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-materials 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

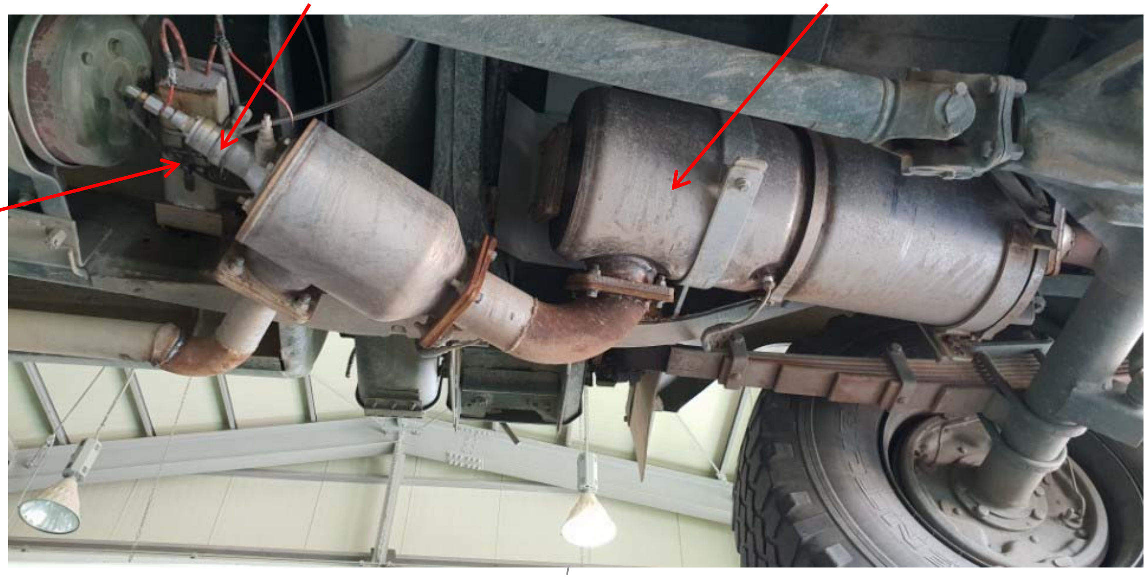
- AAPPS-DPP 2019 -

Song, Young-Hoon

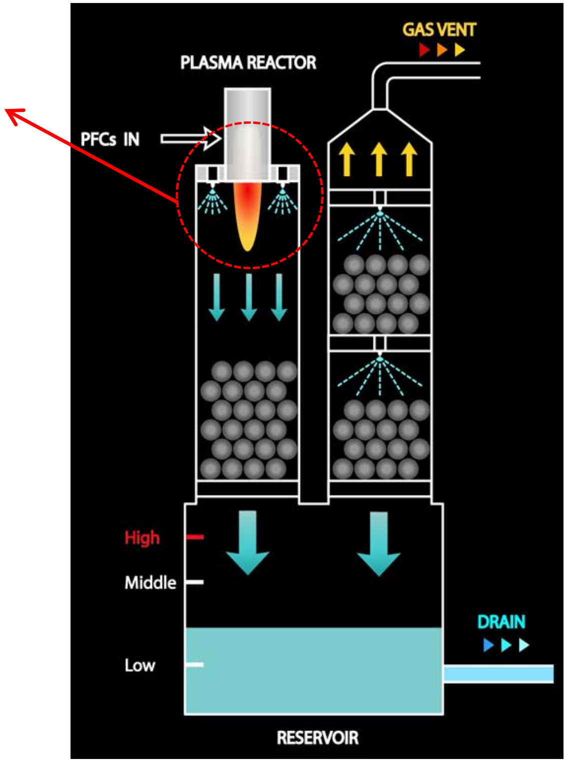
Korea Institute of Machinery & Materials

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,

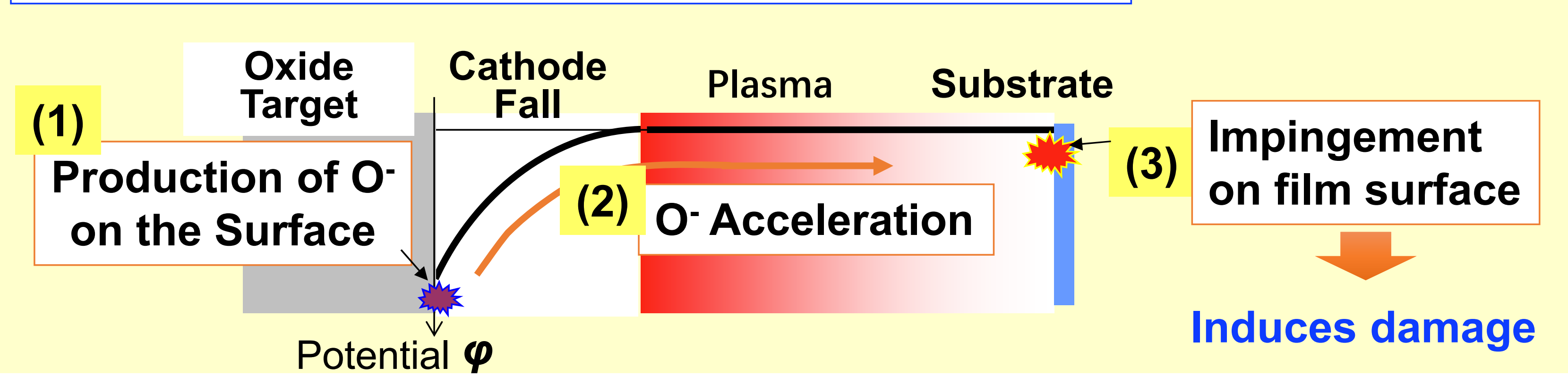
Nagoya University

Major findings

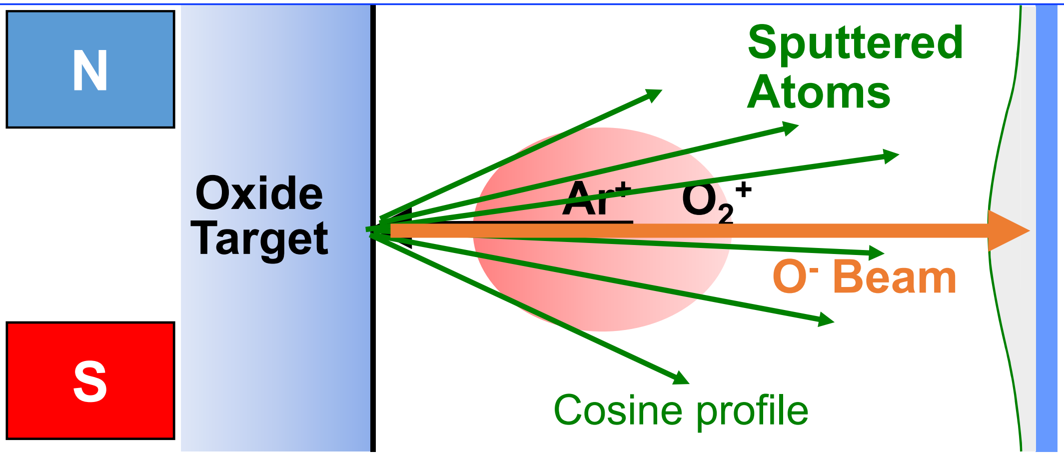
- O- is the major negative ion in DC magnetron sputtering process
- O- with high kinetic energy , can affect the quality of the deposited film on the substrate
- Using heat flux to detect the O- flux
- Spatially resolved heat flux was obtained and the location of the peak of its profile is consistent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

High-energy Negative Ions in Oxide Sputter Plasma

Production mechanism of high-energy negative ion

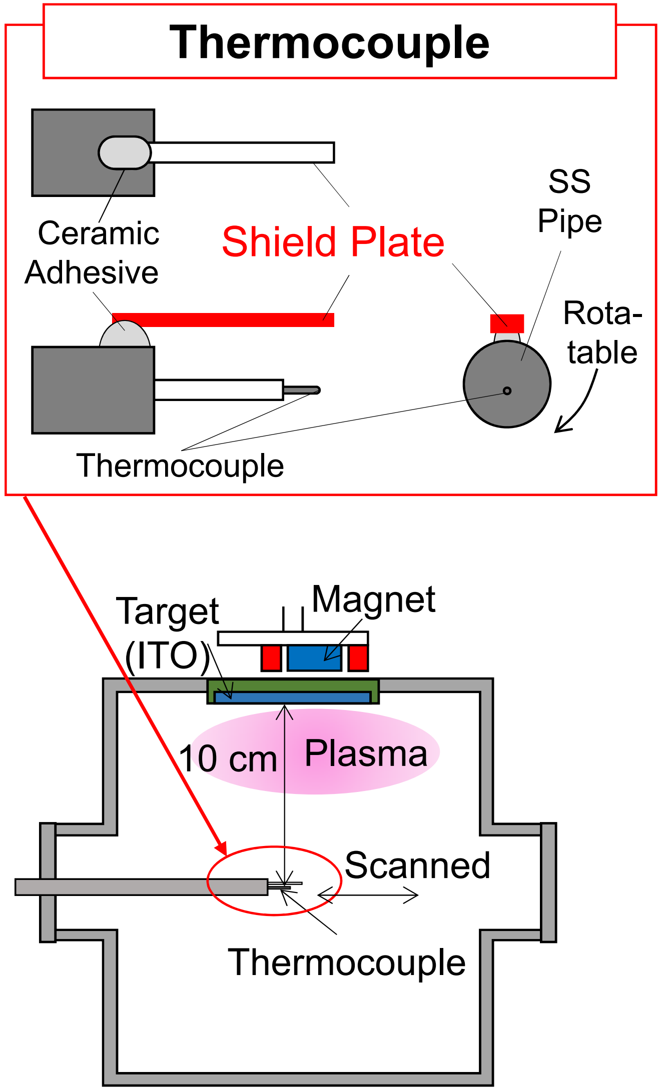


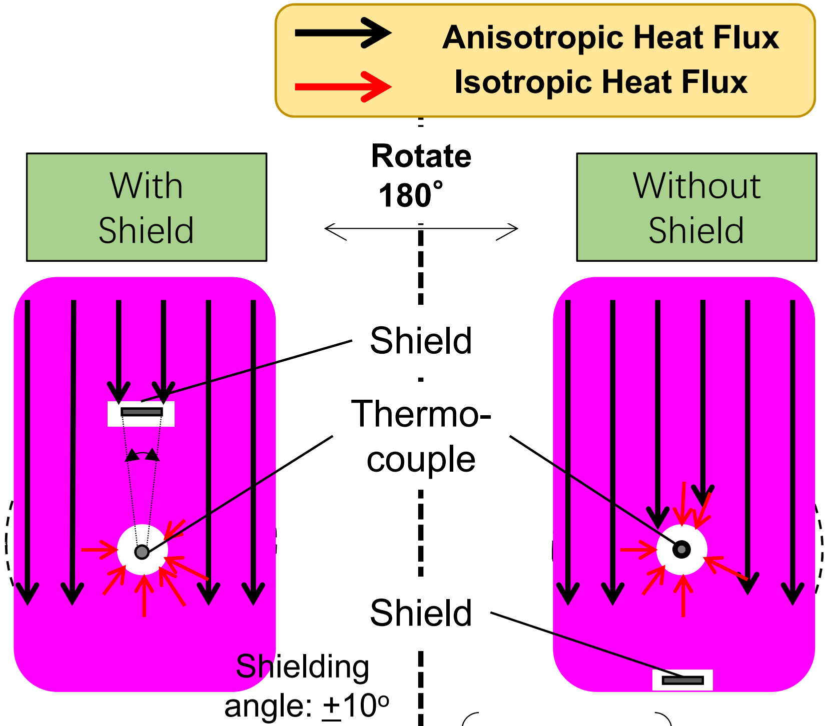
Localized impingement of high-energy negative ion



O^- beam induces localized damage.

O^- Ion Flux Evaluation from Heat Flux





Heat flux from plasma

$$J_{with} = J_{Iso.}$$

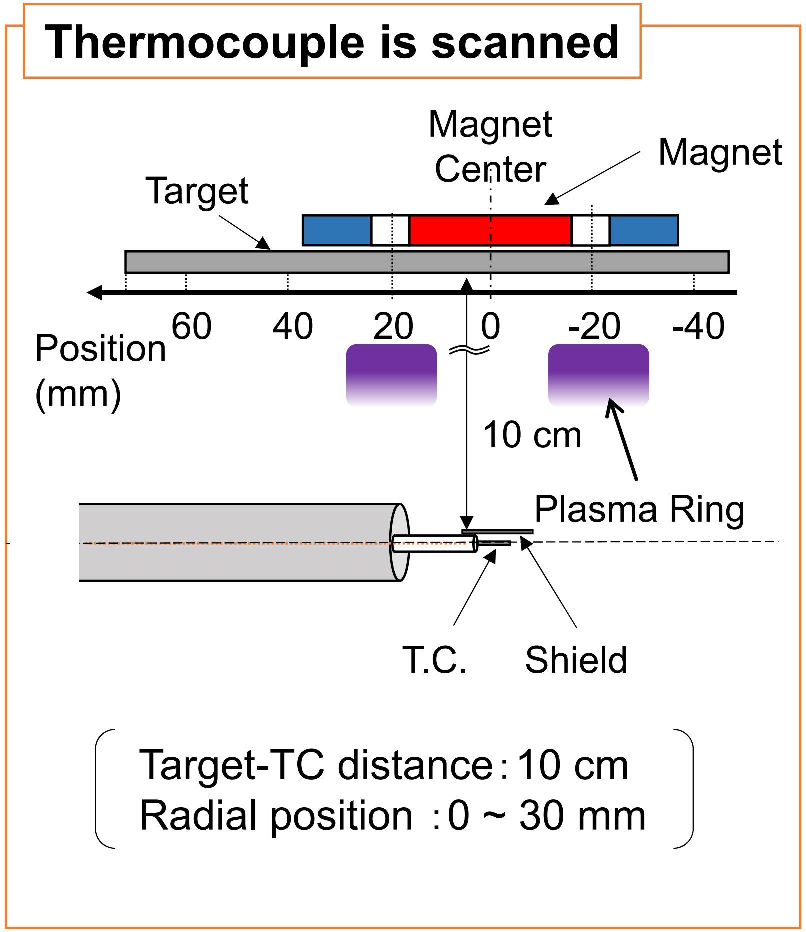
(Plasma / High-E O^-) heat flux

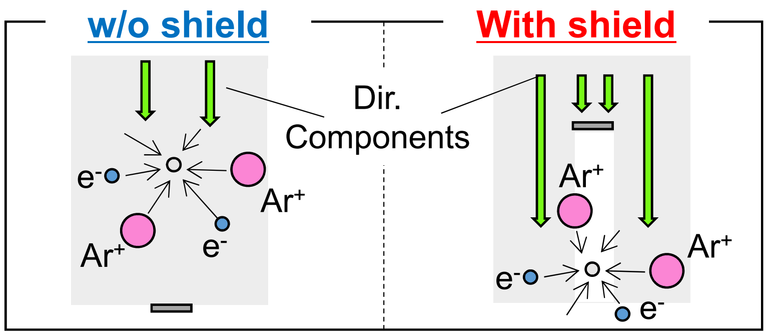
$$J_{without} = J_{Iso.} + J_{Aniso.}$$

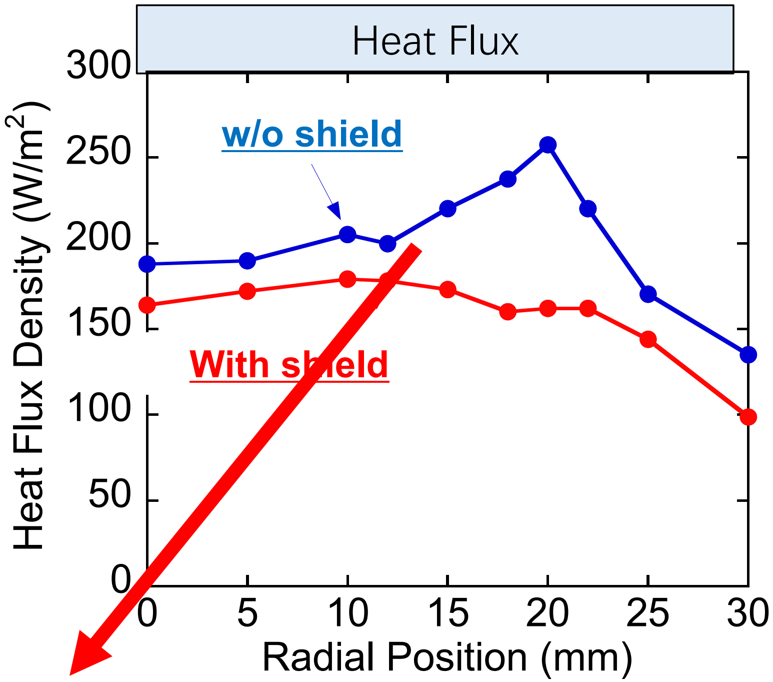
O^- heat flux is evaluated from the difference

$$J_{Aniso.} = J_{total} - J_{Iso.}$$

Spatial Profile of Heat Flux



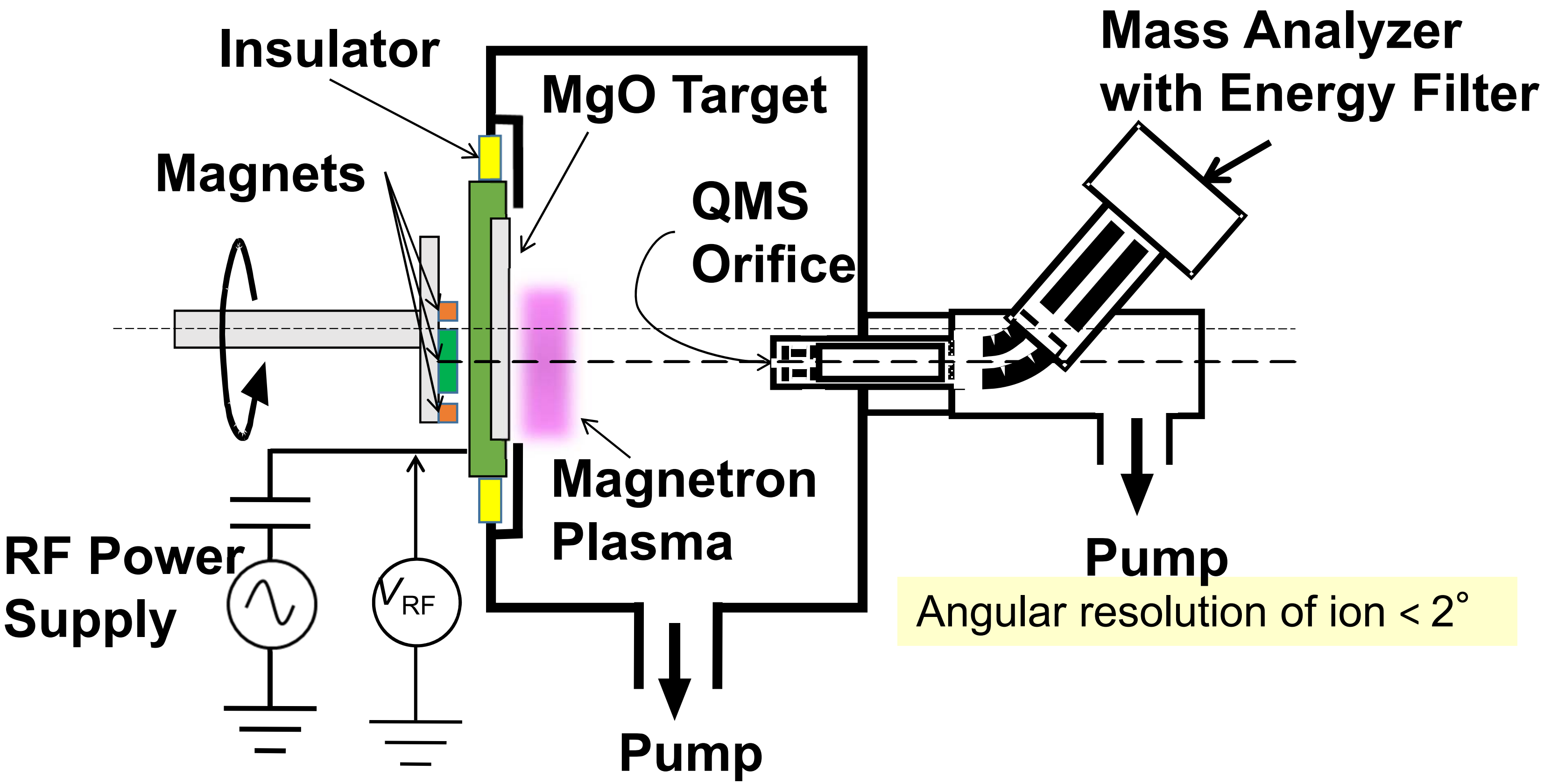




Localized heat flux is observed at plasma ring radius.

RF Magnetron with Insulating Target

Experimental setup



Angular resolution of ion < 2°

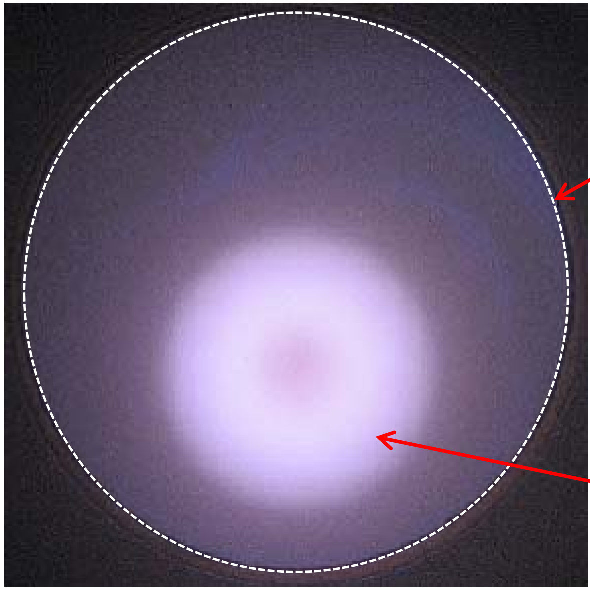
Experimental condition

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

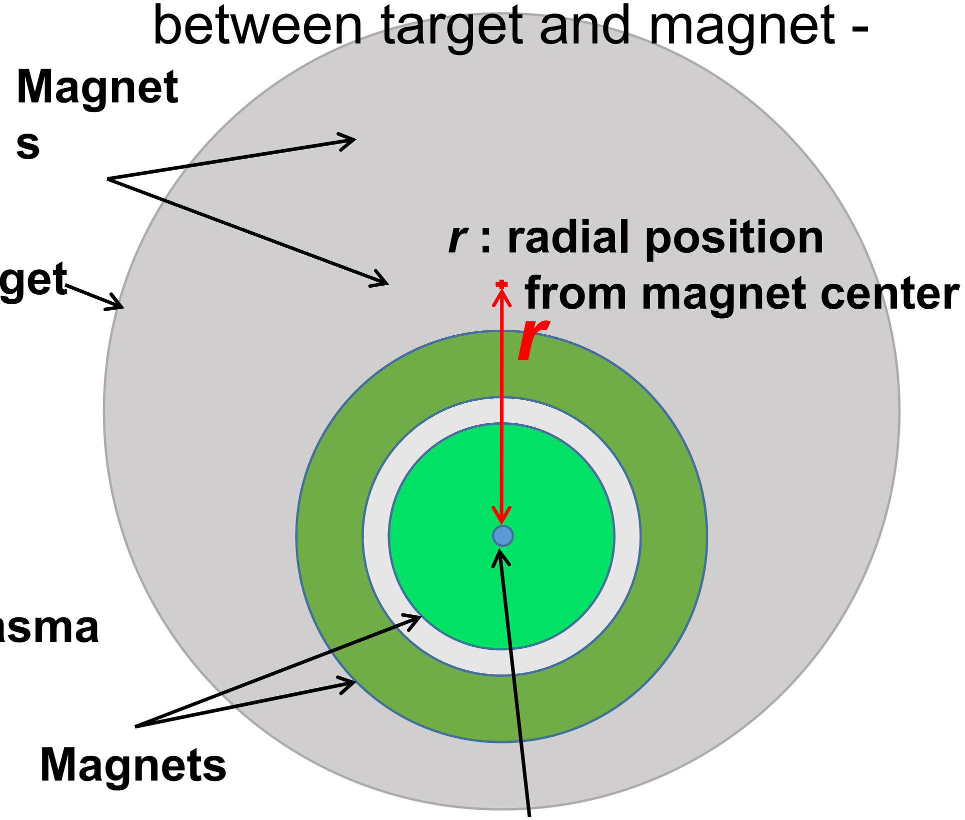
- Plasma emission -

P_{RF}=40 W, p=1 mTorr



➢ **Strong emission along ring magnet**

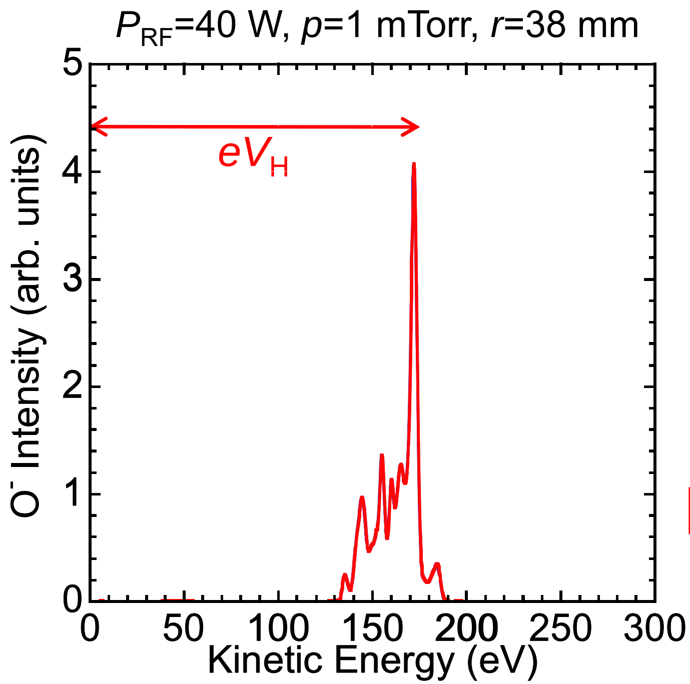
- Relative position between target and magnet -



Rotation of magnet ⇒ Spatial profile is measured

Example of O^- Energy Distribution

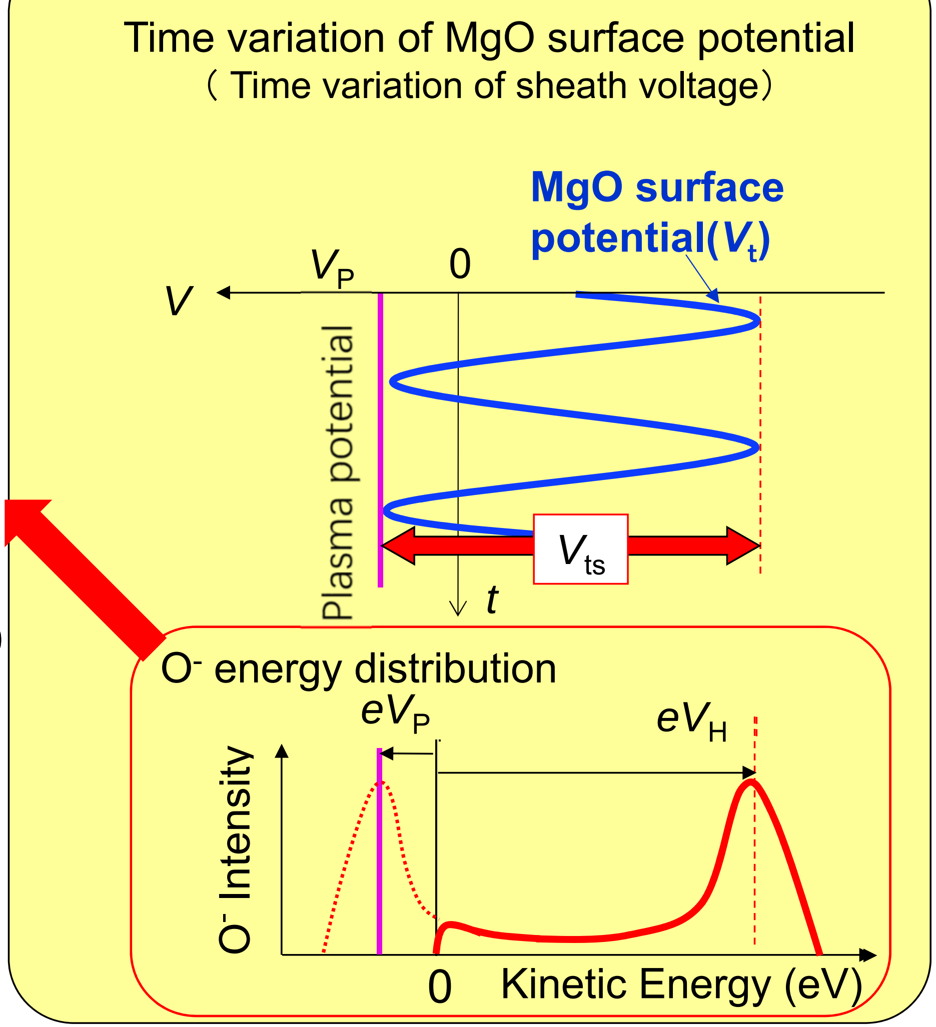
O^- energy distribution



$$V_{ts} \sim V_H + V_P$$

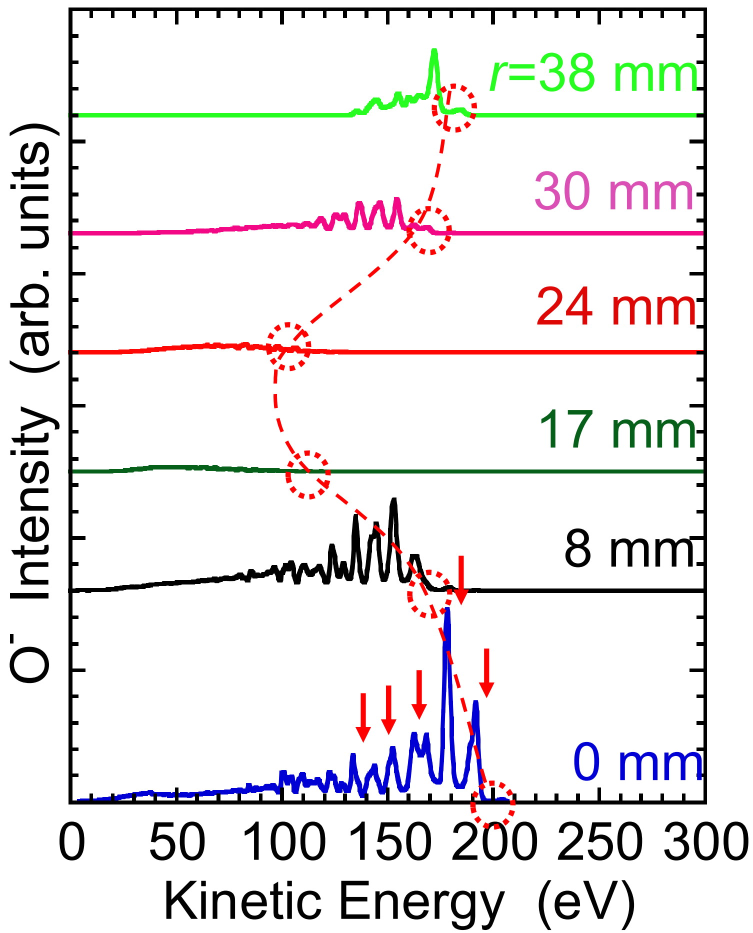
eV_H : Maximum O^- energy
V_P : Plasma potential

Schematic of O^- energy distribution



O^- Energy Distribution

- Radial position dependence-

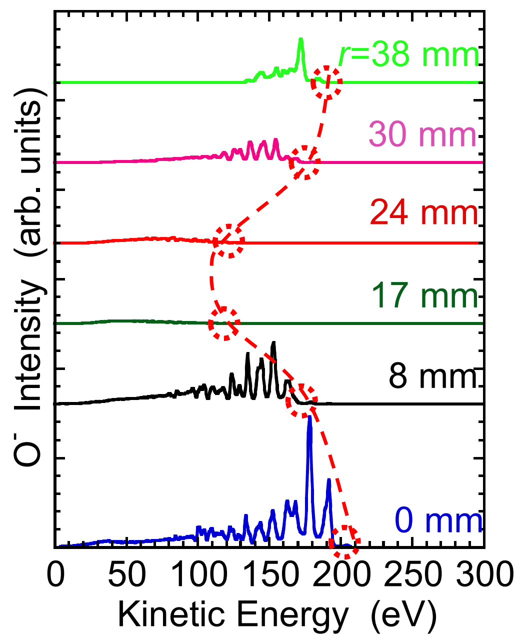


Interesting features

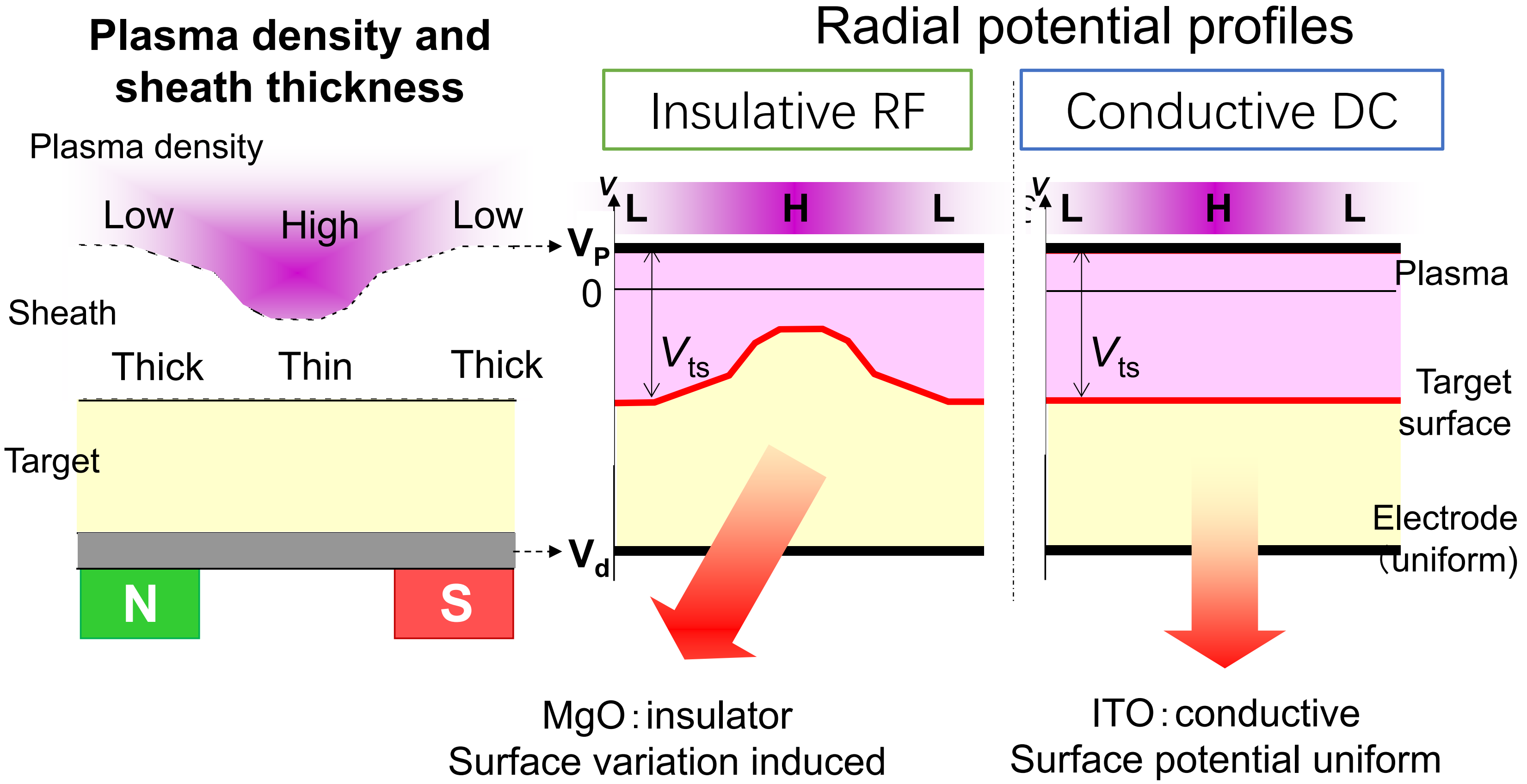
1) Radial variation of maximum O^- energy

2) Fine structure in O^- EDF

Radial variation of maximum O^- energy

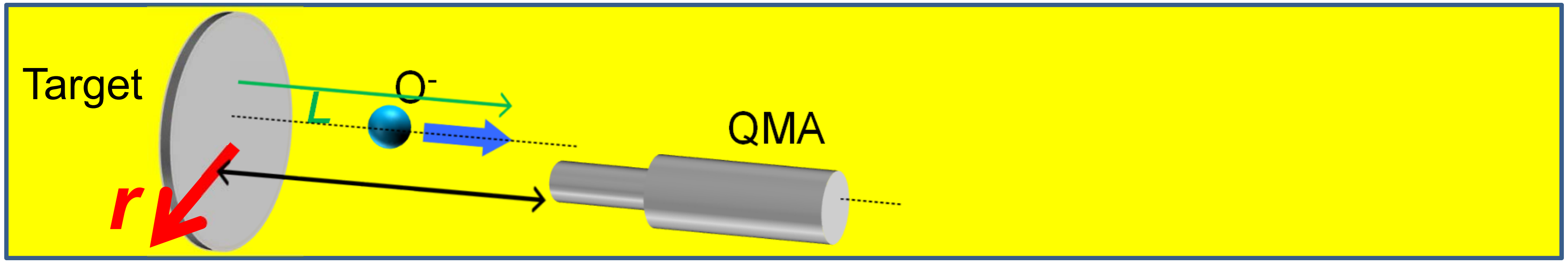


Comparison of DC-conductive/ RF-insulative magnetron plasmas

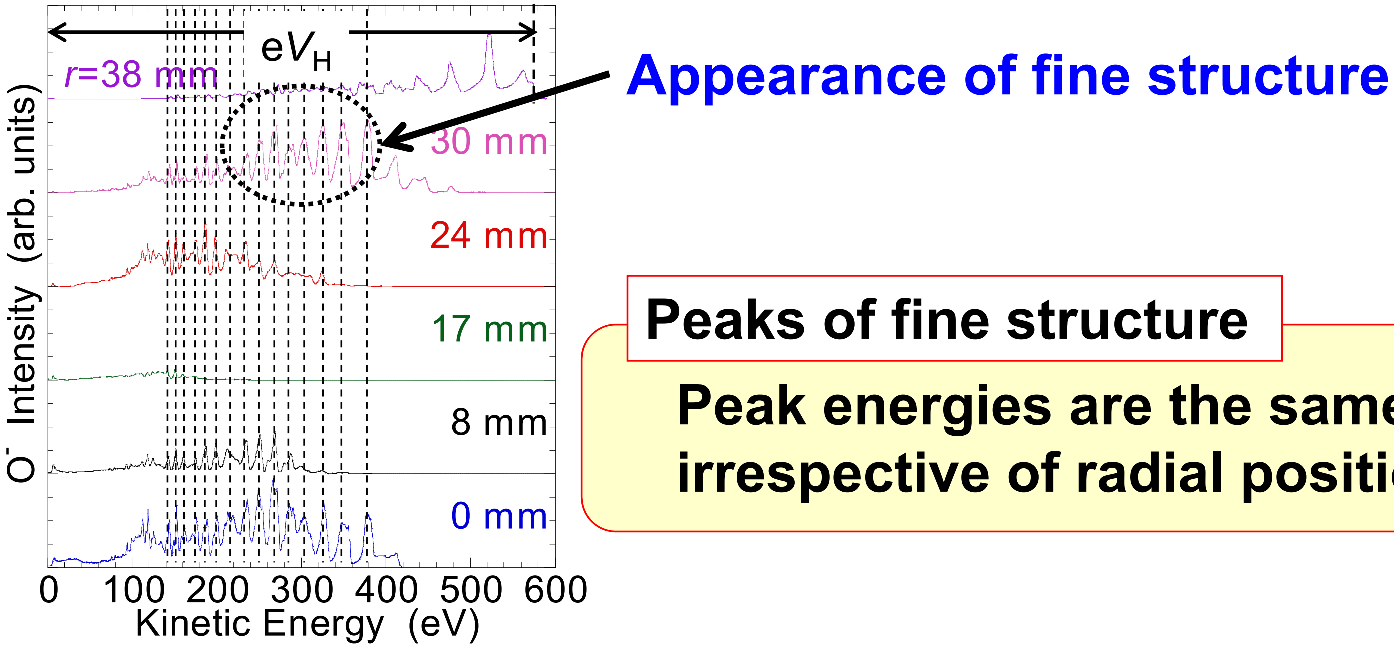


Difference in O^- energy

Radial Profile of O⁻ EDF



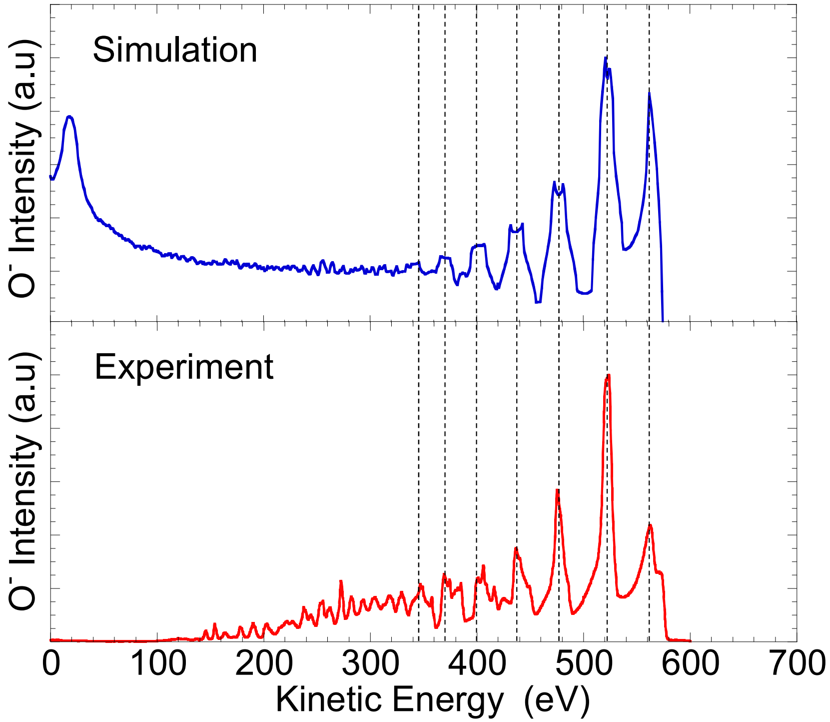
P_{RF}=350 W, p=5 mTorr, L=13.8 cm



Peaks of fine structure

Peak energies are the same irrespective of radial position.

Simulated Result of O^- EDF
- Comparison with experiment-



V_{RF}=290 V
V_P=13 V
L =138 mm
etc…

P_{RF}=350 W
p=5 mTorr
r =38 mm
L=138 mm

Simulation almost explains energy fine structure

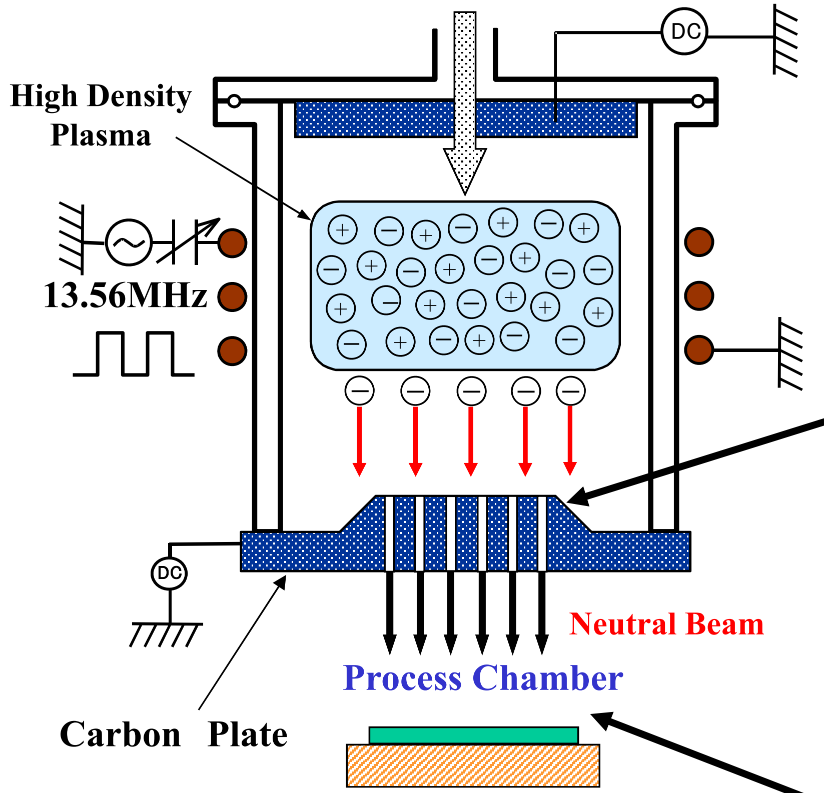
Oscillation of E field in the sheath ➡ **Modulation of O^- Energy**

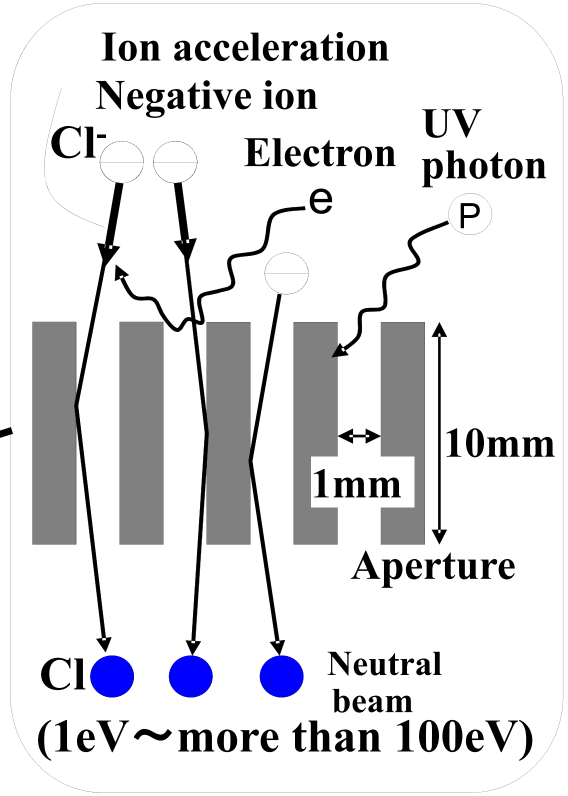
Kazuhiko Endo's Talk

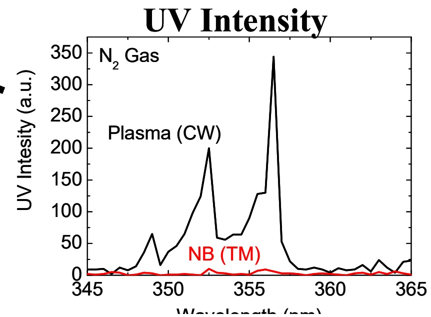
- Title: **Atomic Layer Etching, Deposition and Modification Processes for Novel Nano-materials and Nano-devices**
- The main message: for etching, deposition and other processes in semiconductor industry, neutral beams have a significant advantage over processes involved with energetic ion beams

Newly Developed Neutral Beam Source for Etching

Neutral Beam Source

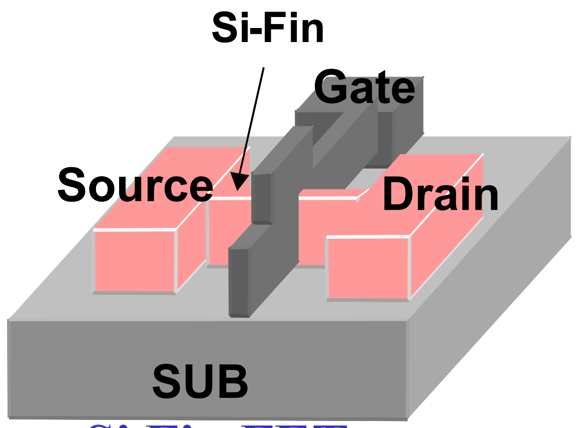




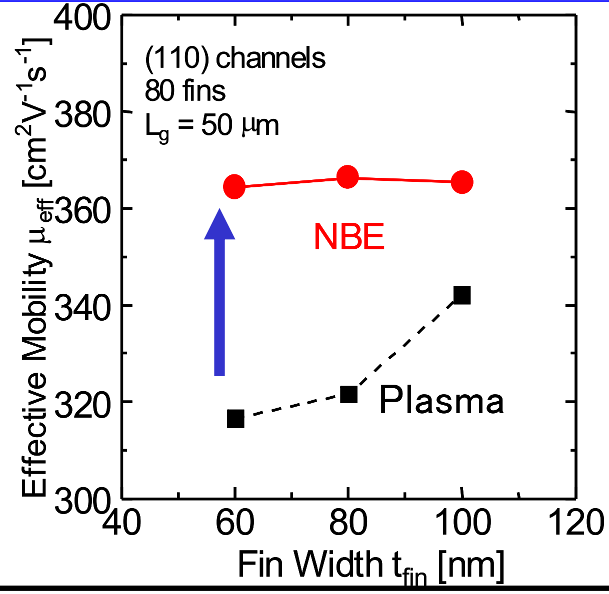


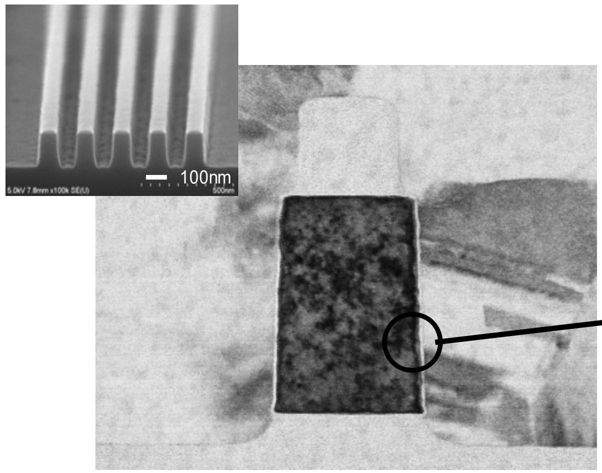
- High Density Neutral Beam (mA/cm^2)
- Lower Energy Beam (10eV～)
- High Neutralization Efficiency (～100%)

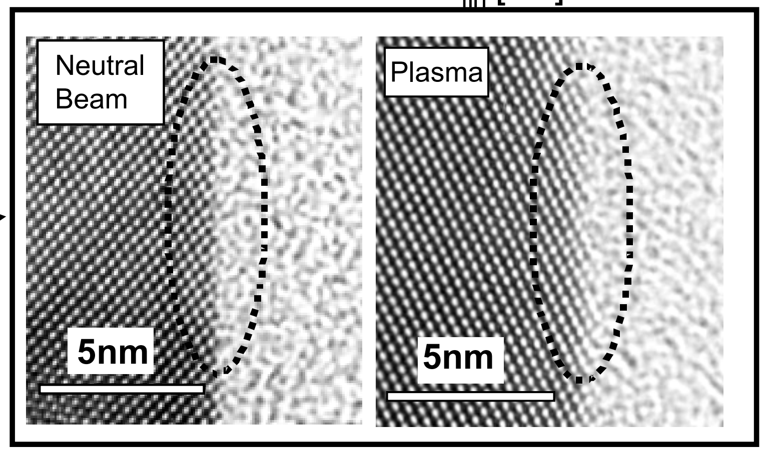
High-Performance Si-Fin-MOS Transistor by Defect-free Etching



Si Fin FETs



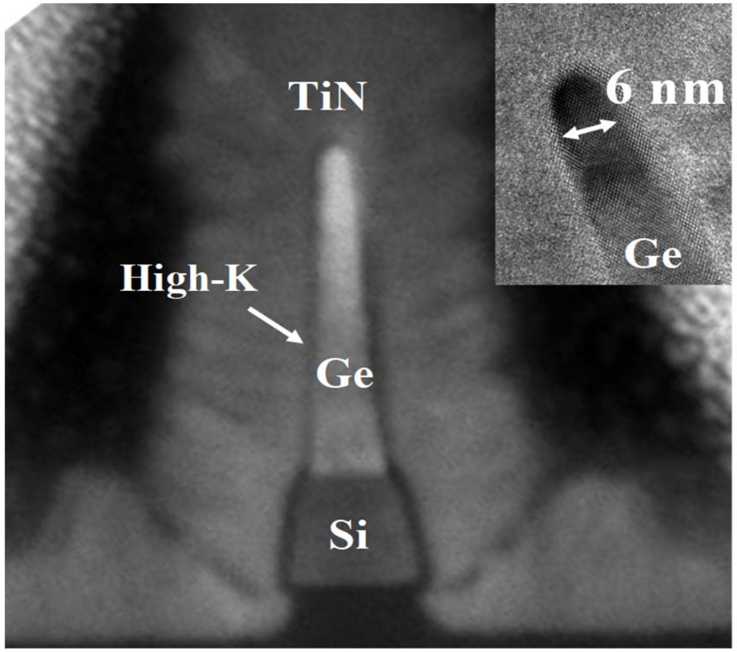


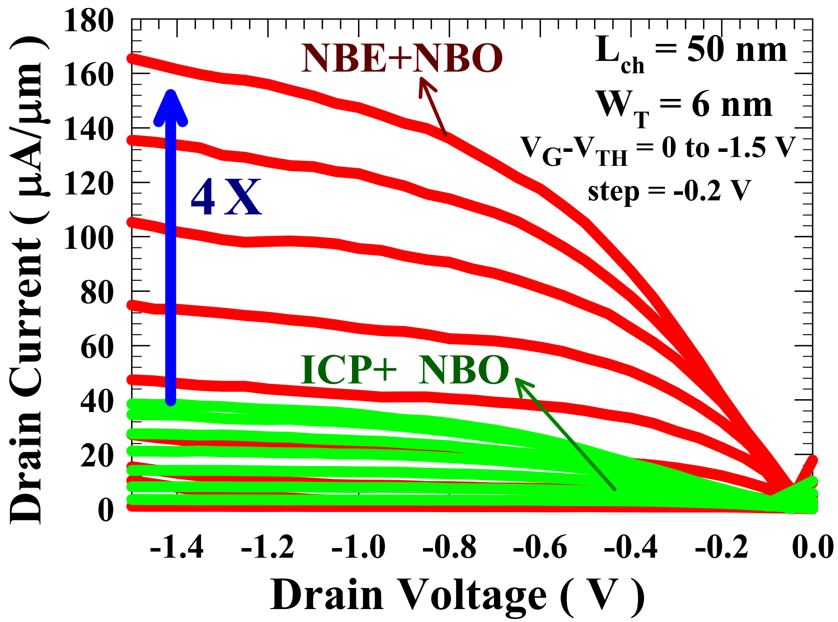


Beam Energy:10eV
Ion Energy:10eV

K.Endo. et. al. IEEE Transcation on Electron DeviceVOL. 53, (2006) 1826

Sub-6nm Ge Fin MOSFET



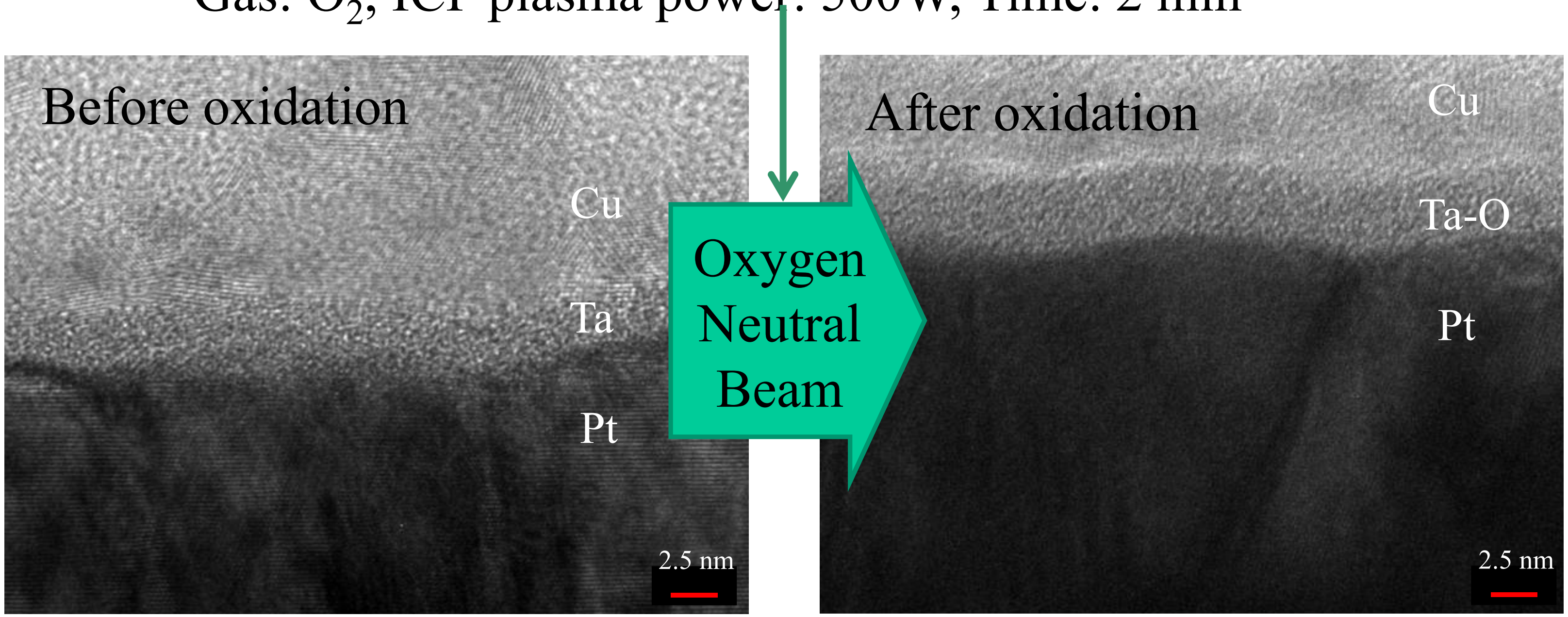


Y.-J. Lee, et. al., IEEE International Electron Devices Meeting, 33.5 (San Francisco, 2016/12/07).

NBO of Transition Metal for ReRAM

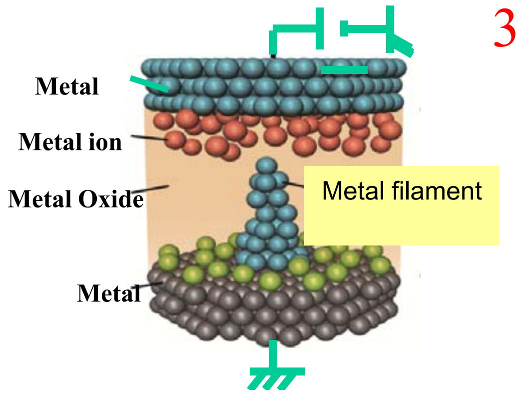
Oxygen neutral beam at RT

Gas: O_2, ICP plasma power: 500W, Time: 2 min



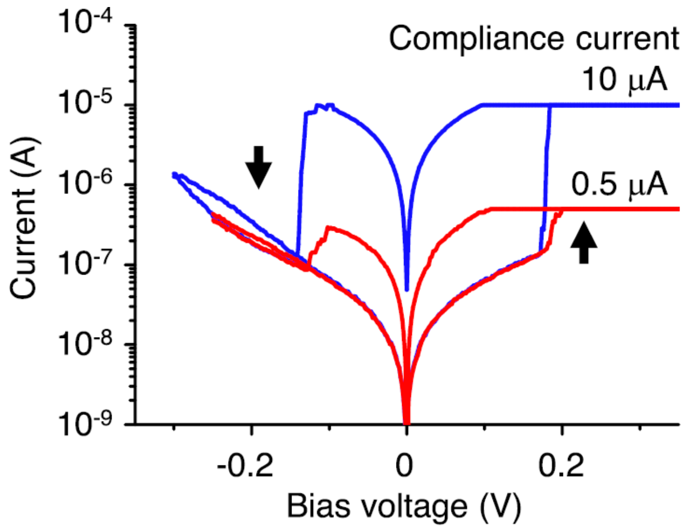
2.5-nm-thick Ta

3.8-nm-thick TaOx

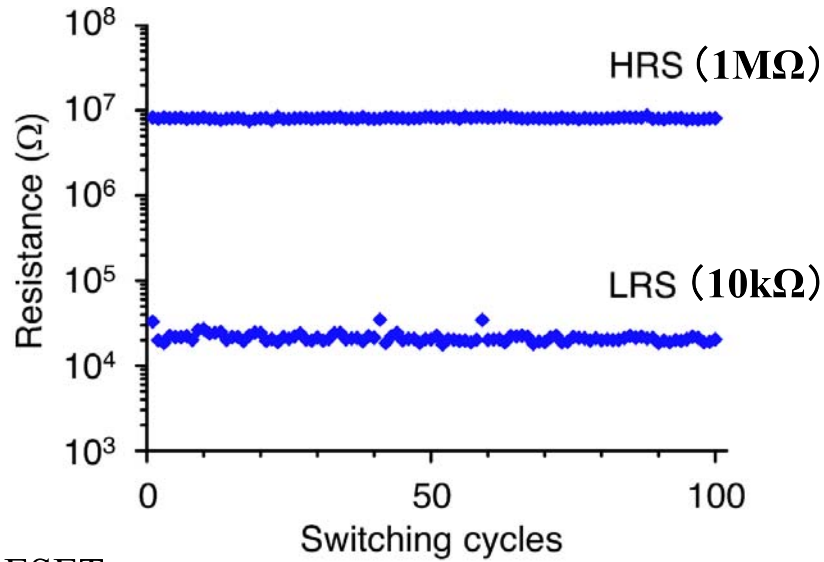


Electrical Characteristics of $Cu/Ta_2O_5/Pt$

Ta_2O_5: 3.2 nm



Bipolar resistive switching with SET and RESET threshold voltages of +0.2 and -0.14 to -0.10V



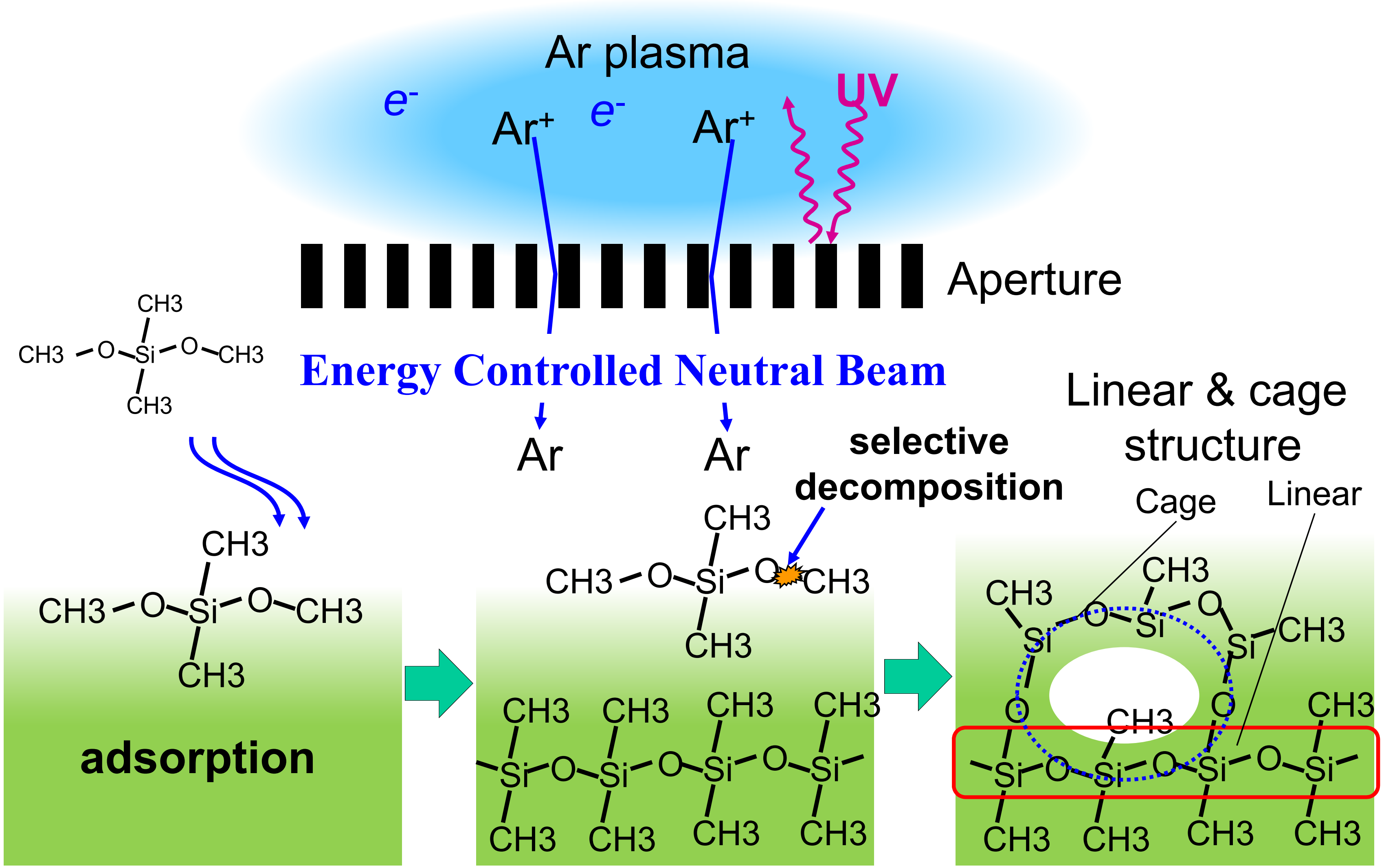
- 0.5 μA operation current
- $R_{OFF}/R_{ON} > 500$
- 100 times endurance

Our Ta_2O_5 film can work as an ionic transport layer for resistive switching.

T. Ohno et al., Appl. Phys. Lett. 106, 173110 (2015).

Surface Reaction in NBECVD

S.Yasuhara, et., al.,J. Phys. D: Appl. Phys. **42** (2009) 055208



Film properties comparison

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

- ✓ 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

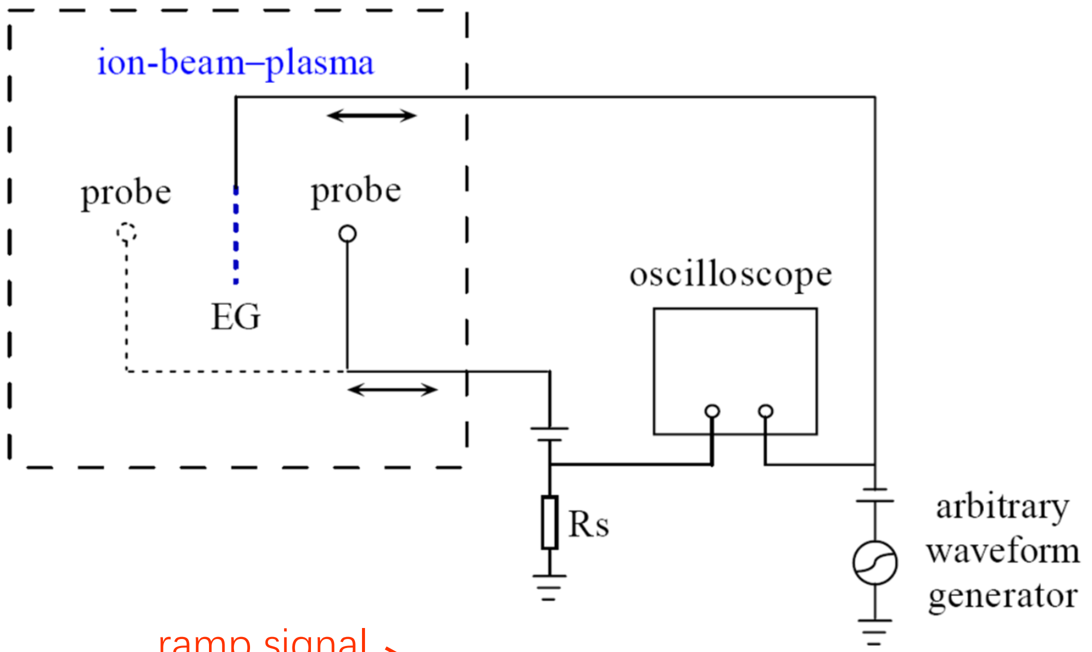
Pseudo-waves in an ion-beam-plasma system*

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



ramp signal

excitation voltage: $V_{EG} = V_{dc} + V_{pp}\tanh(t/\tau)$ $V_{dc} = -52\ \mathrm{V}$

$V_{pp} \rightarrow$ peak to peak amplitude, $\tau \rightarrow$ 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

A-I15

3rd AAPPS-DPP, Hefei, China

November 6, 2019

Tomography-based 2-D plasma imaging for low- and high-temperature large-scale plasmas

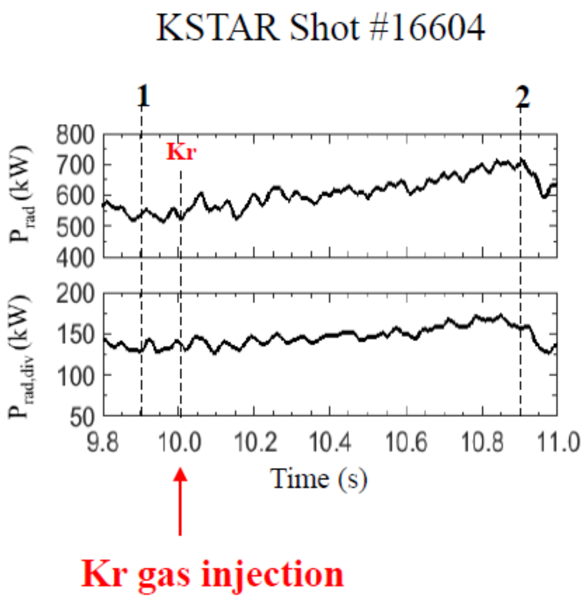
Wonho CHOE[1], J. Jang[2], S. Park[2], I. Song[1], B. Peterson[3]

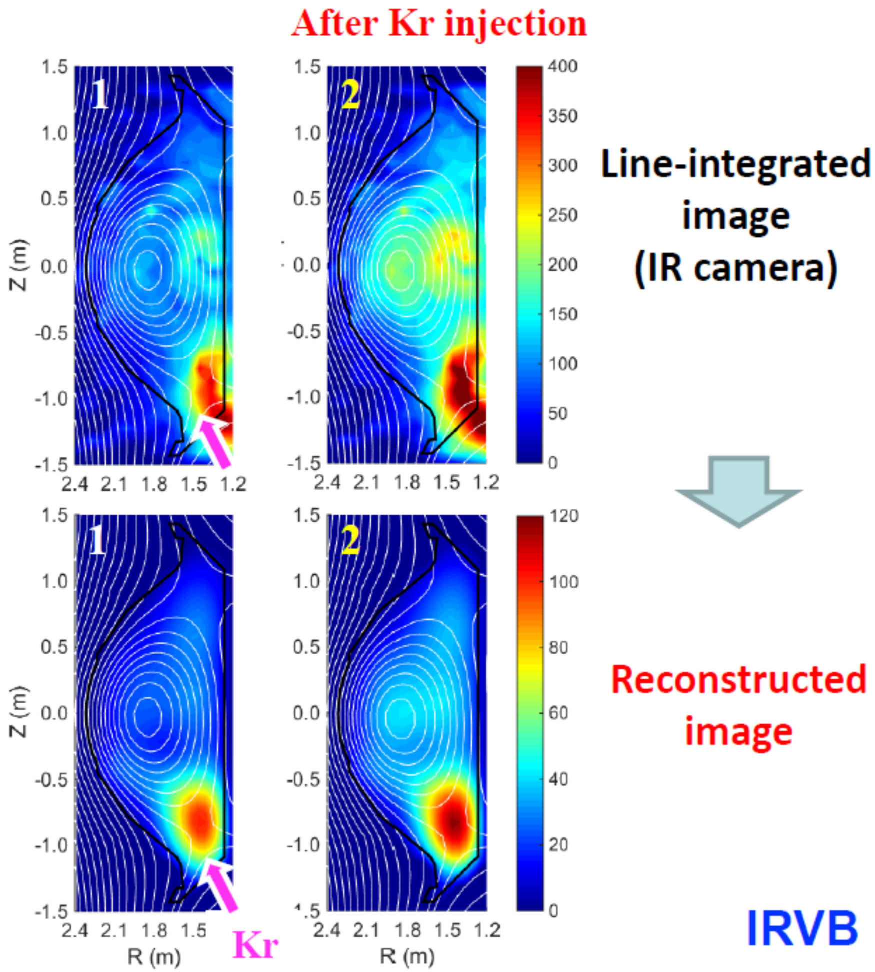
[1]Korea Advanced Institute of Science and Technology (KAIST), Korea

[2]National Fusion Research Institute (NFRI), Korea

[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**

A-I16

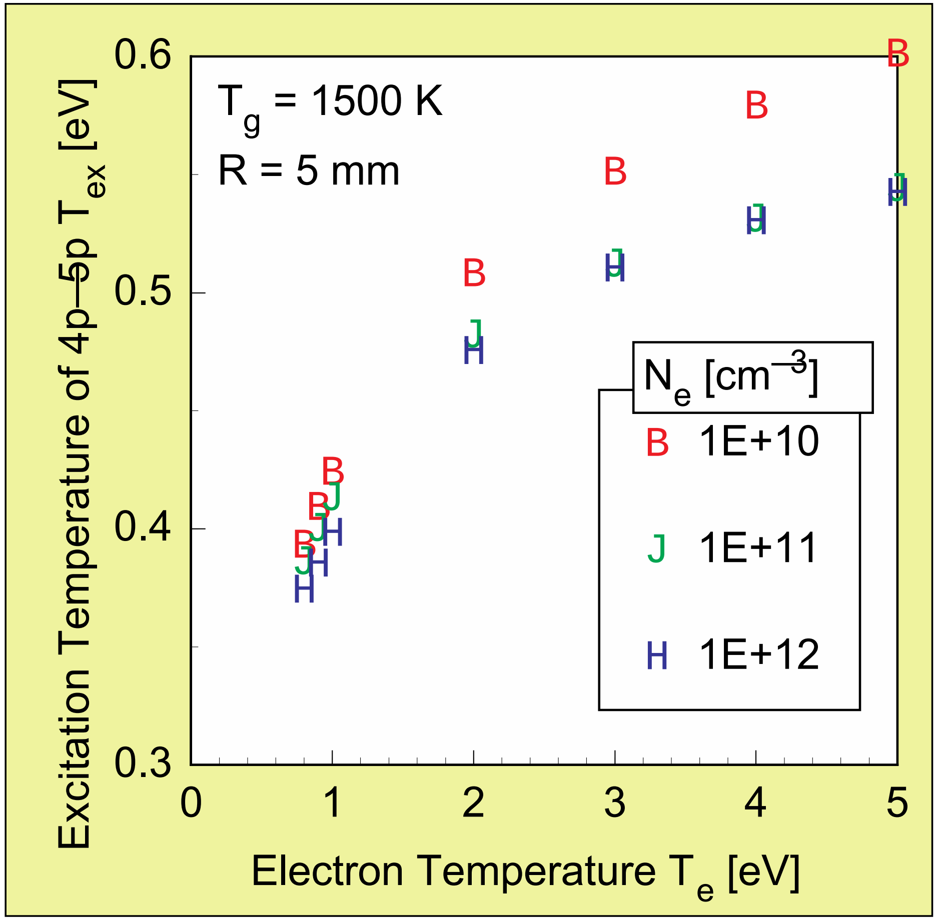
Optical emission spectroscopic (OES) analysis of electron temperature and density in atmospheric-pressure non-equilibrium argon plasmas

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

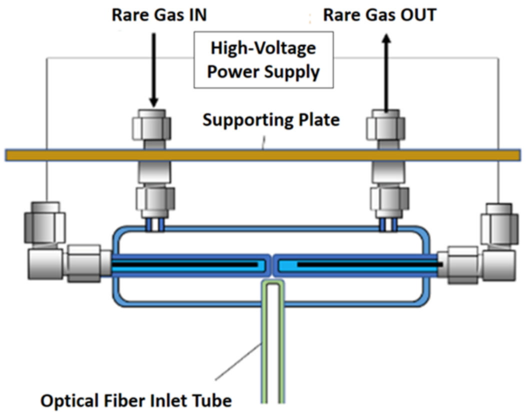
Tokyo Institute of Technology, Tokyo, Japan

N_e-dependence in the low N_e-region of T_e-T_{ex} relation of atmospheric pressure plasma

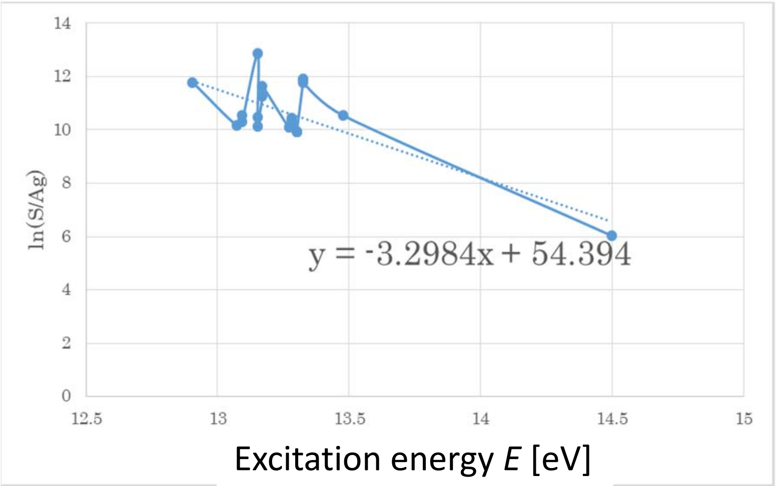
- In the low N_e- region, the influence of N_e on T_{ex} is small.
- At $T_{ex} \sim 0.4$ eV, the error of T_e is about $\pm$ 0.1 eV against the change of 10^{10} – 10^{12} cm^{-3}.



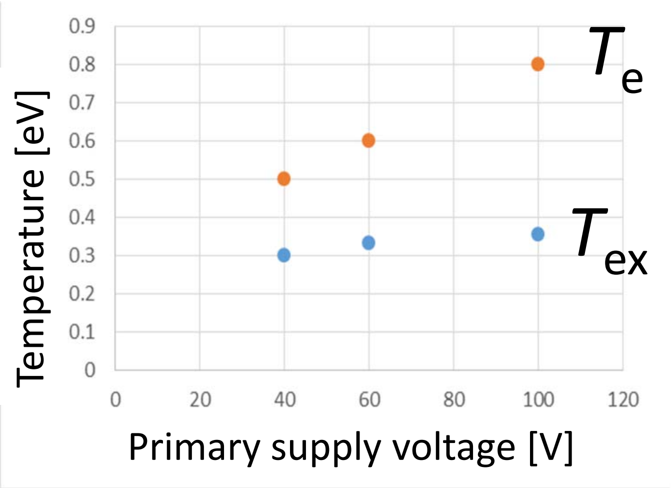
Experimental Example



- 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. Subedi [1], R. Manandhar[1], R. Guragain[1], H. Baniya[1], G. Panta[1], C.S. Wong [2]
[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

A-I2

Improvement of Growth and Yield of Rice Plants with Plasma Treatment

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

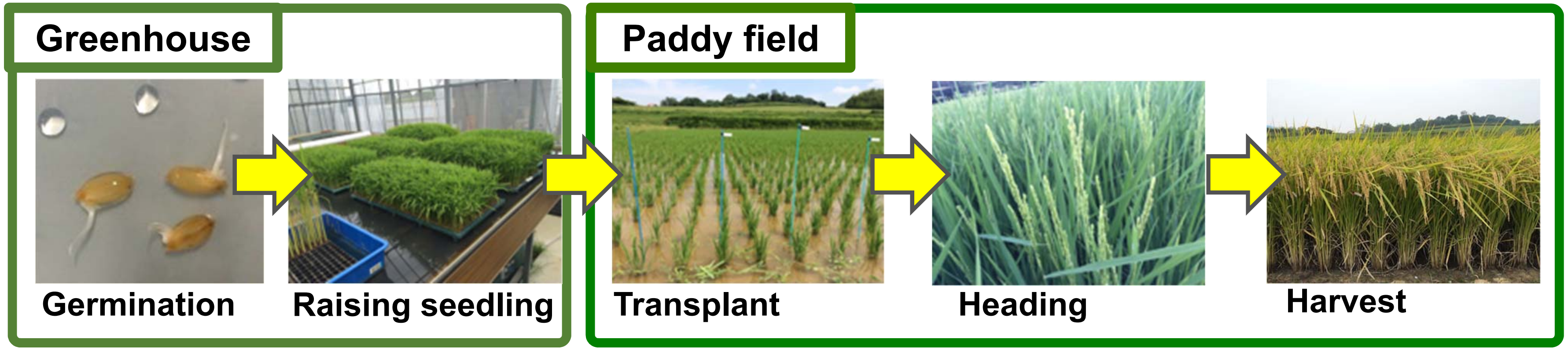
[1]Nagoya Univ., Japan,
[2]Fujitsu Client Computing Ltd., Japan, [3]RIKEN, Japan

3rd Asia-Pacific Conference on Plasma Physics (AAPPS-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.

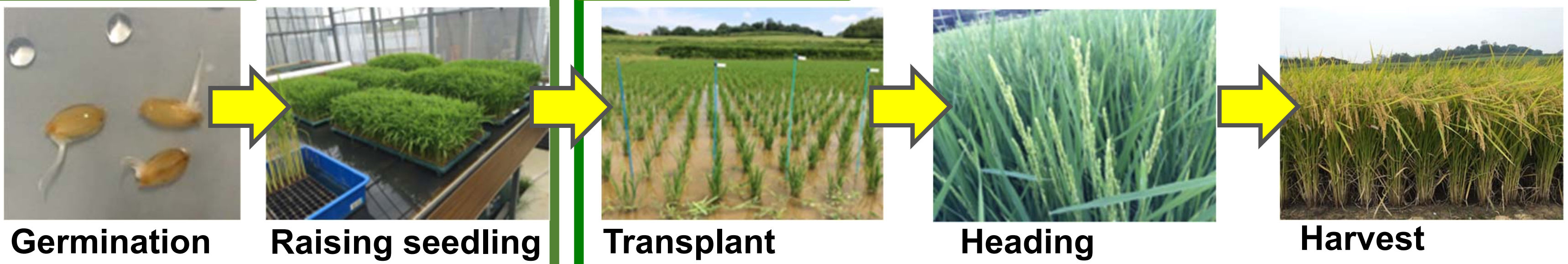
Plasma treatment for cultivation of rice plants

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

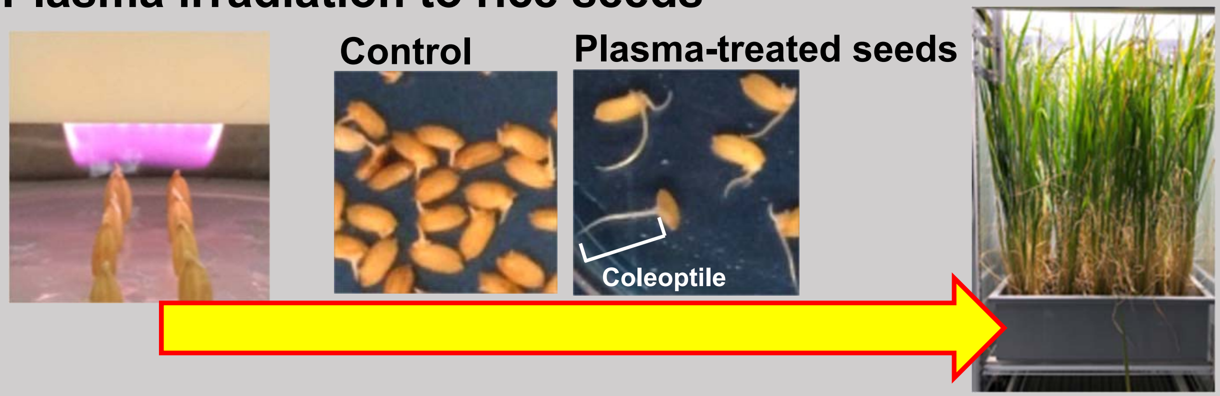
Greenhouse

Paddy field



gh harvest

Plasma irradiation to rice seeds



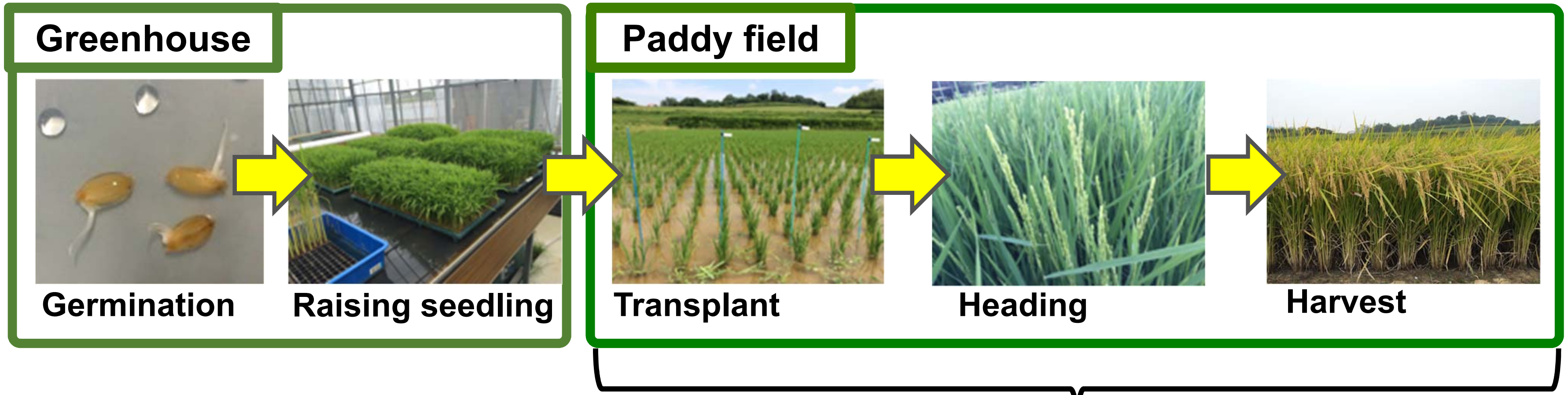
Initial growth promotion to be kept until the harvest

A-I2, Hashizume, Nagoya Univ.

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



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.

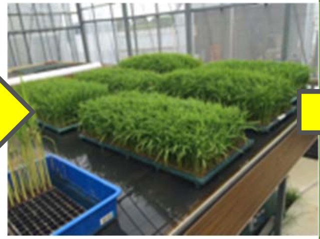
Plasma treatment for cultivation of rice plants

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

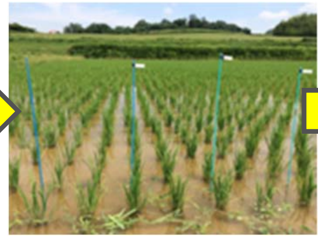
Greenhouse

Germination

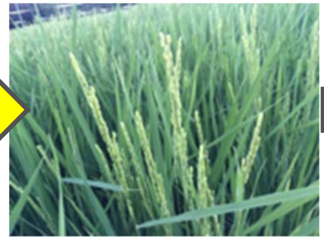


Raising seedling

Paddy field



Transplant

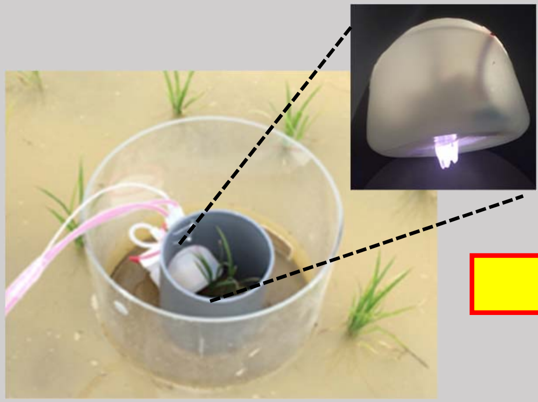


Heading

Harvest

According to the climate cl
the growth shifts from veg
The cultivation in the padd
linked to the harvest throu

Plasma treatment in the paddy field



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.

華中科技大學
Huazhong University of Science & Technology

High throughput production of silicon nanorod from powder feedstock by plasma flash evaporation

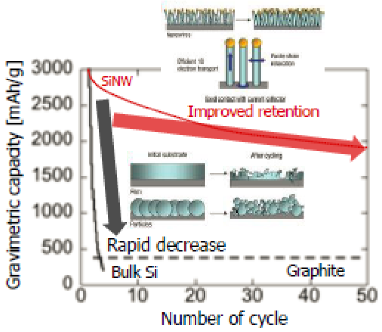
A. Tanaka[1], R. Ohta[1], and M. Kamabara[1]

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

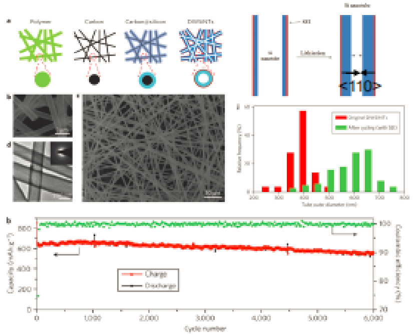
AAPPS-DPP 2019 (A-I17) 2019-11-7 14:00-14:30 @Applied-1 (Birch), Crowne Plaza Hefei, China

Next-G high density Lithium-ion battery

- **Si as high density anode**
  - Si: 10x higher capacity than C
  - Pulverize due to huge Si dilation
    → **Rapid capacity decay**
- **Si nanowire/nanotube**
  - 1D structure
    → **direct contact with current collector**
    → **spaces to buffer dilation**
    → **aligned anisotropic dilation direction**



Ref. C. Chan, *et al., Nat. Nanotechnol.* **3**, 31 (2007).

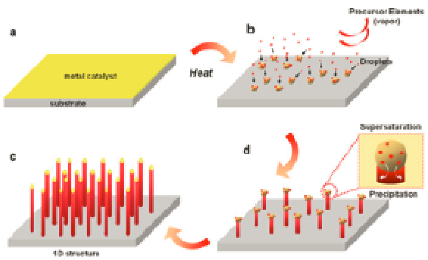


Ref. H. Wu, *et al., Nat. Nanotechnol.* **7**, 310 (2012).

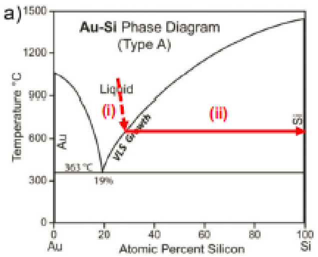
SiNW(SiNT) improvs cycle stability thereby high capacity at longer cycles

Vapor-Liquid-Solid (VLS) mode

VLS mechanism proposed first by Wagner
S. Wagner, W.C. Ellis, Appl. Phys. Lett. **4**, 89 (1964);



Ref. H-J. Choi, *NanoSci. Technol.*, 1 (2012).



Si nanowire grows from molten metallic catalyst (**cap-growth**)

(i) Si dissolution and (ii) NW growth takes place at a constant growth temperature.

VLS requisites:
- ✓ 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)

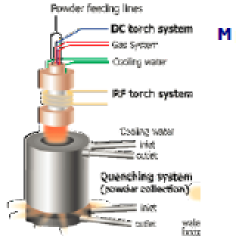


Fig. Schematic of FPE apparatus

Si powders ← M powders, H_2

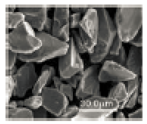
Complete Evaporation

Si Nucleation (homo)

M Nucleation (hetero)

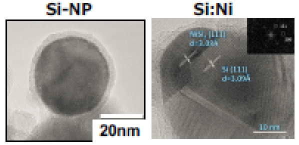
Growth & agglomeration

Raw material



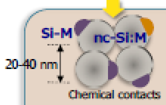
Metallurgy grade silicon powders (MG-Si)
* $2~3/kg, ~99.5% purity

Si-NP **Si:Ni**



C-coating onto SiNP

Ni-NP direct attachment to Si-NP



Nano-particle
- Agglomeration produces composites

Direct attachment of metallic particle
- Uniform M distribution
- E-conducting network
- Mechanical reinforcement

★**Throughputs: >1kg/hr**

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 $CH_4/H_2/N_2$ 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

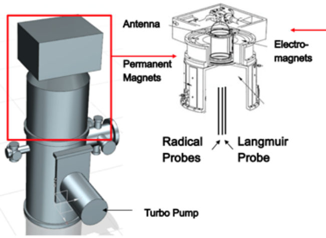
D. N. Ruzic, E. Barlaz, L. Bonova, J. Uhlig, G. Panici, D. Qerimi, J. Mettler, D. Patel, T. Choi, Z. Jeckell, D. Andruczyk

Email: druzic@illinois.edu or andruczy@Illinois.edu

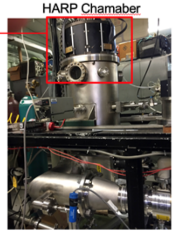
Semiconductor-Processing and Atmospheric Plasma Research

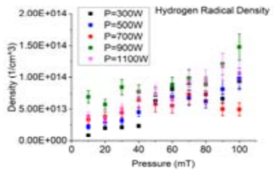
Hydrogen **A**tom **R**adical **P**robe experiment: ***HARP***

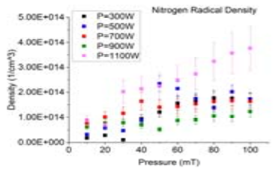
- **Facility to study radical density distributions in processing plasmas**
  - In Situ Measurement of N_2 O_2 and H_2 radicals
  - Study the dependence with pressure and discharge power



HARP Chamaber



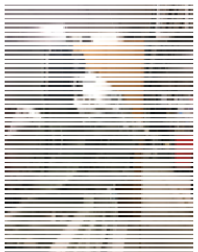




- MFC controlled flow rate of 3 gasses simultaneously
- Base pressure 1*10E-7 Torr
- Available gases: Argon, Helium, Oxygen, Hydrogen, Nitrogen.

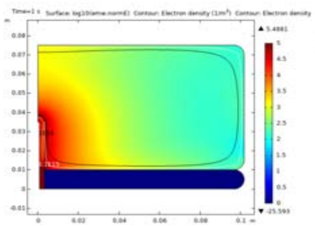
Funded by DuPont and LAM Research

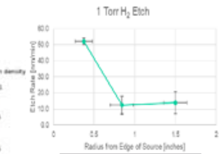
Tin **R**esidue **E**tch e**X**periment: ***TREX***

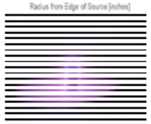


Facility to study Sn deposition cleaning for the semiconductor industry

- 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





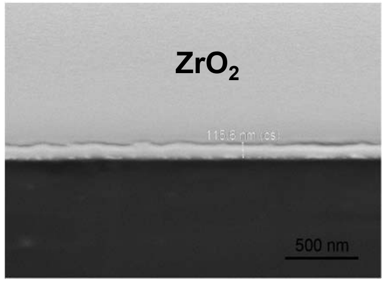


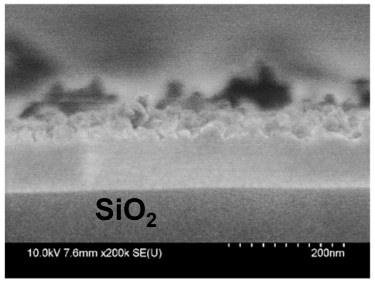
Funded by ASML

Multilayer Zirconia/Silica deposition

Funded by DOD and SERDP

- 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 therfore makes the bond **STRONGER** than the underlying metal itself.





Funded by EERE-General Motors

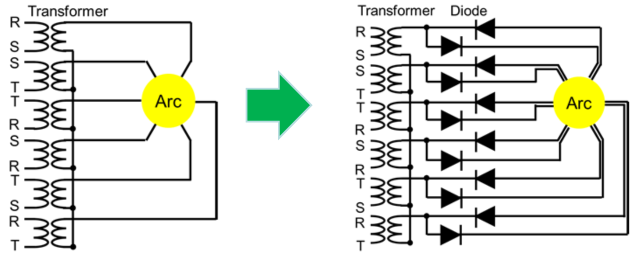
A-I21 Generation of Innovative Thermal Plasma with Diode-Rectification Technique

Manabu Tanaka, Takayuki Watanabe, Kyushu University, japan

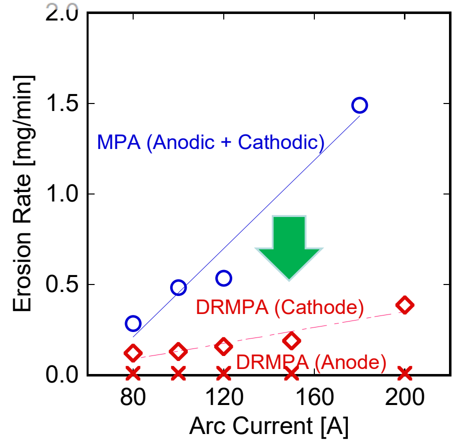
Diode-rectified multiphase AC arc as an innovative thermal plasma generating method was established as **big challenge of thermal plasma industrialization**

(1) Diode-Rectification

- Separation of an AC electrode into pairs of Cathode & Anode

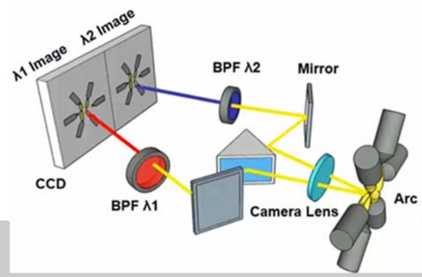


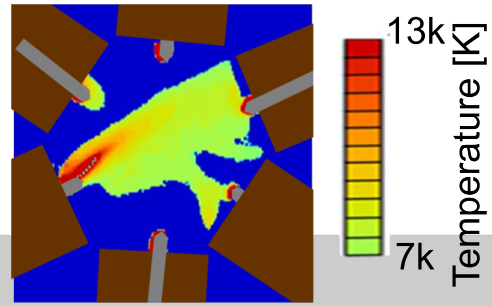
➔ Electrode erosion was drastically reduced.



(2) High-Speed Camera Observation

- Electrode phenomena during processing were understood.
- Arc Temperature Field was clarified.





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

전북대학교 JEONBUK NATIONAL UNIVERSITY

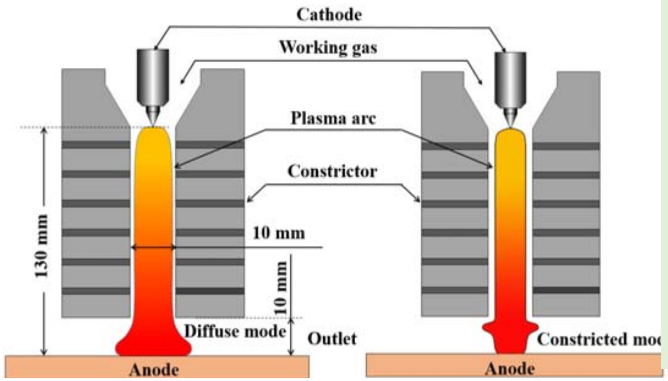
Chonbuk National University (全北大學校)

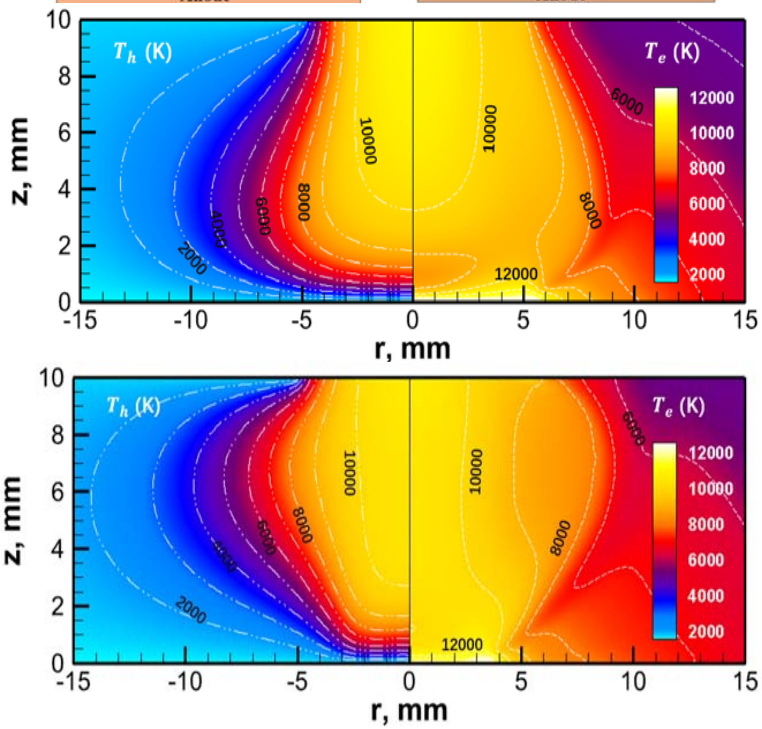
Plasma Experiment & Device Application Lab

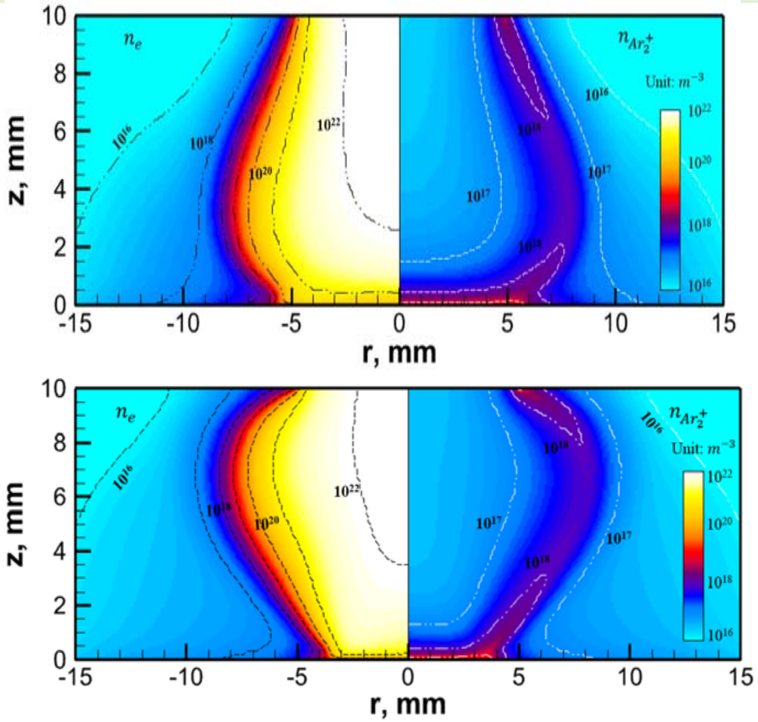
AI22- Chemical non-equilibrium simulation of arc attachment on anode of a high-intensity transferred arc

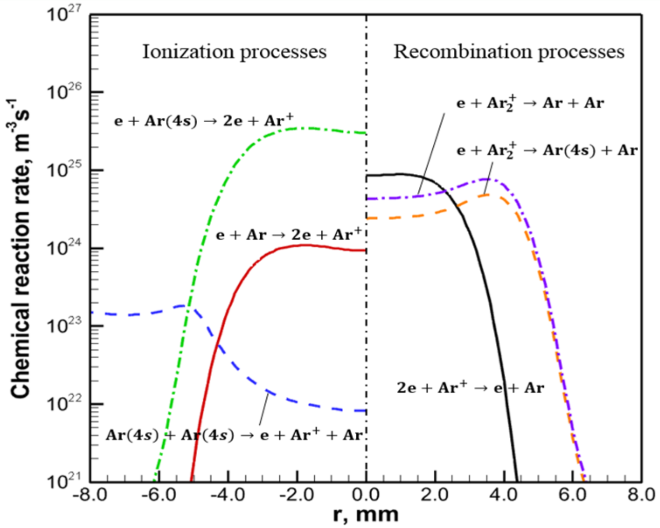
Hai-Xing Wang's talk
Beihang University

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.









Radial evolutions of the kinetic processes rates

南京航空航天大學
NANJING UNIVERSITY OF AERONAUTICS AND ASTRONAUTICS
智周萬物 道濟天下

High-electron-density microplasmas generated inside capillaries

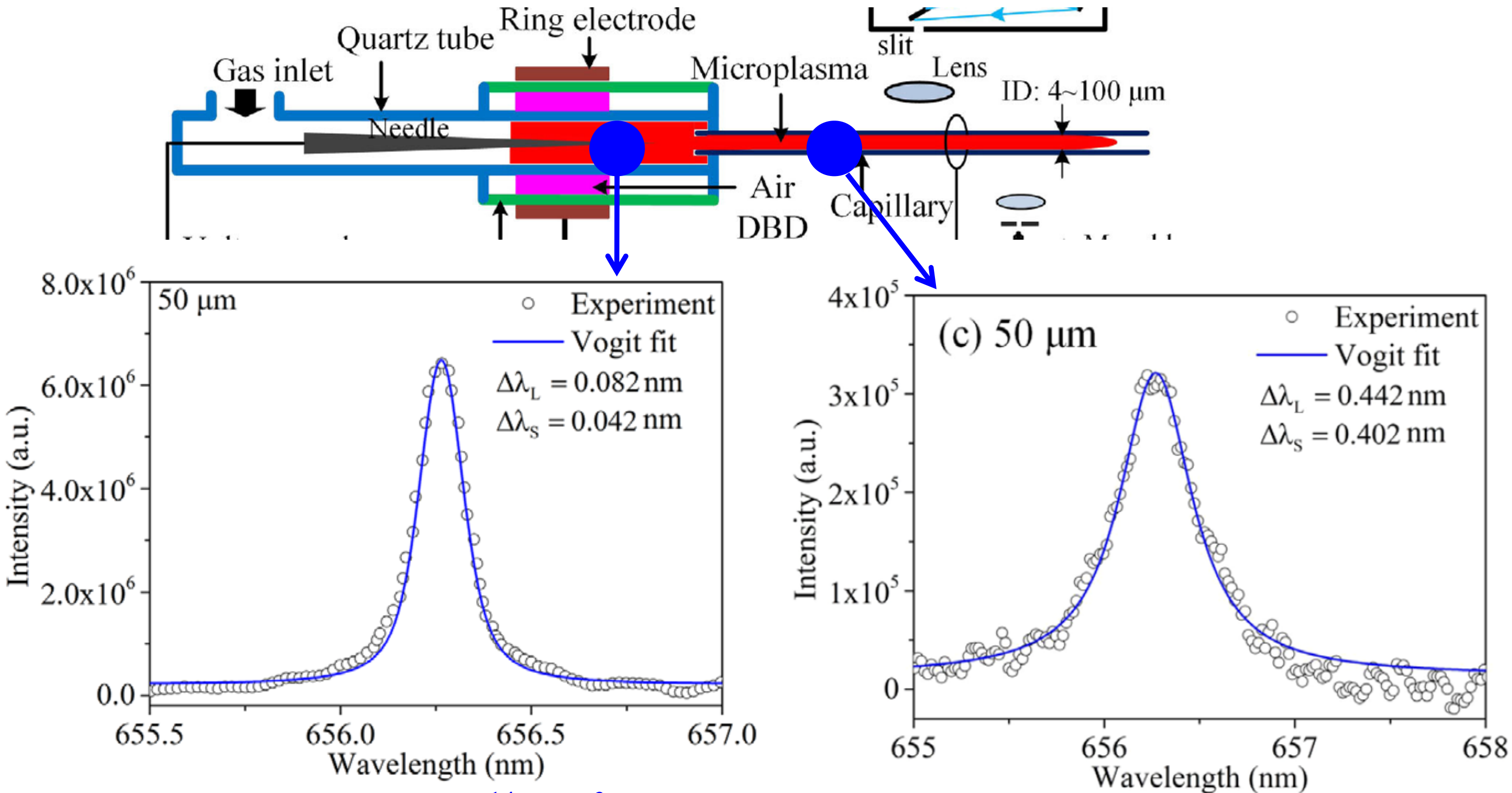
Shuqun Wu, Xueyuan Liu, Fei Wu

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*

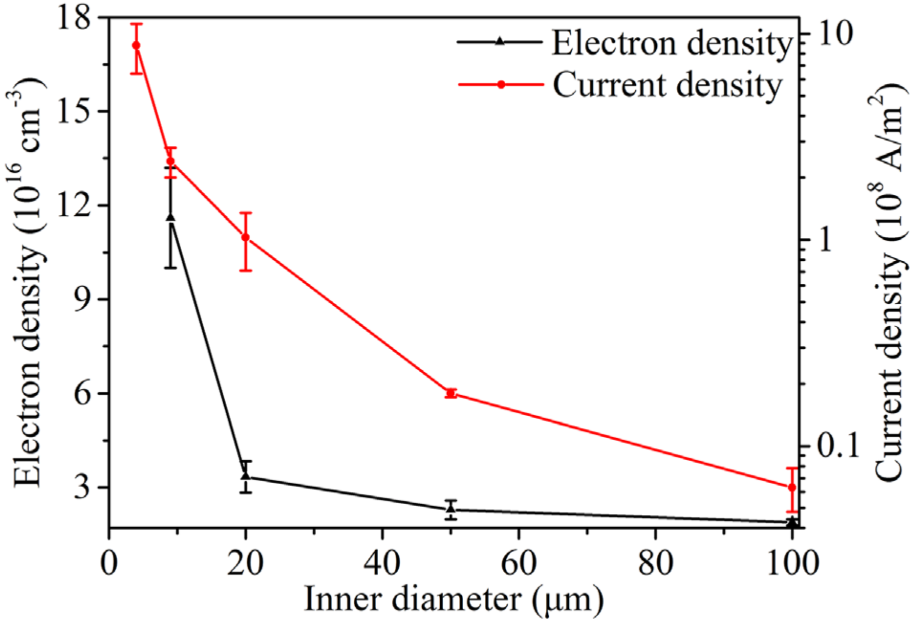


Ne=8.2 × 10^{14} cm^{-3}

Ne= 2.3 × 10^{16} cm^{-3}

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

Electron density *vs* current density



■ Tube diameter decreases from 100 to 4 μm, the current density increases from 2.5×10^7 Am^{-2} to 3.5×10^9 Am^{-2}. Tube diameter decreases from 100 to 9 μm, the electron density increases from 2×10^{16} cm^{-3} to 11×10^{16} cm^{-3}.

■ J and Ne of the microplasma are comparable to those in spark discharge.

3rd Asia-Pacific Conference on Plasma Physics, November 4-8, 2019, Hefei China

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

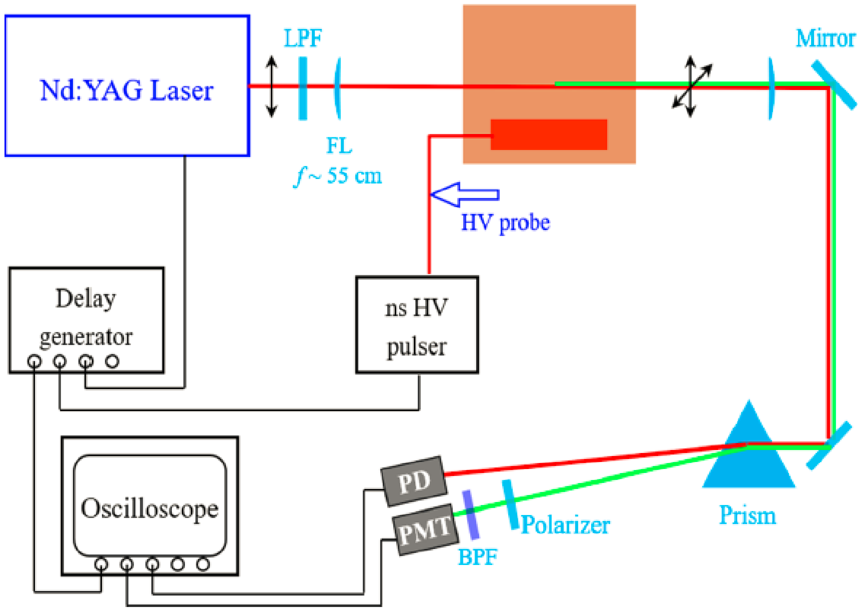
High Voltage and Discharge Plasma Laboratory

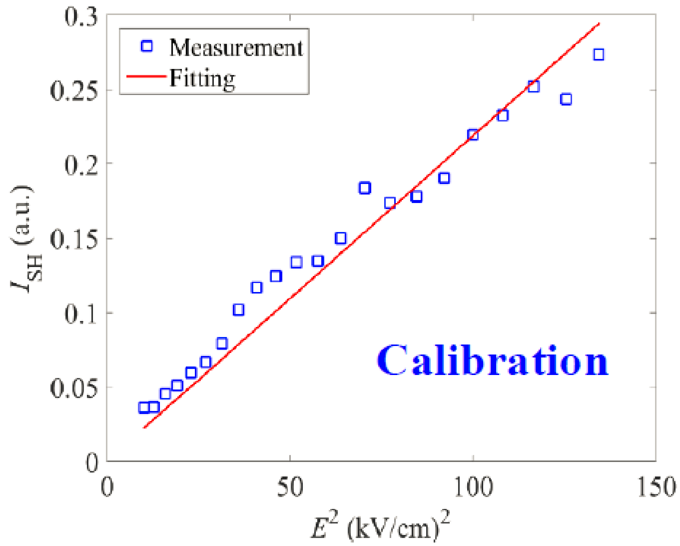
Beijing International S&T Cooperation Base for Plasma Science and Energy Conversion

November 5th , 2019

Electric Field Induced Second Harmonic (E-FISH) Generation

[Goldberg B M et al 2018]
[Chng T L et al 2019]



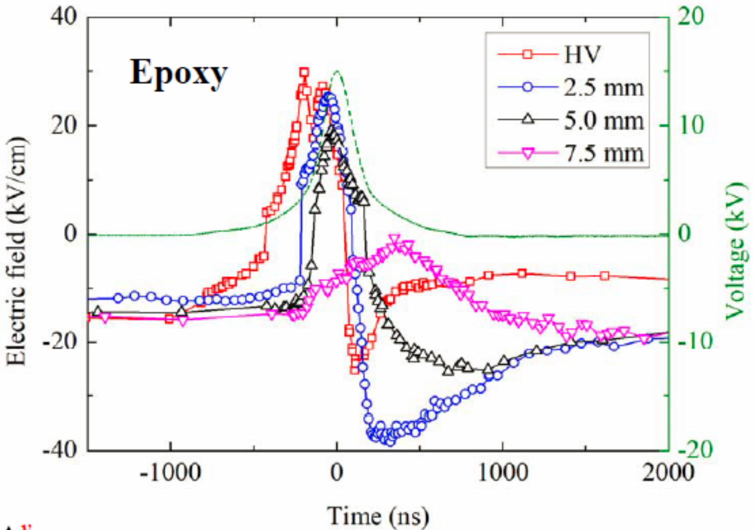


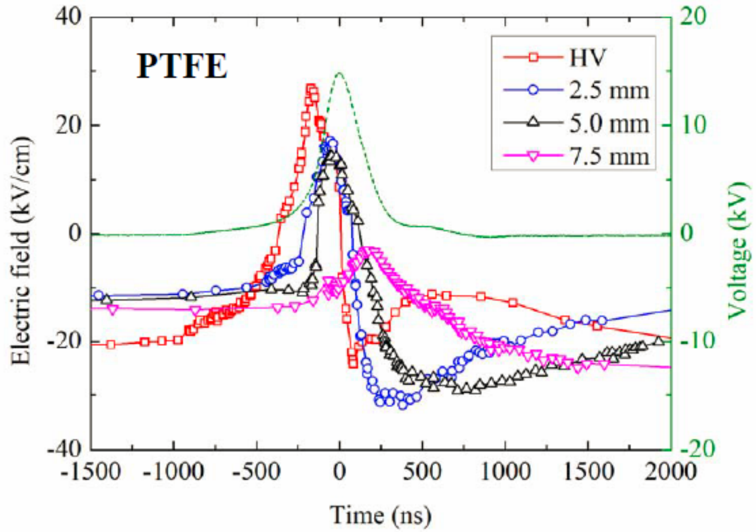
- Nd:YAG laser (Beamtech SGR-S400), 10 Hz
- 1064 nm laser energy: ~ 15 mJ
- Pulse width: 7-9 ns
- Horizontally polarized
- At focal point, beam diameter ~ 120 µm
- Rayleigh range ~ 11 mm

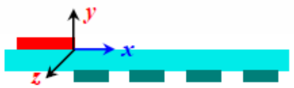
- $I_i^{(2\omega)} = k\, N_g^{\,2}\, (E^{ext})^2\, I_L^{\,2}$
- Calibration with a known electric field.
- Apply a voltage below the breakdown threshold across a parallel-plate electrode geometry

Electric field evolution

- The direction of E_x reverses during the SIW propagation
- Peak E_x decreases away from the HV electrode, $E_{x,\ Epoxy} > E_{x,\ PTFE}$
- 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!