process parameters. In the present work, a theoretical model is developed to describe the growth of CNT and thereafter nucleation and growth of graphene sheets on CNT in the presence of CH4/H2/N2 plasma. The defects generated on the CNT surface during its growth are considered as the nucleation sites for the growth of graphene sheet on CNT surface. The model incorporates the charging rate of the graphene-CNT, kinetics and energy balance of all plasma species i.e., electrons, positively charged ions and neutral atoms along with the process parameters, and growth rate of the graphene-CNT. Numerical calculations on the effect of process parameters on the growth of graphene-CNT have been carried out for typical glow discharge plasma parameters. It is observed that the electron density, electron temperature, and ion energies in the plasma increases on reducing the gas pressure and on increasing the input power and substrate bias, which subsequently enhances the ion bombardment and carbon generation on the CNT surface, and thereby the height as well as number density of VG sheets on CNT increase, and thickness of VG sheet decreases. Some of the results of the present investigation are in compliance with the existing experimental observations.
Advanced Low-Temperature Processes at the University of Illinois


Email: druzic@illinois.edu or andruczy@Illinois.edu
Semiconductor-Processing and Atmospheric Plasma Research

Hydrogen Atom Radical Probe experiment: **HARP**

- **Facility to study radical density distributions in processing plasmas**
  - In Situ Measurement of N₂, O₂, and H₂ radicals
  - Study the dependence with pressure and discharge power

  ![HARP Facility Image]

  **Funded by DuPont and LAM Research**

Tin Residue Etch eXperiment: **TREX**

- **Facility to study Sn deposition cleaning for the semiconductor industry**
  - Sn etching from EUV source collector and walls
  - In situ process by formation of surface wave plasma (SWP)
  - Modeling activities to determine influence of pressure and power on etching rate

  ![TREX Facility Image]

  **Funded by ASML**

Multilayer Zirconia/Silica deposition

- **Novel coating method for Department of and GM formed with an atmospheric plasma torch**
- **Multilayer coating based on ZrO/SiO films**
- **ZrO acts as passivation layer for corrosion resistance**
- **SiO works as water barrier coating and adhesion promoter**
- **Stress testing of SiO layers including resistance to water soaking.**
- **The application of an AP adhesión layer creates covalent bonding of the glue to the metal, and therefore makes the bond STRONGER than the underlying metal itself.**

  ![ZrO2 and SiO2 Films Image]

  **Funded by EERE-General Motors**
Generation of Innovative Thermal Plasma with Diode-Rectification Technique

Manabu Tanaka, Takayuki Watanabe, Kyushu University, Japan

Diode-rectified multiphase AC arc as an innovative thermal plasma generating method was established as big challenge of thermal plasma industrialization.

(1) Diode-Rectification
- Separation of an AC electrode into pairs of Cathode & Anode

(2) High-Speed Camera Observation
- Electrode phenomena during processing were understood.
- Arc Temperature Field was clarified.

⇒ Electrode erosion was drastically reduced.
Atmospheric pressure plasma surface modification: from surface treatment to thin film deposition

Nov. 4th (Mon)

Se Youn Moon (文世連)

Plasma Experiment & Device Application Lab
Department of Quantum System Engineering

Chonbuk National University (全北大學校)
A numerical simulation is conducted to investigate the arc-anode attachment behavior, especially the formation mechanism of constricted arc attachment mode at the water-cooled anode of wall-stabilized transferred argon arcs. Argon molecular ions and the corresponding kinetic processes are included to the finite-rate chemistry model in order to capture the chemical nonequilibrium characteristics of arc near anode region. Modeling results show that the constricted and diffusive arc anode attachments can be self-consistently obtained at different arc currents while keeping other parameters unchanged.
High-electron-density microplasmas generated inside capillaries

Shuqun Wu, Xueyuan Liu, Fei Wu
Email: wushuqun2010@hotmail.com

College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu 210016, China

AAPPS-DPP 2019
Hefei, China
Electron density inside and outside

Ne of the microplasma inside capillary is much higher than Ne of the plasma in the quartz tube.

Ne = $8.2 \times 10^{14}$ cm$^{-3}$

Ne = $2.3 \times 10^{16}$ cm$^{-3}$
Electron density vs current density

- Tube diameter decreases from 100 to 4 μm, the current density increases from $2.5 \times 10^7$ Am$^{-2}$ to $3.5 \times 10^9$ Am$^{-2}$. Tube diameter decreases from 100 to 9 μm, the electron density increases from $2 \times 10^{16}$ cm$^{-3}$ to $11 \times 10^{16}$ cm$^{-3}$.
- $J$ and $Ne$ of the microplasma are comparable to those in spark discharge.
The discharge propagation and the evolution of electric field and surface charge in nanosecond-pulse surface dielectric barrier discharge

Cheng Zhang, Bangdou Huang, Tao Shao
010-82547294, zhangcheng@mail.iee.ac.cn

Institute of Electrical Engineering, Chinese Academy of Sciences
High Voltage and Discharge Plasma Laboratory
Beijing International S&T Cooperation Base for Plasma Science and Energy Conversion
November 5th, 2019
Electric Field Induced Second Harmonic (E-FISH) Generation

- Nd:YAG laser (Beamtech SGR-S400), 10 Hz
- 1064 nm laser energy: \( \sim 15 \) mJ
- Pulse width: 7-9 ns
- Horizontally polarized
- At focal point, beam diameter \( \sim 120 \) \( \mu \)m
- Rayleigh range \( \sim 11 \) mm

\[ I_i^{(2\omega)} = k N_g^2 (E_{\text{ext}})^2 I_L^2 \]

Calibration with a known electric field.

Apply a voltage below the breakdown threshold across a parallel-plate electrode geometry.
Electric field evolution

- The direction of $E_x$ reverses during the SIW propagation
- Peak $E_x$ decreases away from the HV electrode, $E_{x, \text{Epoxy}} > E_{x, \text{PTFE}}$
- Residual $E_x$ appears before the breakdown due to the surface charges (negative $E_x$)
- $E_x$ is uniform before the breakdown at every position for epoxy, $E_x$ is stronger near the HV electrode for PTFE

Applied voltage: 14 kV; PRF: 100 Hz
Thank you very much for staying around for my talk!