Low Temperature Plasmas:

A Foundation for Future Technologies

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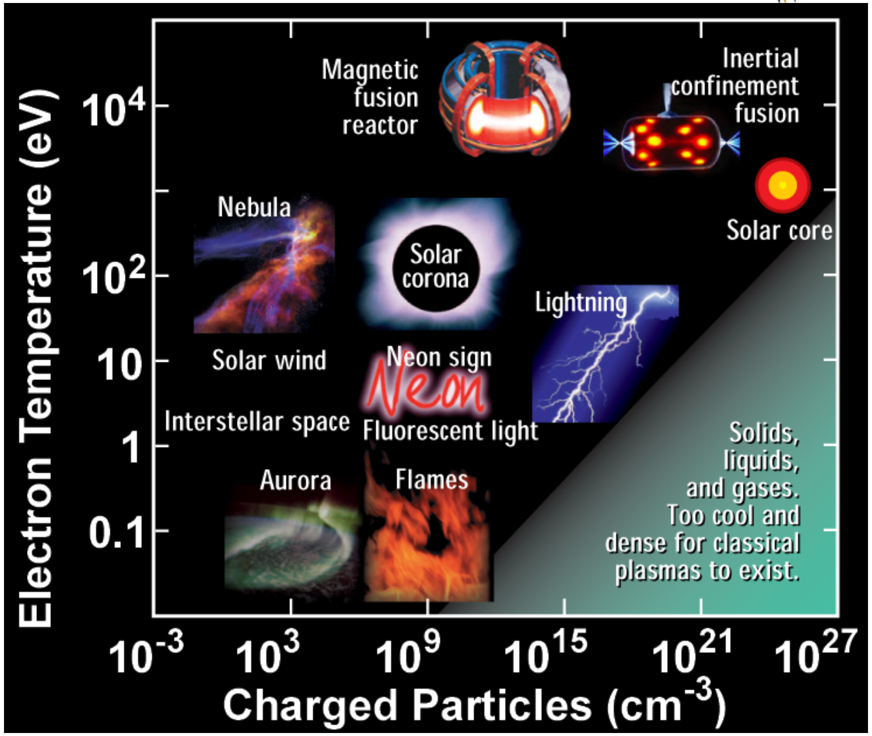
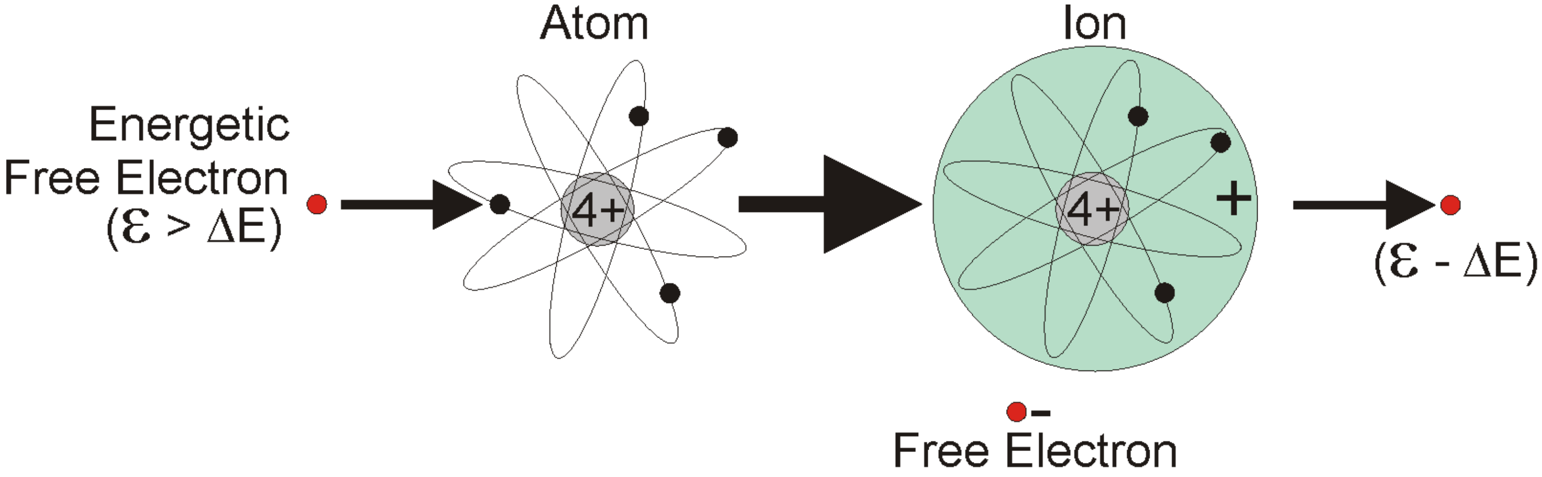
Low Temperature (Cold) Plasmas

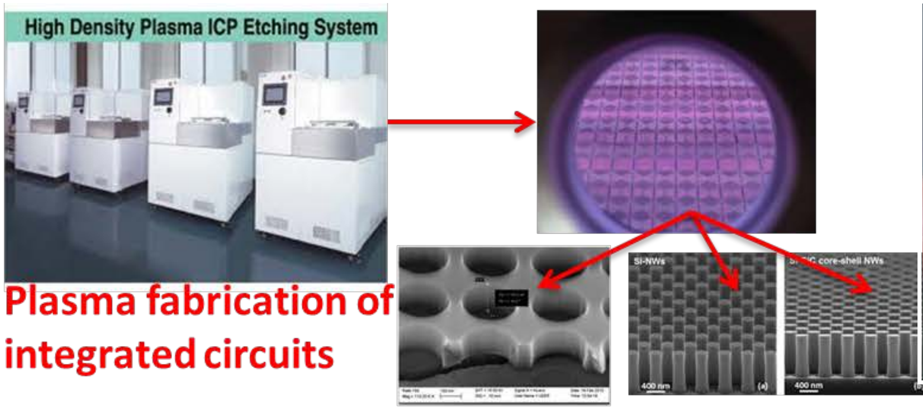
- **Plasmas (ionized gases), the "fourth state of matter", account for > 99.9% of the mass of the universe (dark matter aside).**
- **An energetic free electron collides with an atom, creating a positive ion and another free electron**
- **In cold plasmas, only 1 atom in a 1,000 – 10,000,000 is ionized, gas is cold (~room temperature), but electrons are very hot**





Cold Plasmas: Now

Compact Fluorescent Lamp

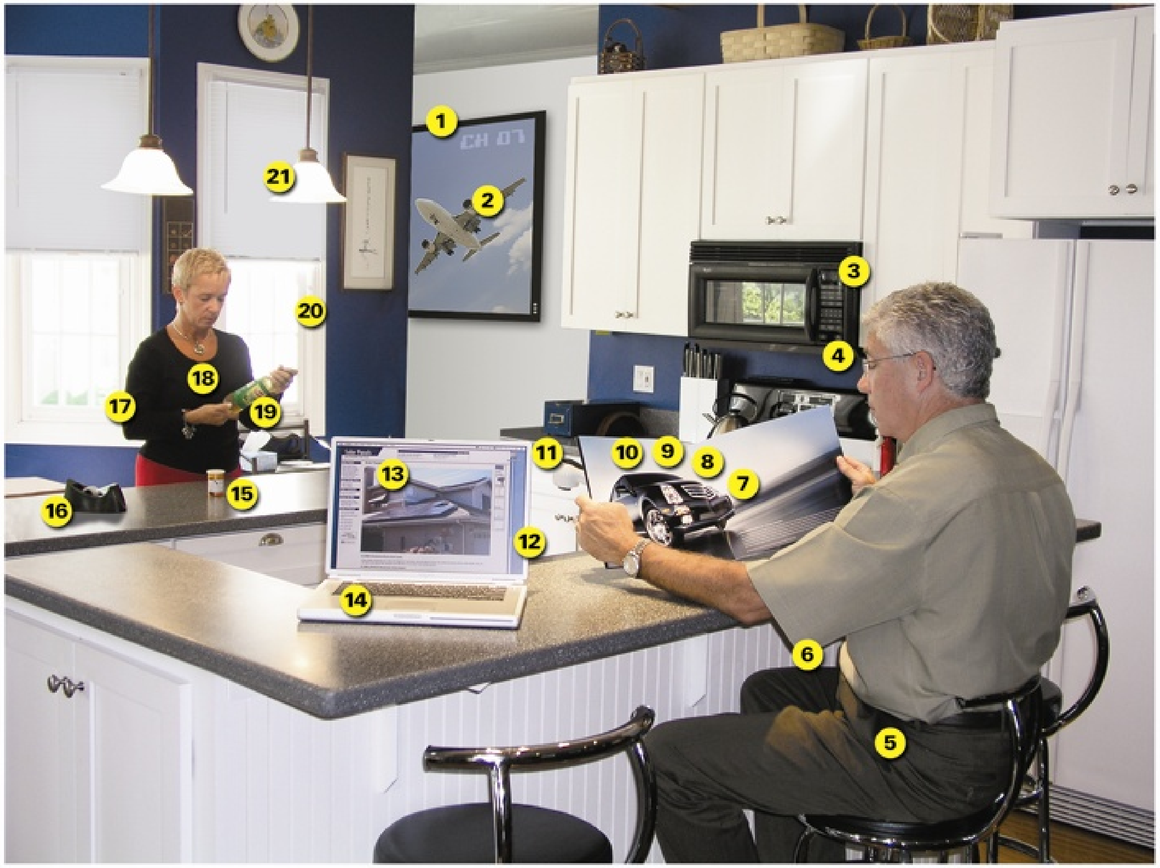


Plasma fabrication of integrated circuits

Jet Engine Spray Coatings

- **Low Temperature Plasma (LTP) -** ionized gas in extreme thermodynamic nonequilibrium: room temperature gas, but very hot (10,000 – 40,000 K) electrons and very high populations of excited atomic and molecular states.
- 2012: 12% of US electricity was expended by lighting; ~2/3 of that was used in LTP lighting sources.
- The entire current and future information technology (IT) infrastructure owes its very existence and Moore’s Law development (transistor number in a dense IC doubles every 2 years) to LTPs.
- Renewable energy sources such as solar cell arrays, cannot be economically produced without deposition and etching by LTPs.
- High efficiency jet engines, military and commercial, would not exist in the absence of thermal barrier coatings produced by LTPs.
- Spacecraft rely on propulsion from LTP thrusters.
- The estimated impact on the US economy **$650 billion – 1.2 trillion** today

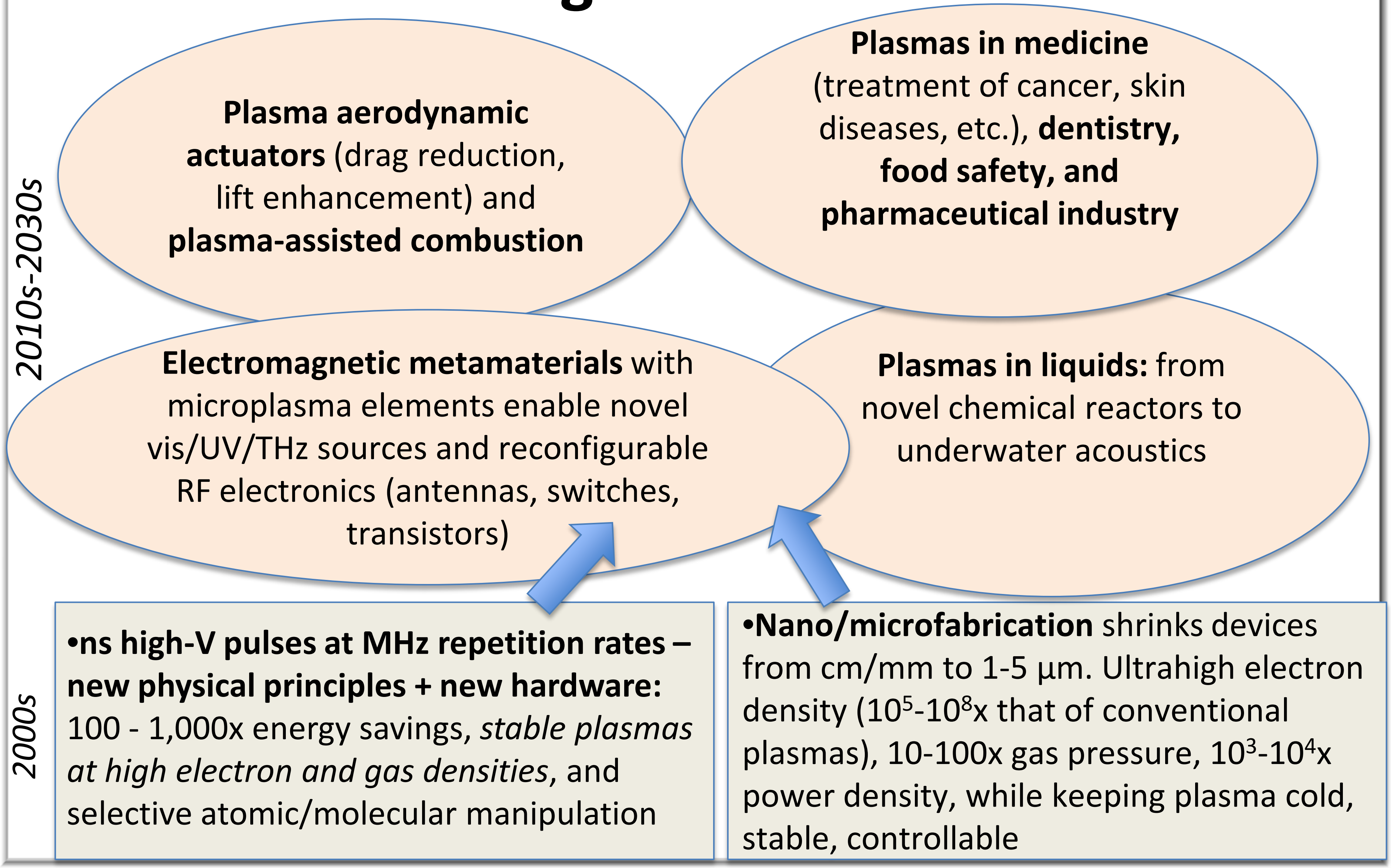
Cold Plasmas: Societal Benefits



01—Plasma TV
02—Plasma-coated jet turbine blades
03—Plasma-manufactured LEDs in panel
04—Diamondlike plasma CVD eyeglass coating
05—Plasma ion-implanted artificial hip
06—Plasma laser-cut cloth
07—Plasma HID headlamps
08—Plasma-produced H_2 in fuel cell
09—Plasma-aided combustion
10—Plasma muffler
11—Plasma ozone water purification
12—Plasma-deposited LCD screen
13—Plasma-deposited silicon for solar cells
14—Plasma-processed microelectronics
15—Plasma-sterilization in pharmaceutical production
16—Plasma-treated polymers
17—Plasma-treated textiles
18—Plasma-treated heart stent
19—Plasma-deposited diffusion barriers for containers
20—Plasma-sputtered window glazing
21—Compact fluorescent plasma lamp

Ref:
“Plasma Science: Advancing Knowledge in the National Interest”,
US National Research Council, 2007.

Breakthroughs Enabling Transformative Plasma Technologies



2010s-2030s

Plasma aerodynamic actuators (drag reduction, lift enhancement) and **plasma-assisted combustion**

Plasmas in medicine (treatment of cancer, skin diseases, etc.), **dentistry, food safety, and pharmaceutical industry**

Electromagnetic metamaterials with microplasma elements enable novel vis/UV/THz sources and reconfigurable RF electronics (antennas, switches, transistors)

Plasmas in liquids: from novel chemical reactors to underwater acoustics

2000s

- **ns high-V pulses at MHz repetition rates – new physical principles + new hardware:** 100 - 1,000x energy savings, *stable plasmas at high electron and gas densities*, and selective atomic/molecular manipulation

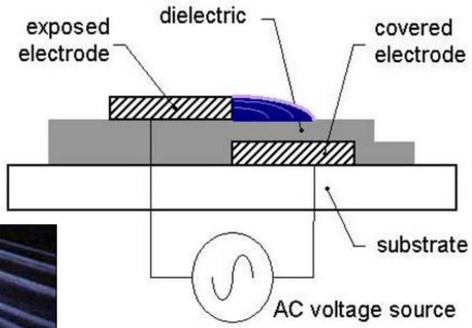
- **Nano/microfabrication** shrinks devices from cm/mm to 1-5 µm. Ultrahigh electron density (10^5-10^8x that of conventional plasmas), 10-100x gas pressure, 10^3-10^4x power density, while keeping plasma cold, stable, controllable

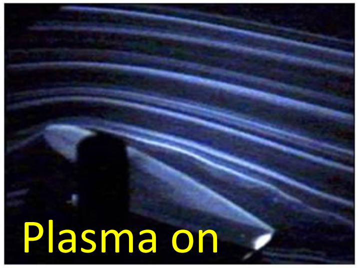
Cold Plasmas for Aerospace

Aerodynamics and Flow Control

Cold microplasma arrays:

- Low-power tunable actuation → ***30-50% higher fuel efficiency and range:*** military apps; est. **$15B savings in US airline industry**
- aircraft noise suppression.





Hypersonics

X-51: Mach>5 for 210 sec (2013)

Plasma would increase hypersonic lift-to-drag ratio by 30-50% and would also enable scramjet ignition and stable combustion

Plasma-Assisted Combustion & Cold Plasma Micropropulsion

Nanosecond-pulsed cold plasma sources:

- Tune in/out specific molecular and atomic processes → ***Ultimate control of chemistry***
- Chemistry activation and quenching control → ***less fuel, lower temperature, higher speeds***
- **Novel plasma microthrusters**: enabling orbital control and maneuvering for nanosatellites

Food/Medical Technology

Kevin Keener
(Food Science & ABE)

Purdue invention:
30-120 kV atmospheric cold plasma technology

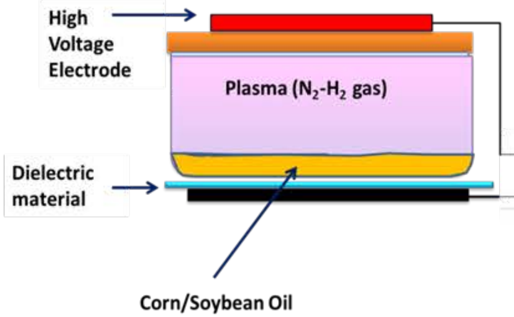
Food Safety

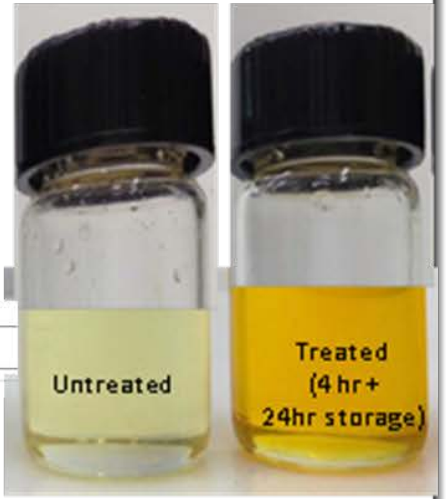
Cold plasma extends shelf-life by 4 weeks
$140M annual loss prevention – fresh tomatoes

Industrial Processing

Food Oil Hydrogenation
a. No catalyst required
b. Trans-fat free
c. Low energy

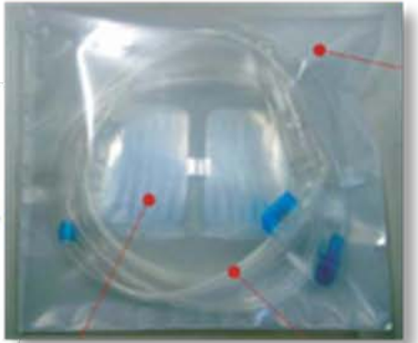
Food Oil $28B annual market value





Medical Device Sterilization

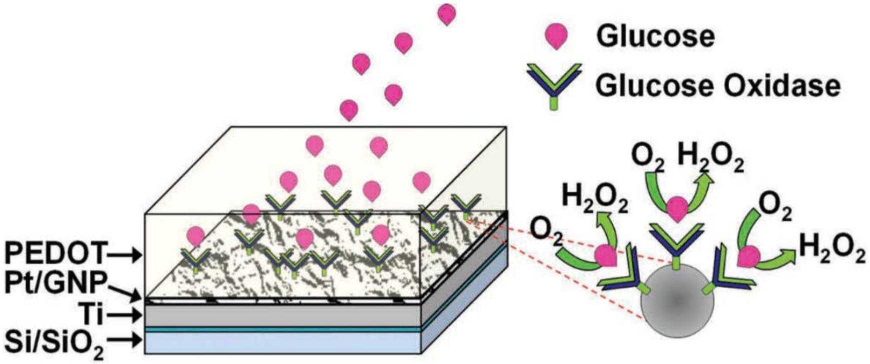
$100B annual market opportunity



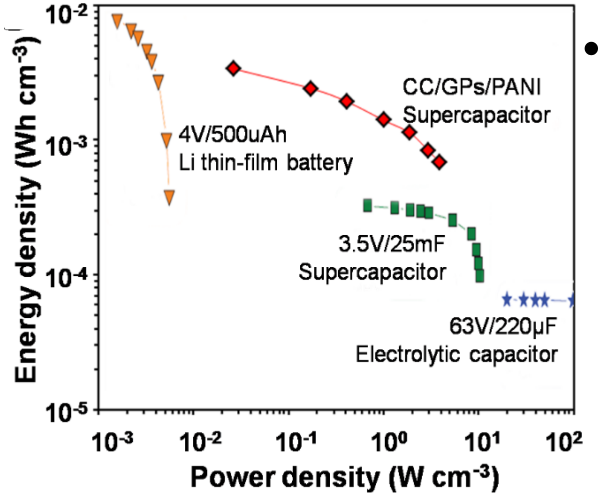
Plasma Enhanced CVD of Nanostructures

- **PECVD is an efficient process to grow nanomaterials due to lower operation temperatures.**

- **Nanostructured devices enabled by PECVD:**
  - ❖ **Electrochemical Biosensors: Glucose detection limit of 0.3 µm, linear sensing range of 0.01–50 mM.**
  - ❖ **Supercapacitors: Higher power density, faster power delivery and better cycle to cycle stability**

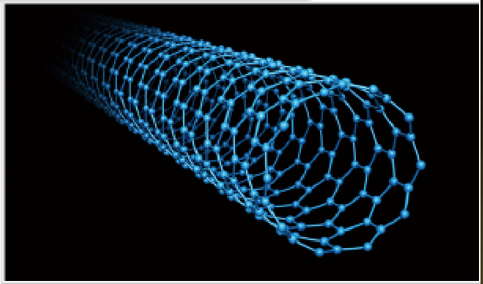


- **Glucose biosensor.** (Ref: Claussen et al. Adv. Funct. Mater. **2012**, 22, 3399–3405).



- **Supercapacitors specific energy and power density compared to Li-ion battery.** (Ref: Xiong et al. Adv. Energy Mater. **2014**,4, 1300515)

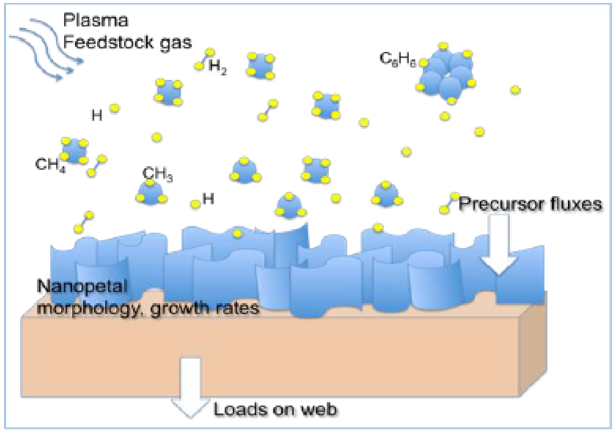
Microwave Plasma Chemical Vapor Deposition



MPCVD refers to Microwave Plasma Chemical Vapor Deposition. This is a technique used to grow carbon nanotubes, graphitic sheets and nanopetals, and graphene.

Procedure:

- Pure hydrogen introduced into reactor.
- Microwaves generate electric field, ionize gas and form plasma.
- Nitrogen and methane are introduced after reactor reaches steady state.
- Methane dissociates due to plasma, gets deposited on substrate, growth occurs.



Schematic of Plasma Assisted CVD

Advantages of MPCVD over other CVD techniques:

- Energy efficient due to lack of electrodes.
- Stable and reproducible non-isothermal plasmas allow deposition for long time.
- Low temperature synthesis of nanomaterials.
- Potential to be scaled up to larger substrates.

Microplasma for Reconfigurable RF Electronics

Why it is important:

- Unprecedented bandwidth growth on a global scale leads RF engineers to think of creative solutions that move beyond the existing but inadequate “add-one-more-channel” solution to mobile handsets, satellite terminals, and base stations.
- Reconfigurable RF electronics enable total transceiver reconfiguration leading to new functions and optimal utilization of spectral resources at a minimum form factor and cost.
- The next 20-30 years will demand completely reconfigurable RF electronics.
- Existing solutions (solid state, ferroelectrics, MEMS) cannot handle high power and are susceptible to electromagnetic attacks
- Plasmas offer the ultimate platform for novel electronics.

Microplasma for Reconfigurable RF Electronics

Plasmas offer the ultimate platform for reconfigurable RF electronics.

Vision: plasma-based switches, reconfigurable antennas, transistors.

Added benefit: can handle much higher power than semiconductor electronics.

Impact:

- Reconfigurable antennas and amplifiers for future personal mobile devices
- Modern airplanes (e.g. F-22) have ~100 antennas, strongly affecting design
  - Miniaturizing and combining antennas would open new design space

In 1950s, semiconductors have killed the vacuum and gaseous (i.e. plasma) electronics.

The gaseous/vacuum electronics is about to make a [limited] comeback.

Past

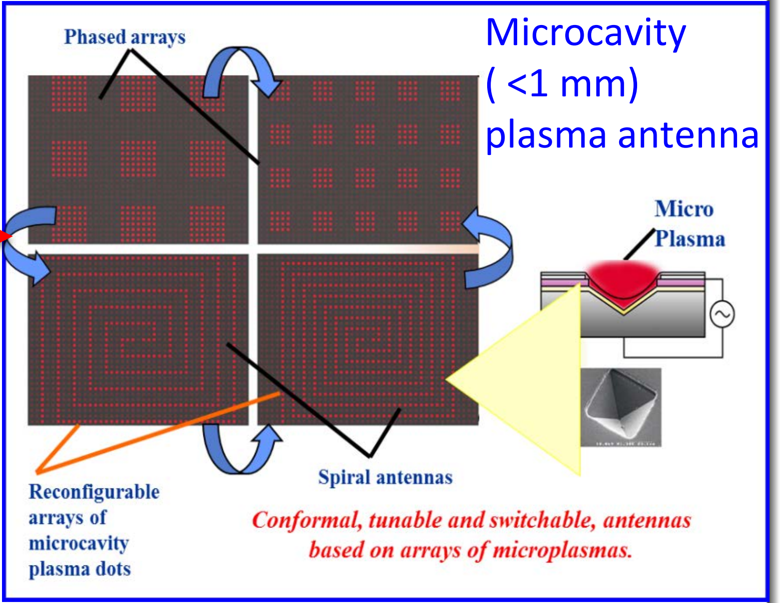
Static antennas

Present

Bulky (1 meter) plasma antenna

http://www.antentop.org/004/plasma.htm

Future



Microcavity (<1 mm) plasma antenna

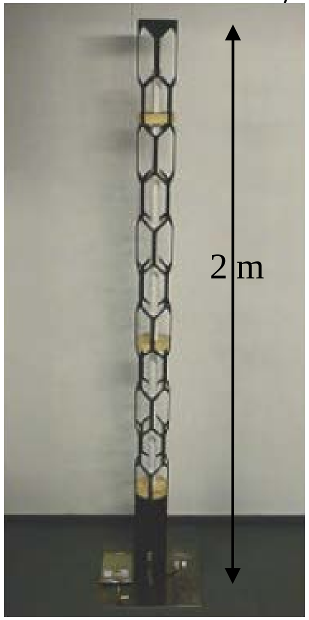
Plasma Antennas

- As any conductor, plasmas can be used as antennas
- Can be rapidly turned on/off (no antenna when plasma is off)
- With microcavity plasmas, plasma antennas can be miniaturized
- Microplasmas incorporated into complex metallic/dielectric antenna structure can be used to reconfigure the antenna
- Lower gain than metallic antennas (due to lower electrical conductivity) – not good
- Reduced cross-coupling between array elements - good
- Lower high-frequency EM noise than metallic antennas (due to low electron collision frequency), thus potentially higher Figure of Merit: Gain/Noise

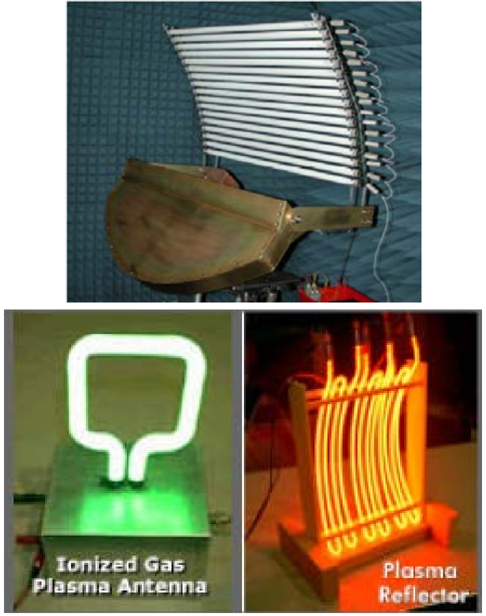
Plasma Antennas: Background

First patent on plasma antennas: J. Hettinger, "Aerial Conductor for Wireless Signaling and Other Purposes," US Patent 1,309,031, issued July 8, 1919 (filed June 4, 1917)

Australian Nat'l University



University of Tennessee



Surface wave driven plasma antenna

- **RF driven, 30 MHz**
- **Argon at 1 Torr**
- **$n_e = 5.3 \cdot 10^{11}$ cm^{-3}, σ=28 S/m**

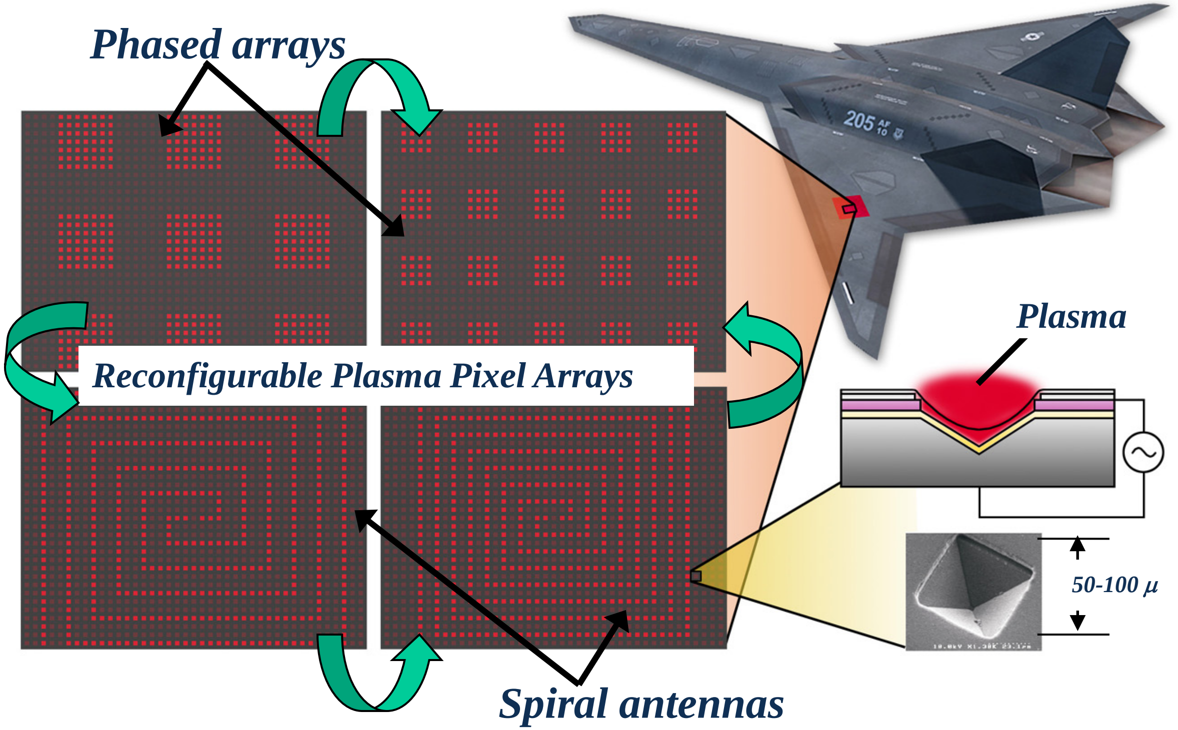
Large, glow discharge plasma antennas

- **500 MHz–20 GHz performance similar to Cu wire**
- **Flexible plastic tubes for mechanical robustness**
- **Switchable**
- **Bulky**

Macroscale discharge antennas: good, but bulky

New Plasma Antennas

New concept: conformal, tunable and switchable, antennas based on surface arrays of microplasmas

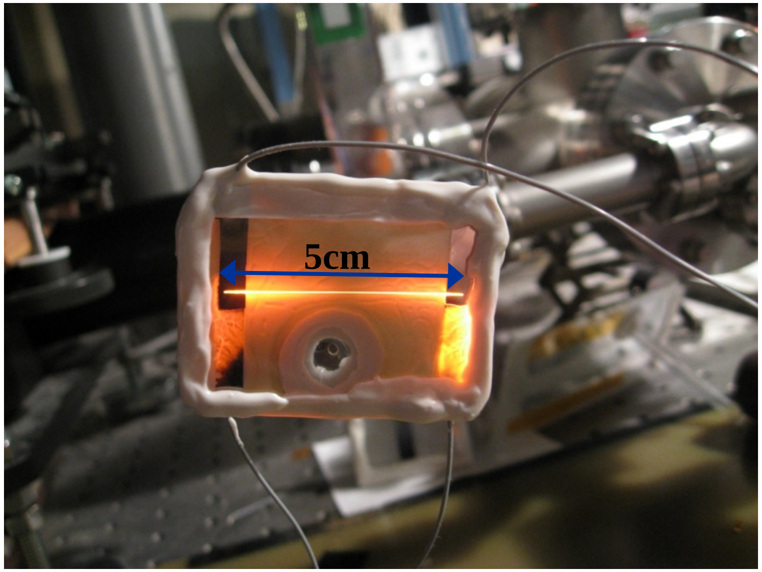


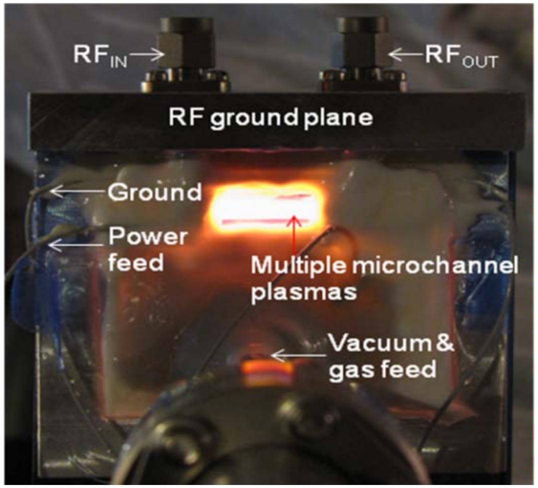
- **Rapid (<1 μs) electronic switching; no antenna when powered off**
- **Frequency-tunable over several octaves – multiple antennas within one aperture**
- **Dramatic (100x in thickness) miniaturization of plasma antennas**
- **Conformal to any surface**
- **Can handle high power (EW)**
- **Multi-element design – phased arrays possible**
- **Lower EM noise than that of metallic antennas**

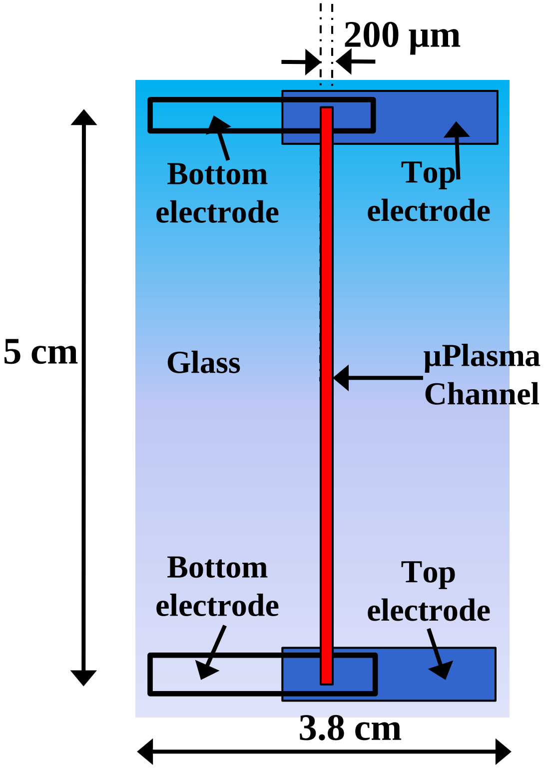
Potential for revolutionary antennas

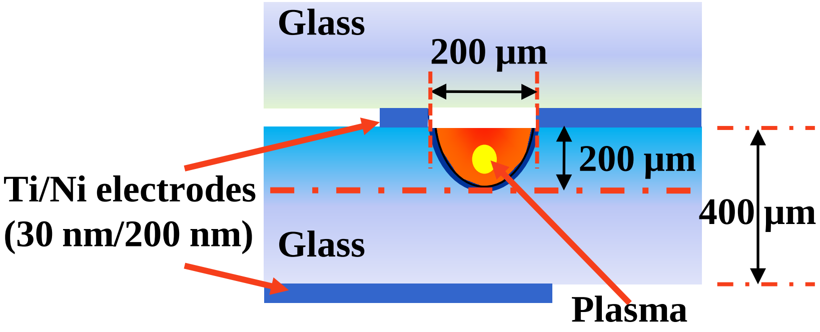
Microchannel Plasma Dipole Antenna

380 Torr Neon, 1.7 kVAC, 20 kHz



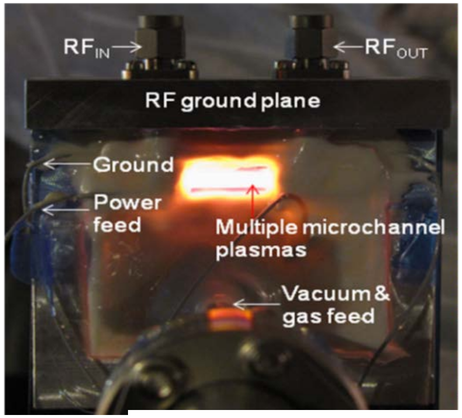






Microplasma Dipole Antenna

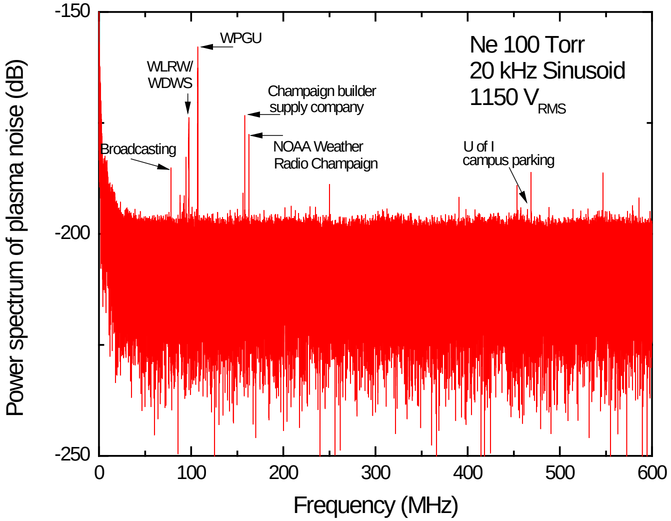
Multichannel plasma devices in glass: antenna reception measurements



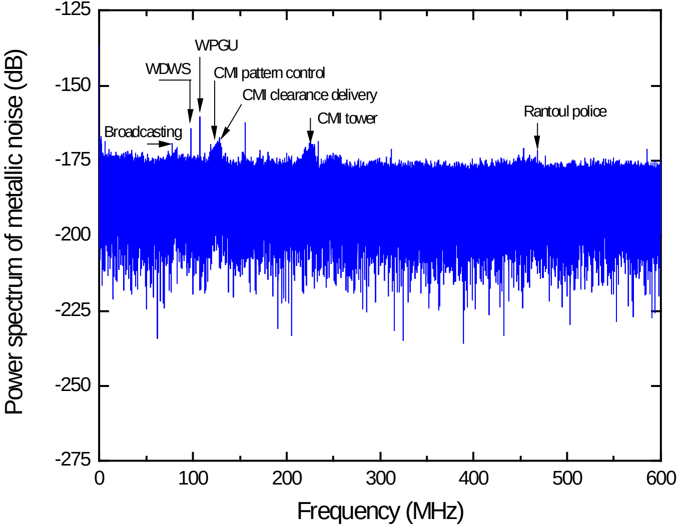
Plasma antenna noise is 23 dB lower than that of copper wire:

- **Low duty cycle and power**
- **Fundamental reasons**
  - **Stochastic noise is determined by charge carrier scattering, but collision frequency in plasma is << that in metal, thus lower noise at high frequencies**

Plasma antenna resolves local FM stations



Copper wire antenna performance



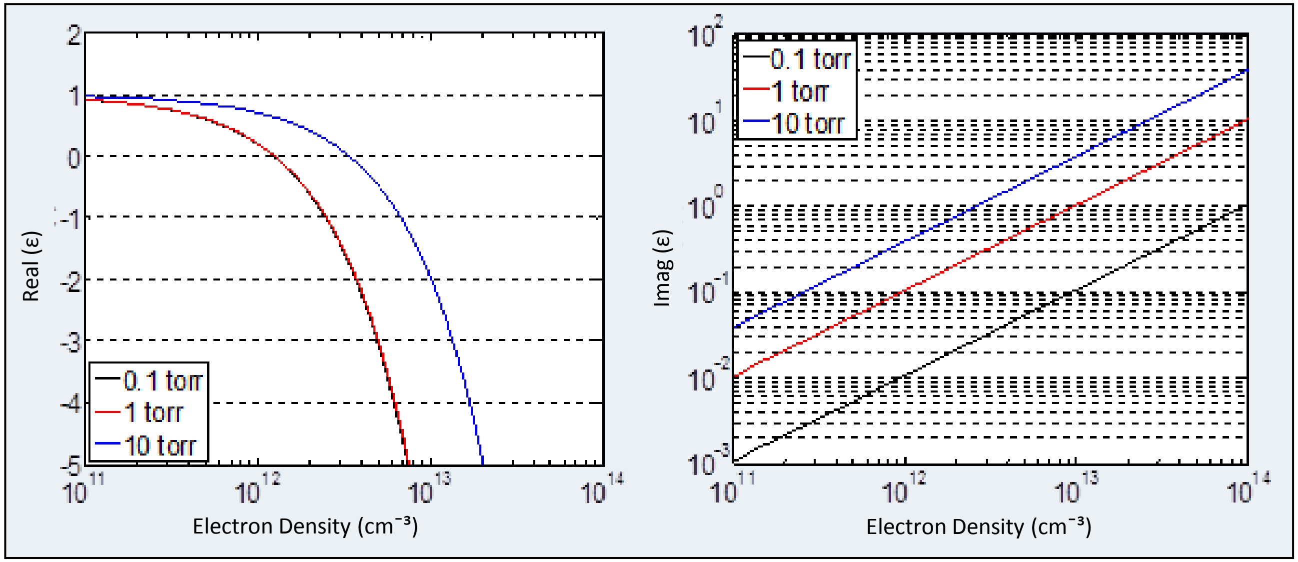
Electrically small μ-plasma antennas: low noise; resolve FM stations

Plasma as Tunable Dielectric

$$\varepsilon_r = \left(1 - \frac{\omega_p^2}{\omega^2 + \nu_m^2}\right) - j \cdot \frac{\nu_m}{\omega} \cdot \frac{\omega_p^2}{\omega^2 + \nu_m^2}$$

The real part of permittivity is always <1 and can be negative! In fact, it can vary from -∞ to 1. Recall that conventional dielectric have ε_r>1. In this regard, plasma is unique.

By varying the gas pressure and the electron density, the collision frequency and the plasma frequency can be changed. Thus, plasma is a tunable dielectric! This can be practically useful.



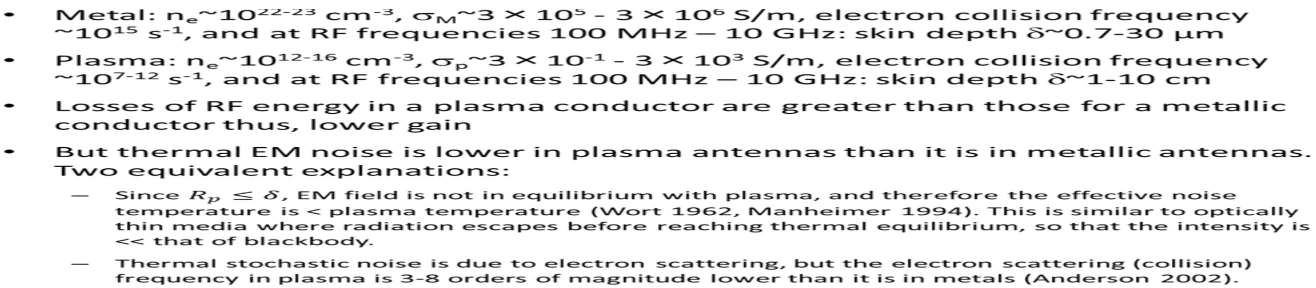
The real (left) and imaginary (right) parts of the electrical permittivity for a wave frequency of 10 GHz. By changing the electron density and gas pressure (argon is assumed), ε' can be tuned from positive to negative, and ε'' can be tuned over four orders of magnitude.

Microplasma Capacitor

$$\varepsilon_r = \left(1 - \frac{\omega_p^2}{\omega^2 + \nu_m^2}\right) - i \cdot \frac{\nu_m}{\omega} \cdot \frac{\omega_p^2}{\omega^2 + \nu_m^2};$$

$$\omega_p = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m}} \text{ - plasma frequency}$$

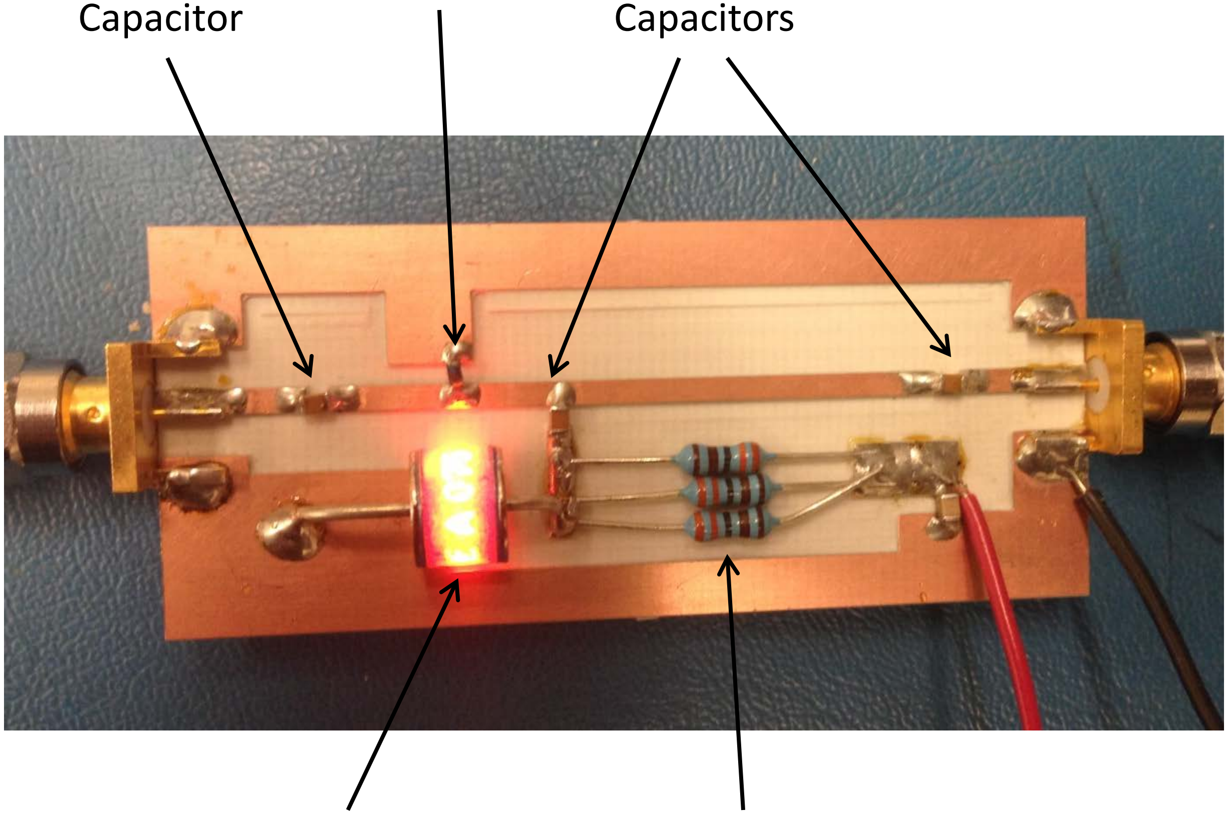
ν_m - electron collision frequency; n_e - electron number density



- Metal: n_e~$10^{22\text{-}23}$ cm^{-3}, σ_M~3×10^5 - 3×10^6 S/m, electron collision frequency ~10^{15} s^{-1}, and at RF frequencies 100 MHz – 10 GHz: skin depth δ~0.7-30 μm
- Plasma: n_e~$10^{12\text{-}16}$ cm^{-3}, σ_p~3×10^{-1} - 3×10^3 S/m, electron collision frequency ~$10^{7\text{-}12}$ s^{-1}, and at RF frequencies 100 MHz – 10 GHz: skin depth δ~1-10 cm
- Losses of RF energy in a plasma conductor are greater than those for a metallic conductor thus, lower gain
- But thermal EM noise is lower in plasma antennas than it is in metallic antennas. Two equivalent explanations:
  - Since $R_p \leq \delta$, EM field is not in equilibrium with plasma, and therefore the effective noise temperature is < plasma temperature (Wort 1962, Manheimer 1994). This is similar to optically thin media where radiation escapes before reaching thermal equilibrium, so that the intensity is << that of blackbody.
  - Thermal stochastic noise is due to electron scattering, but the electron scattering (collision) frequency in plasma is 3-8 orders of magnitude lower than it is in metals (Anderson 2002).

Plasma Tunable Parallel LC Resonator

Preliminary experiments:
A. Semnani, D. Peroulis,
(Purdue)



DC Block
Capacitor

120 nH
Inductor

DC Block
Capacitors

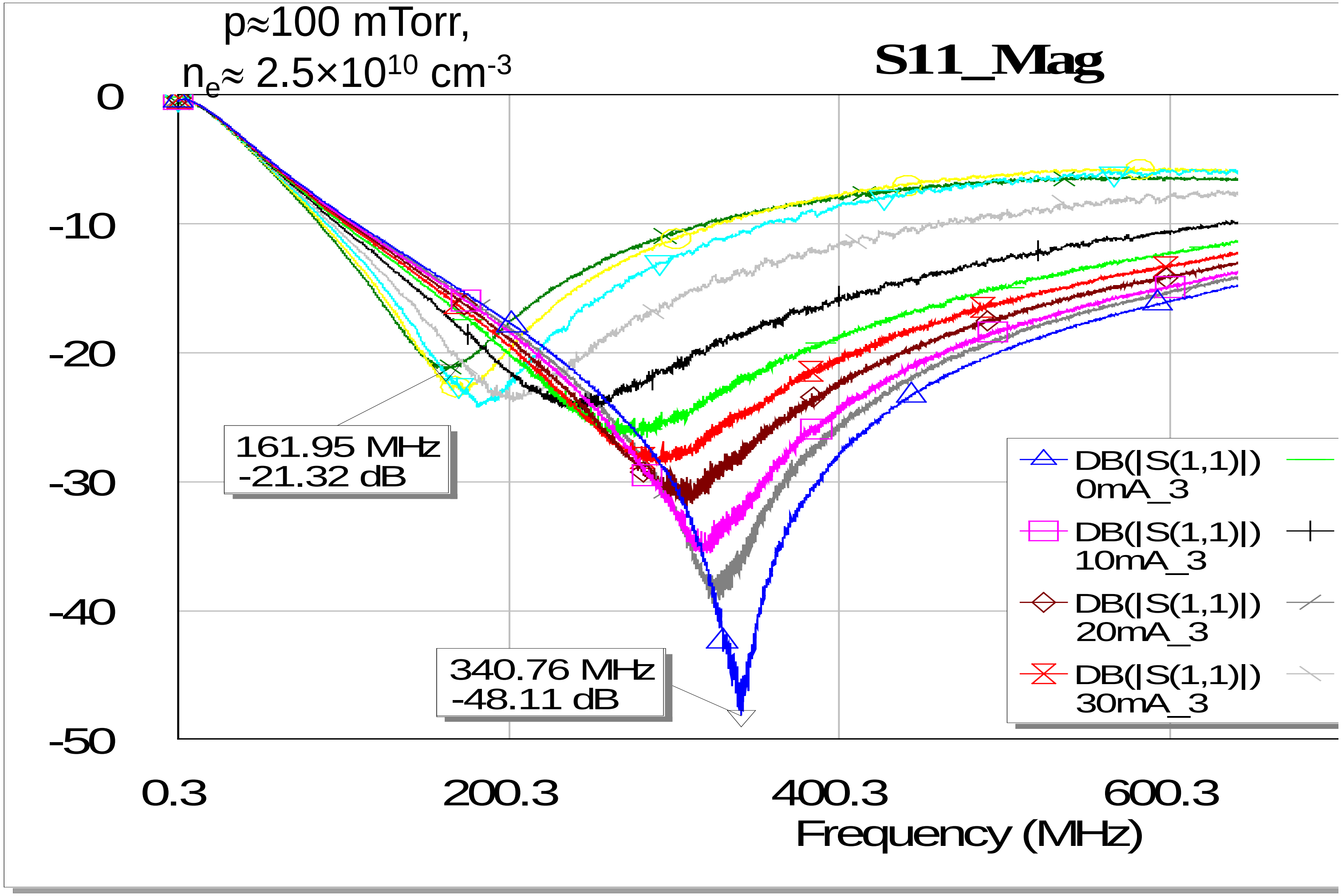
Gas Discharge Tube (GDT)
As Tunable Capacitor

Ballast
Resistors

Plasma Tunable Parallel LC Resonator

Measured change in resonant frequency (S11) from 340 MHz down to 162 MHz (52%)
by increasing the GDT current up to 90 mA.

Preliminary experiments:
A. Semnani, D. Peroulis,
(Purdue)



p≈100 mTorr,
$n_e \approx 2.5\times10^{10}$ cm^{-3}

Microplasma for Tunable RF Systems

- For low loss tangent, $\tan\delta \approx \frac{\sigma\omega}{\varepsilon_0 \omega_p^2} = \frac{\nu_m}{\omega} \leq 10^{-3}$, and also for low EM noise, need very low collision frequency, thus low pressure (<10 mTorr)
- Need electron density >10^{11} cm^{-3} for tunability in RF regime
- How can a microplasma with substantial electron density be sustained at p≤10 mTorr and d≤100 μm, i.e. at pd≤0.0001 cm × Torr???
- Additionally, it would be desirable to operate the microplasma at low voltage (<100 V).
- But the basic physics of electron impact ionization dictates high voltages (100s and 1000s V) and pd≥1 cm × Torr
- Need completely new way of plasma generation

New Plasma Generation Principle

- Electrons are generated at the cathode by field emission (FE) from Carbon Nanotubes (CNT) or similar emitters
- Ions are independently generated in tunneling field ionization (FI) at atomically-sharp tips of protrusions from the anode
- Electrons and ions move in the opposite directions, mix, and create a plasma
- Low pressure results in collisionless (ballistic) motion with no electron-impact ionization
- Plasma in general is not quasineutral
- Space charge affects FE and FI (coupling)

Field Emission and Field Ionization

Fowler-Nordheim Field Emission

$$j_{FN} = \frac{A_{FN}\beta^2 E^2}{\phi_w t^2(y)} \exp\left[-\frac{B_{FN}\phi_w^{\frac{3}{2}} v(y)}{\beta E}\right]$$

j_{FN} = field emission current density

E = electric field

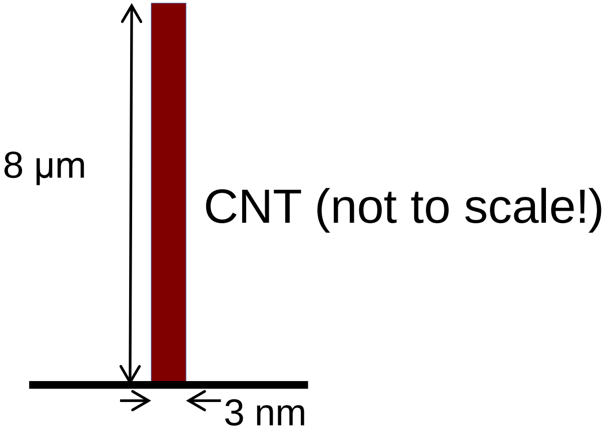
ϕ_w = work function

β = field enhancement factor

A_{FN}, B_{FN} = Fowler-Nordheim constants

$v(y) \approx 0.95 - y^2$; $t^2 \approx 1.1$

$$y = 3.79x10^{-4}\sqrt{\beta E}/\phi_w$$

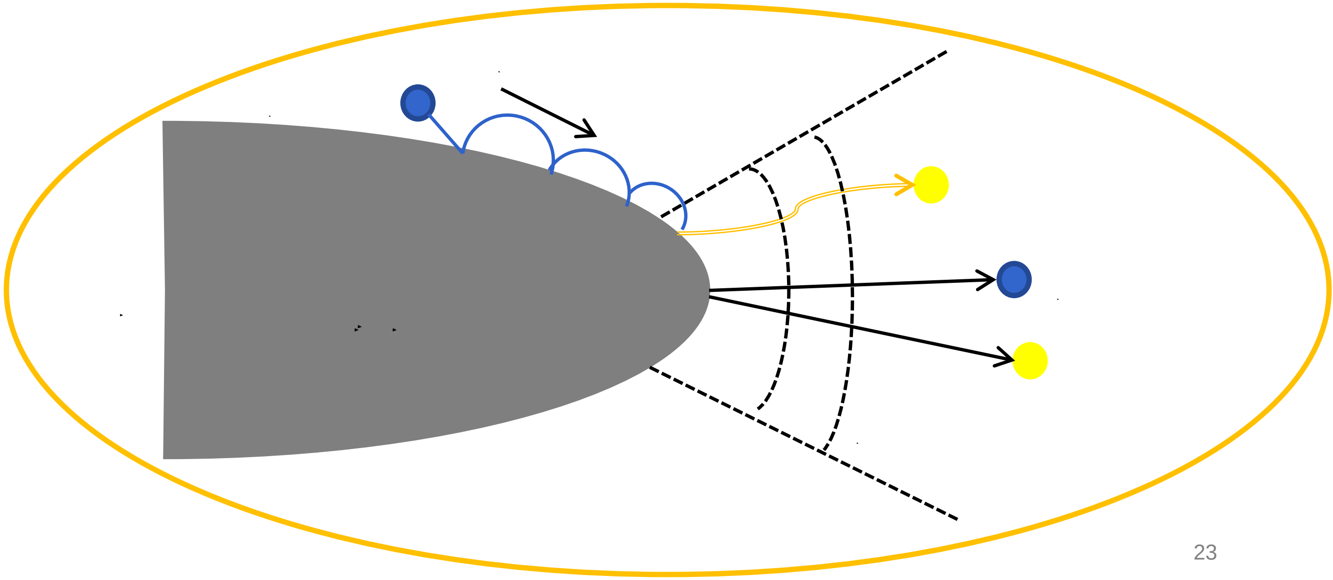


Field enhancement factor

β = H/(0.7r) (~aspect ratio)

Field ionization:

(Used in atom-probe microscopy and mass spectrometry)

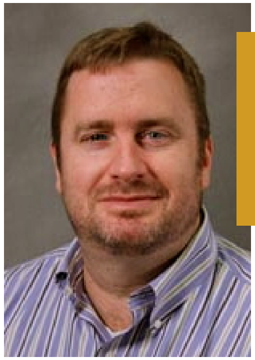


Building Purdue Plasma Preeminent Team

Sergey Macheret (AAE)
Plasma theory
Nanosecond-pulse plasma sources
Applications: from **plasma antennas** to **aerodynamics**

Alina Alexeenko (AAE)
Plasma **modeling**
Plasma material processing
Microplasma

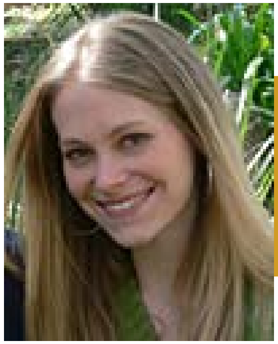
Ahmed Hassanein (NE)
Plasma-materials interactions



Tim Fisher (ME)
Plasma CVD
Nanofabrication

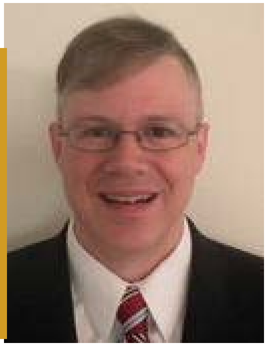
Kevin Keener (ABE)
High-V cold plasma
Food safety
Medical devices

Robert Lucht (ME)
Laser diagnostics, including plasma-enhanced combustion and CVD

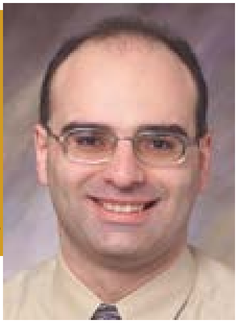


Sally Bane (AAE)
Plasma-assisted combustion and
Aero **flow control**

Allen Garner (NE)
Pulsed power,
Biomedical applications



Dimitri Peroulis (ECE)
Microplasma for reconfigurable RF
RF/THz electronics



Jonathan Poggie (AAE) – formerly USAF
Modeling of plasmas and plasma aerodynamics

Alex Shashurin (AAE)
Plasma propulsion, microplasmas, diagnostics, 2D materials