APPLICATIONS OF LOW TEMPERATURE PLASMAS: STATUS, SCIENTIFIC ISSUES AND OPPORTUNITIES*

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AGENDA

- Applications of Low Temperature Plasmas

- What challenges and opportunities lie ahead for plasma technologies?

    - Materials Processing
    - Lighting
    - Atmospheric Pressure Plasmas
    - Bioscience
    - Nanoscience

- Concluding remarks

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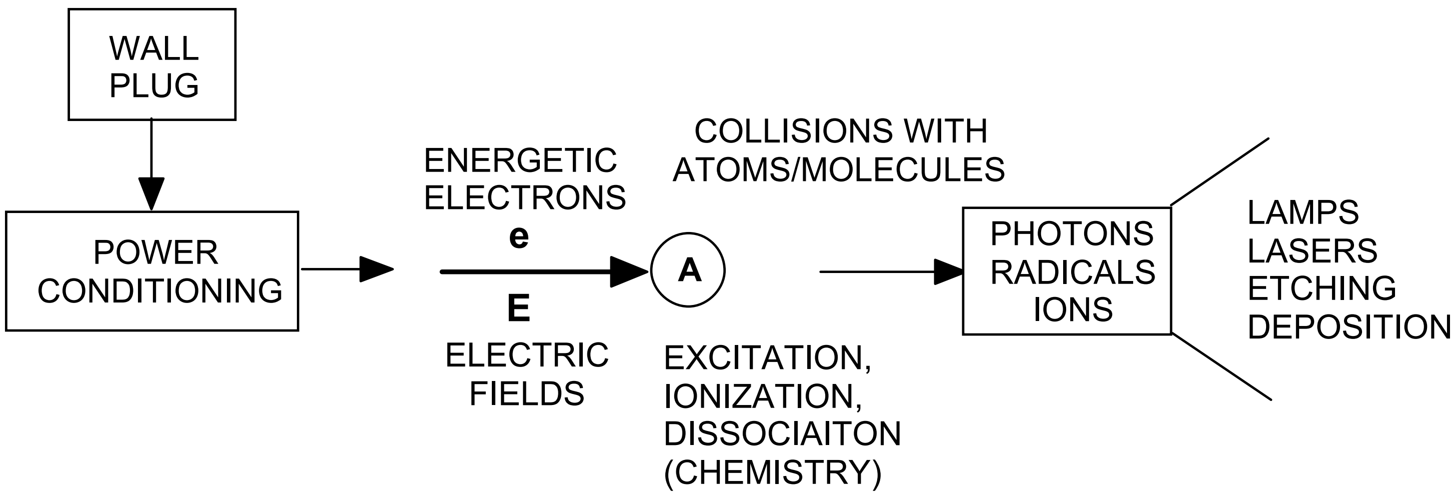
DEFINITION OF TECHNOLOGICAL PLASMAS

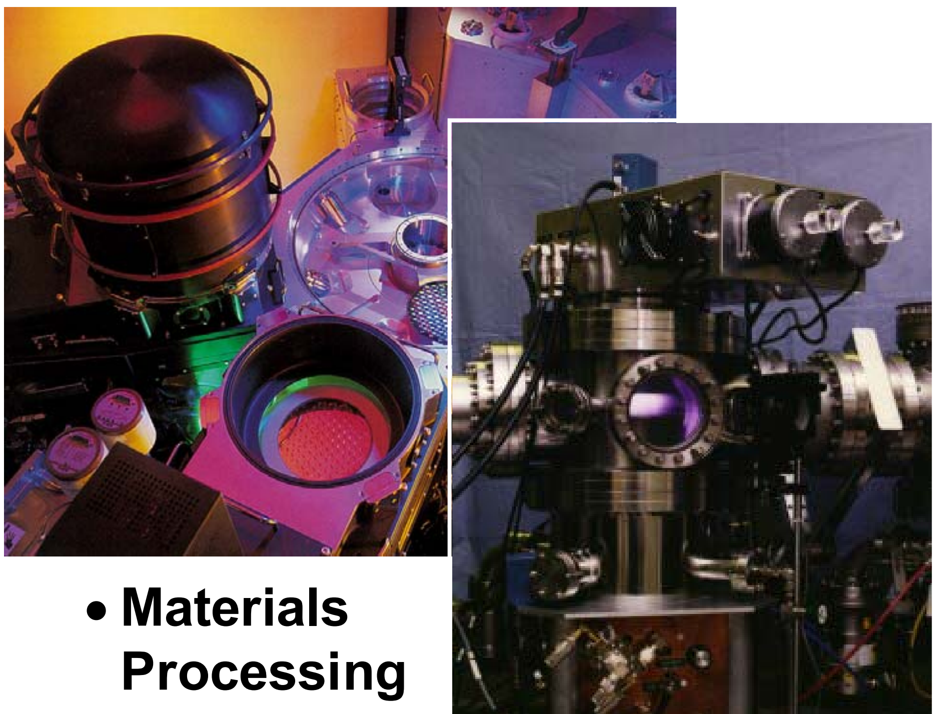
- Technological plasmas are a power transfer media.
- Electrons transfer power from the "wall plug" to internal modes of atoms / molecules to make “benign” species into “reactive” species.



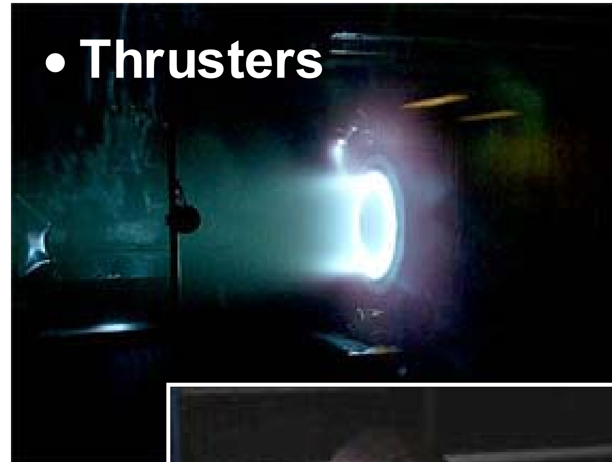
- Once activated, their physical or chemical potential may be used to make products (add or remove materials, photons…)

COLLISIONAL LOW TEMPERATURE PLASMAS

• Lighting



• Materials Processing



• Thrusters

• Spray Coatings

• Displays

PLASMA MATERIALS PROCESSING FOR MICROELECTRONICS

PLASMA MATERIALS PROCESSING FOR MICROELECTRONICS

- The fabrication of conventional microelectronics has met and bested extreme challenges as the nm scale is approached and exceeded.

- Plasma science has played a critical role in virtually all aspects of meeting these challenges

  - Physical Vapor Deposition
  - Plasma Enhanced Chemical Vapor Deposition
  - Etching
  - Cleaning
  - Passivation
  - Plasma sources of UV radiation for lithography (Hg lamps to EUV)

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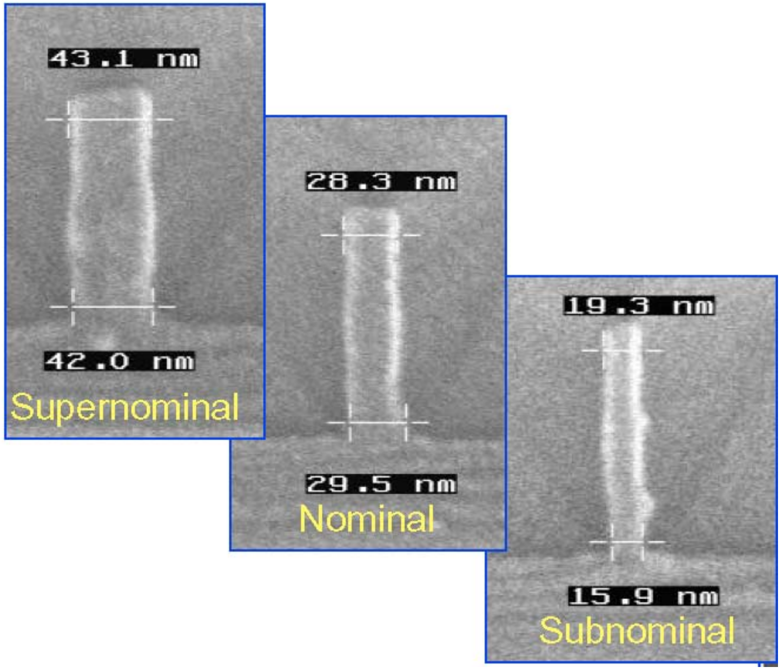
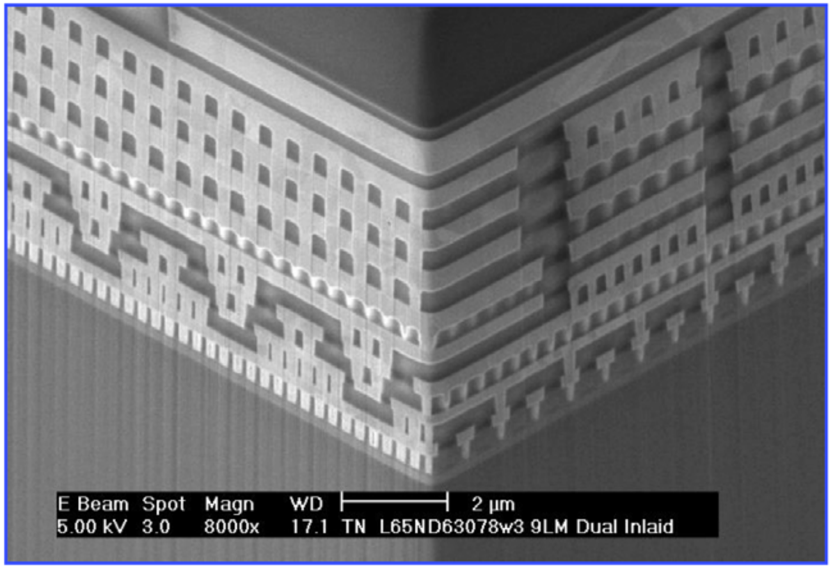
PLASMA ETCHING-TRANSISTORS, INTERCONNECT

- **Plasma etching is at the heart of microelectronics fabrication. Advance techniques have produced feature sizes below lithography limits.**
- **Challenges for etching novel low-k (dielectric) materials for interconnect have been met.**





- **Ref: F. Huang, P. Ventzek**

SOPHISTICATED PLASMA TOOLS

- **AMAT-Komatsu PECVD for flat panel displays**

- **AMAT Ionized Metal PVD**

- **Ref: Ashok Das**

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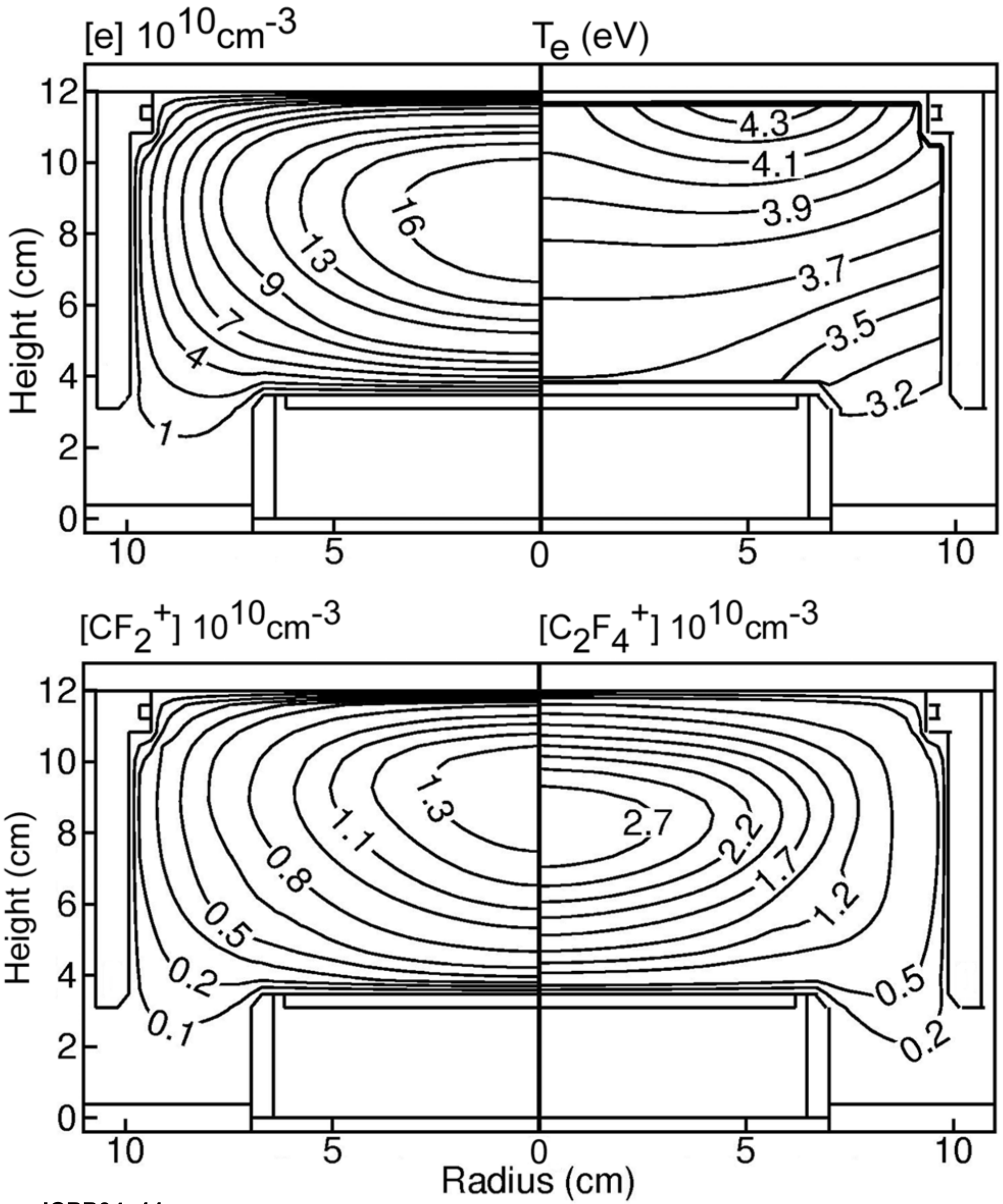
PLASMA PROPERTIES: ICPs IN $Ar/c\text{-}C_4F_8/CO/O_2$



- **Complex multi-component gas mixtures are used to optimize the flux of reactants to the substrate.**
- **Dozens of radicals and ions may be generated by dissociation and ionization of the feedstock gases.**
- **$Ar/c\text{-}C_4F_8/CO/O_2$ = 60/5/25/10, 10 mTorr, 600 W ICP, 13.56 MHz, 20 sccm.**

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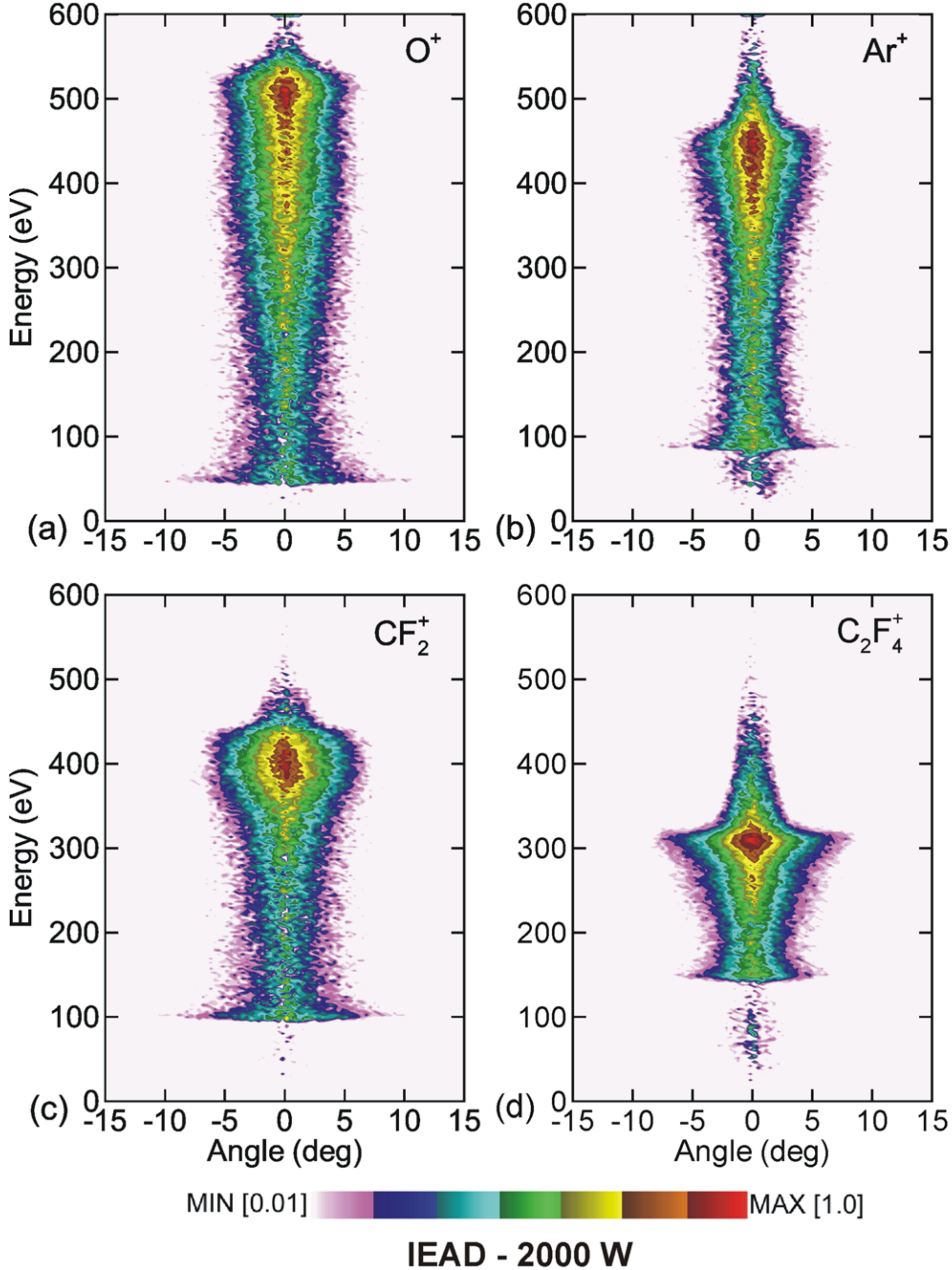

IEADs TO SUBSTRATE: MERIES IN $Ar/C_4F_8/O_2$

- **Acceleration of ions into the wafer by applied bias generates fluxes of a wide variety of ions.**
- **These Ion Energy and Angular Distributions (IEADs) activate etching processes.**

- **40 mTorr, 2000 W MERIE, 215 sccm, $Ar/C_4F_8/O_2$ = 200/10/5, 100 G**

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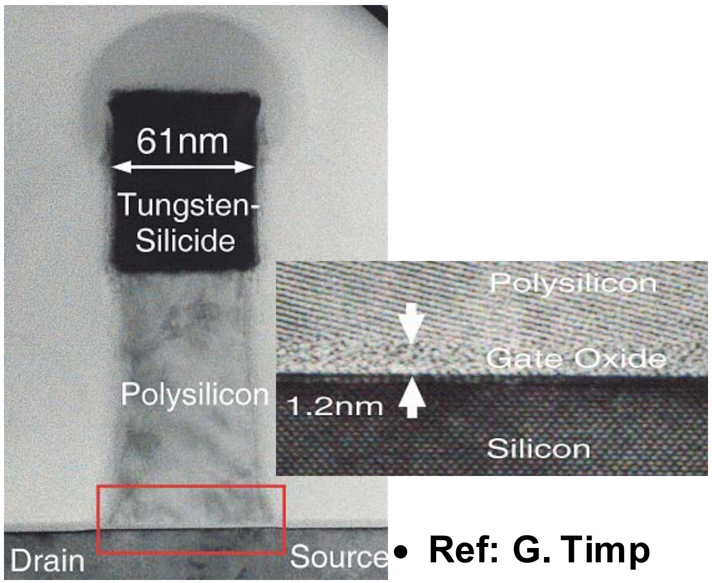
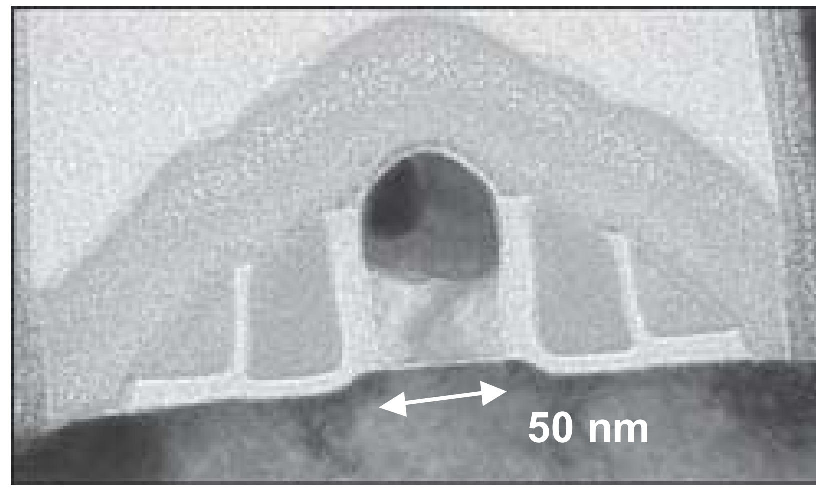
SELECTIVITY IN MICROELECTRONICS FABRICATION

- Fabricating complex microelectronic structures made of different materials requires extreme *selectivity* in, for example, etching Si with respect to SiO_2.



- Ref: G. Timp



- AMD 90 nm Athlon 64

- Complex features are fabricated by selectively removing one material but not another with near monolayer resolution.

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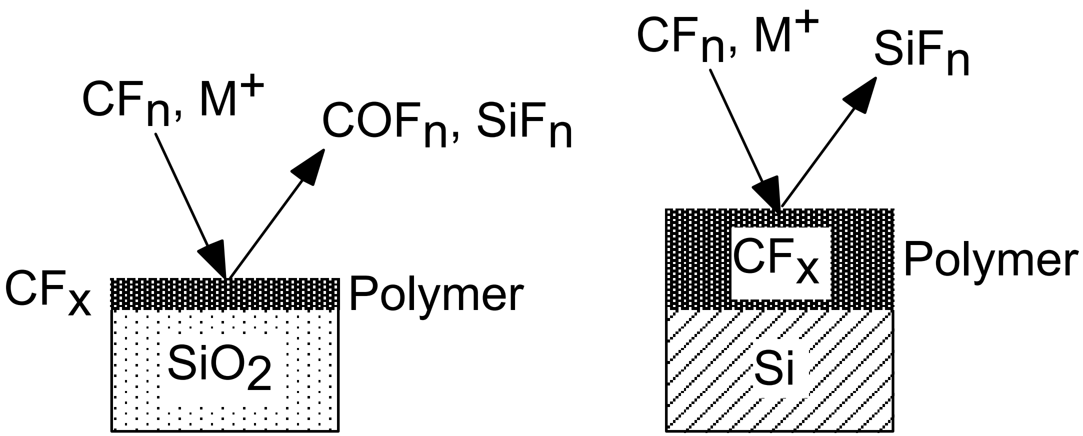
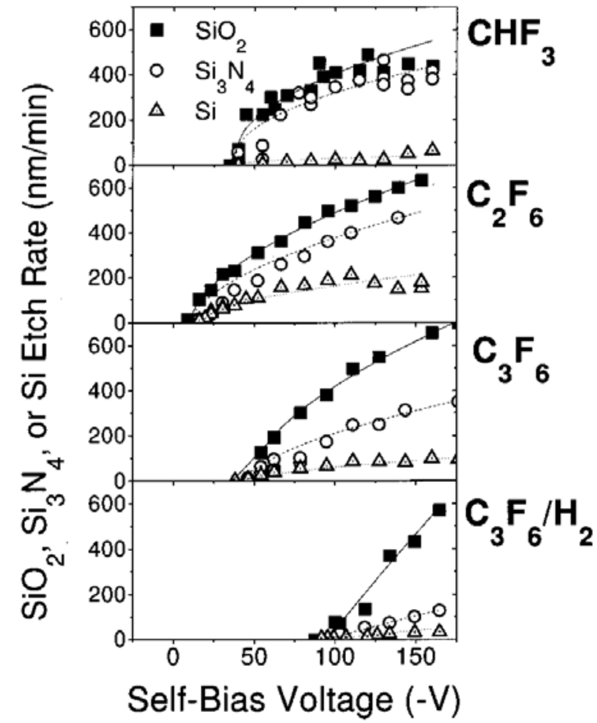
FLUOROCARBON PLASMA ETCHING: SELECTIVITY

- **Selectivity in fluorocarbon etching relies on polymer deposition from dissociation of feedstock gases.**

$$e + Ar/C_4F_8 \longrightarrow CF_n, M^+$$





- **Compound dielectrics contain oxidants which consume the polymer, producing thinner polymer layers.**
- **Thicker polymer on non-dielectrics restrict delivery of ion energy (lower etching rates).**

  - **G. Oerhlein, et al., JVSTA 17, 26 (1999)**

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CHALLENGES IN TAILORING PLASMAS FOR SELECTIVE ACTIVATION

- **Advanced applications will require extreme selectively by producing desired plasma chemical reactions and preventing undesirable.**
- **The ability to tailor the energy distributions of plasma particles is key to this selectivity.**
  - ***Tailored electron energy distributions:*** **Control formation of radicals and ions; best if also spatially segregated.**
  - ***Tailored Ion energy distributions:*** **Should be narrow to differentiate thresholds.**
  - ***Tailored synergy between ions and neutrals:*** **Necessary for monolayer control of selectivity, deposition, end-point.**
- **Robust diagnostics to monitor, develop and control processes.**

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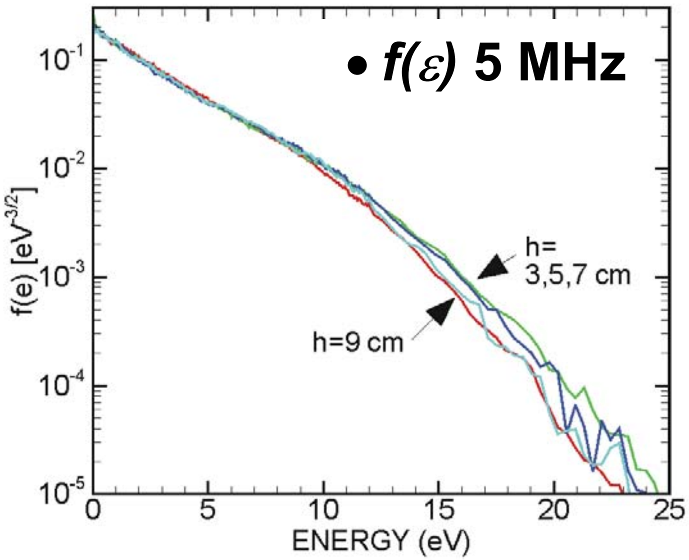
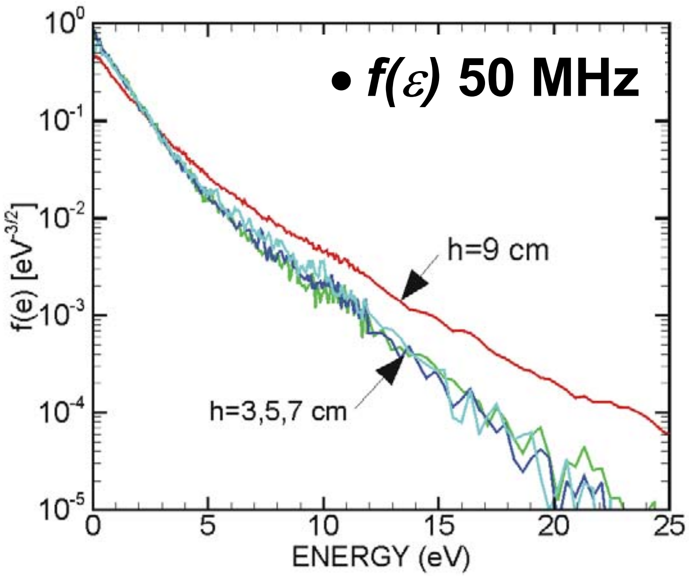
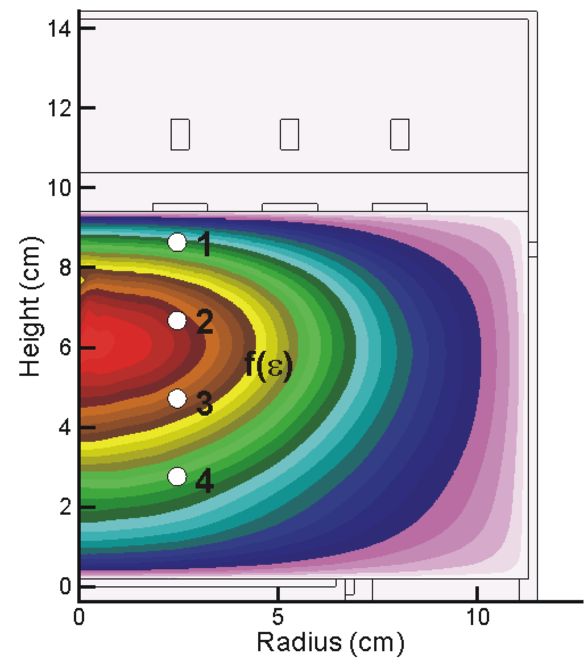
TAILORING *f(ε)* BY FREQUENCY





- **Plasma tools for multiple processes or recipes (different chemistries) require control of electron energy distribution for optimum generation of precursors.**



- **[e], ICP, 10 mTorr, Ar/Cl_2 = 70/30.**

Model results from HPEM
Ref: K. Seaward, S. Samakawa

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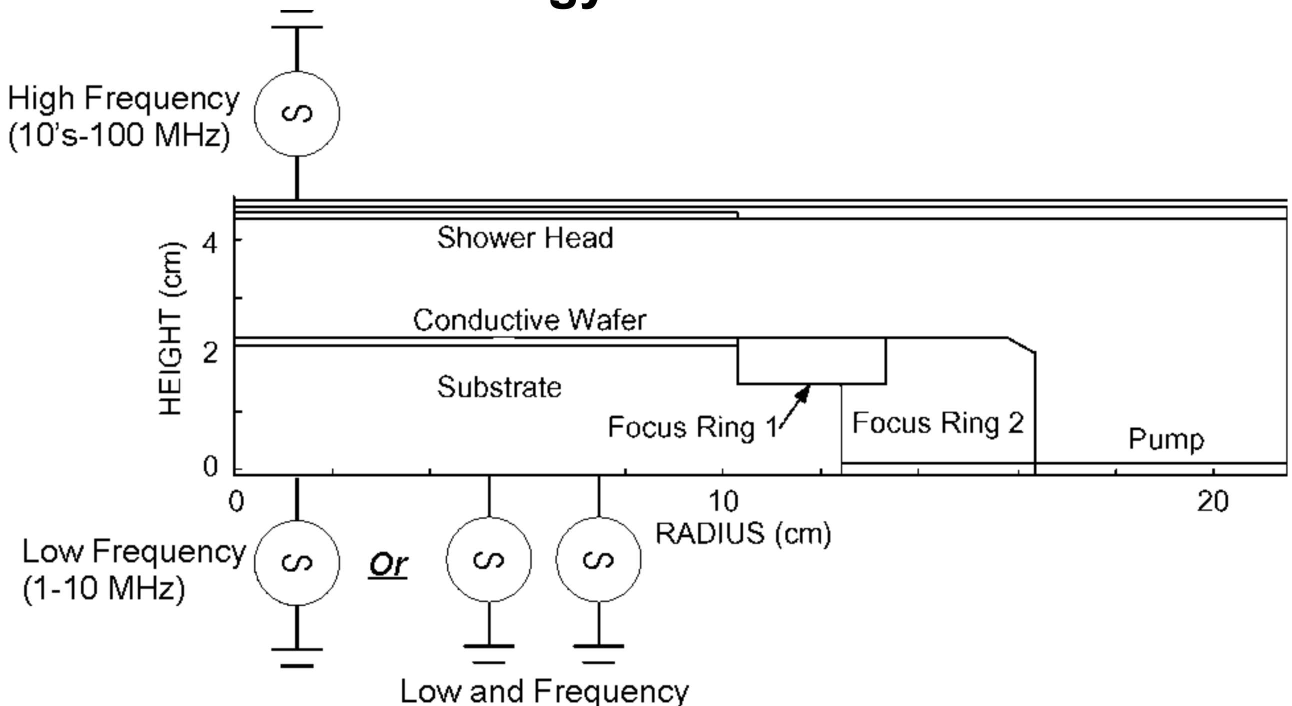
TAILORING FLUXES USING MULTIPLE FREQUENCIES

- **2 Frequency RIEs are rapidly becoming the tool of choice for dielectric etch.**
  - **High frequency is more efficient for heating electrons and so controls ionization and the magnitude of ion flux**
  - **Low frequency produces little electron heating but controls ion energy incident on the wafer.**



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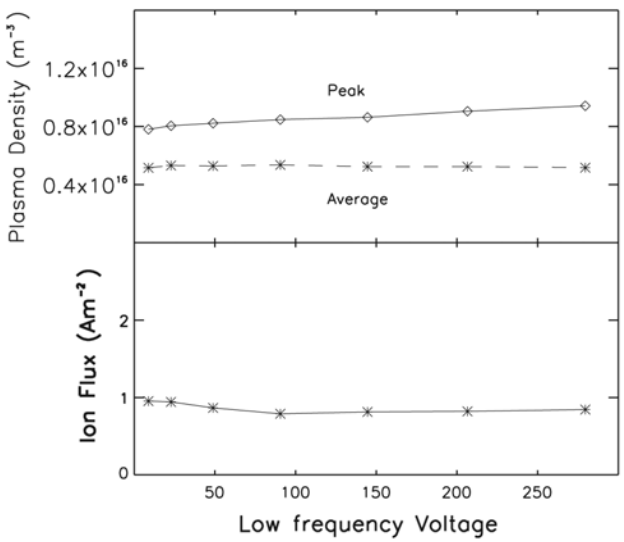
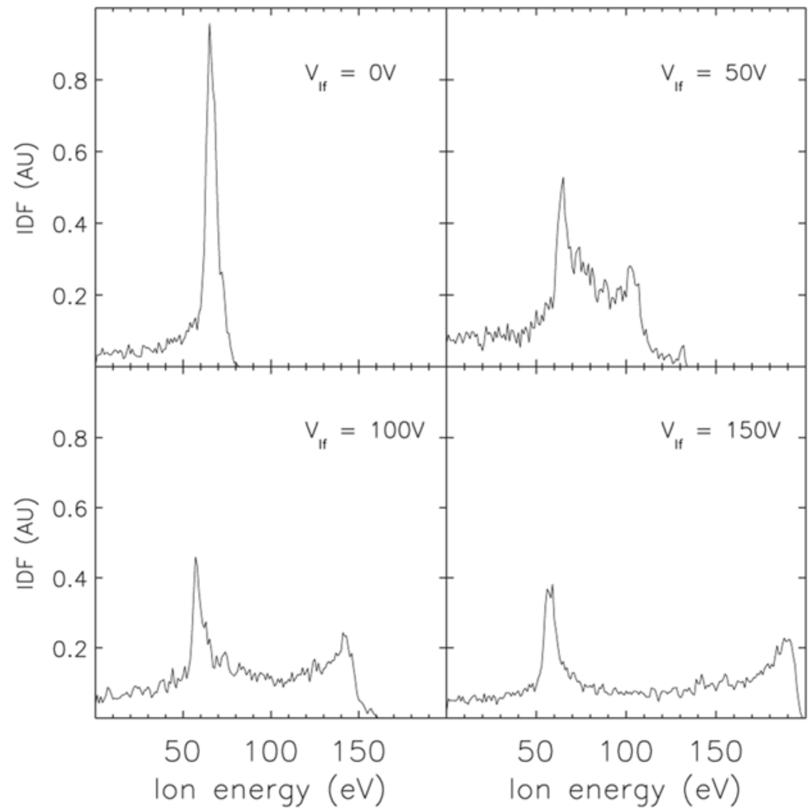
TAILORING FLUXES USING MULTIPLE FREQUENCIES

- Over a wide parameter space, ion fluxes can be controlled by high frequency power; ion energy distribution controlled by low frequency.

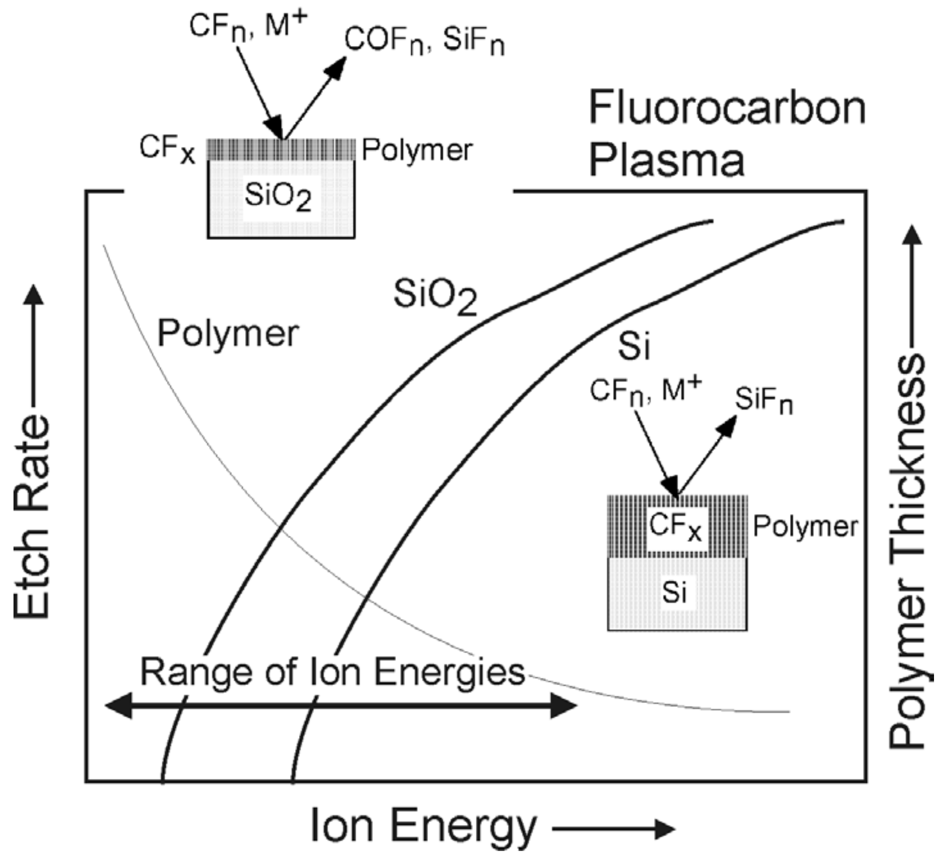


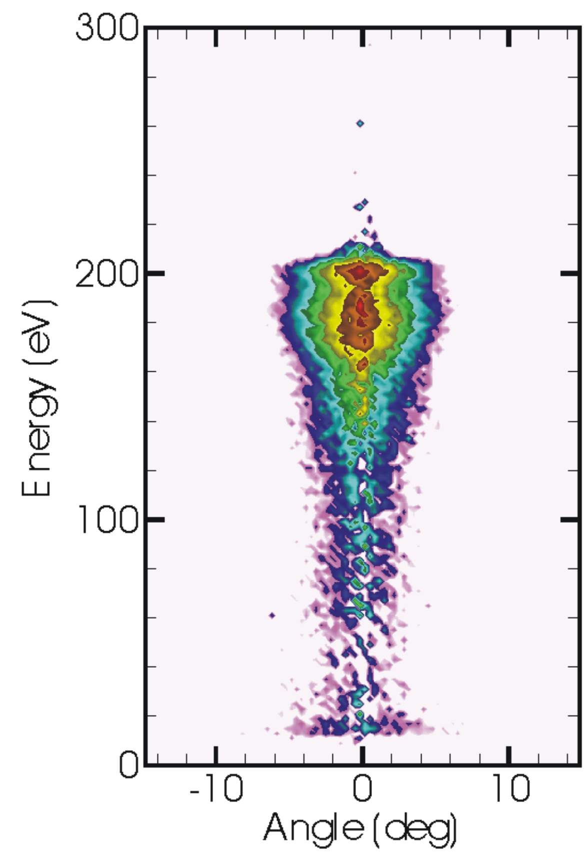
- Plasma density, Ion flux



- Argon, 10 m Torr
- Ion Energy Distributions
- Boyle, Ellingboe, Turner, PSST 13, 493 (2004)

DIFFICULT TO ACHIEVE SELECTIVITY: BROAD IEADS





- **Broad ion energy distributions makes it difficult to resolve thresholds for etching; and so selectivity is poor.**

- **Ar, 40 mTorr, 300 sccm, 500 W 40 MHz (top), 500 W 5 MHz (bottom), 100 G**

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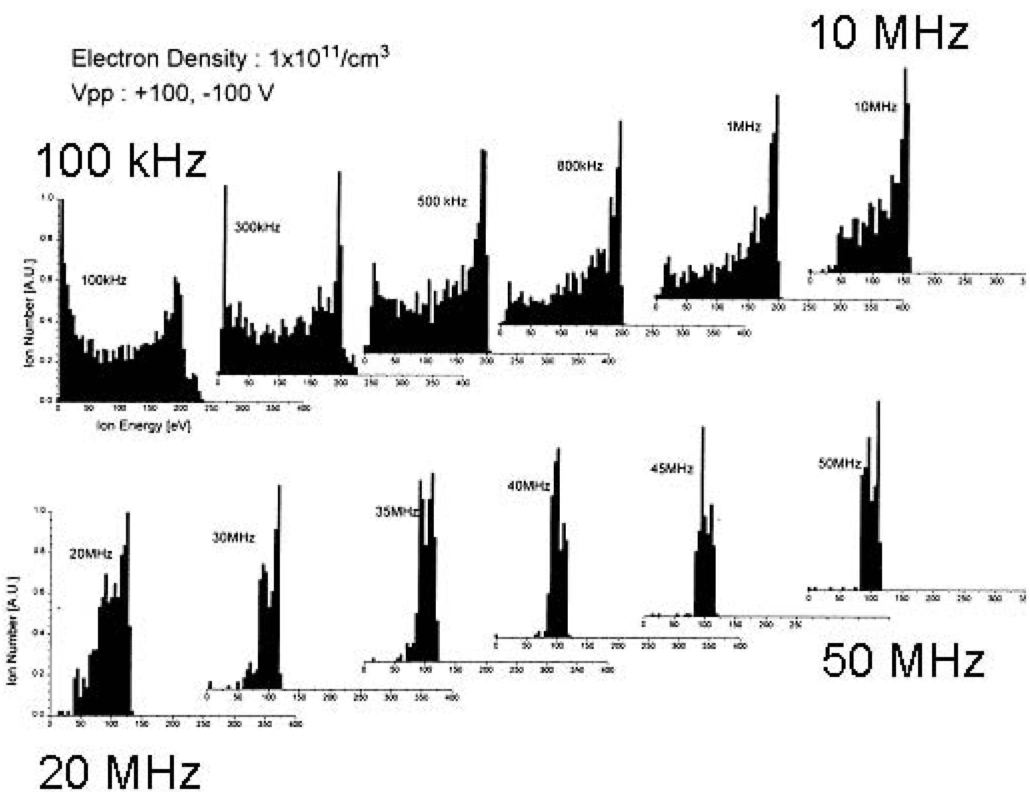
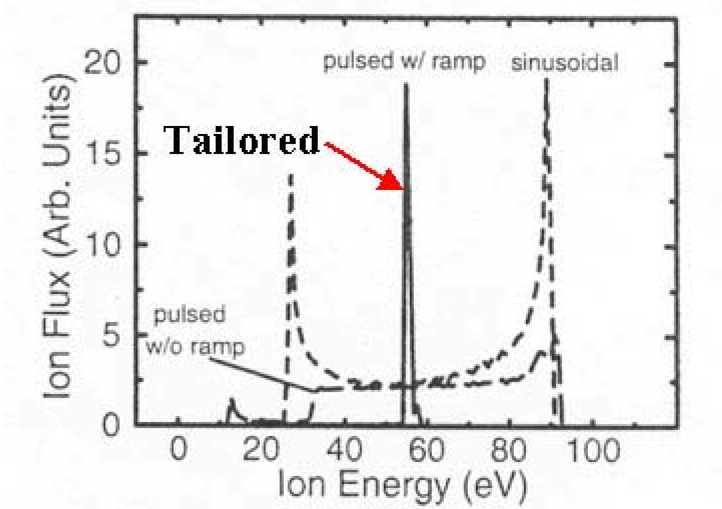
Ion Energy Control – Tailored Waveform through Frequency and Active Electronics



• From from Hyun-Ho Doh, et al, JVST A 15 664 (1997).

Tailored bias waveform: Single peak, FWHM 2 eV



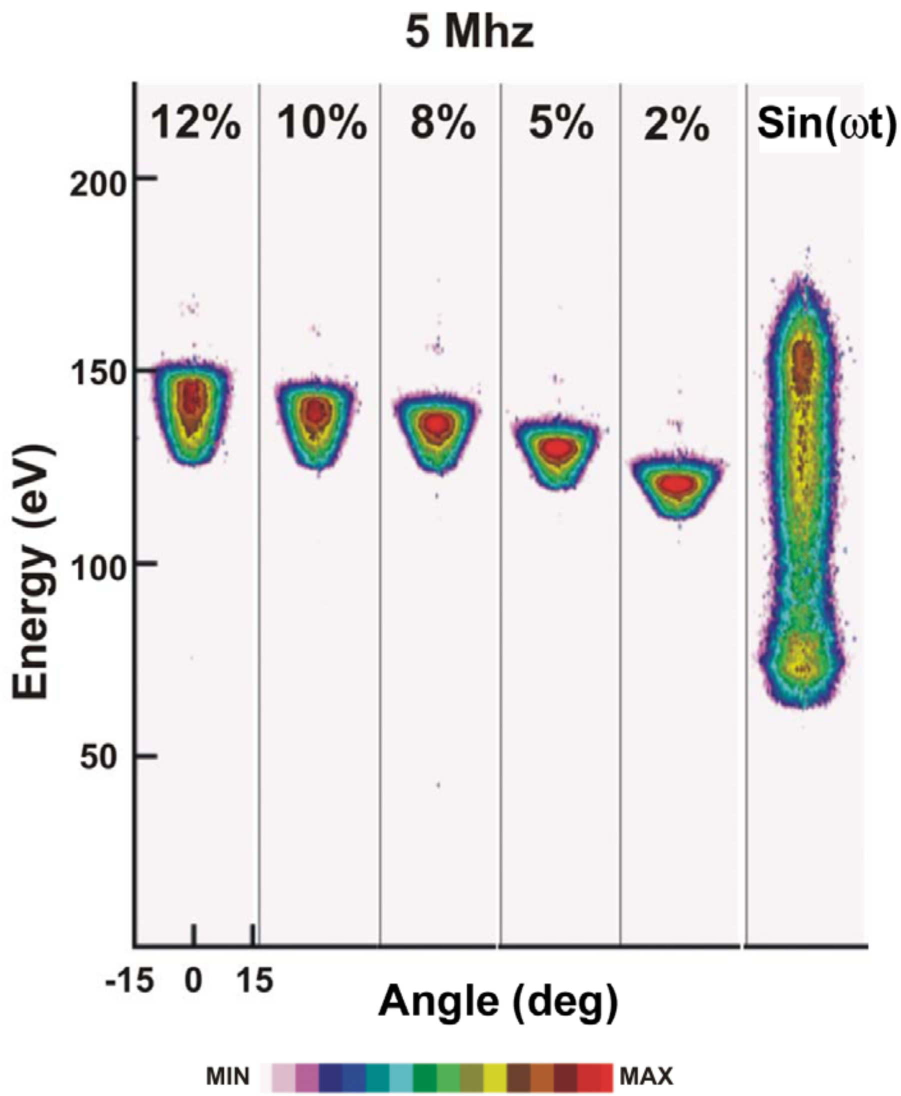
• From S.-B. Wang and A.E. Wendt, JAP 88 643 (2000)

Ref: K. Seaward

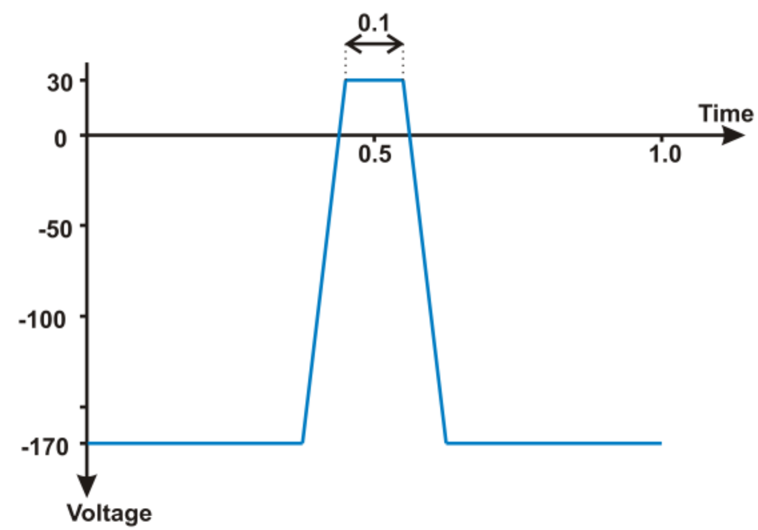
Agilent Technologies

ERL

NARROW IEDS: CUSTOMIZED BIAS WAVEFORM



- Non-sinusoidal biases enable control of sheath potential, and narrowing of the IED.



- 15 mTorr, 500 W, 200 V_{p-p}, Ar/C_4F_8 = 75/25, 100 sccm

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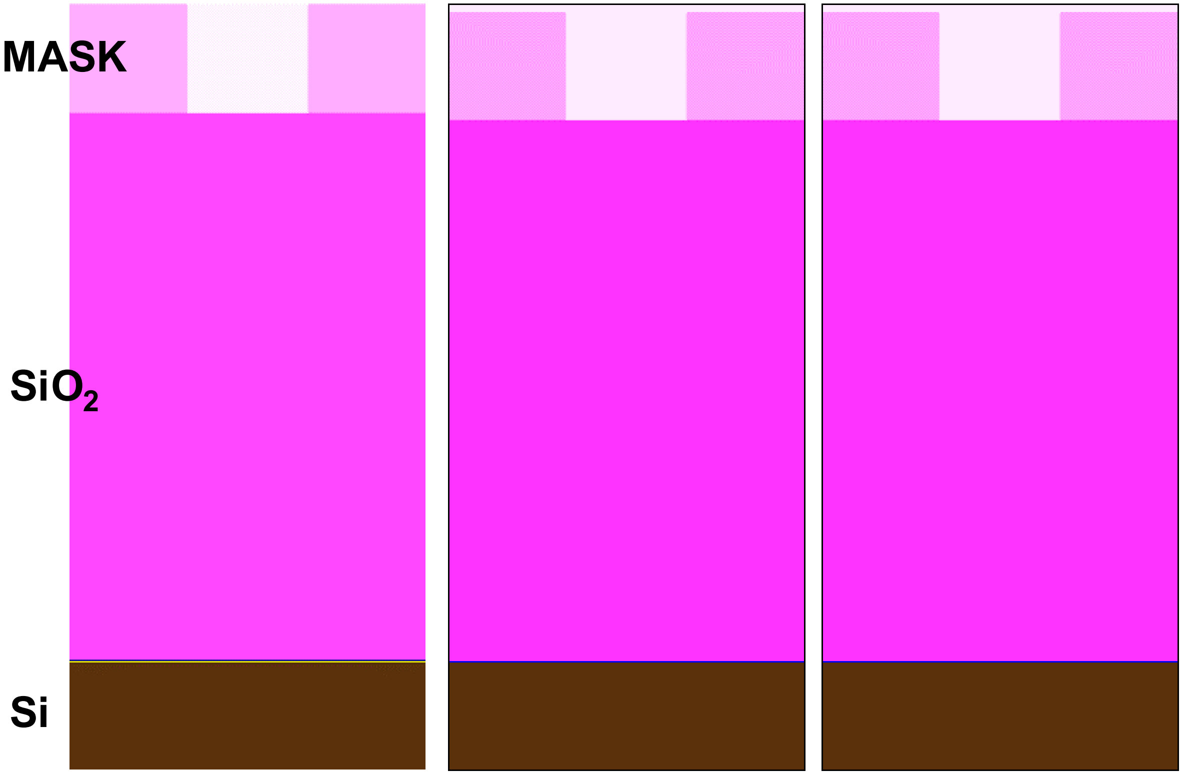
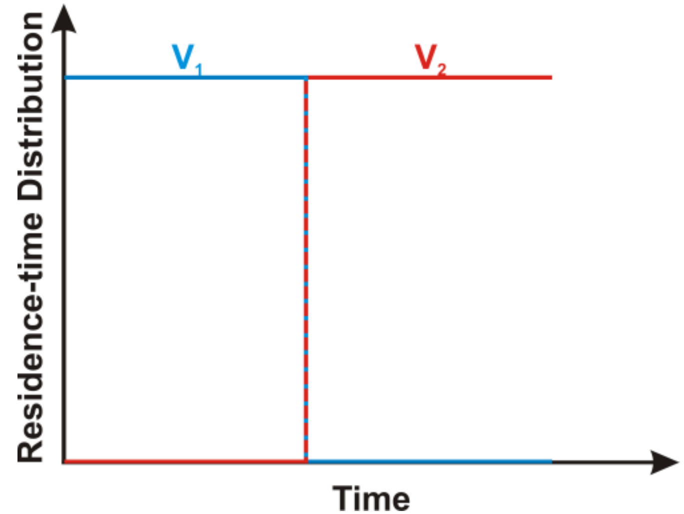
SPEED AND SELECTIVITY: CUSTOM WAVEFORMS



200 V (Slow, selective) **1500 V** (Fast, non-selective) **1500/200 V** (Fast, selective)



- 15 mTorr, Ar/C_4F_8 = 75/25, 100 sccm, 10 MHz/10%

- Recipies combining custom waveforms and dynamically adjusted biases optimize speed and selectivity.

ANIMATION SLIDE
CLICK ON FIGURES-AVI FILES IN SAME DIRECTORY
See icpp_animate.ppt

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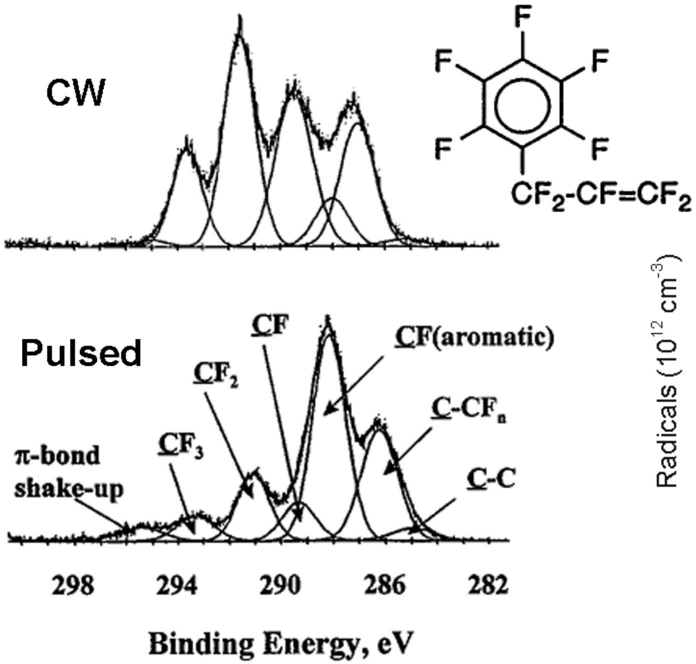
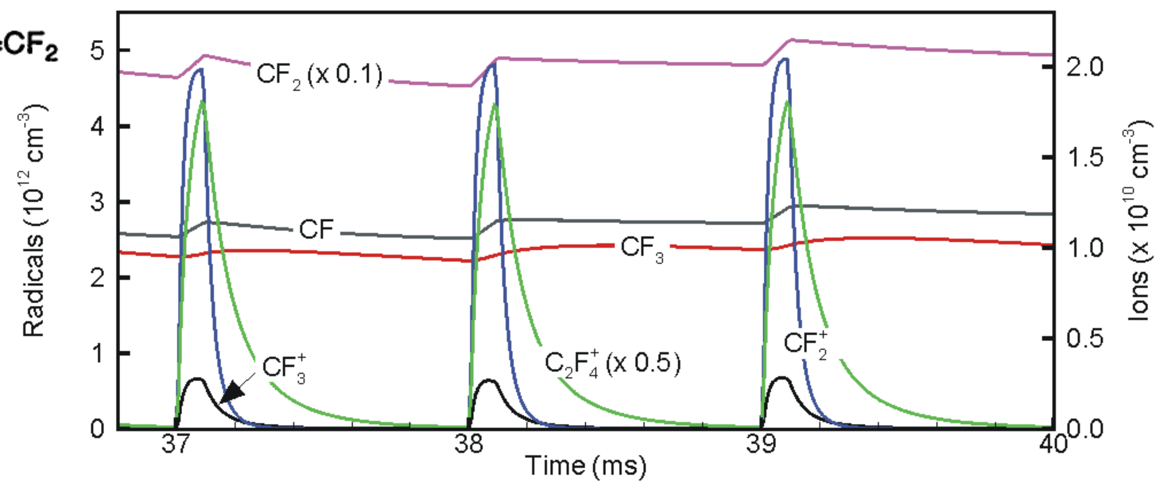
TAILORING *FLUXES* THROUGH PULSING

- **Processing of thin films depends on the synergy between energetic ions and radical fluxes. Pulsed plasmas which control these contributions produce unique films not otherwise attainable.**





- **Deposition of low-k fluorocarbon film from perfluoroallyl benzene** [L. Han, JVSTB 18, 799 (2000)]
- **Pulsed ICP Ar/C_4F_8=70/30, 15 mTorr**
- **Model results from GLOBAL_KIN Ref: K. Seaward**

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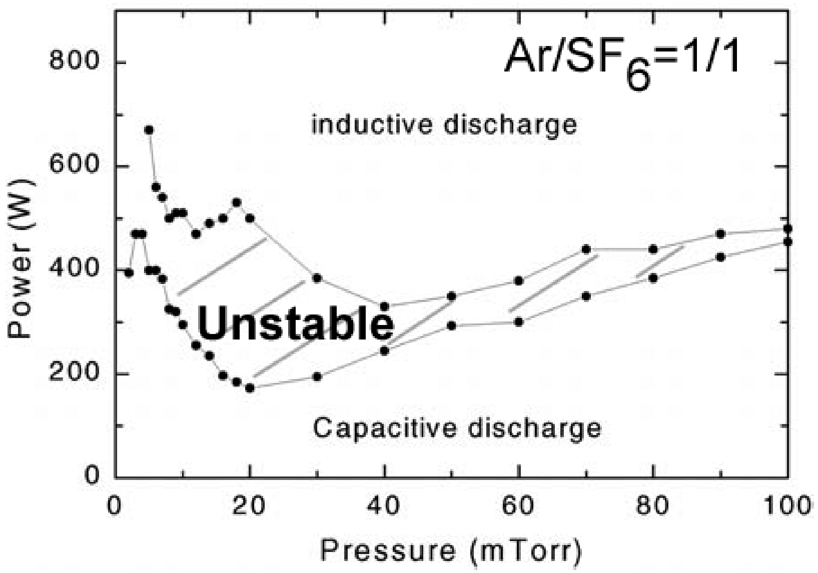
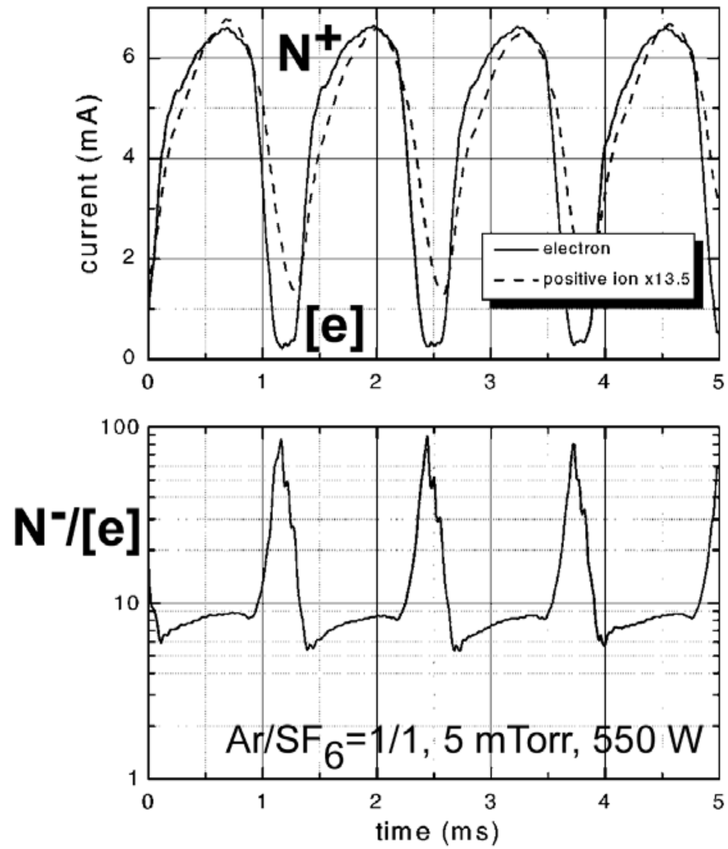
INSTABILITIES: ELECTRONEGATIVE PLASMAS

- **Although rf (10's MHz) excited plasmas operate in a quasi-dc basis, instabilities regularly occur. Most plasma processing tools likely have instabilities which make reproducibility difficult.**





- **Ionization instability in inductively coupled Ar/SF$_6$ plasma for etching.**

- **Chabert, Lichtenberg, Lieberman, Marakhtanov PSST 10, 478 (2001)**

PLASMA DIAGNOSTICS HAVE PLAYED A CRITICAL ROLE AND ARE MOVING CLOSER TO THE PRODUCT

- **Plasma process and equipment design have and will continue to critically rely on advanced plasma diagnostics.**

- **Real time control strategies, a requirement for sub-90 nm processing, must also rely on robust, cost-effective diagnostics.**

- **The most mature plasma diagnostics are typically too far removed from critical measurements of activation of surface processes.**

- **Non-intrusive diagnostics which provide the state of activating species impinging on surfaces are required for a complete picture.**

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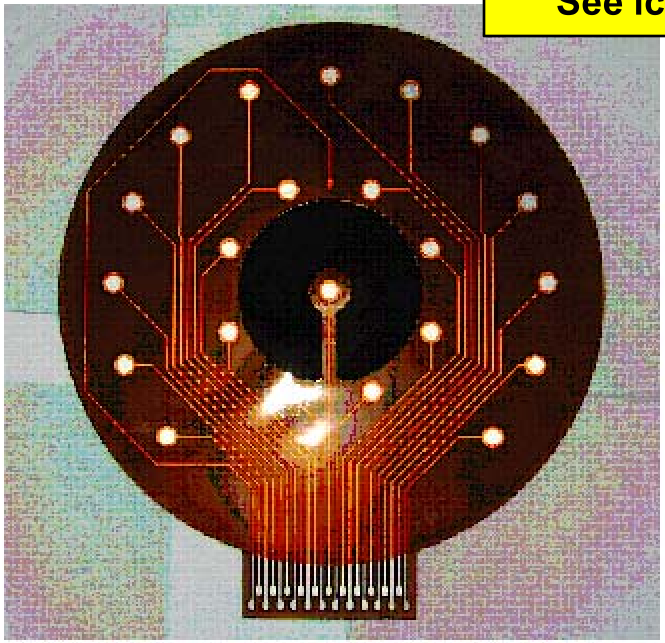
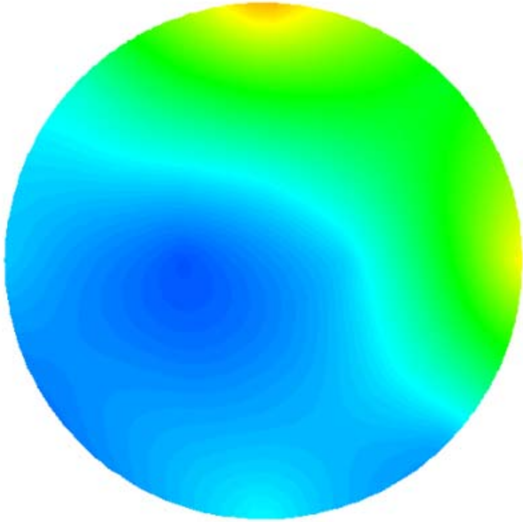
On-Wafer Ion Flux Probe Array

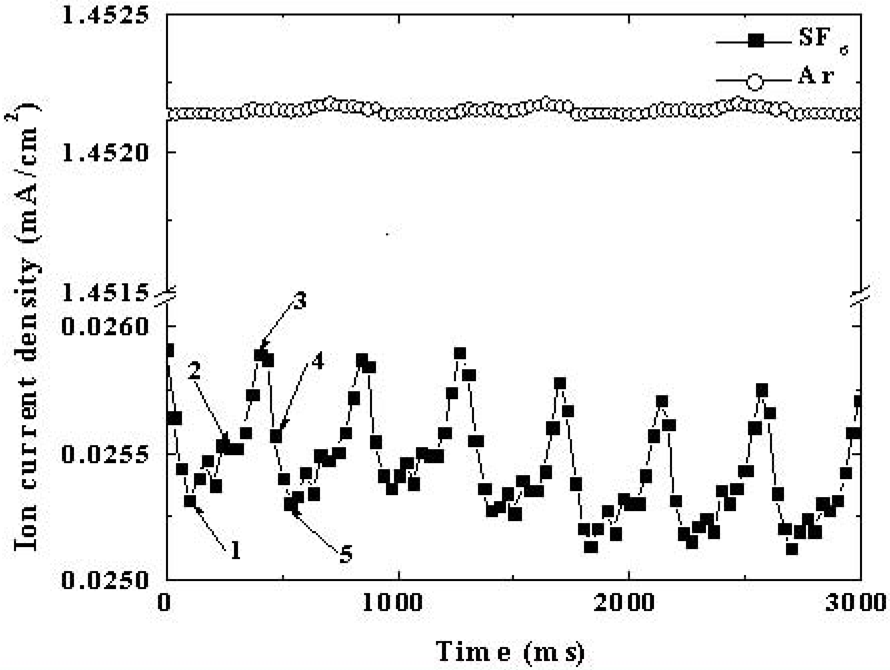
- An on-wafer probe array providing $J_+(r,\theta)$ is used to investigate factors that affect the plasma stability and etching uniformity using plasma etching chemistries.



ANIMATION SLIDE
See icpp_animate.ppt



80 mTorr SF_6, 200 W

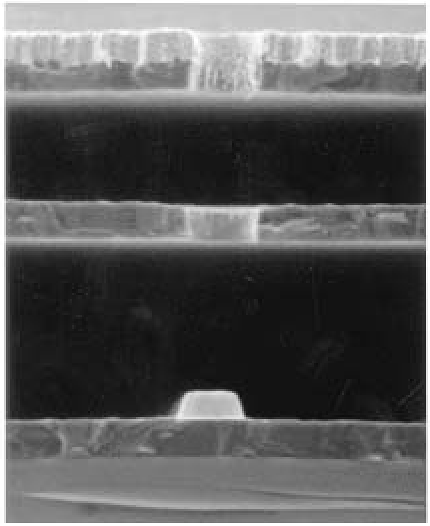


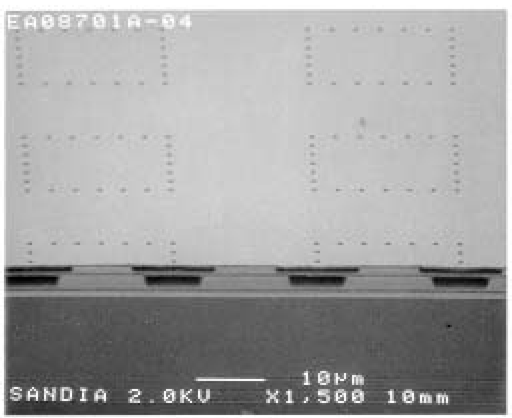
Ref: E. Aydil

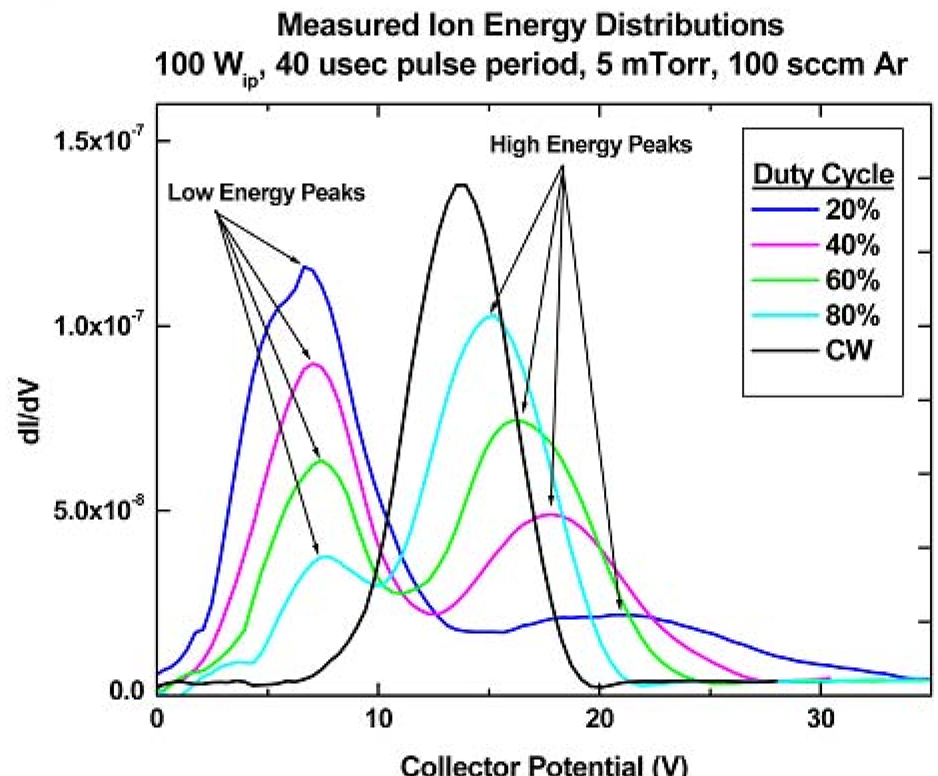
Kim *et al., Rev. Sci. Instrum. 73, 3494 (2002)*

Sub-micron Retarding Field Energy Analyzer on a Si Substrate

- MEMS fabricated analyzers (0.7~0.8 µm grid holes on 3.75 µm centers) provide inobstrusive measurements of ion energy distributions directly on surfaces of interest.





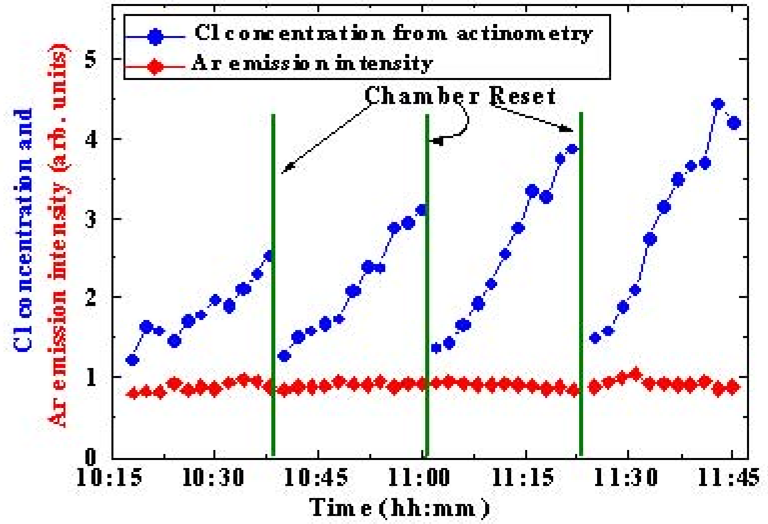


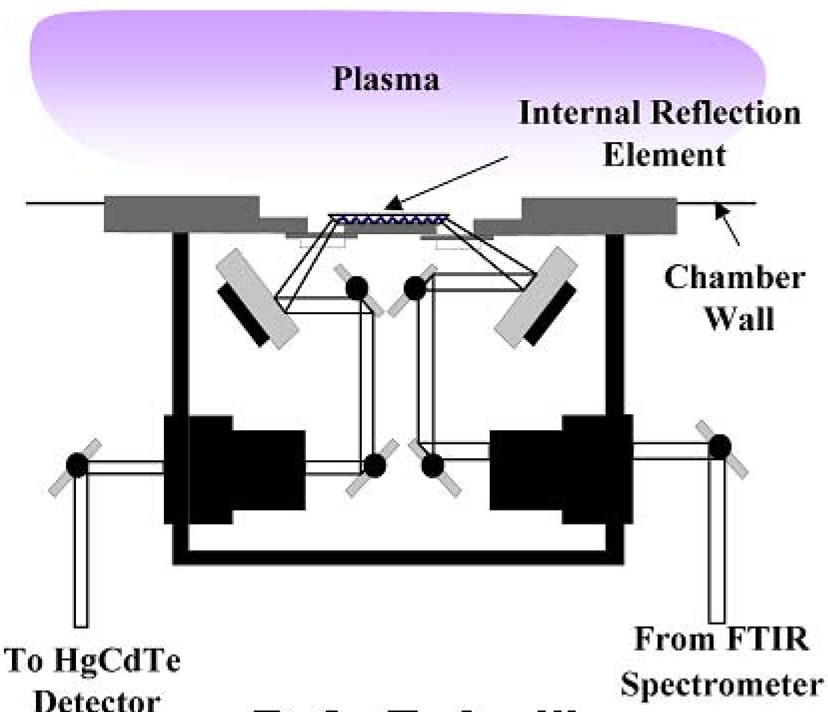
Ref: M. Blain

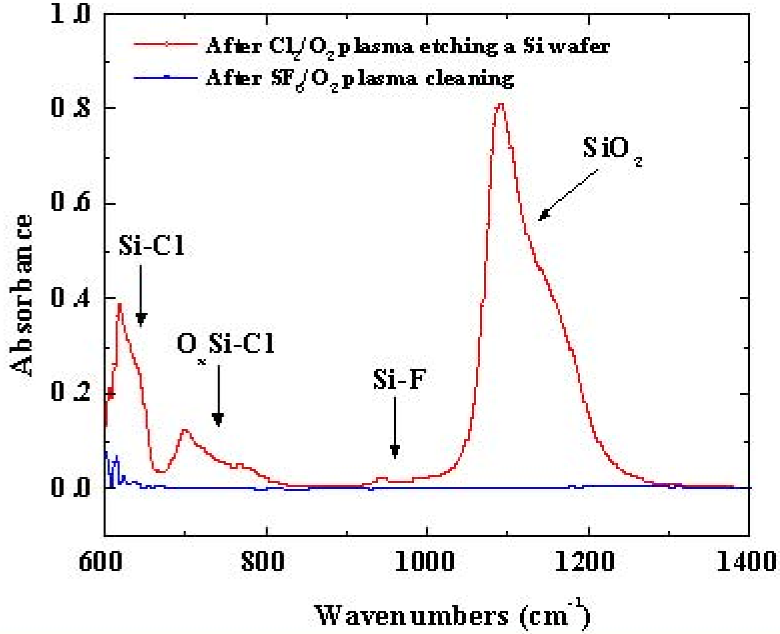
Sandia National Laboratories

MTIR-FTIR Wall Probe

- Drift in Cl results from change in the Cl recombination on the walls due to deposition of Si-O-Cl products.
- Exposure to SF_6/O_2 plasma resets the walls to a reproducible condition.







Ref: E. Aydil

Lam RESEARCH

Cl_2 10 mTorr, 800 W, 100 sccm

UCSB

MATERIALS PROCESSING: CHALLENGES

- New materials (metal gates, low-k dielectrics, high-k dielectrics, SiGe/SOI substrates, porous materials).
- Increasing demands on etch selectivity.
- Shorter development cycle (6 months…)
- Lower thermal budgets (lower temperature processes)
- More controllable knobs to provide reliable real time control.
- Use of plasmas as processing tools (e.g., self assembly) as opposed to pattern replication.
- Reduced cost of ownership through plasma tools which are used for multiple processes.
- Improved and more relevant contributions from modeling.

- Ref: J. Cook, T. Mantei, P. Schenborn, P. Ventzek, D. Manos

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PLASMAS FOR LIGHTING

IMPACT OF PLASMA LIGHTING TECHNOLOGIES

- Annual US energy use for lighting is 750 TWH (8.2 quads)
    - 8.3 % of total energy consumption
    - 22% of total electrical energy consumption.
- Plasmas are 59% of lighting energy use (13% of total). There are 2.6 billion plasma lighting sources in the US.
- Replacing incandescent lamps with plasma sources will decrease US electrical energy use 5% [20 nuclear power plants or 1.2 Million barrels of oil/day (10% of imports)].
- Greenhouse gas emission commensurately reduced.
- Improving efficiencies and use of plasma lighting will enormously impact the worldwide economy and improve the environment.

- Ref: U.S. Lighting Market Characterization, Navigant Consulting, 2002
- DOE Annual Energy Outlook 2003

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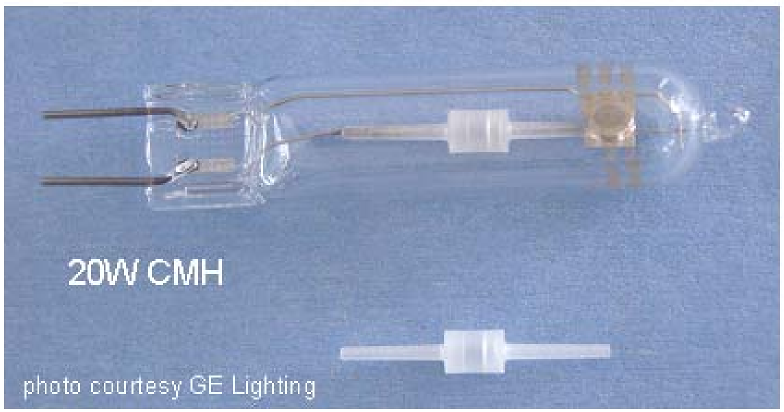
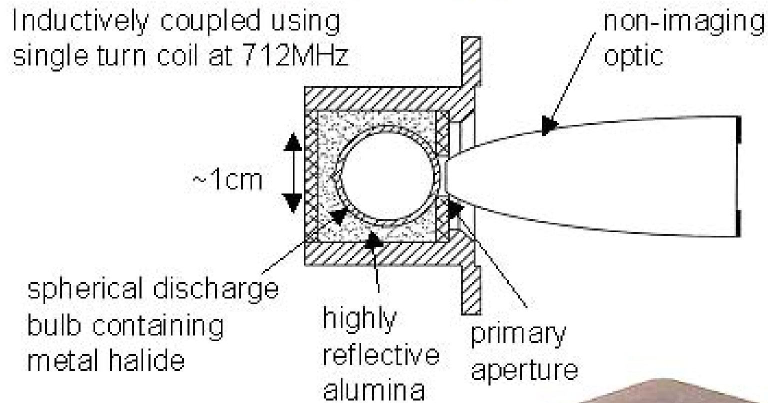
HID lamps for illumination and Projection

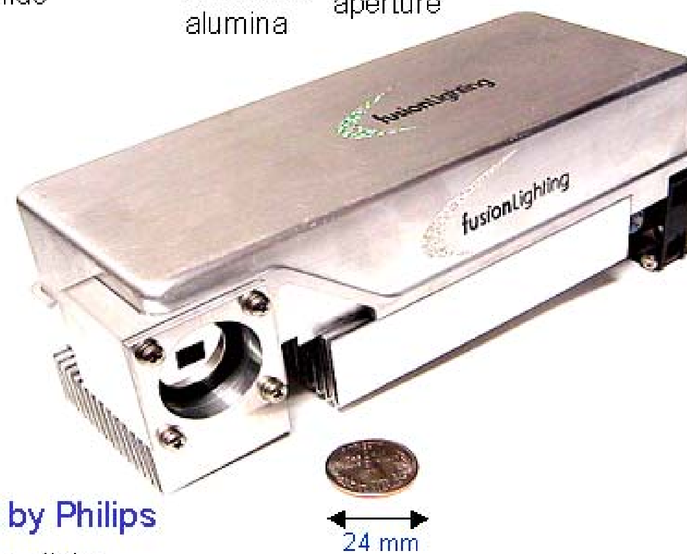
CMH white-light metal halide

- precision arc tube made from alumina
- Na, Tl and rare earth iodides + Hg
- high efficacy and good colour result from high vapour pressures
- designed to be operated from electronic control gear



Fusion Lighting LCD projector unit





HID projection lamps pioneered by Philips

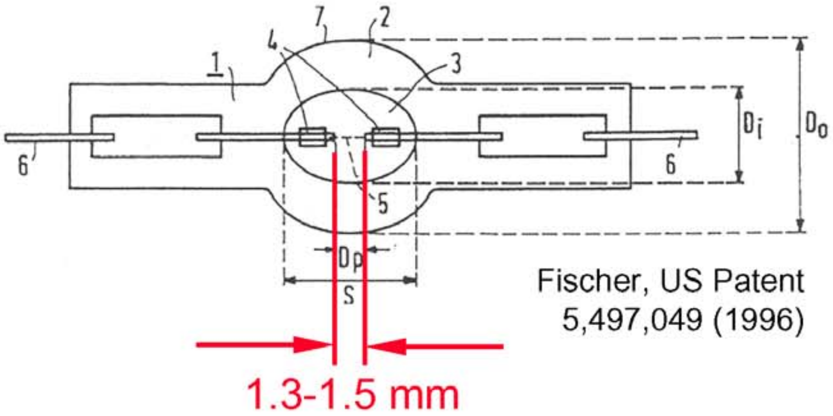
Short arc mercury (~200 bar) arc tube – light produced by atomic lines and molecular bands.

Materials advances – System Design - Models

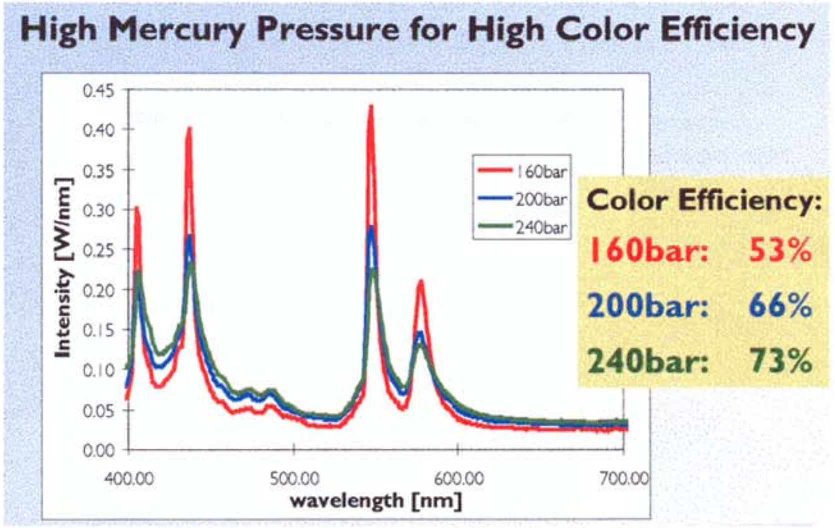
Ref: David Wharmby

Quartz lamps
State of the art

- ***Ultra-high-pressure mercury***
  - –quartz arctube
  - –mercury + bromine dose
  - –200–240 bar operating pressure
  - –1.3–1.5 mm arcgap
  - –8500 K color temperature
  - –excellent lumen maintenance
  - –minimal color separation and color shift over life
  - –1000–2000 hour life
  - –100–150 watts (6000–10000 lumens)
- ***Limitations and shortcomings***
  - –spectrum is deficient in red
    - *color efficiency ~70 percent*
  - –cannot scale up wattage
    - *without shortening life*
  - –cannot scale down arcgap
    - *without reducing efficacy*



Fischer, US Patent 5,497,049 (1996)

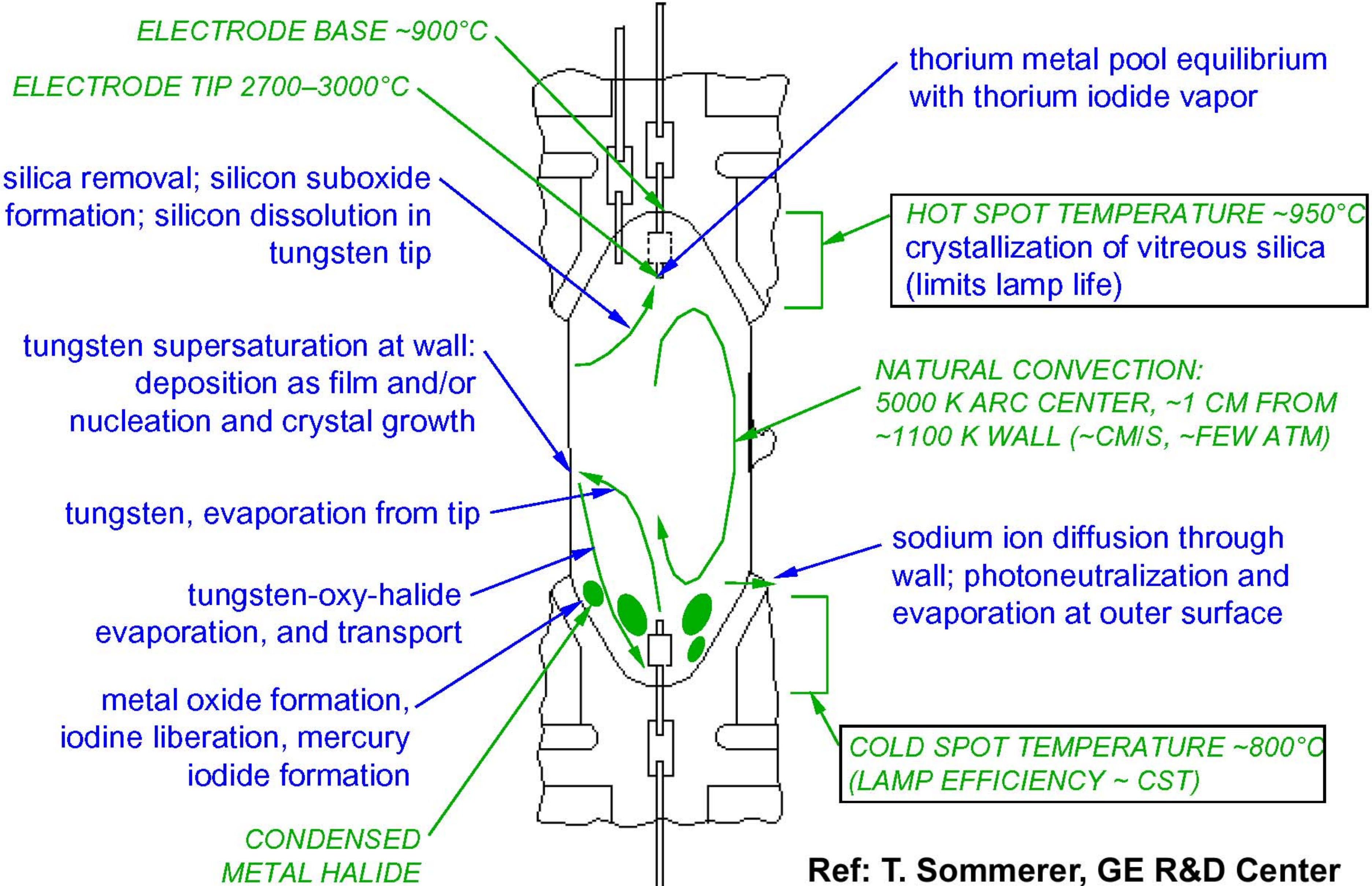


Mönch, Fischer, and Derra

Ref: T. Sommerer, GE R&D Center

Material transport processes

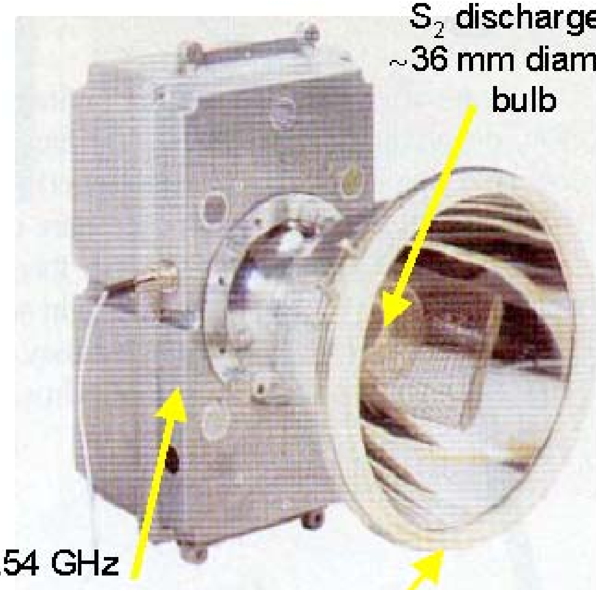
Quartz metal halide lamp



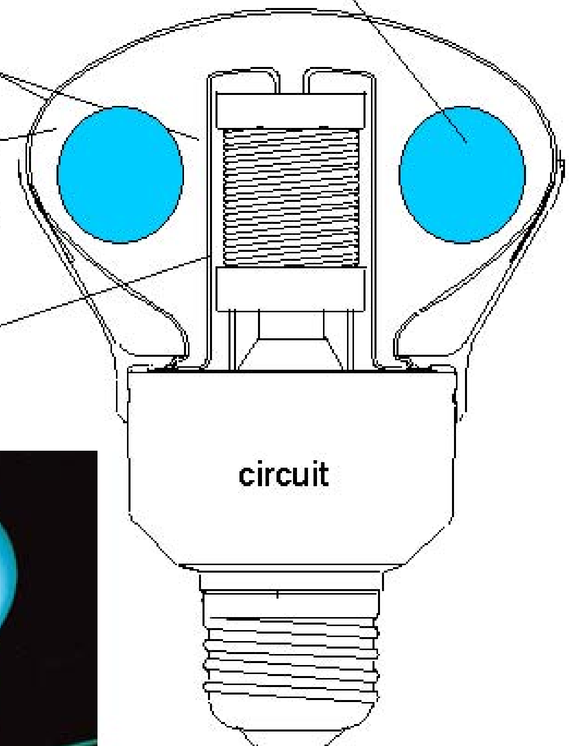
Ref: T. Sommerer, GE R&D Center

Electrodeless – μwave and RF sources

- Sulphur discharge – Fusion Lighting record 170 lumen/microwave W



- Inductively coupled Rg/Hg lamps



System design

Ref: David Wharmby

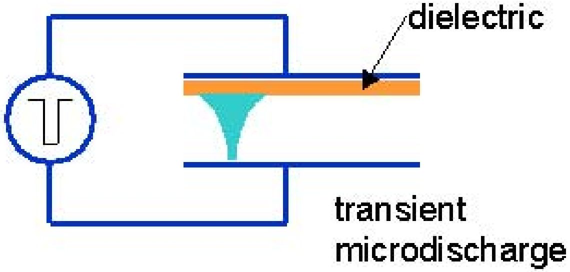
LIGHTING: ACCOMPLISHMENTS AND CHALLENGES

- Efficient white sources based on Hg plasmas in fluorescent and arc lamps; and non-white metal vapor lamps.
- Challenges:
  - Highly efficient non-Hg (or Cd, Pb,…) plasma white-light sources or near UV which match phosphors (rare gases, excimers, metal halides, molecular radiators)
  - Thermodynamics of high pressure plasmas.
  - Improving understanding of plasma-surface interactions to extend lifetimes (cathodes); and glow-to-arc transition.
  - Quantum splitting phosphors to improve utilization of UV (2 visible photons from 1 UV reduces US energy use 5-10%).
  - Leverage lighting technologies to other application (e.g., UV sources for water treatment, and vice-versa.
  - Radiation driven non-LTE effects in high pressure lamps.

Dielectric barrier discharge (DBD)

- Osram Planon lamp
- Xe discharge with UV radiation from Xe_2^* excimer
- 60% efficiency to UV – then converted to visible with phosphor

Schematic diagram

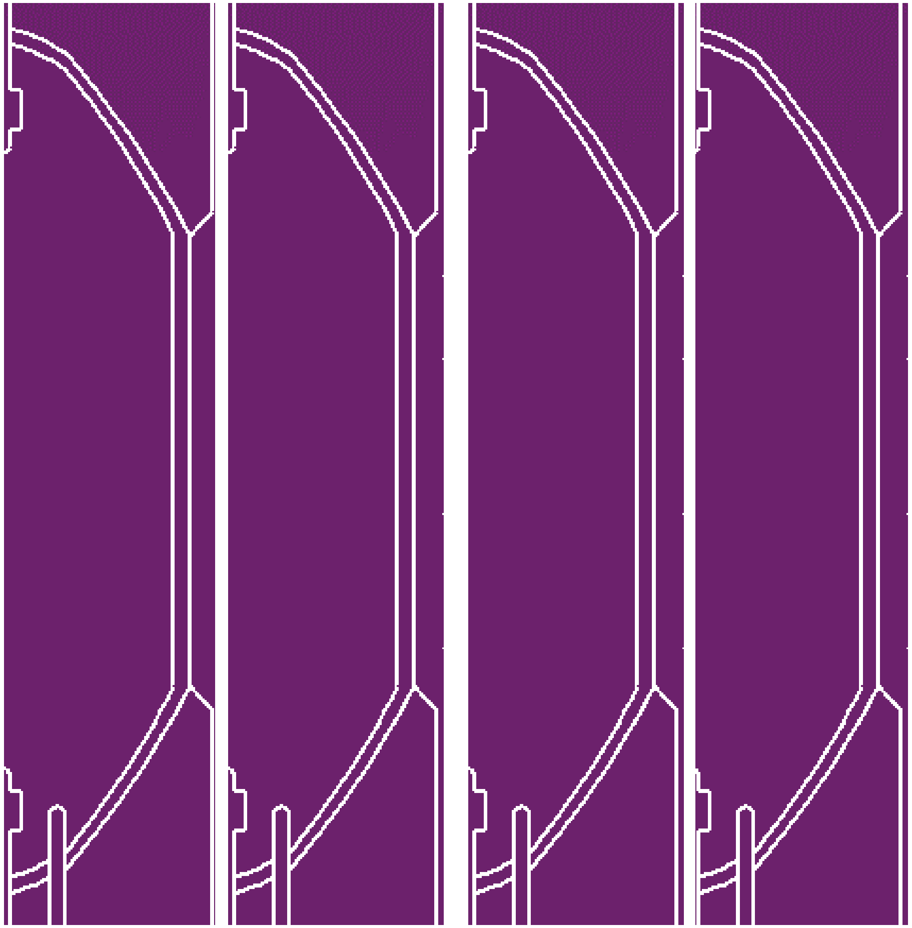


- Osram innovations in electrode structure and pulse power format for uniformity.

Ref: David Wharmby
U. Kogelshatz

MODELING ADVANCES ADDRESS TECHNOLOGY DEVELOPMENT

GE R400



100/ 0.001	99.9/0.1	97/3	7/3
Ambient	50 C	140 C	220C

Ar (75 Torr cold fill) / Hg

5×10^8 - 5×10^{11} cm^{-3}
0-450 ns

- The pressure of (hot) HIDs is many atm.
- After turn off, the tube must cool to reduce the metal density (increase E/N) so that the available voltage can re-ignite the lamp.
- Lamp designs are often driven by startup considerations.
- Electron density

ANIMATION SLIDE
CLICK FIGURES-AVI FILES IN SAME DIRECTORY
See icpp_animate.ppt

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ATMOSPHERIC PRESSURE PLASMAS

ATMOSPHERIC PRESSURE PLASMAS

- **Atmospheric Pressure Plasmas (APP) have had tremendous technological impact**
  - **High power lasers (e.g., Excimer lasers)**
  - **Lighting Sources (e.g., HID lamps)**
  - **Ozone generators**
  - **Modification of surfaces**
  - **Toxic gas abatement**

- **Atmospheric pressure DBD ozone generator**

Ref: U. Kogelshatz

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Optical and Discharge Physics

OPPORTUNITIES: ATMOSPHERIC PRESSURE PLASMAS THE CHALLENGE

- APP's provide the potential to selectively generate activated species (radicals, ions and photons) for modification and cleaning of surfaces at low cost.
- Most (many) industrial processes performed with liquid solvents could in principle be performed with APP generated radicals.
- The environmental impact of eliminating liquid solvents for cleaning of parts, removal of paint, functionalizing or sterilizing surfaces would be immense.
- Advanced concepts include improvement of combustion processes, chemical and biological remediation, sterilization, microplasma devices, control of aeronautical flows.
- The potential for APPs to perform "high value" manufacturing is literally untapped.

Ref: B. Ganguly

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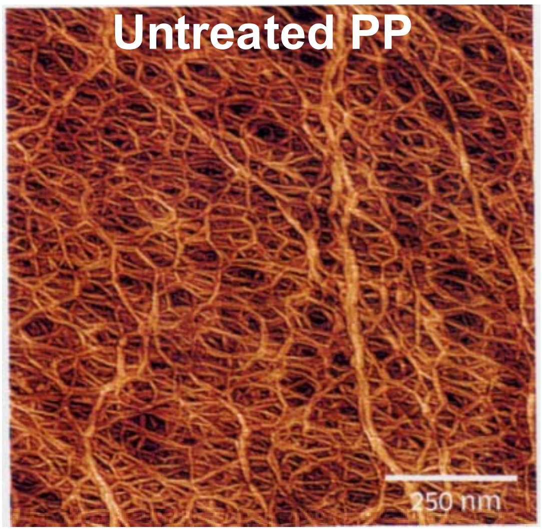
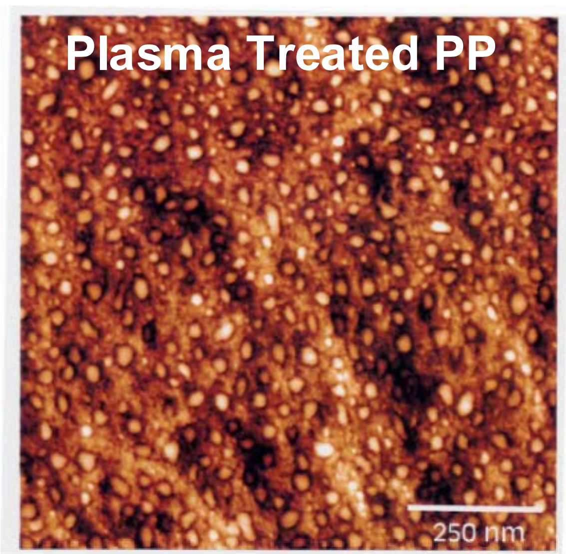
ATMOSPHERIC PRESSURE PLASMAS FOR MATERIAL AND SURFACE PROCESSING: COMMODITY TO HIGH VALUE

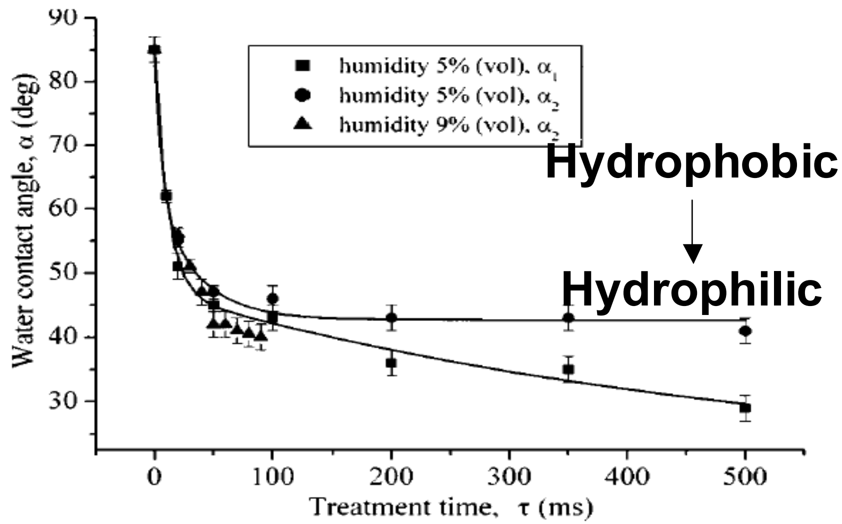
PLASMA SURFACE MODIFICATION OF POLYMERS





- M. Strobel, 3M

- To improve wetting and adhesion of polymers atmospheric plasmas are used to generate gas-phase radicals to functionalize their surfaces.



- Polyethylene, Humid-air

- Akishev, Plasmas Polym. 7, 261 (2002).

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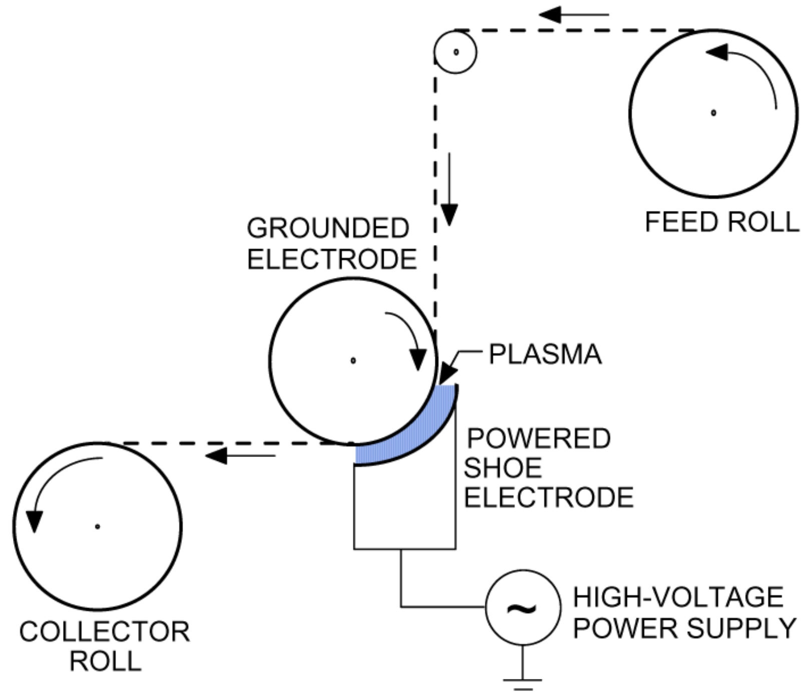
POLYMER TREATMENT PLASMA TOOL

- **Web based corona plasmas treated sheet polymers for improved surface functionality.**



- TYPICAL PROCESS CONDITIONS:

Web speed	: 10 - 200 m/min
Residence time	: a few s
Energy deposition	: 0.1 - 1.0 J cm^{-2}
Applied voltage	: 10-20 kV at a few 10s kHz
Gas gap	: a few mm

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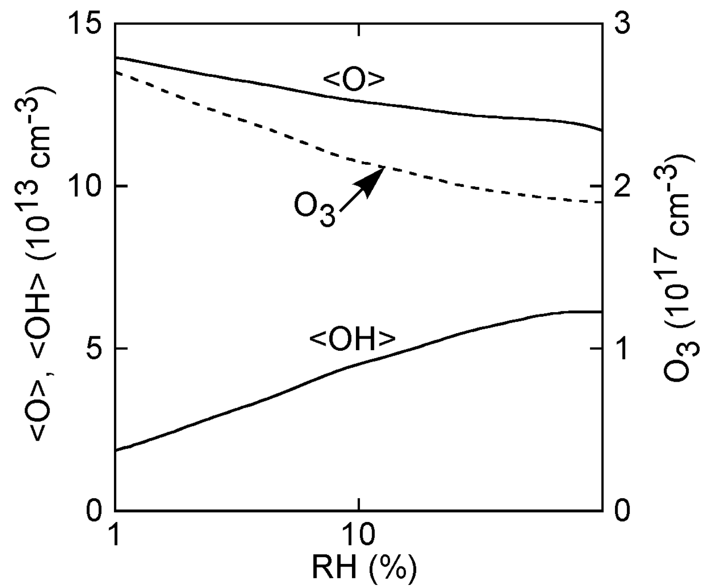
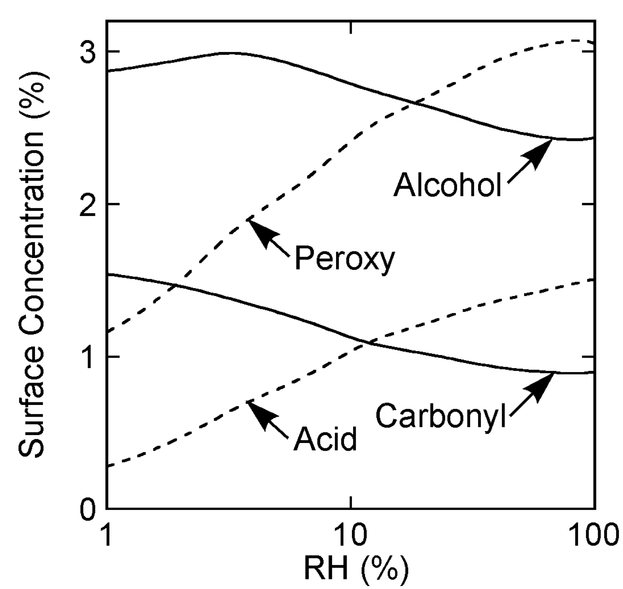
FUNCTIONALIZATION OF POLYPROPYLENE

- **Control of surface energy by plasma treatment results from functionalization with hydrophilic groups.**

    - **Carbonyl (-C=O)**
    - **Alcohols (C-OH)**
    - **Peroxy (-C-O-O)**
    - **Acids ((OH)C=O)**

- **Functionalization depends on radical fluxes and process parameters [gas mix, energy deposition, relative humidity (RH)].**





- **Air, corona plasma, 300 K, 1 atm**

THE ROLE OF PLASMAS IN BIOSCIENCE

- **Plasmas, to date, have played important but limited roles in bioscience.**
  - **Plasma sterilization**
  - **Plasma source ion implantation for hardening hip and knee replacements.**
  - **Modification of surfaces for biocompatibility (in vitro and in vivo)**
  - **Artificial skin**
- **The potential for use of "commodity" plasmas for biocompatibility is untapped.**

STERRAD® 200

ADVANCED STERILIZATION PRODUCTS®

a Johnson & Johnson company

Division of Ethicon, Inc.

- **Low pressure rf H_2O_2 plasma (www.sterrad.com)**

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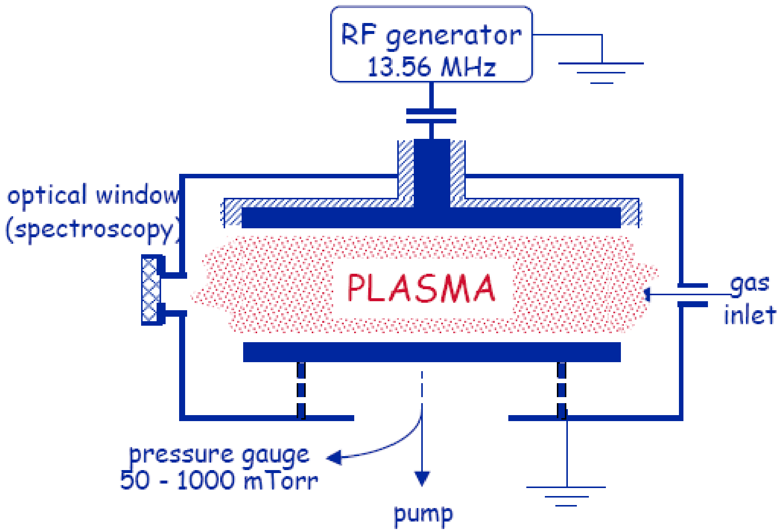
Plasma Processes for Cell Adhesion



INHIBITION

PEO-like coatings

PROMOTION

Grafted N-groups

-COOH functional coatings

pattern

MICROSTRUCTURED SURFACES

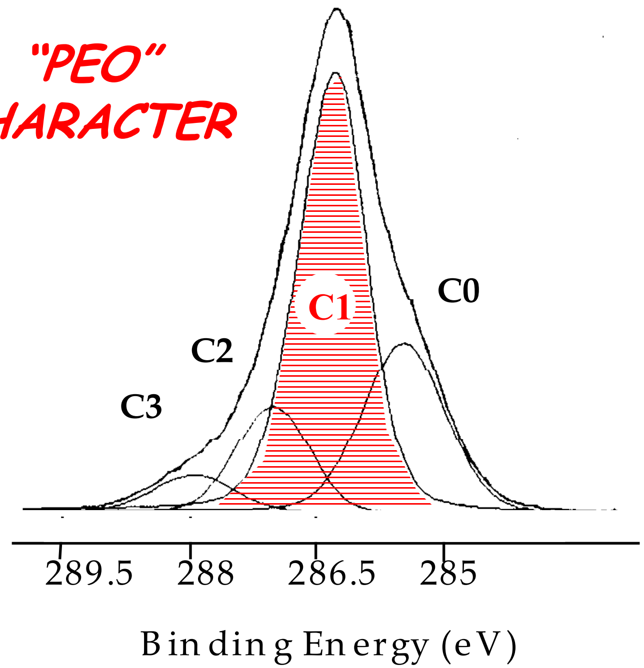
adhesive zones/ non fouling zones

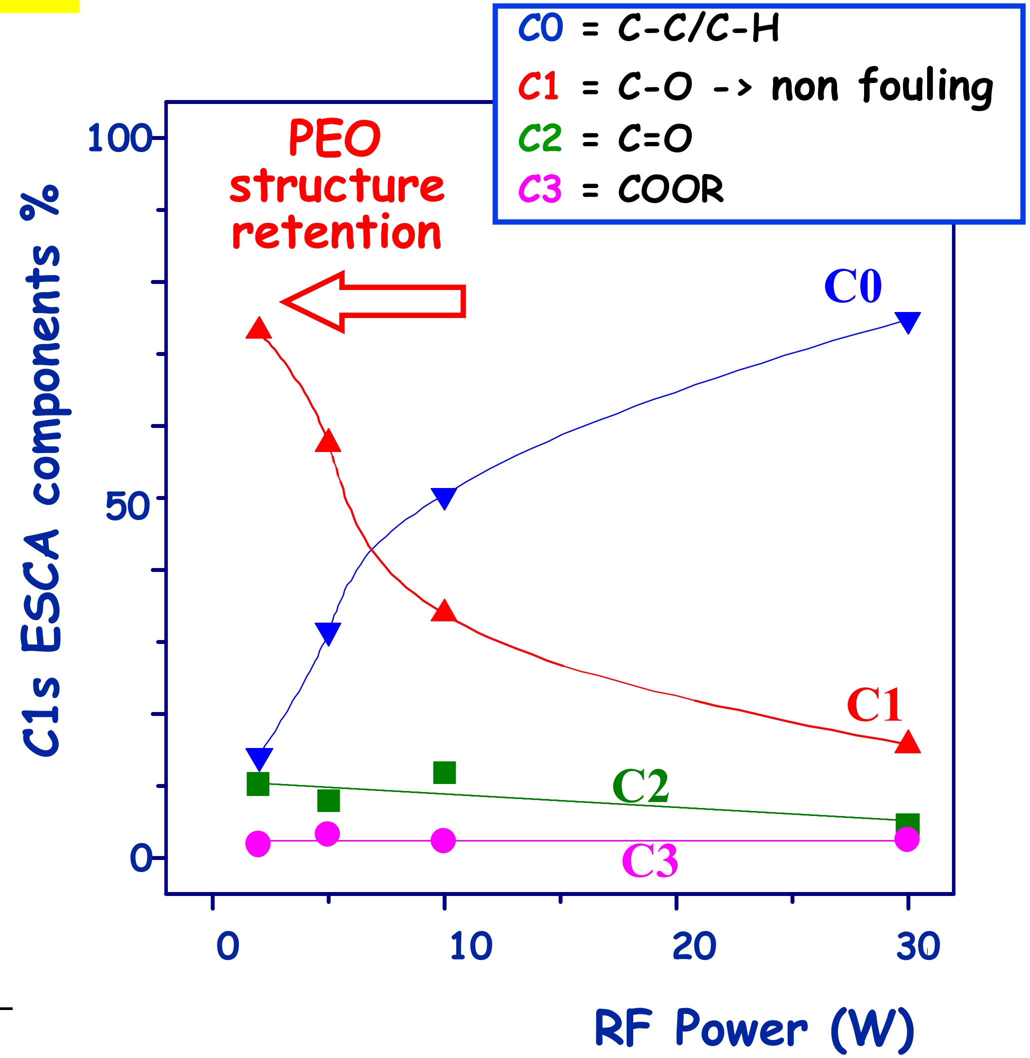
Ref: P. Favia

PE-CVD PEO-like COATINGS
XPS MEASUREMENTS

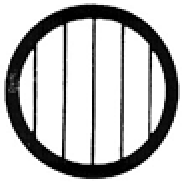
$CH_3O-(CH_2CH_2O)_3-CH_3$
TEGDME monomer

"PEO" CHARACTER





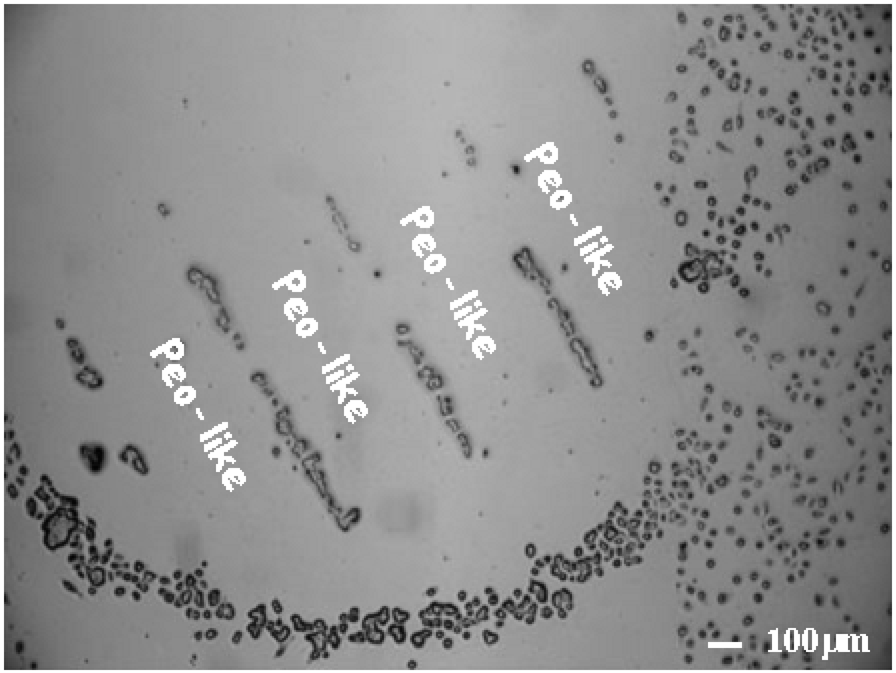
Ref: P. Favia

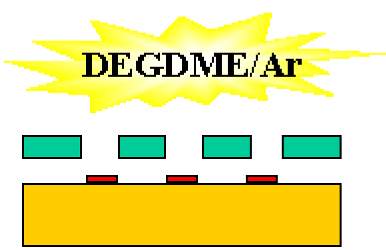


G50P
holes= 416μm
bar= 84μm

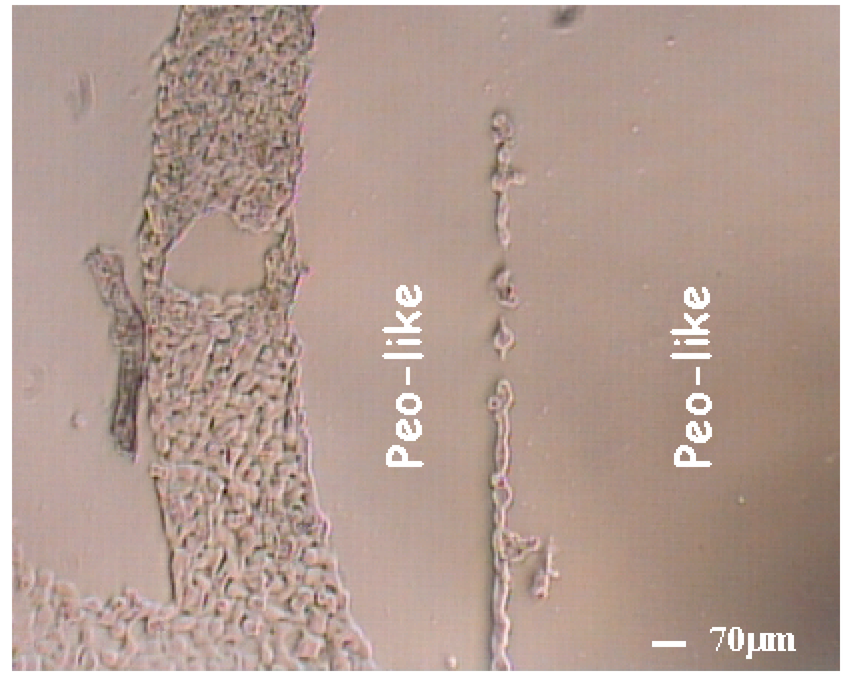
NCTC2544 human keratinocytes onto microstructured PS

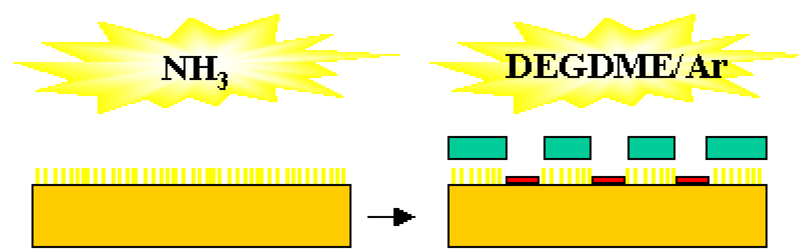
PS/PEO-like





N-groups/PEO-like

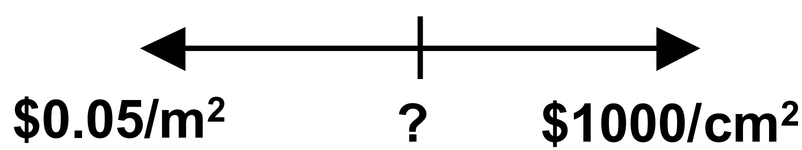




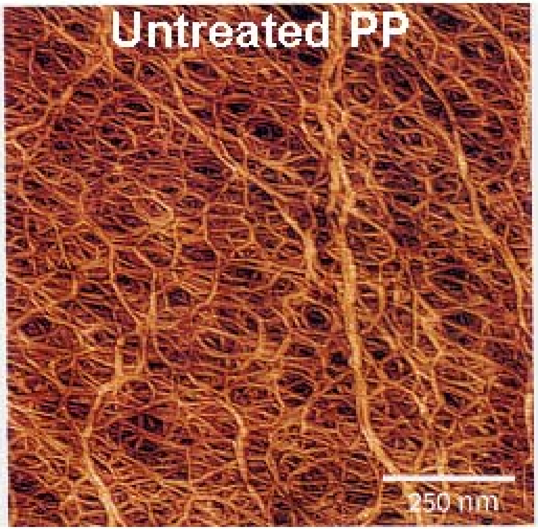
Ref: P. Favia

ATMOSPHERIC PRESSURE PLASMAS: *THE CHALLENGE*

- ***Controlling functional groups on polymers through fundamental understanding of plasma-solid interactions will enable engineering large area biocompatible surfaces*.**
- **10,000 square miles of polymer sheets are treated annually with atmospheric pressure plasmas to achieve specific functionality. Cost: < $0.05 /m^2**
- **Low pressure plasma processing technologies produce biocompatible polymers having similar functionalities. Cost: up to $100's /cm^2 ($1000's/cm^2 for artificial skin)**
- ***Can commodity, atmospheric pressure processing technology be leveraged to produce high value biocompatible films at low cost? The impact on health care would be immeasurable.***

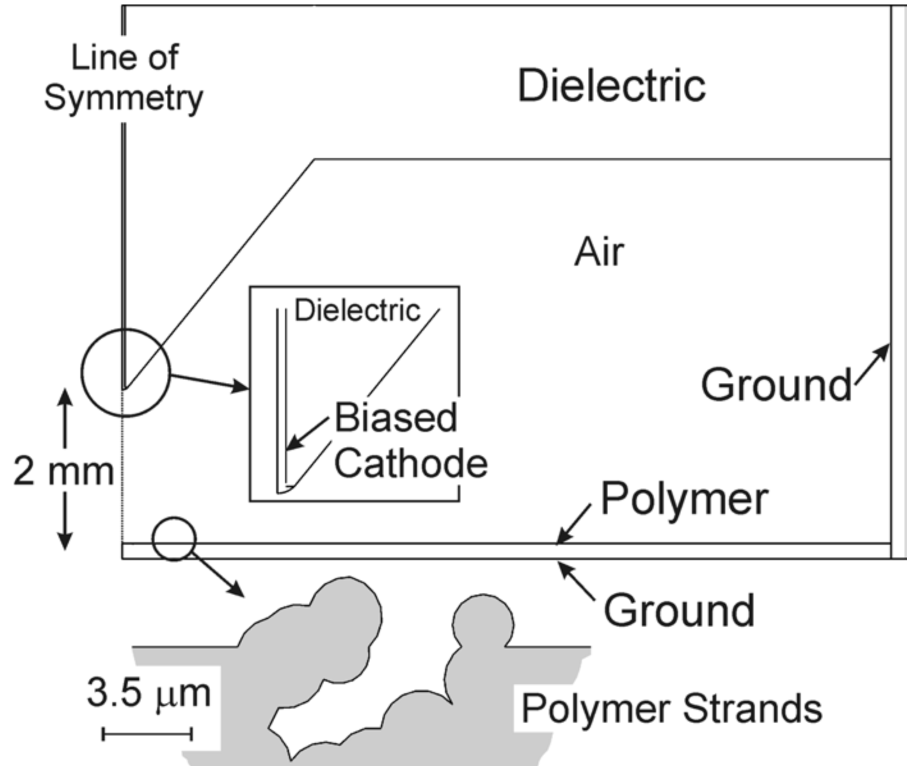


CAN COMMODITY PROCESSES PRODUCE HIGH VALUE MATERIALS?



- M. Strobel, 3M

- Tantec, Inc.

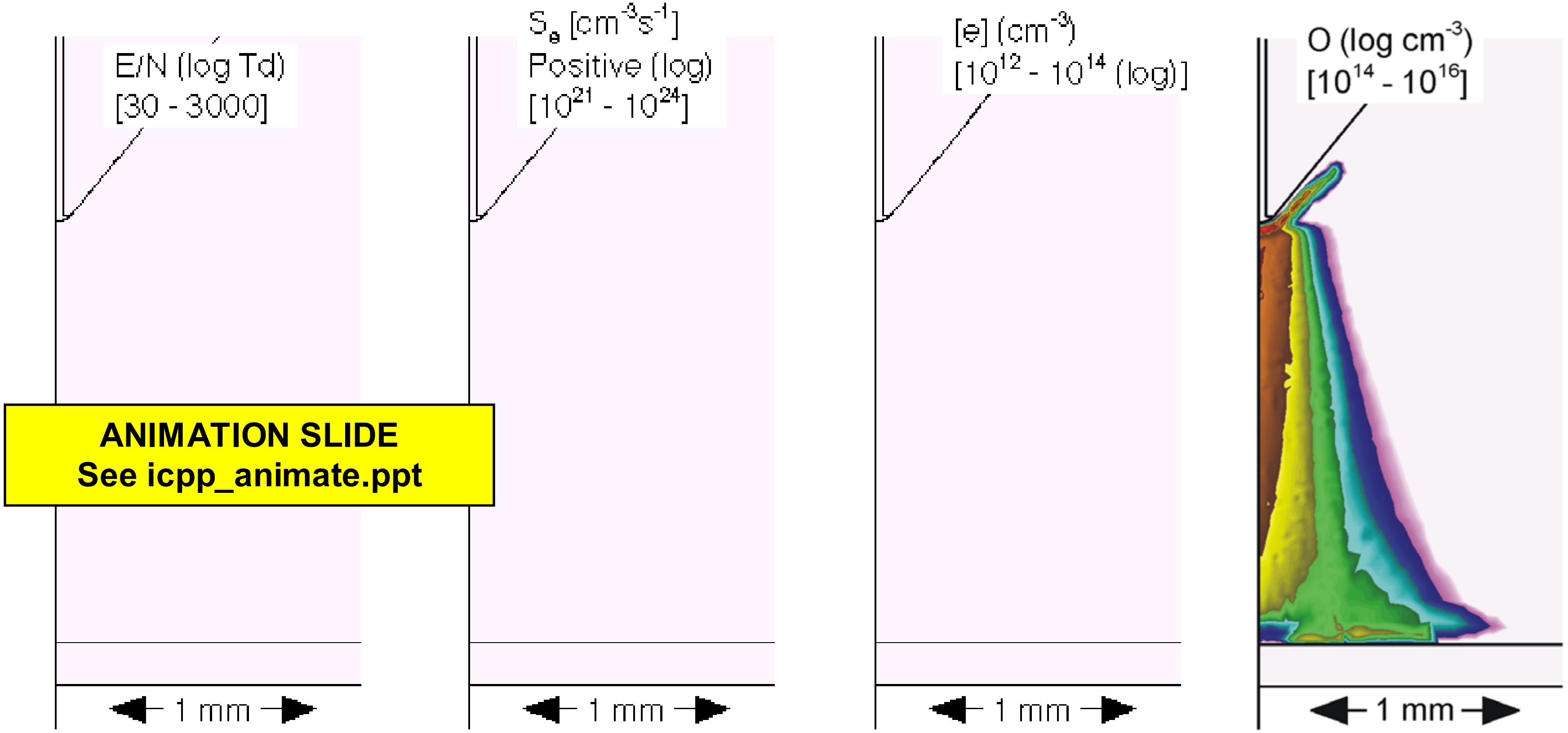


- Demonstration: corona-rod, 2 mm gap, 15 kV pulse, $N_2/O_2/H_2O$ =79.5 / 19.5 / 1, 1 atm

PLASMA PROPERTIES: PULSED NEGATIVE CORONA

Animation Slide

- Development of plasma streamer produces large electric field, electron sources, ionization and radical production.

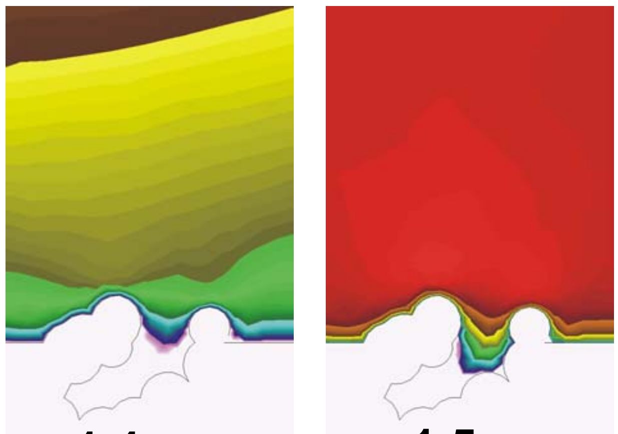


- E/N
- Net Ionization
- [e]
- O

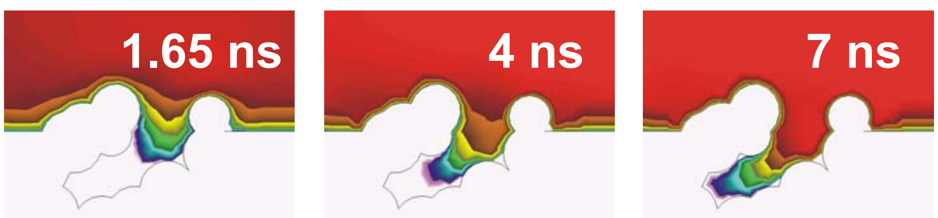
- $N_2/O_2/H_2O$ =79.5 / 19.5 / 1, 1 atm, 15 kV, 0-15 ns

SURFACE INTERACTIONS: O RADICALS, IONS

10^9- 10^{12} $5x10^{10}$- $5x10^{13}$



1.4 ns 1.5 ns

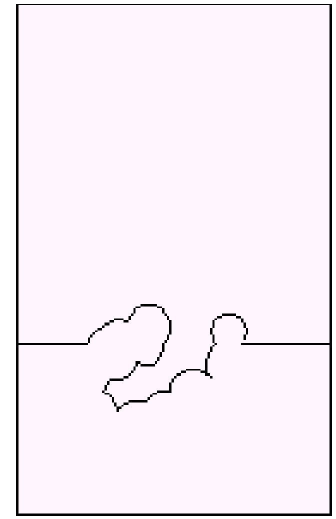


10 μm

$1x10^{11}$- $1x10^{14}$

- [O] cm^{-3}

+15 kV cycle



10 μm

- Positive Ions (10^9 – $5x10^{13}$ cm^{-3})
- Ion penetration is ultimately controlled by surface charging.
- O radicals penetrate deeper into the features.

ANIMATION SLIDE
See icpp_animate.ppt

- 15 kV, 1 atm, $N_2/O_2/H_2O$=79.5/19.5/1

MIN (log scale) MAX

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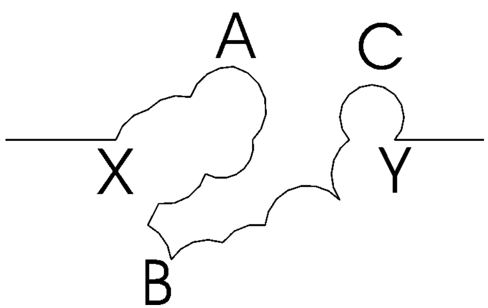
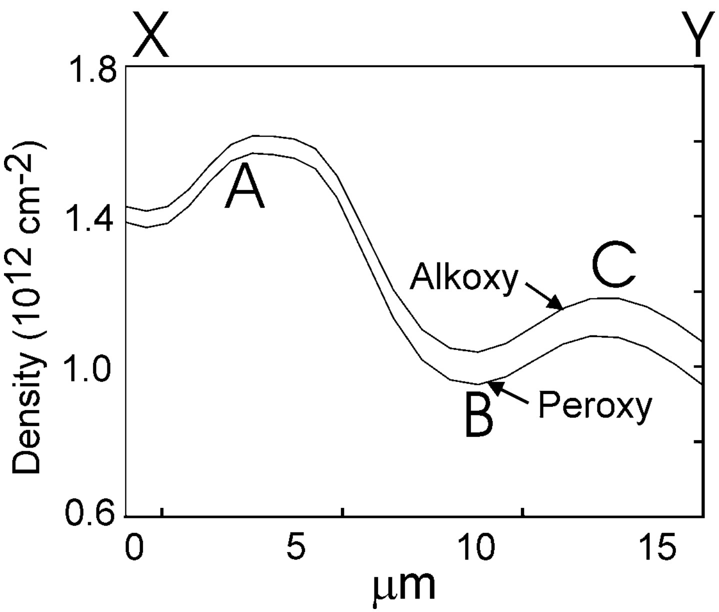
FUNCTIONAL GROUP DENSITIES ON POLYPROPYLENE

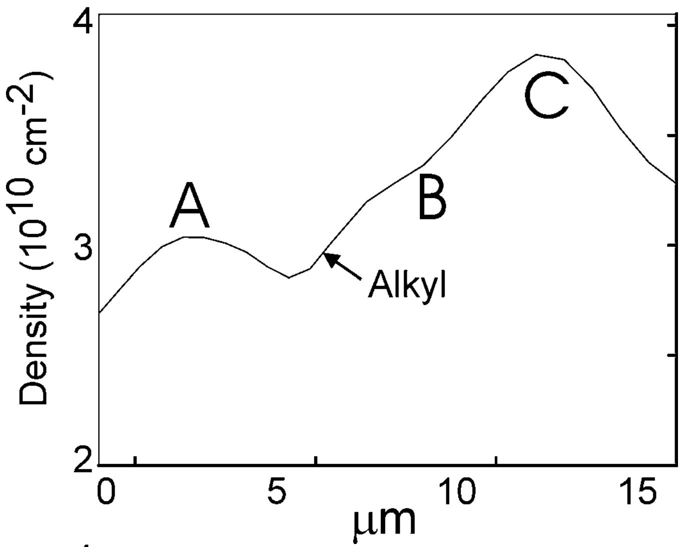
PP --> ALKYL --> ALKOXY, PEROXY

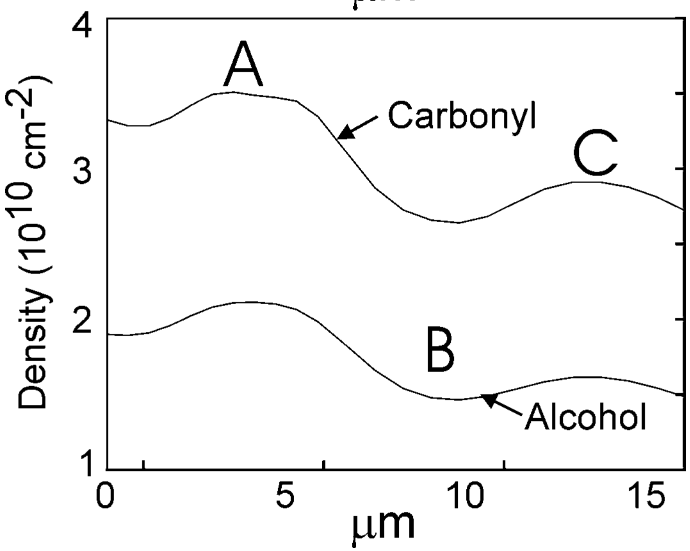
|
V

CARBONYL , ALCOHOL









- **1 atm, $N_2/O_2/H_2O$=79.5/19.5/1, 1.5 ms, 10 kHz.**

ICPP04_44

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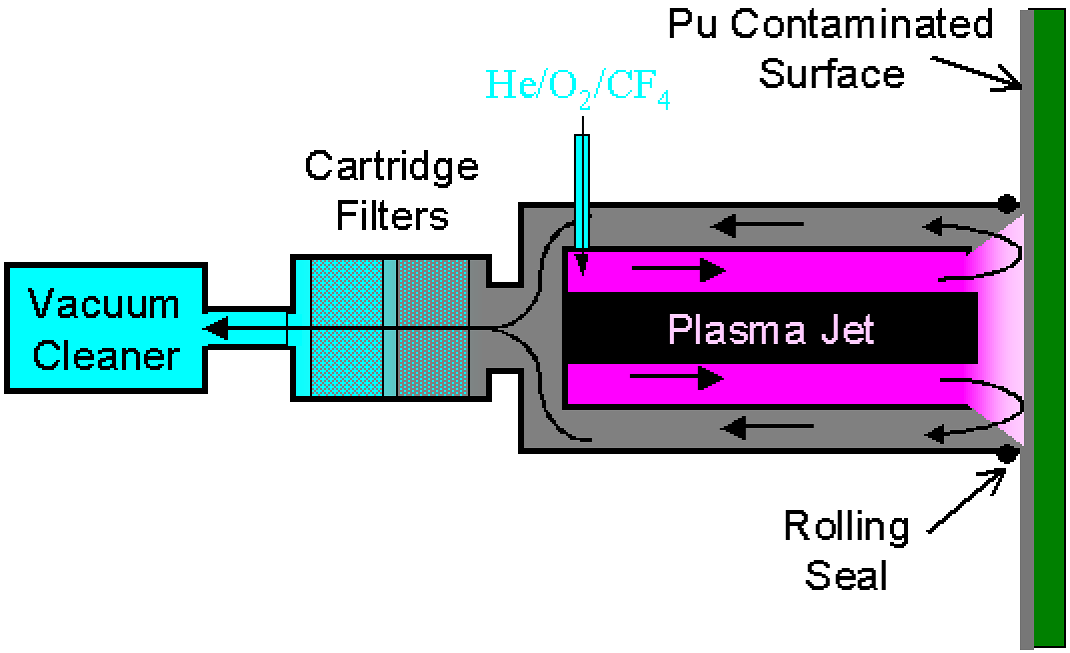
ATMOSPHERIC PRESSURE PLASMAS: SURFACES, PHOTONS, FLOW

APPJ-based Decontamination

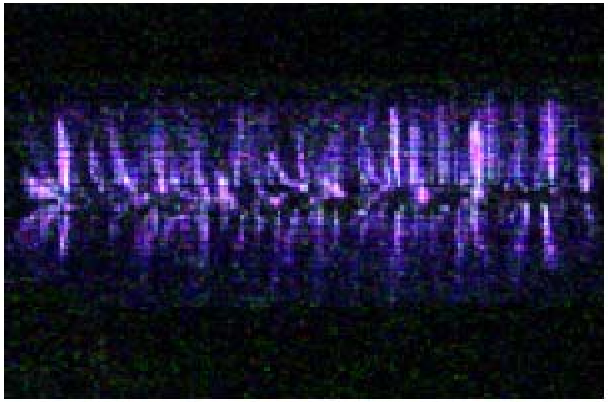


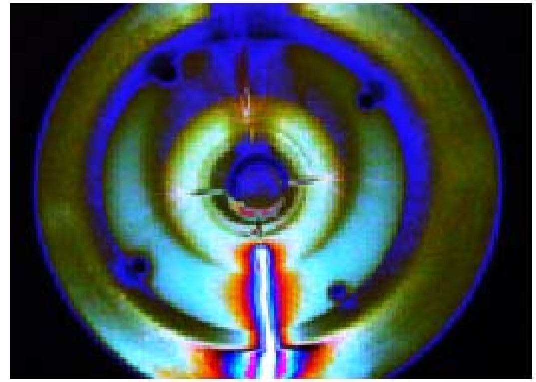
Decon Benefits:
- Innocuous feed gases (He, CF_4, O_2)
- Dry - no secondary waste stream
- Actinides potentially recoverable
- Endpoint detection possible

- **Decontamination Concept ⇒ Volume Reduction**
- Energetic plasma electrons dissociate CF_4 forming F atoms
- Oxygen reacts with CF_x molecules to prevent recombination
- Atomic Fluorine etches contamination: $Pu(s) + 6F(g) \Rightarrow PuF_6(g)$
- Volatile byproducts (e.g., PuF_6) captured in adsorbent and HEPA filters
- "Rolling Seal" allows motion while eliminating spread of contamination

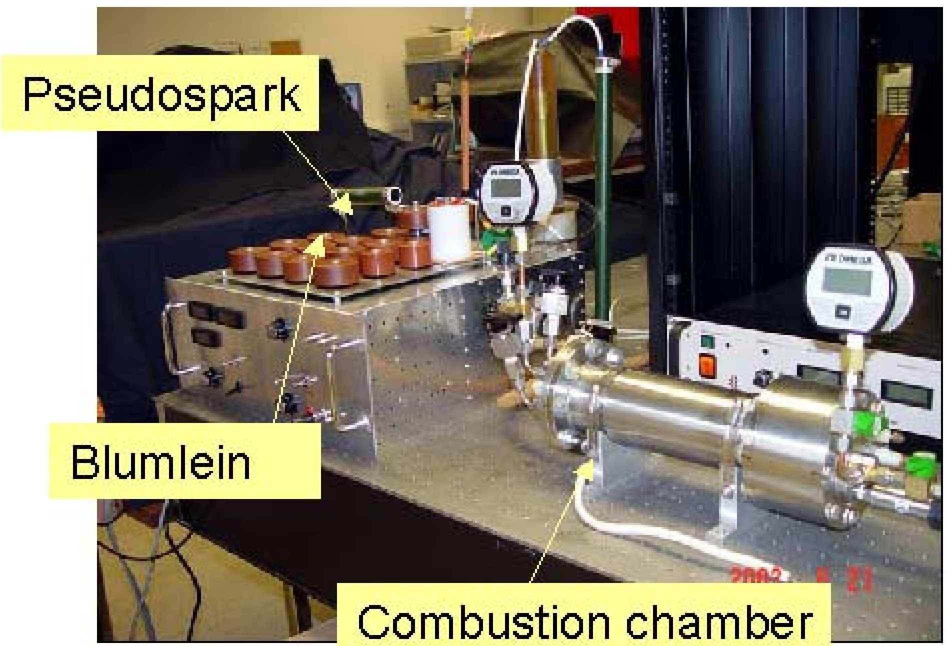
Ref: L. Rosocha

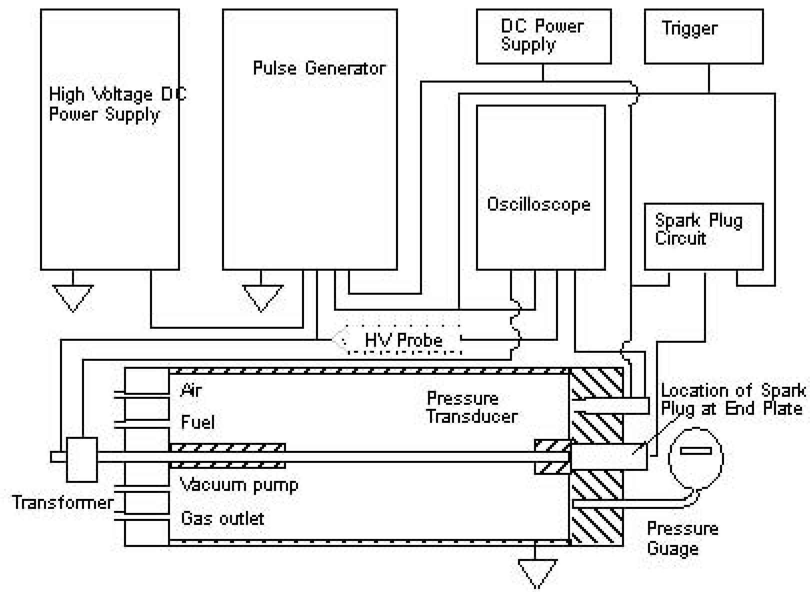
Transient Plasma ignition experiments





Transient (left) vs. Arc (Right)



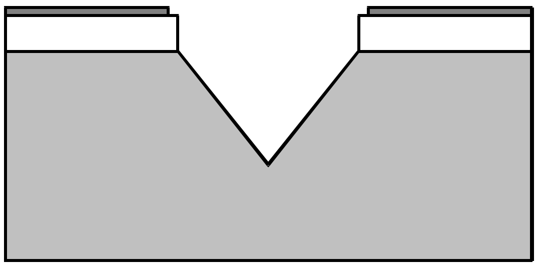


Ref: M. Gundersen

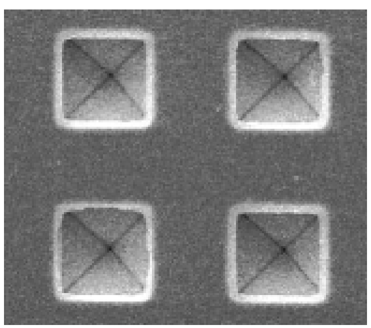
PulsedPower USC

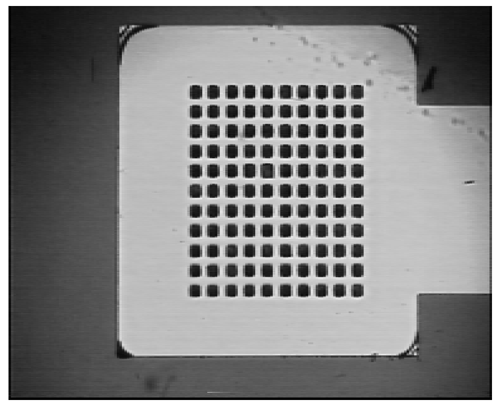
MICRODISCHARGES: MEMS FABRICATION

- **Microdischarges leverage pd scaling to operate at atmospheric pressure with sizes < 10s μm (pd = 6 Torr-cm, p=1 atm, d = 65 μm)**

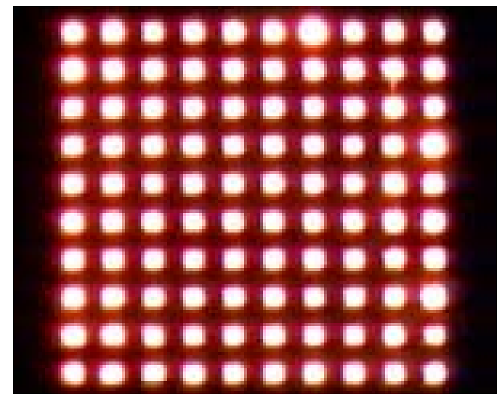


Inverted Pyramidal Elctrode





$(30\ \mu m)^2$ 10 X 11 arrays



1200 Torr Ne

- **Using MEMS techniques, arrays of addressable MDs can be fabricated for UV generation, displays, "coherent" photonics with "incoherent" sources.**

Ref: J. G. Eden, UIUC

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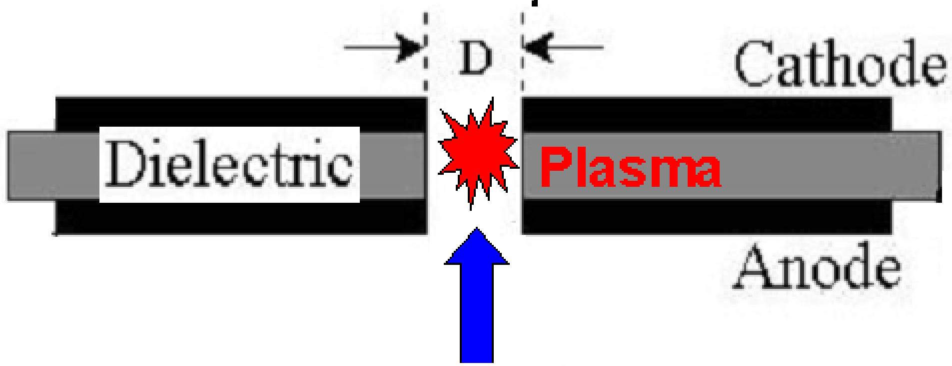
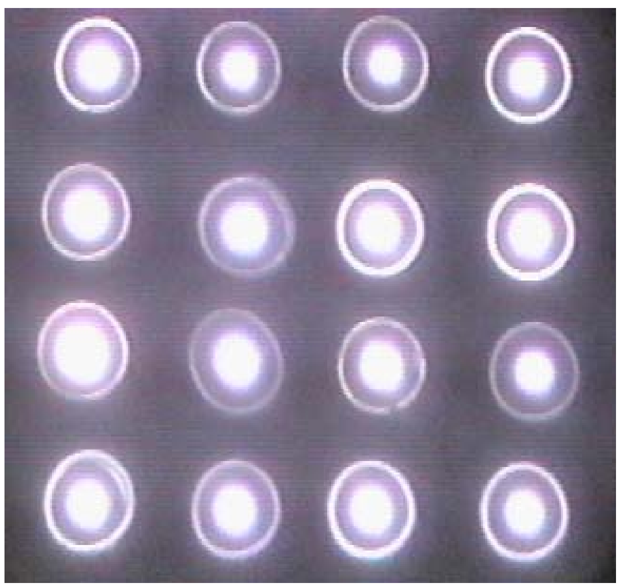
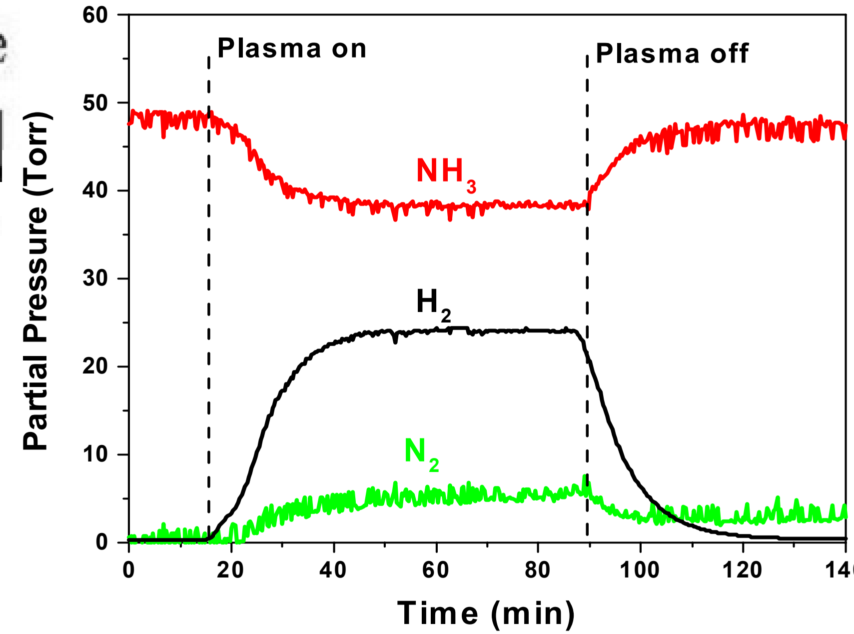
In-situ H_2 Generation for Small Scale (i.e. Low Power) Fuel Cells Using a Microhollow Cathode Discharge





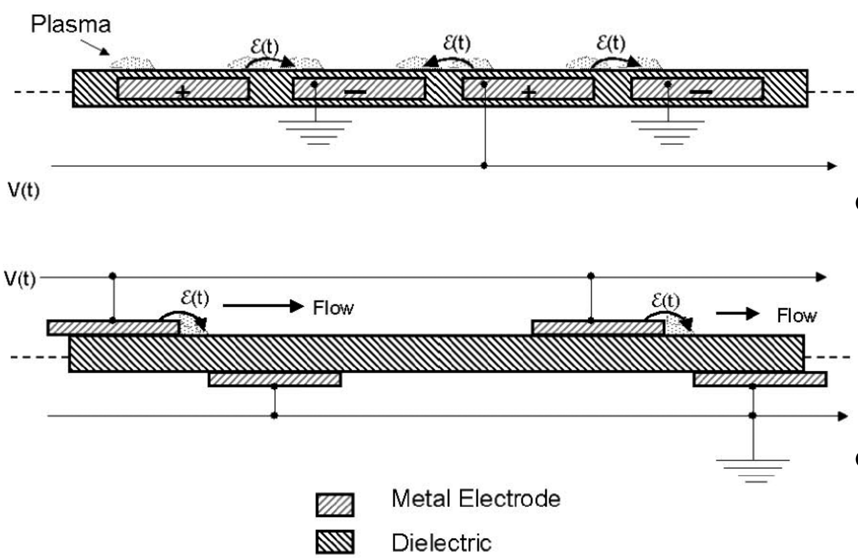


- **High throughput is facilitated by microplasma arrays**

- **Ref: Kurt Becker**

CONTROL OF AERONAUTICAL FLOWS USING PLASMAS

- **Charged particles accelerated in electric fields can produce advective motion of gases through momentum transfer.**



$$\frac{Force}{Volume} = q\left(\sum_i Z_i n_i - n_e\right)E = \rho E = \varepsilon_o E \nabla \cdot E$$

- **The flight characteristics of airfoils are sensitive functions of the "adherence" of the boundary layer.**

- **Strategically generated plasmas on wings can beneficially and controllably affect lift and steering.**

- **Example of dielectric barrier discharges for flow control**

Ref: R. Roth

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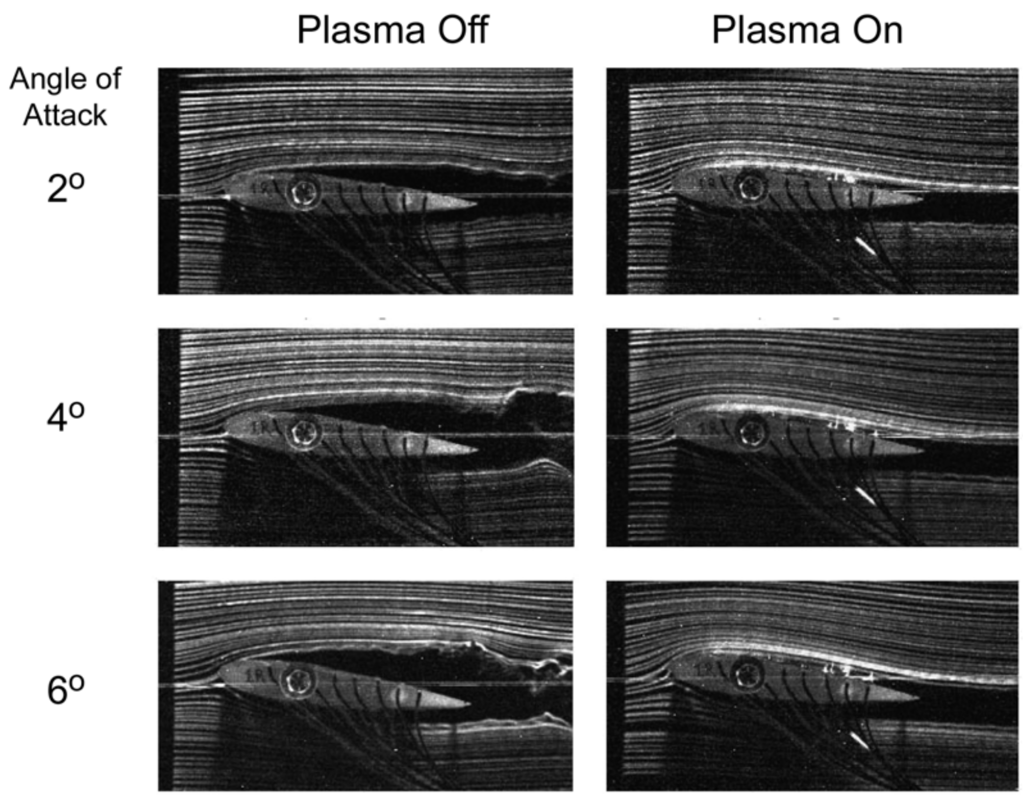
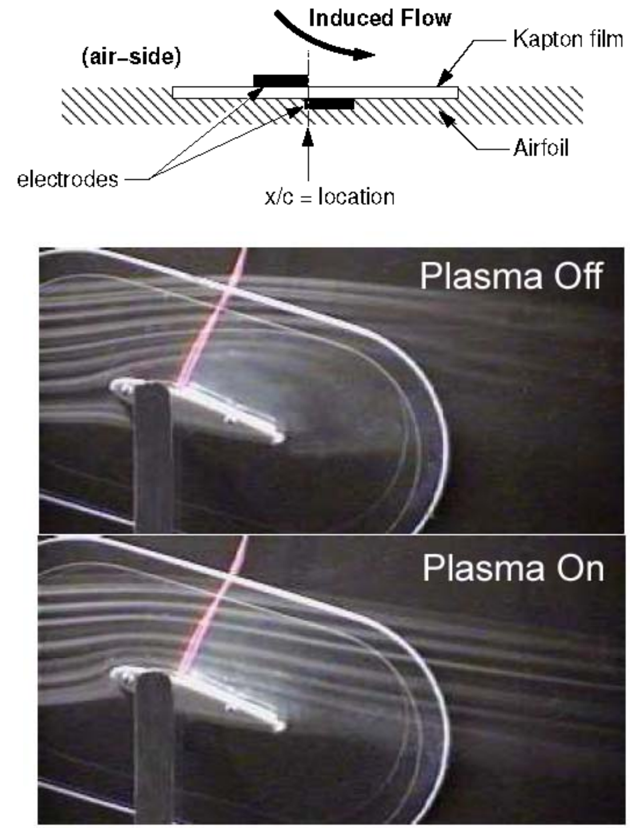
Optical and Discharge Physics

CONTROL OF AERONAUTICAL FLOWS USING PLASMAS



Ref: R. Roth, Phys. Plasma 10, 2117 (2003)



Ref: T. Corke, AIAA 2004-2127

- **A dielectric barrier discharge on the surface of an airfoil prevents separation of the boundary layer.**

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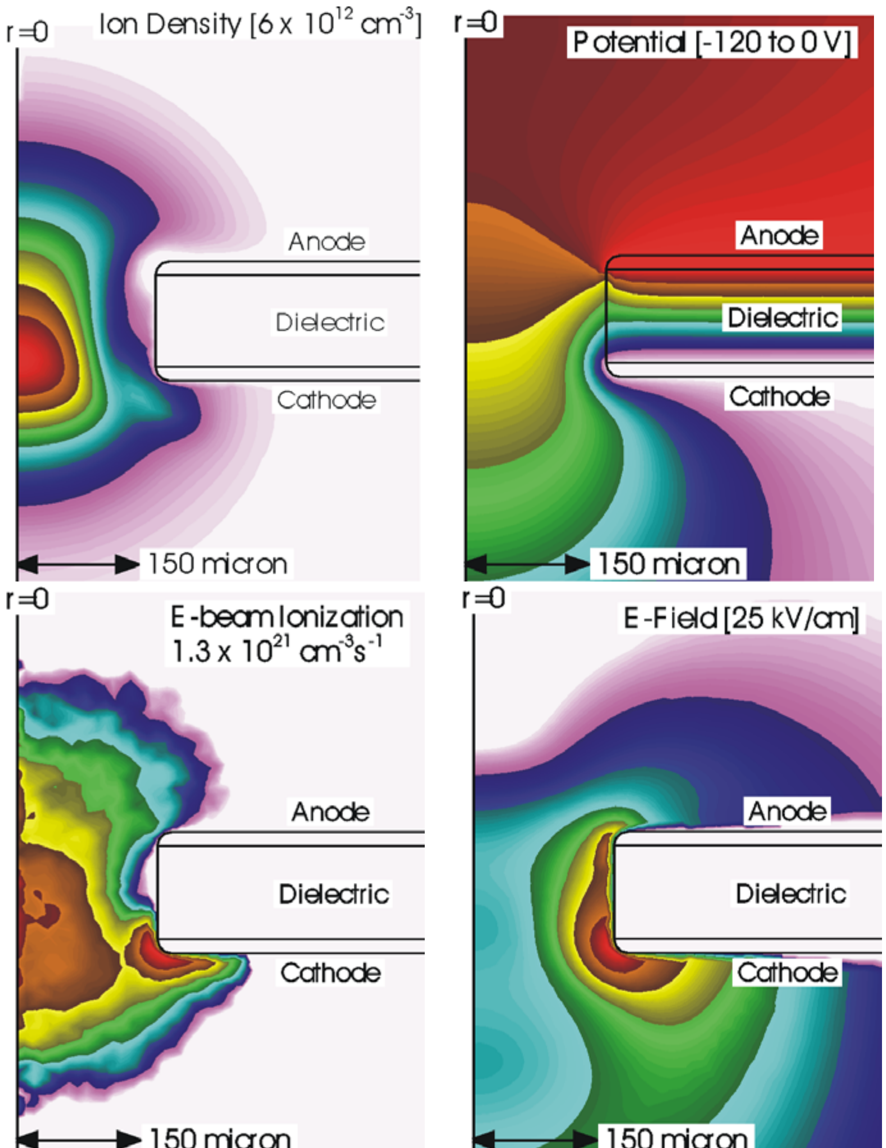
KEY TO PROGRESS IS LEVERAGING TECHNOLOGIES: MICRODISCHARGE ACTUATORS



- **Microdischarges were developed as photon and radial sources.**
- **Leveraging these technologies enable advances in other areas.**
- **Arrays of micro-discharges may enable control of flow characteristics in “programmable” fashion.**
- **600 Torr Ne, 180 V**

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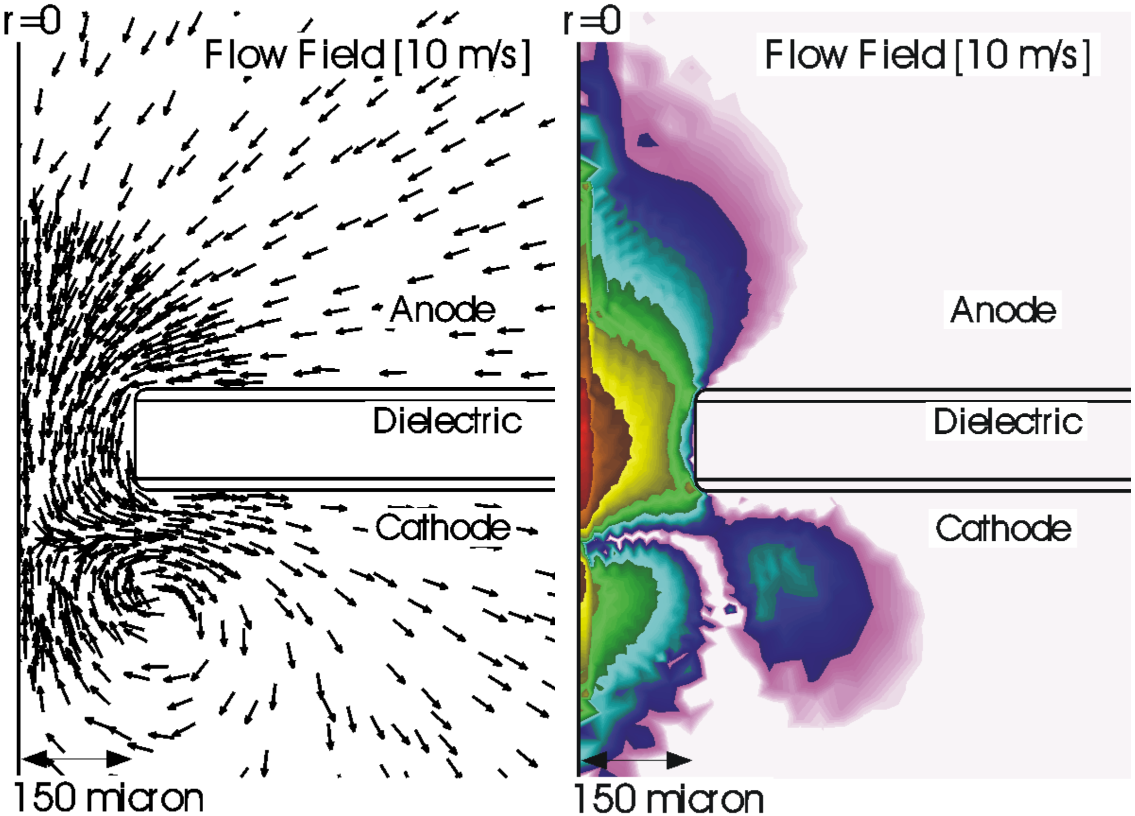
GAS PUMPING USING MICRODISCHARGS



- **Ion pumping is efficient due to ability to produce large cw ion current densities.**
- **Flexible arrays enable large areas.**
- **600 Torr Ne, 180 V**

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PLASMAS IN NANOSCIENCE

THE ROLE OF PLASMAS IN NANOSCIENCE

- Plasma science has been absolutely critical to the development of conventional microelectronics structures.

- What will the role of plasma science be in facilitating these advances in truly nanoscale science and technology?

  - Atomic layer processing (etch and deposition)
  - Plasma aided lithography (trimming)
  - Selective activation or functionalization of materials on molecular scales (inanimate and living)
  - Self- and directed-assembly
  - Commodity production of nanostructures and nano-particles.
  - Plasma physics laboratories

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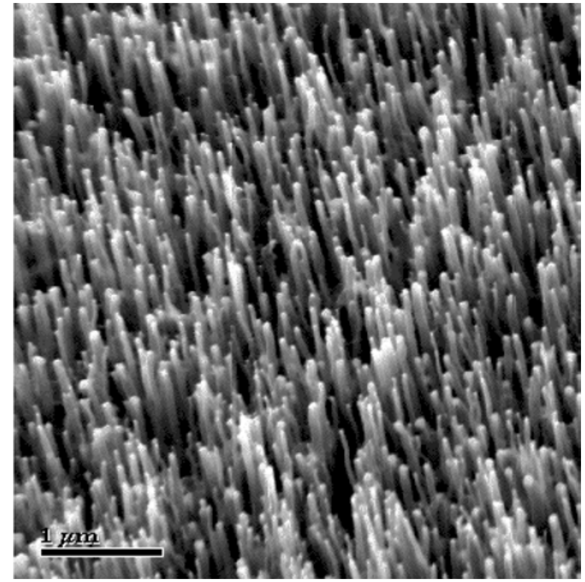
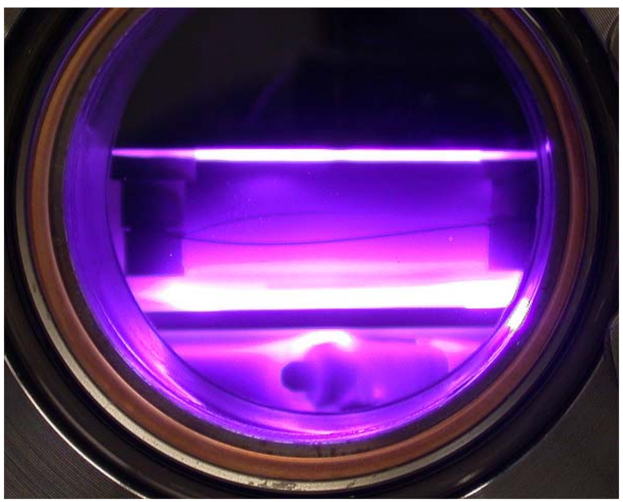
SELECTIVE, ALIGNED PLASMA GROWTH OF CARBON NANOTUBES

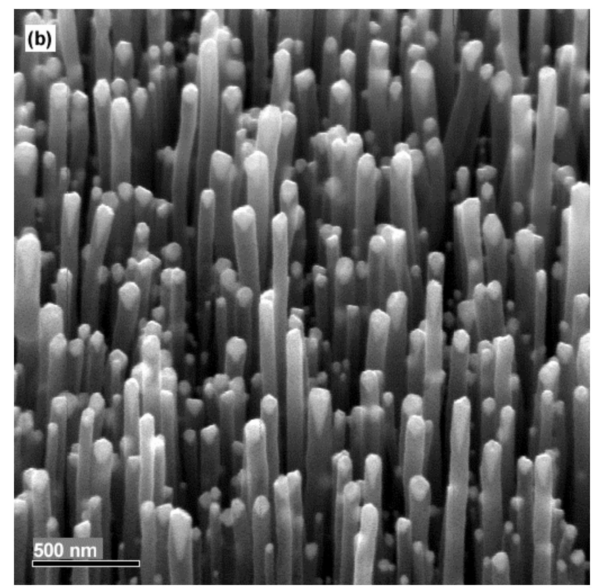
- **Aligned CNT growth can be obtained in a low pressure rf and dc plasmas using different feedstocks.**
- **Catalyst choice and configuration may dominate.**



RF Plasma (C_2H_4/NH_3)



DC Plasma CVD

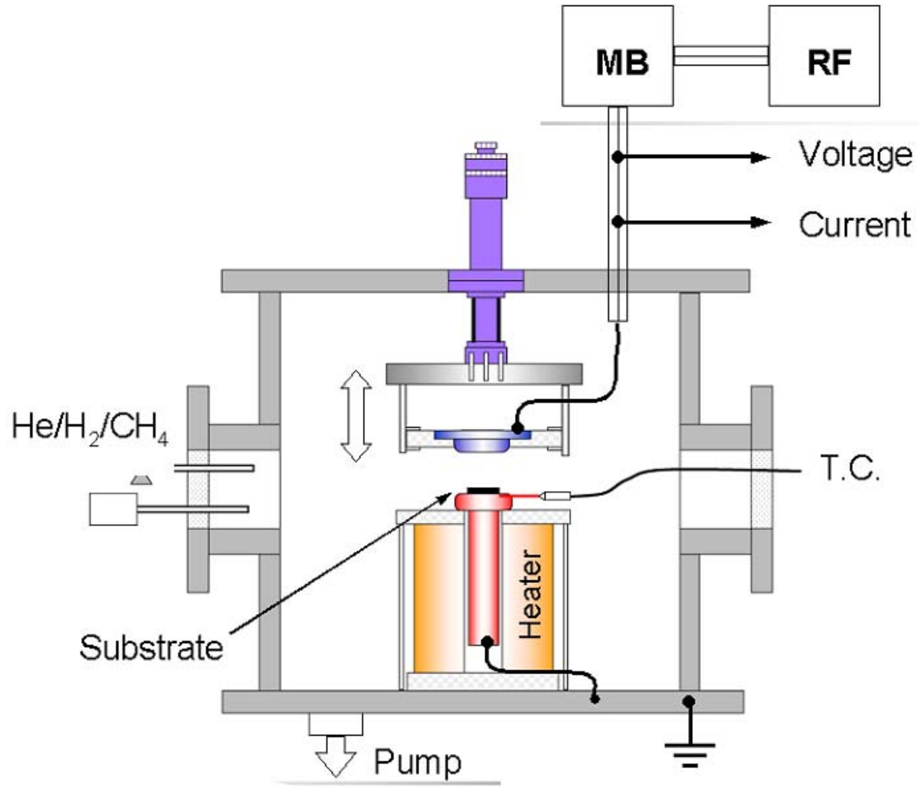


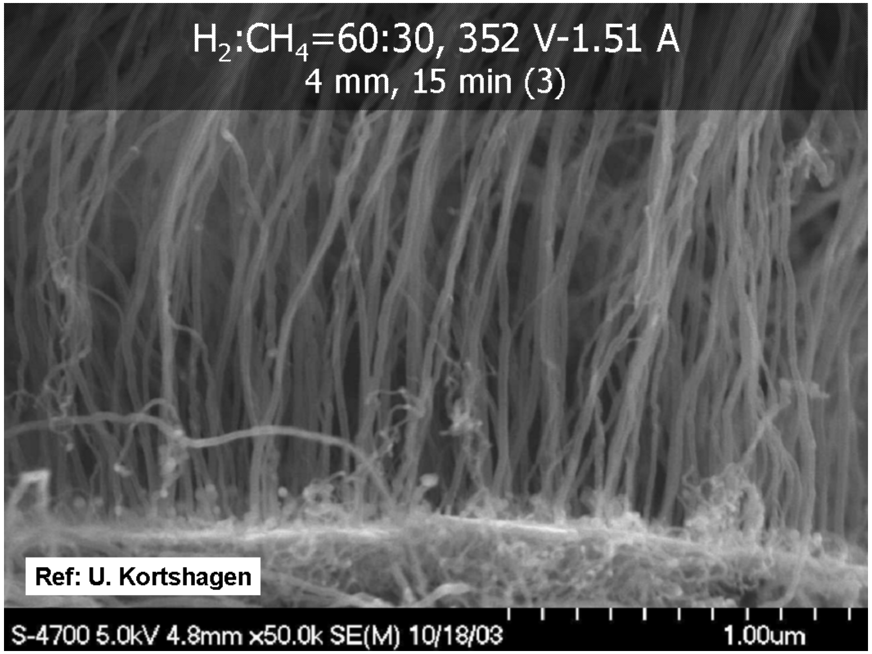
DC Plasma (C_2H_2/NH_3)

Ref: B. Cruden

Cruden et al., J Appl Phys, 12, 363 (2001).

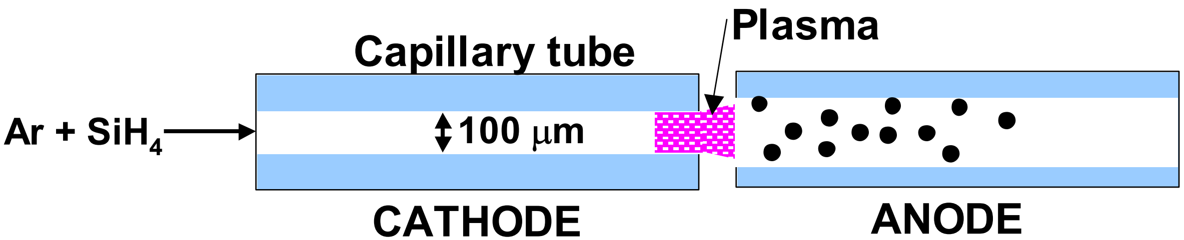
Atmospheric Pressure Plasmas for Carbon Nanotube Deposition

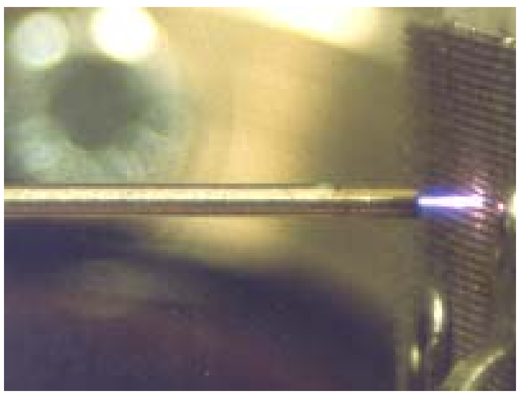




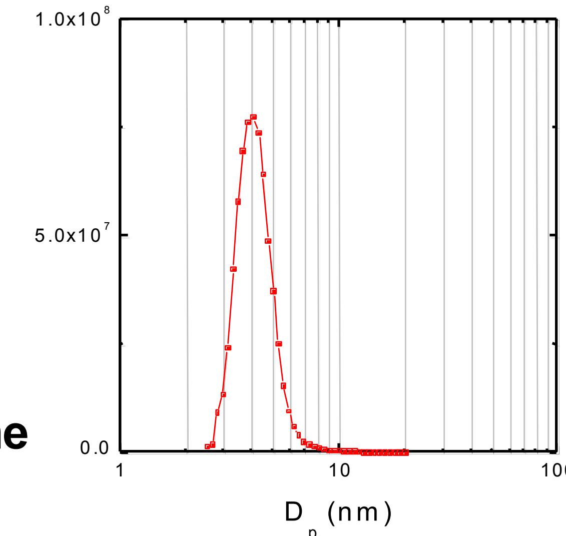
Ref: U. Kortshagen, U. Minnesota

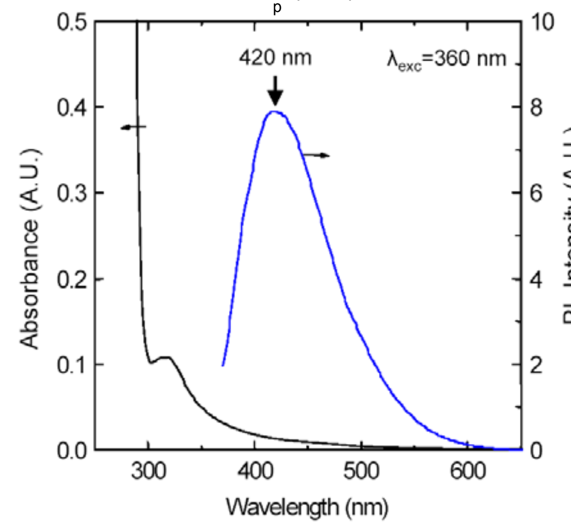
Microplasmas as Micro-reactors: Nanostructures





- **Short residence time of reactants in plasma zone of microdischarge enables controlled fabrication of fluorescent Si nanoparticles.**





Typical operating conditions

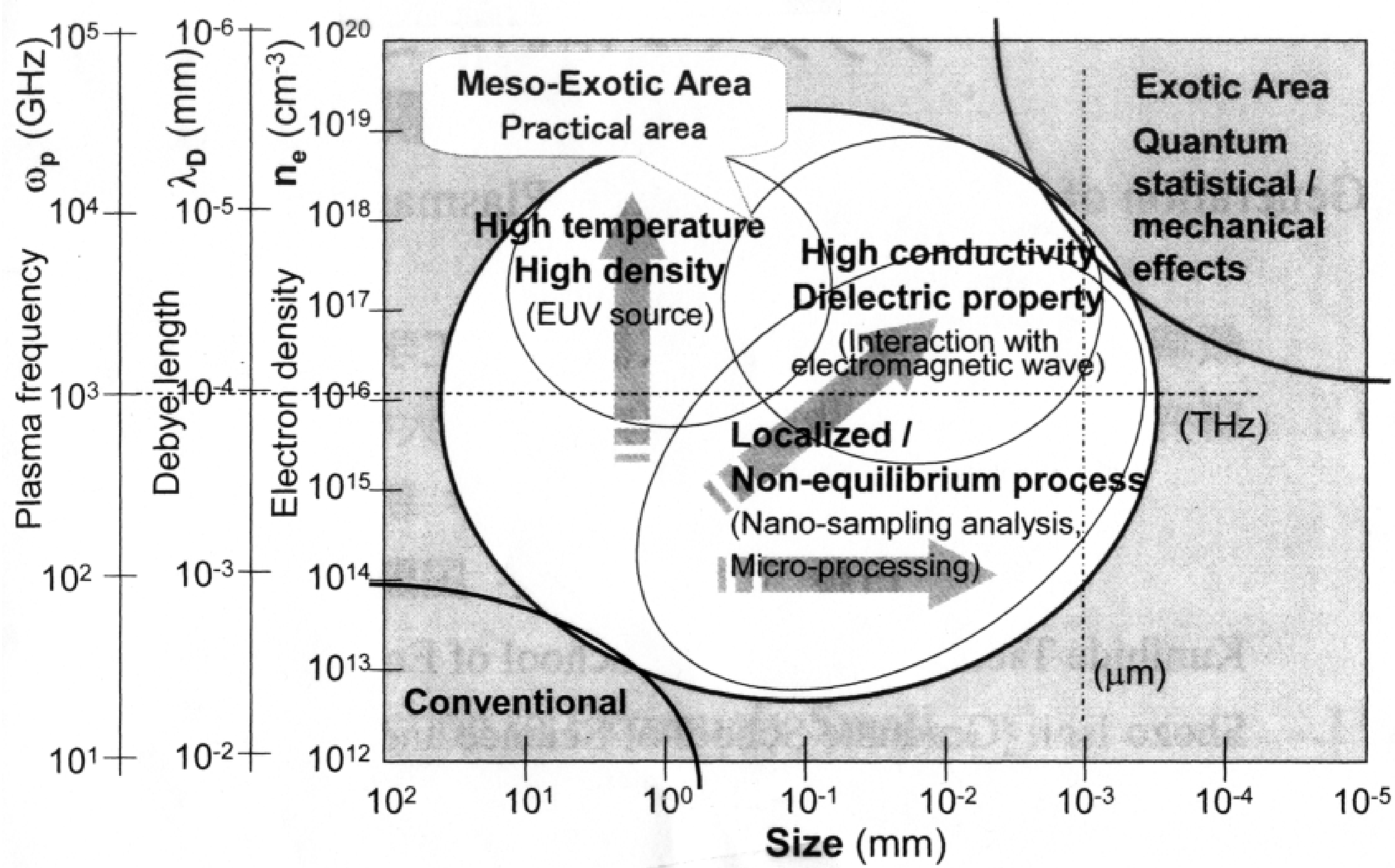
- ***100 sccm Ar in air***
- ***V_{plasma}=450 VDC, I_{plasma}=10.0 mA***
- ***d_{hole}=180 μm, L=2 mm***

US Patent No. 6,700,329 – Issued 3/2/04

- **K. P. Giapis, Caltech**

MICRODISCHARGES: MINIATURE PLASMA PHYSICS LABS

- Following microdischarges scaling to ≥ 10s atm, [e] > 10^{19} cm^{-3}, d < 0.1 μm provides a cw source of quantum mechanical plasma(?)



- Ref: Annual Progress Report, "Generation of Micro-Scale Reactive Plasmas and Development of Their New Applications" K. Tachibana, Project Leader, March 2004

CONCLUDING REMARKS

- Low temperature, technological plasmas address an array of high technology and commodity applications.

- The widest use of low temperature plasmas is production of extremely high value materials (e.g., microelectronics) and low values materials (e.g., polymer functionalization).

- The key to advancing the state of the art is improving fundamental understanding while leveraging low cost processes for high value materials. For example,

    - Plasma modified polymers for artificial skin
    - Microplasma produced nanoparticles

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