INDUSTRIAL APPLICATIONS OF LOW TEMPERATURE PLASMA PHYSICS

PART B: VUGRAPHS

Francis F. Chen

Electrical Engineering Department

PPG- 1528 November, 1994

Vugraphs from a review paper presented at the Annual Meeting of the APS Division of Plasma Physics, Minneapolis, MN on Nov. 11, 1994. The text in Part A will be published in Physics of Plasmas.

We are indebted to the following colleagues for lending their vugraphs for this talk:

John Conrad	Los Alamos National Lab
David Graves	UC Berkeley
Kevin Ilcisin	Technical Visions, Inc.
Tsu-jae King	Xerox Palo Alto Research Ctr.
Mark Kushner	Univ. of Illinois
Ian Morey	Lam Research Corp.
Emil Pfender	Univ. of Minnesota
Bob Piejak	Osram Sylvania
Don Rej	Los Alamos National Lab
Gary Selwyn	Los Alamos National Lab
Vahid Vahedi	Lawrence Livermore Lab
John Whealton	Oak Ridge National Lab
Claude Woods	Univ. of Wisconsin

.... and to the following, whose vugraphs were used unbeknownst to them!

Rick Gottscho	AT&T Bell Labs
Jim McVittie	Stanford Univ.
C.R. Viswanathan	UCLA

Theme

- There is a new field in plasma physics that is rapidly growing.
- This field comes along just at the right time--when resources for basic research are dwindling.
- This field will have a larger impact on society in the near future than other fields in plasma physics.
- Work in this field will bear fruit within our lifetimes.
- This is the field of low-temperature plasma applications. In plasma processing of semiconductors alone, the number of papers appearing monthly exceeds those in fusion at its peak.
- Partially ionized plasmas have many species and are collisional, but they may be no more complicated than plasmas in toroidal magnetic fields.
- Gas discharges have progress beyond the stage of black magic and poses intellectual challenges for the skills that we have developed for fully ionized plasmas.

Industrial Applications of Low-Temperature Plasma Physics

Francis F. Chen, UCLA

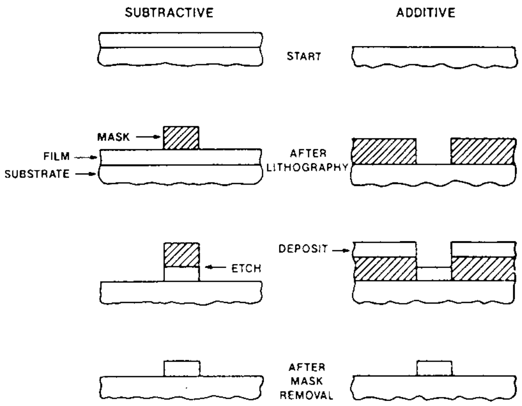
APS-DPP Meeting, Minneapolis, 1994

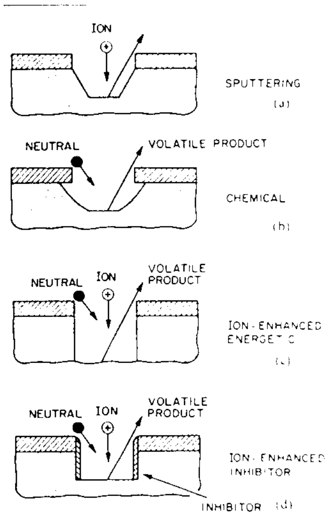
General Areas

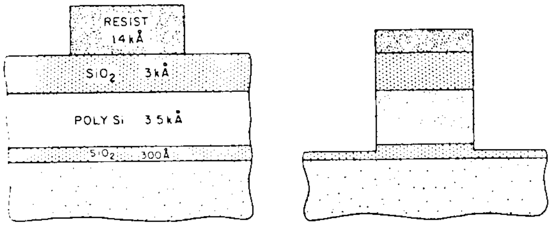
- Semiconductor processing
- Flat panel displays
- Ion implantation
- Plasma polymerization and coating
- Thermal plasmas
- Basic physics of L.T. plasmas

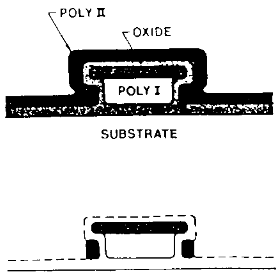
Semiconductor Processing

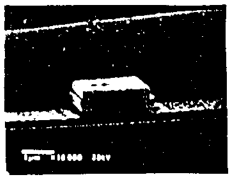
- ➢ Physical mechanisms in etching
- ➢ Plasma sources
- ➢ Modeling
- ➢ Problems at the forefront
- ➢ Diagnostics and sensors
- ➢ PECVD, PVD, cleaning, stripping







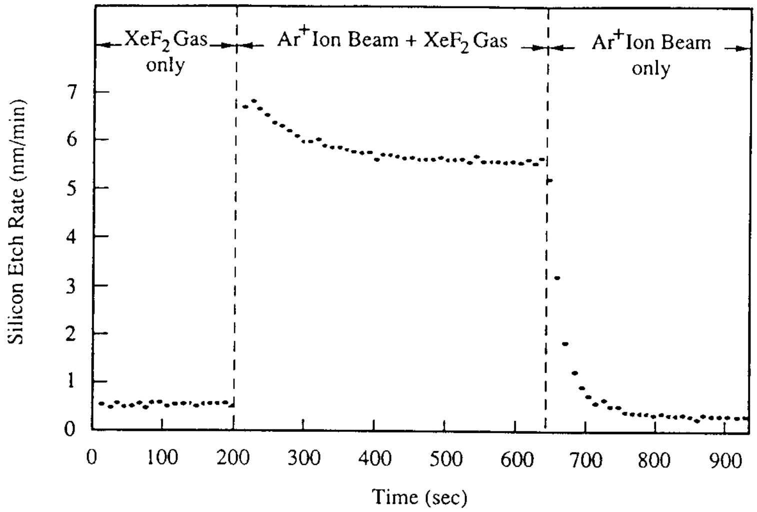




Role of the plasma in etching

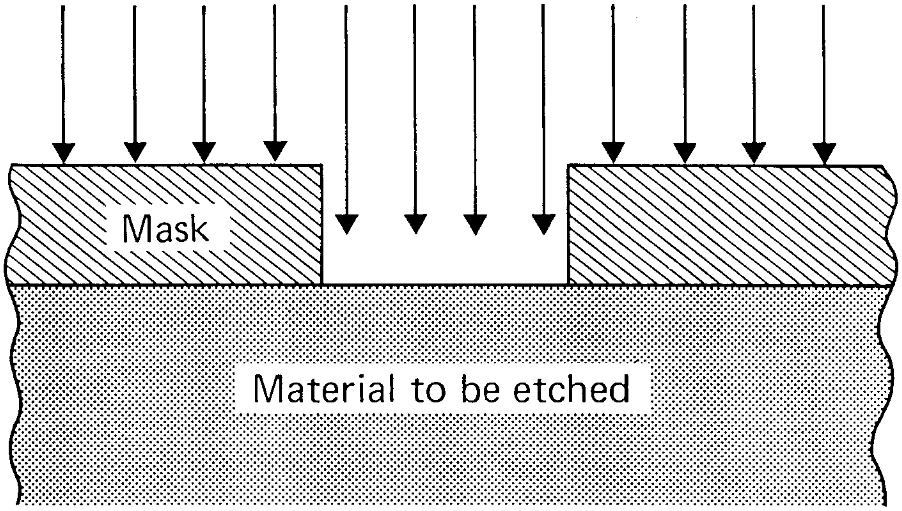
- Plasma electrons dissociate molecules to produce neutral **Cl** or **F**, which etch.
- Plasma ions prepare the surface, greatly increasing the etch rate .
- Plasma ions give directionality for anisotropic etching.
- The plasma itself need not touch the wafer.

Coburn's famous graph



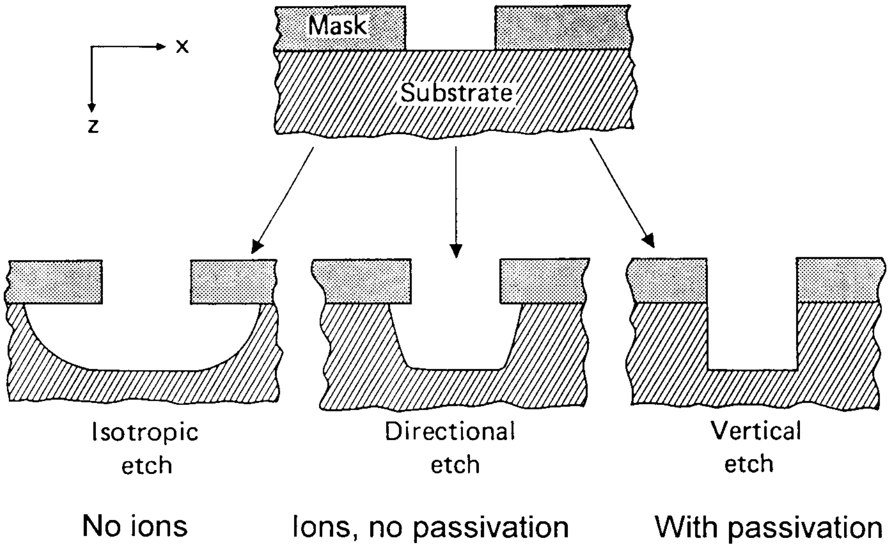
J.W. Coburn and H.F. Winters, J. Appl. Phys. **50**, 3189 (1979).

Ions accelerated in a planar sheath provide anisotropy



A.J. van Roosmalen, J.A.G. Baggerman, and S.J.H. Brader, *Dry Etching for VLSI* (Plenum, 1991).

Need for profile control



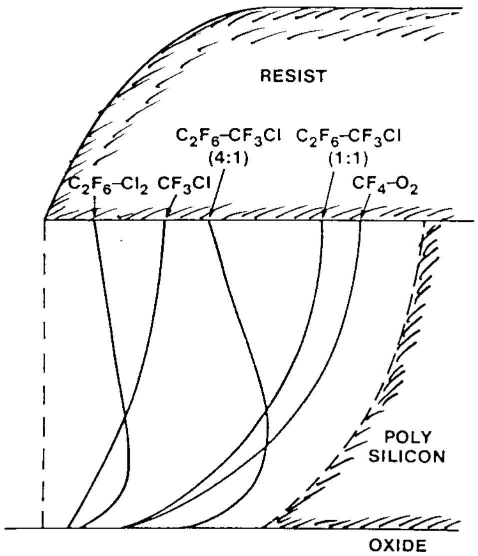
No ions

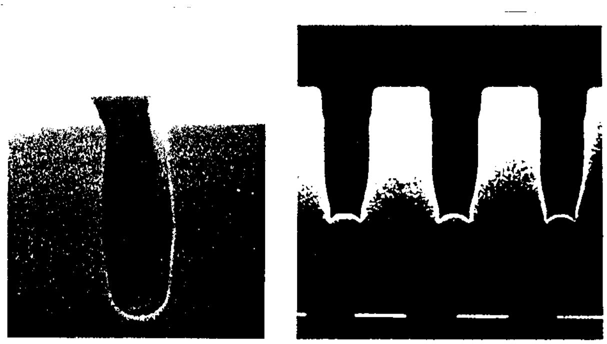
Ions, no passivation

With passivation

A.J. van Roosmalen, J.A.G. Baggerman, and S.J.H. Brader, *Dry Etching for VLSI* (Plenum, 1991).

Straight sidewalls depend on a delicate balance between ion assisted etching and passivation.





D.M. Manos and D.L. Flamm, *Plasma Etching* (Academic, 1989).
A.J. van Roosmalen, J.A.G. Baggerman, and S.J.H. Brader, *Dry Etching for VLSI* (Plenum, 1991).

Materials to be etched

- Silicon
  - monocrystalline, **poly**crystalline
  - undoped, doped
- Dielectric
  - SiO_2, SiN_x
- Metal
  - Aluminum; tungsten, molybdenum
- Photoresist

Etching of silicon

$Cl_2 \rightarrow 2Cl$

$Si + 2\,Cl \rightarrow SiCl_2$

$SiCl_2 + 2\,Cl \rightarrow SiCl_4 \quad (\textit{gas})$

$n\,SiCl_2 \rightarrow [SiCl_2]_n \quad (\textit{polymer})$

To increase polymerization, add H_2:

$SiCl_4 + 2\,H \rightarrow SiCl_2 + 2\,HCl$

Oxide etch

$CF_4 \rightarrow 2\,F + CF_2 \quad (\textit{monomer})$

$SiO_2 + 4F \rightarrow SiF_4 + 2\,O \quad (\textit{gases})$

$SiO_2 + 2\,CF_2 \rightarrow SiF_4 + 2\,CO \quad (\textit{gases})$

Meanwhile,

$Si + 4F \rightarrow SiF_4$

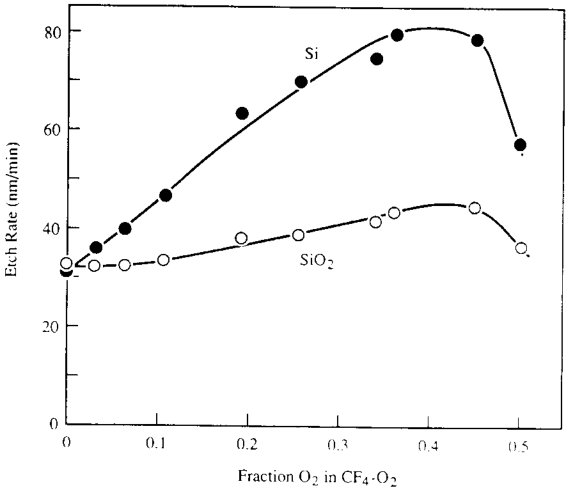
$Si + 2CF_2 \rightarrow SiF_4 + 2C$

Adding O_2 increases the Si etch rate relative to SiO_2

$$O_2 + F \rightarrow FO_2$$

$$FO_2 + F \rightarrow F_2 + O_2$$

(Decreases free fluorine)

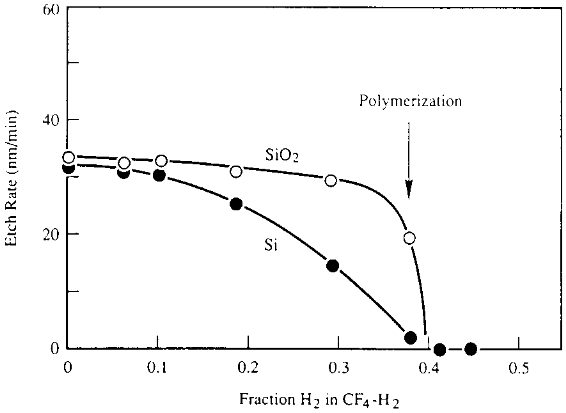


A.J. van Roosmalen, J.A.G. Baggerman, and S.J.H. Brader, *Dry Etching for VLSI* (Plenum, 1991).

Adding H_2 decreases the Si etch rate relative to SiO_2

$$H_2 \rightarrow 2H$$

$$H + F \rightarrow HF \quad \textit{(stable)}$$



With too much H2, a polymer forms, and the sidewalls are passivated. Ion bombardment removes the polymer from the bottom of the trench, allowing straight walls. There is thus a delicate balance between selectivity and etch rate.

A.J. van Roosmalen, J.A.G. Baggerman, and S.J.H. Brader, *Dry Etching for VLSI* (Plenum, 1991).

Etching Aluminum & Resist

Aluminum forms an oxide layer with O_2 from walls:

$$4\,Al + 3\,O_2 \rightarrow 2\,Al_2O_3$$

After this is etched off in "incubation" period, then

$$2\,Al + 3\,Cl_2 \rightarrow Al_2Cl_6$$ (This evaporates slowly)

Photoresist: Let R_nH be an organic polymer. Add O_2 & CF_4:

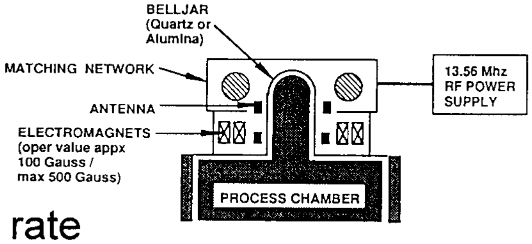
$$R_nH + F \rightarrow R_n + HF$$

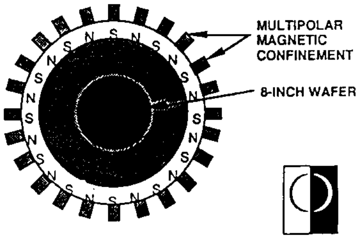
$$R_n + O \rightarrow R_{n-m} + R_mO$$

Forefront topics: VLSI etch

- Dense plasma sources
- Micro-loading
- Particulates (dust)
- Device damage
- Electrostatic chucks
- Neutral beam etching
- Low ε dielectrics

Features of an ideal source



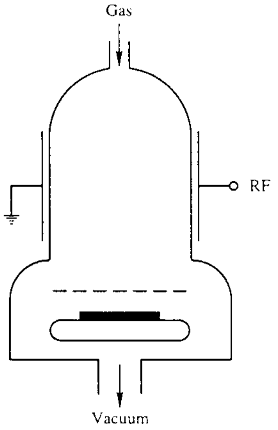


- Uniformity over large area
- Simplicity and compactness
- High density, etch and deposition rate
- Low pressure, high efficiency
- Straight ion orbits, controllable energy
- Low damage: no fast electrons
- Good selectivity
- Benign materials

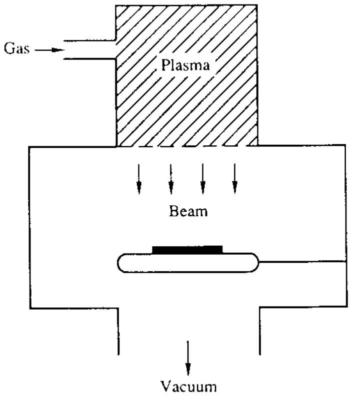
Plasma Sources

- RIE (Reactive Ion Etcher)
- ECR (Electron Cyclotron Resonance)
- TCP (Transformer Coupled Plasma)
- RFI (RadioFrequency Inductive)
- Helicon
- ICP (Inductively Coupled Plasma)

Remote-plasma Sources



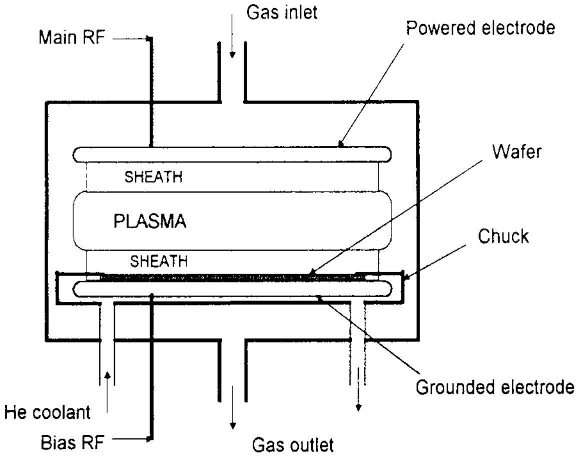
Downstream reactor



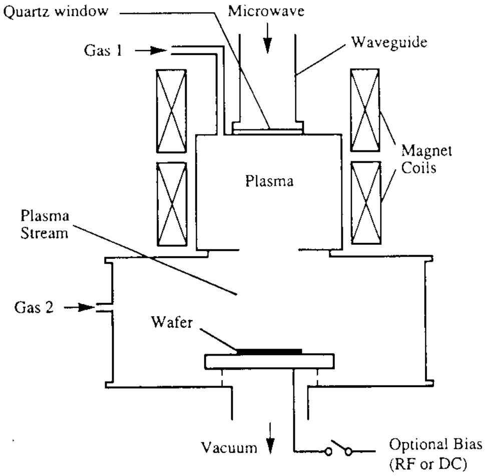
Ion beam reactor

A.J. van Roosmalen, J.A.G. Baggerman, and S.J.H. Brader, *Dry Etching for VLSI* (Plenum, 1991).

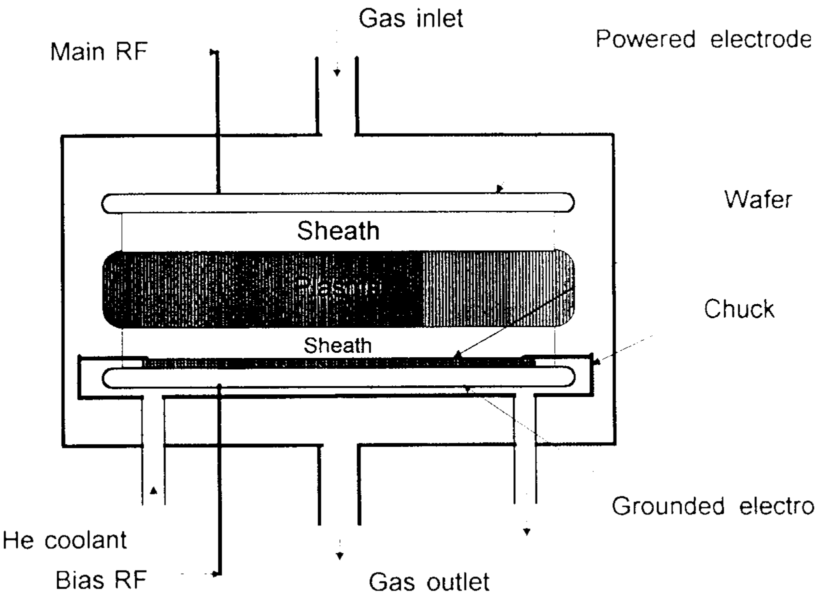
“Standard” plasma sources

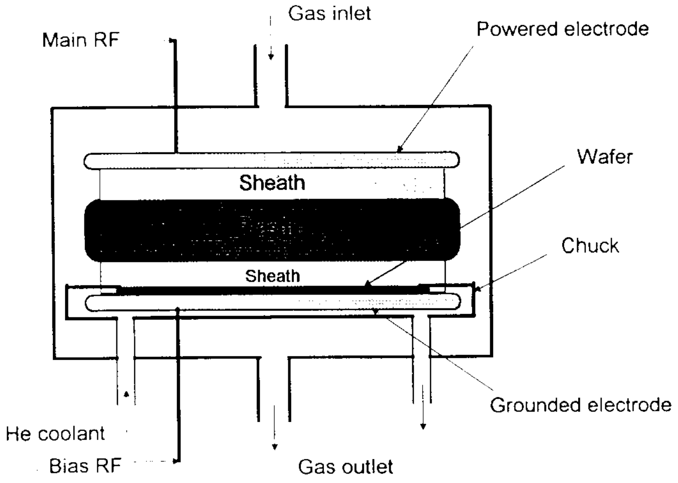


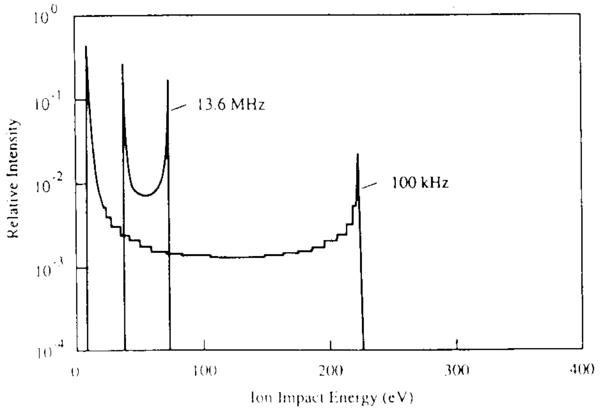
Parallel-plate capacitive discharge (RIE)



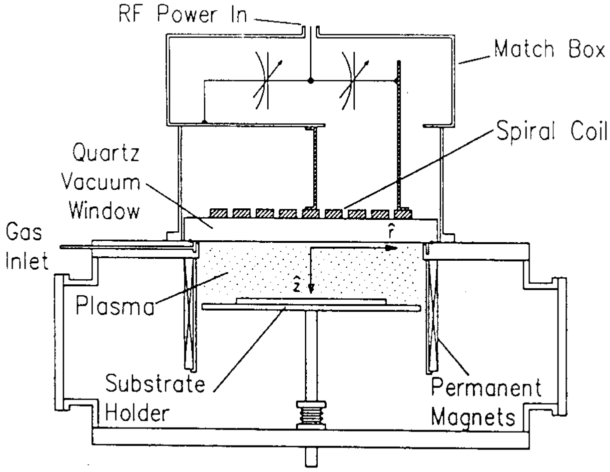
Electron cyclotron resonance discharge (ECR)


Gas inlet
Main RF
Powered electrode
Wafer
Sheath
Plasma
Chuck
Sheath
Grounded electro
He coolant
Bias RF
Gas outlet

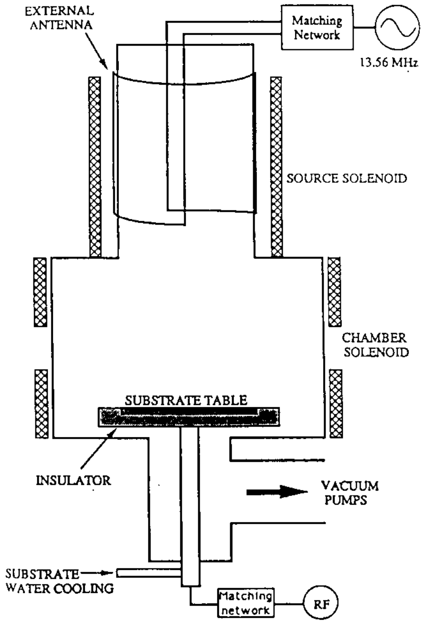

Gas inlet
Main RF
Powered electrode
Wafer
Sheath
Plasma
Chuck
Sheath
Grounded electrode
He coolant
Bias RF
Gas outlet


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Relative Intensity
13.6 MHz
100 kHz
0
100
200
300
400
Ion Impact Energy (eV)

Inductive plasma sources



RFI or TCP source



Helicon wave source

U.S. Patent Aug. 14, 1990 Sheet 1 of 3 4,948,458

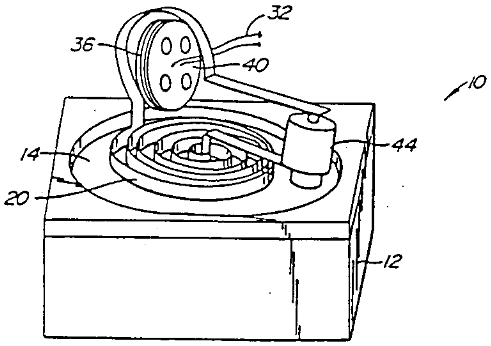


FIG._1.

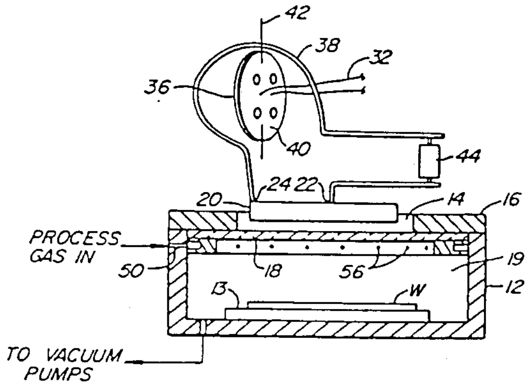
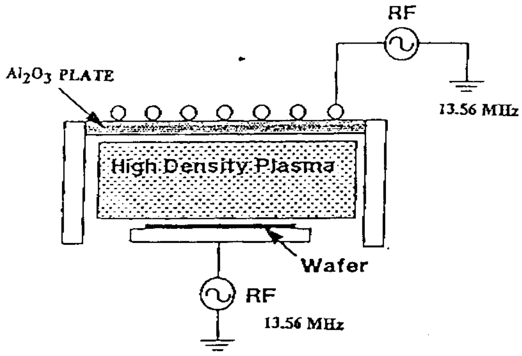


FIG._2.

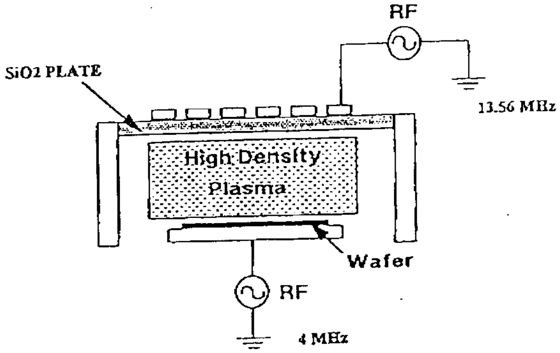
TCP Source Differentiation

TCP Poly, Metal



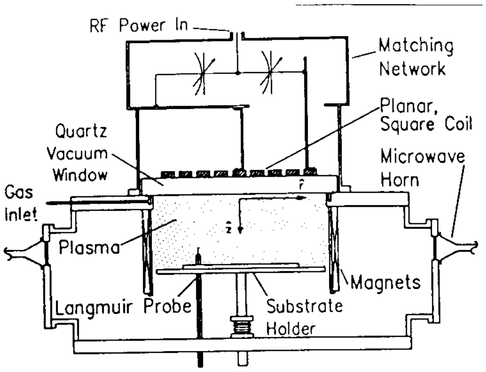
- ribbon coil
- high frequency bias
- ceramic/anodized chamber surface

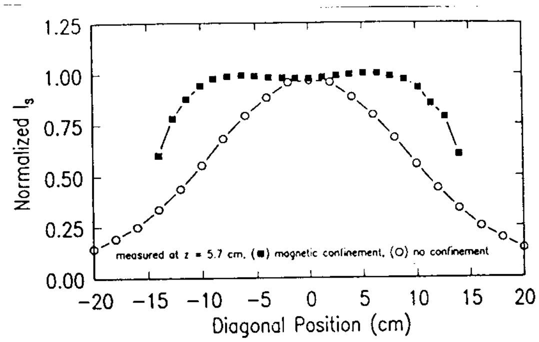
TCP Oxide



- flat coil
- low frequency bias
- dielectric chamber surface

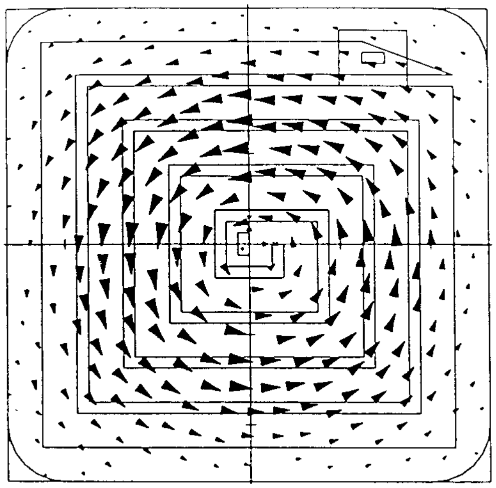
RFI plasma measurements 1

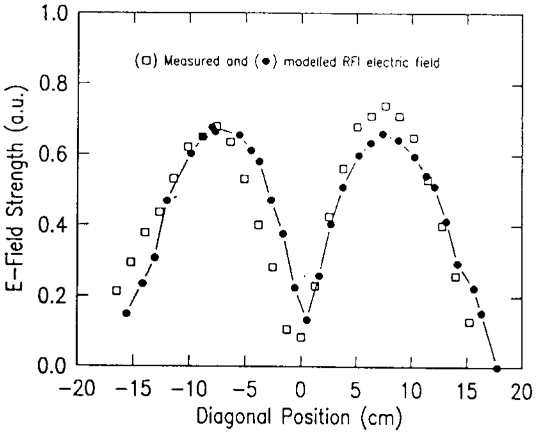




J. Hopwood, C.R. Guarnieri, S.J. Whitehair, and J.J. Cuomo, JVSTA **11**, 147 and 152 (1993).

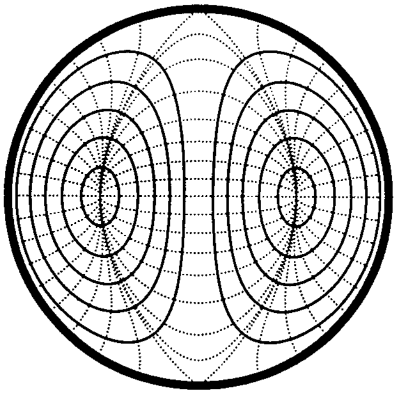
RFI plasma measurements 2

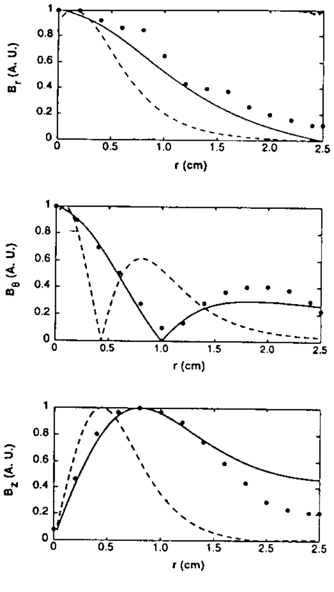




J. Hopwood, C.R. Guarnieri, S.J. Whitehair, and J.J. Cuomo, JVSTA **11**, 147 and 152 (1993).

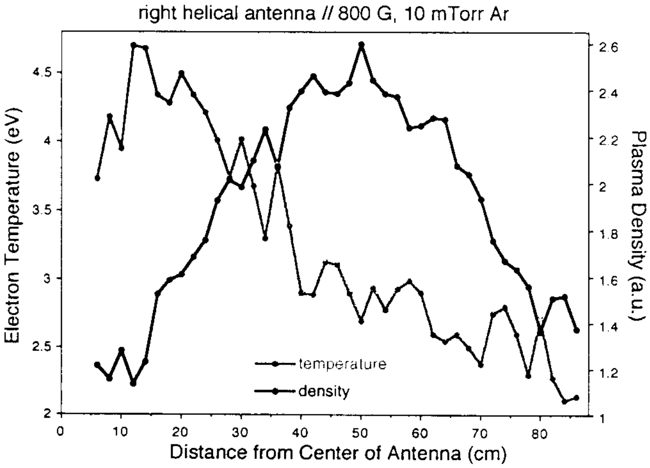
Helicon measurements 1

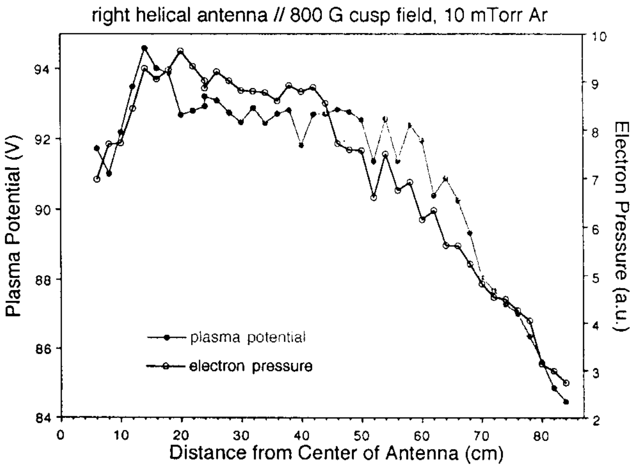




M. Light and F.F. Chen, submitted to Phys. Fluids (1994).

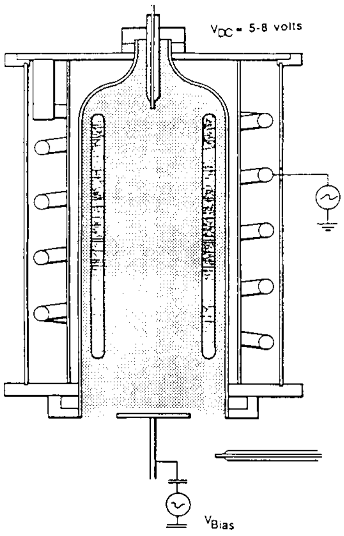
Helicon measurements 2


right helical antenna // 800 G, 10 mTorr Ar

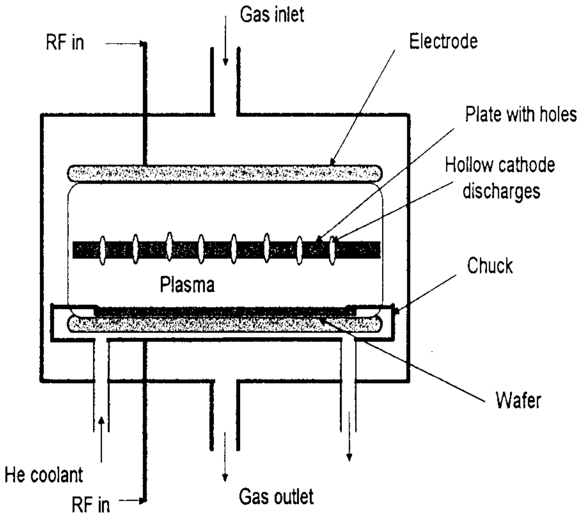

right helical antenna // 800 G cusp field, 10 mTorr Ar

I.D. Sudit, M. Light, and F.F. Chen, submitted to Phys. Fluids (1994).

Other plasma sources

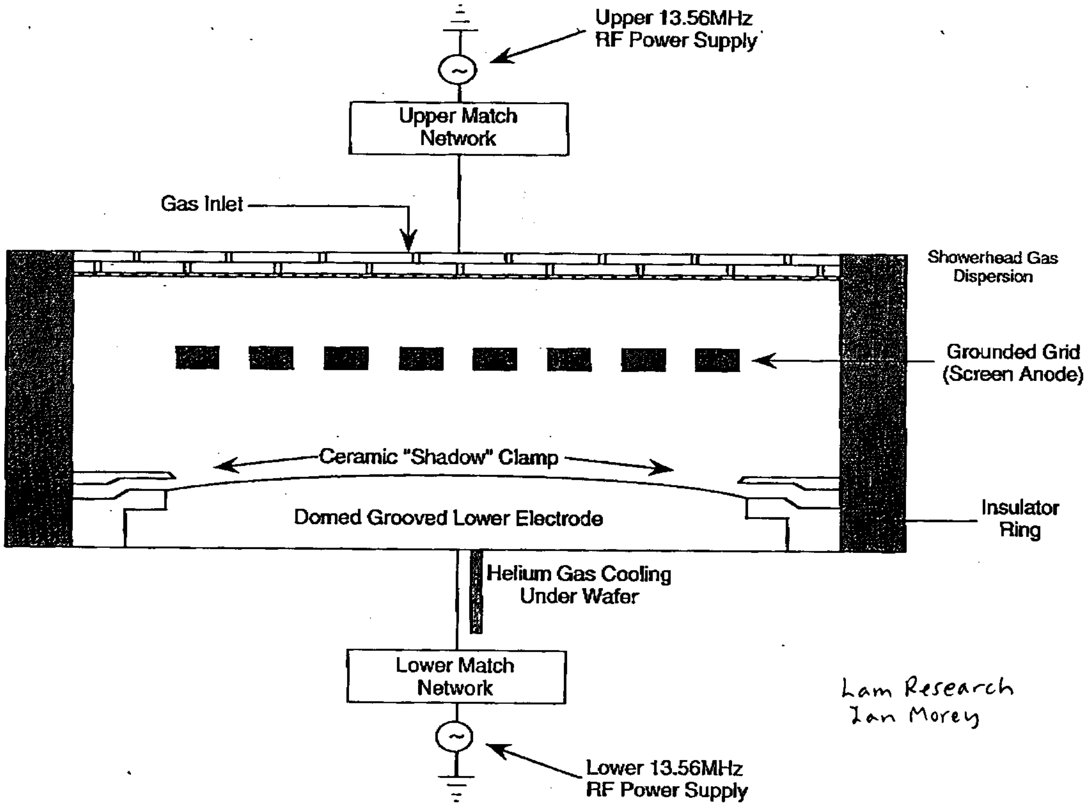


Inductively coupled or helical resonator source



"Hollow cathode" parallel plate source

Oxide 9500 Chamber Configuration



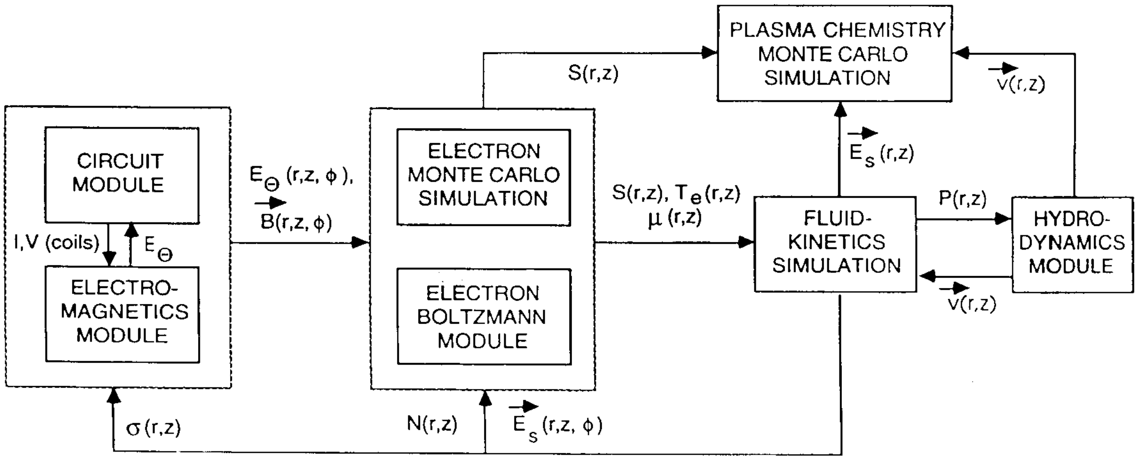
Lam Research
Ian Morey

---

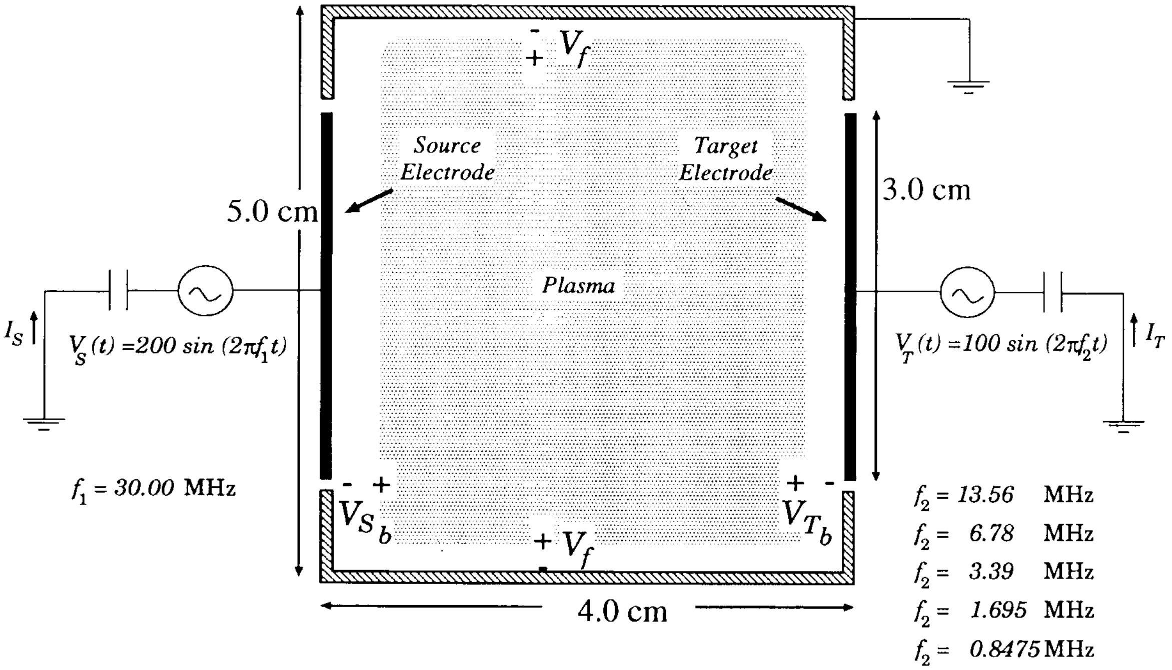
time out for...

Computer modeling

- The hybrid equipment model iteratively combines electromagnetic, electron kinetic, plasma chemistry and hydrodynamic modules.

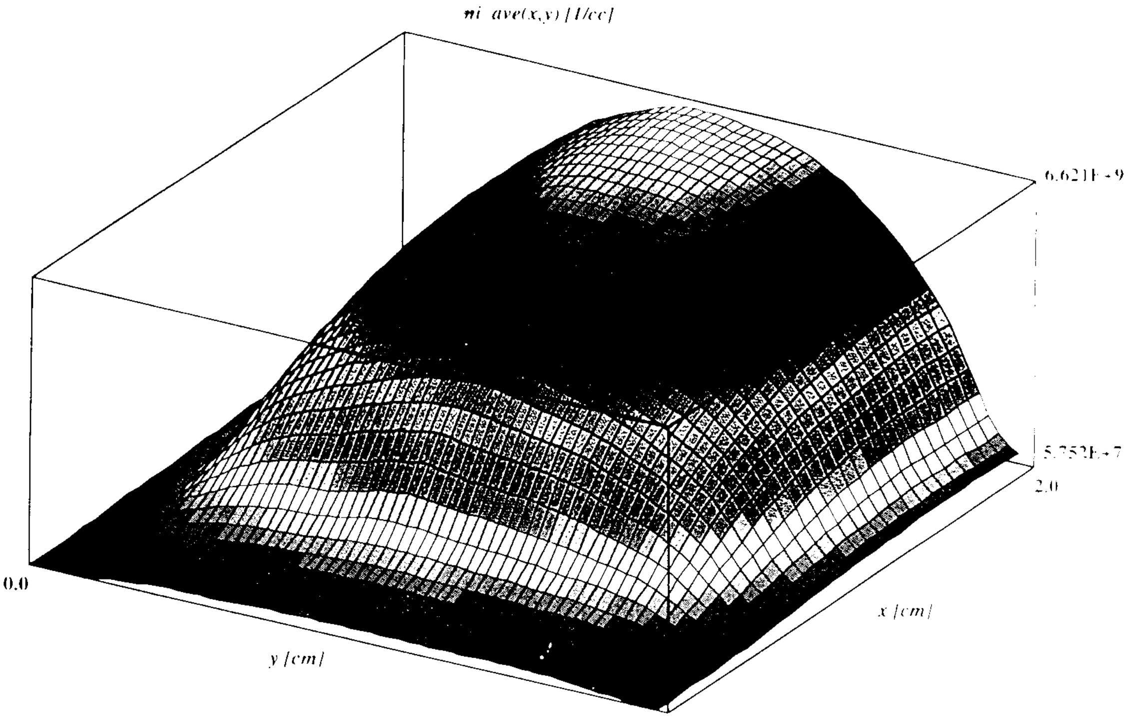


Source: Mark Kushner



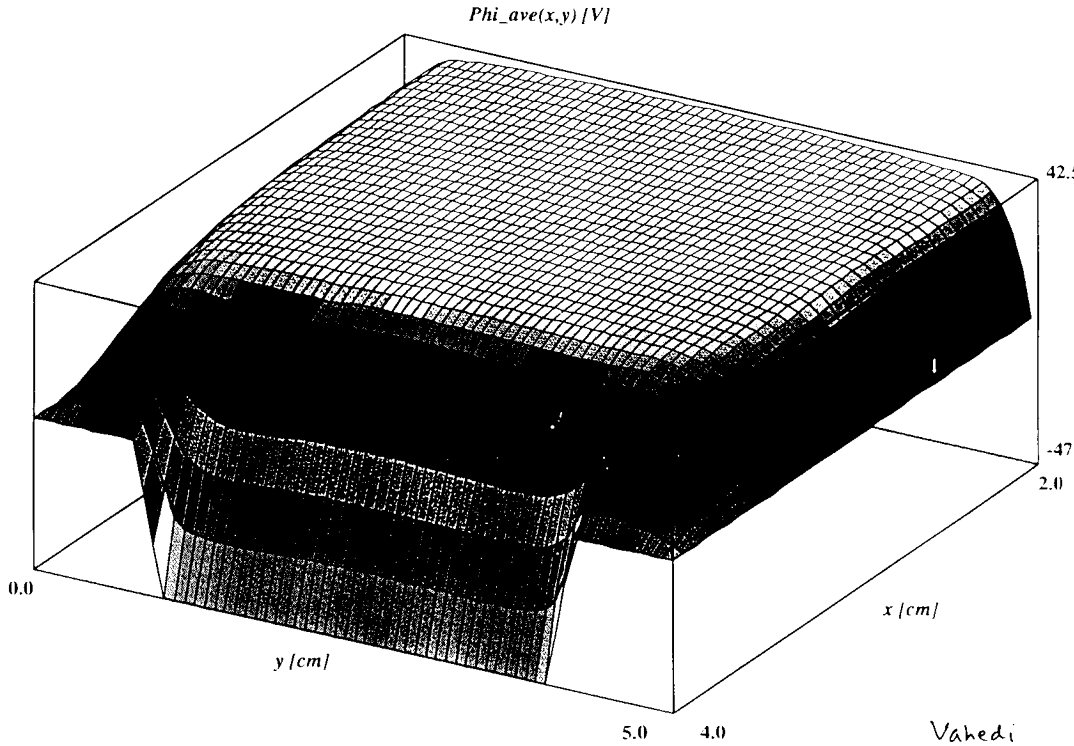
Vahid Vahedi, LLNL

Time-averaged ion density in argon (f bias = 0.8475 MHz, p = 10 mTorr, V = 100 V



Vahid Vahedi
LLNL

Time-avegared potential in argon (f_bias = 0.8475 MHz, p = 10 mTorr, V = 100 V)

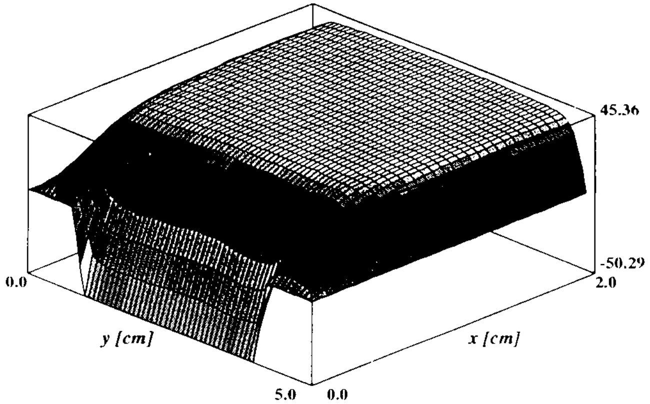


Vahedi

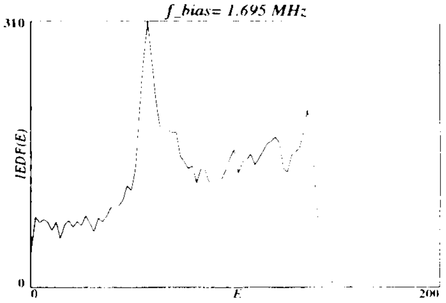
2D Characterization of RF Biased Targets Using PIC-MCC Simulations

(Frequency dependence of IEDFs in an argon plasma at p = 10 mTorr)

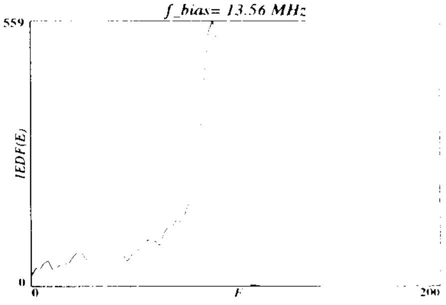
Phi_ave(x,y) [V] (f_bias = 13.56 MHz)



f_bias= 1.695 MHz

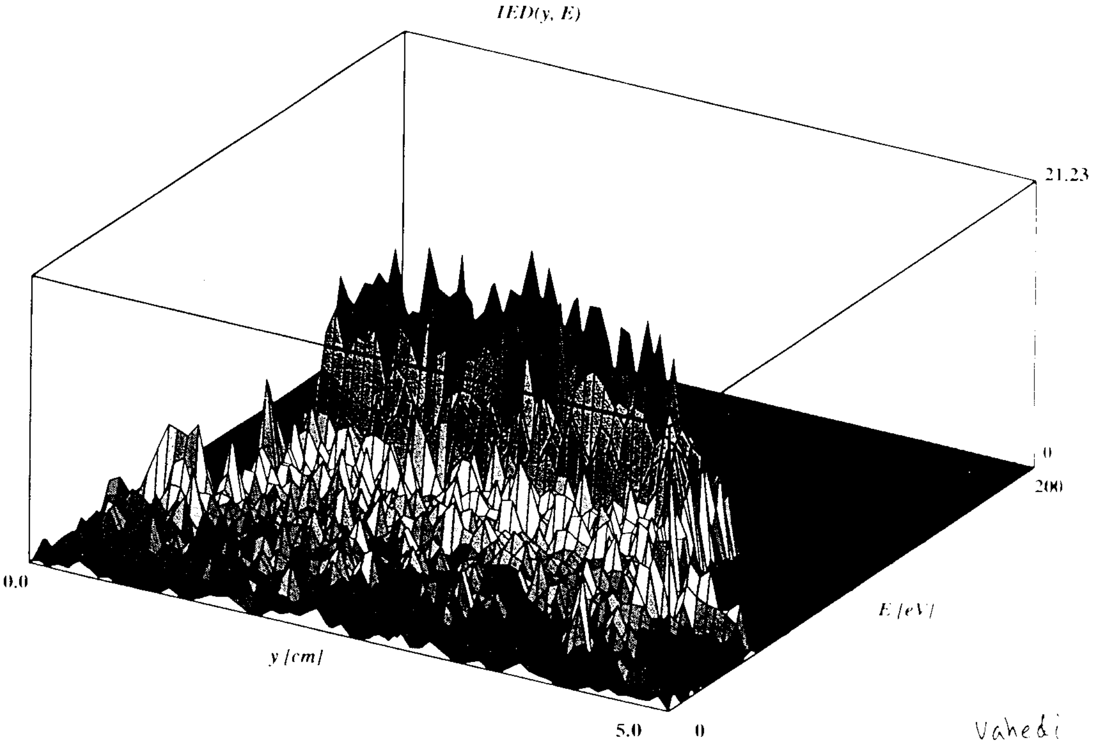


f_bias= 13.56 MHz



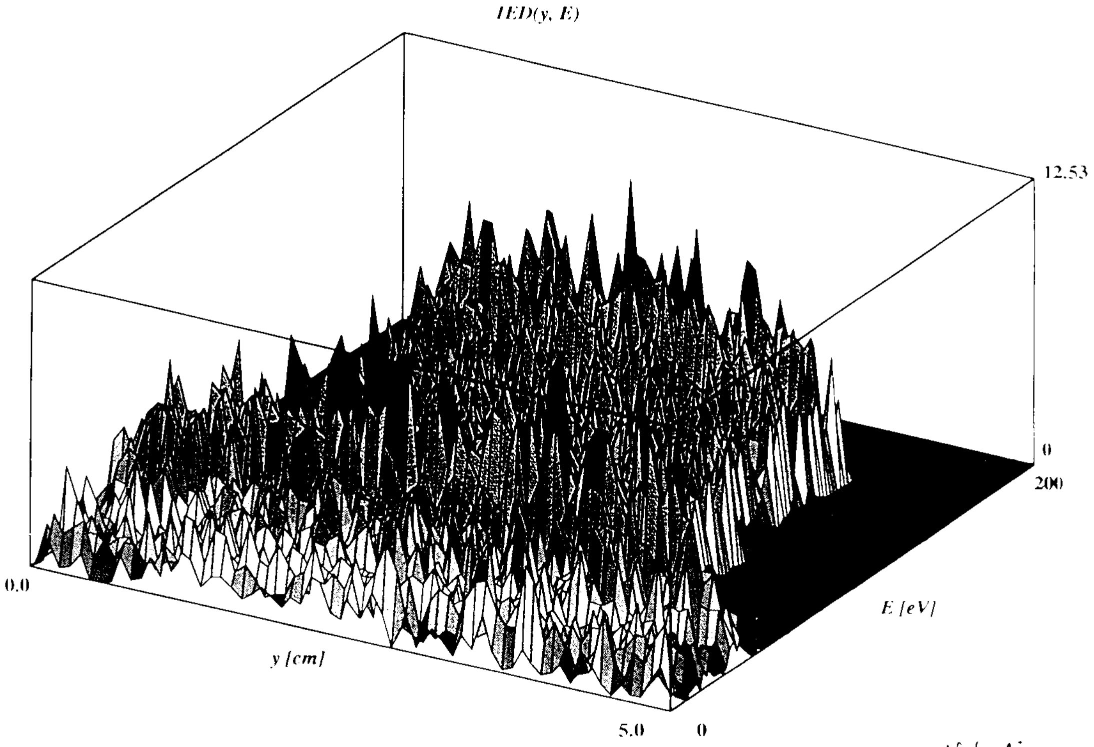
When the applied RF frequency to the target is higher than the ion transit frequency, the ions only see the time-averaged self-consistent potential (top) and arrive at the target mono-energetically (lower right). At low RF frequencies, ions are modulated and can arrive at the target at multiple energies (top right). The low-energy ions can be influenced by local potential variations and can cause damage.

Ion energy distribution in argon (f bias = 13.56 MHz, p = 10 mTorr, V = 100 V)



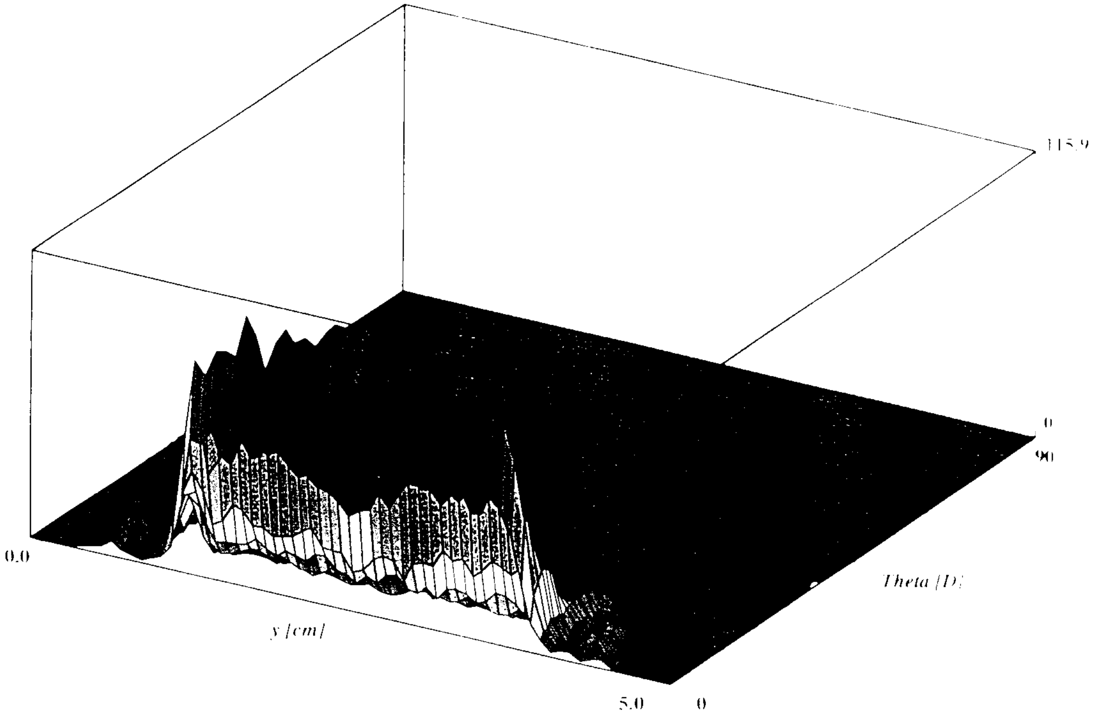
Vahedi

Ion energy distribution in argon (f bias = 0.8475 MHz, p = 10 mTorr, V = 100 V)



Vahedi

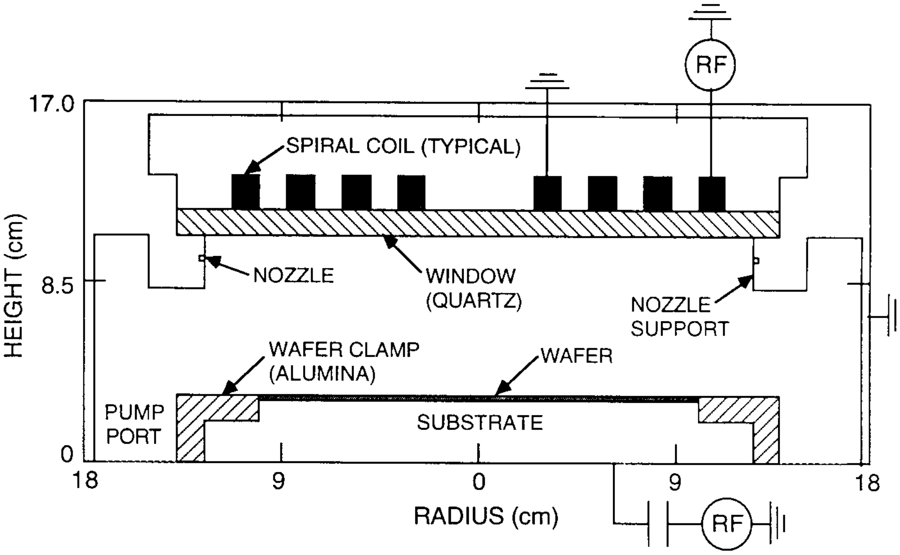
Ion angular distribution in argon (f bias = 0.8475 MHz, p = 10 mTorr, V = 100 V



TRANSFORMER COUPLED PLASMA ETCHING TOOL

- Typical Operating Conditions:

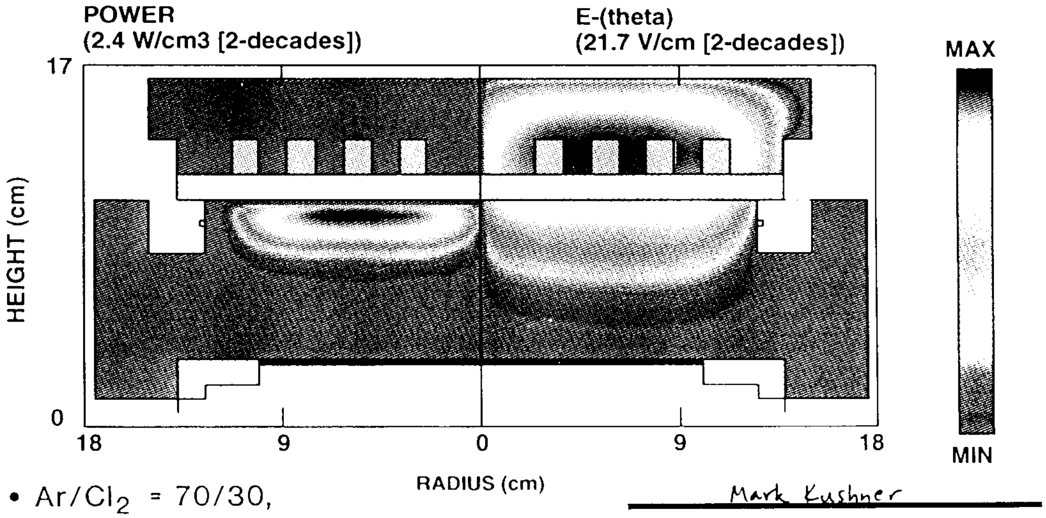
- 5-20 mTorr
- 50-200 sccm
- 200-1500 W (ICP)
- 50-500 W bias
- [e] = 10^{11}- 10^{12}/cm^3
- T_e = 3-5 eV
- T_I = 0.05 - 0.1 eV



- "Generic" LAM 9X00 Reactor (Ref. M. Barnes)

LAM TCP ETCHING TOOL:
POWER DEPOSITION AND INDUCTIVE ELECTRIC FIELD

- The metal gas injector restricts the inductive field and contributes to the toroidally confined power deposition.



- Ar/Cl_2 = 70/30, 5 mTorr, 80 sccm, 700 W

Mark Kushner

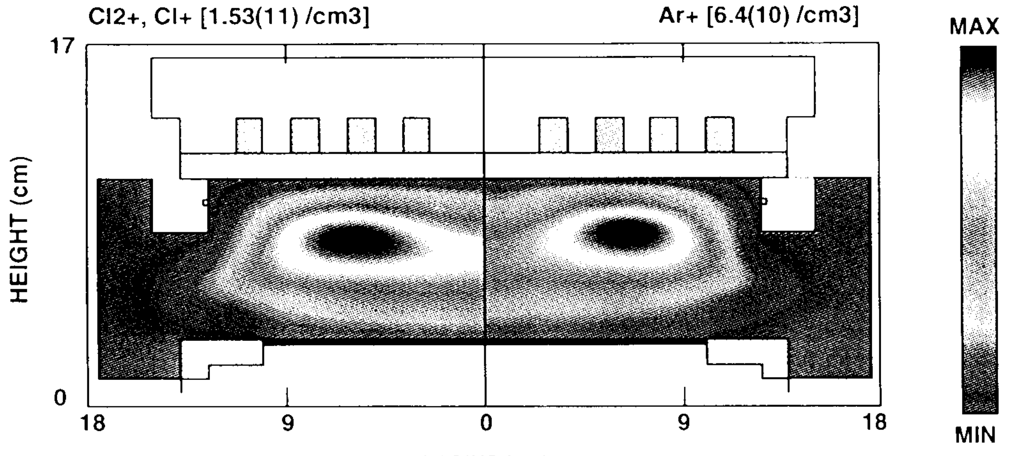
University of Illinois

Optical and Discharge Physics

GEM94001

LAM TCP ETCHING TOOL:
POSITIVE ION DENSITIES

- Charge exchange results in chlorine ions dominating. The balance between Cl+ and Cl2+ depends largely on depletion.



- Ar/Cl_2 = 70/30, 5 mTorr, 80 sccm, 700 W

Mark Kushner

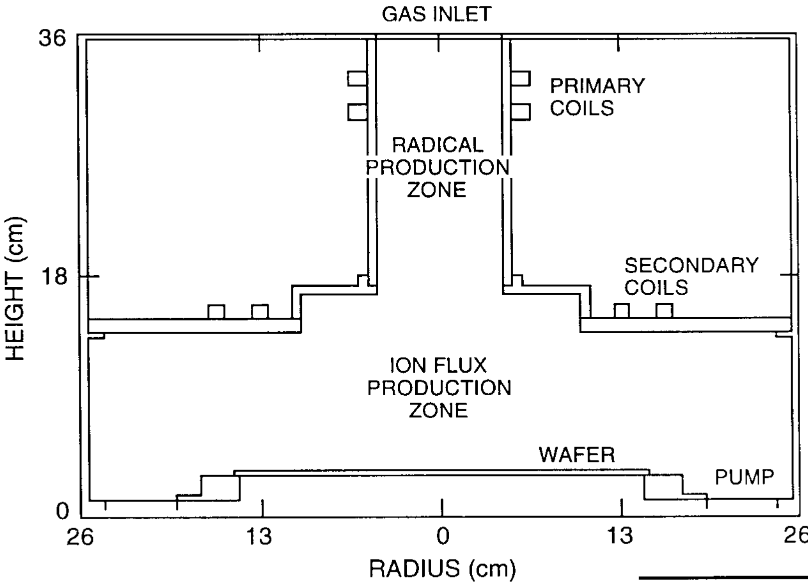
University of Illinois

Optical and Discharge Physics

GEM94003

ADVANCED CONCEPTS: 30 cm ETCHING TOOLS

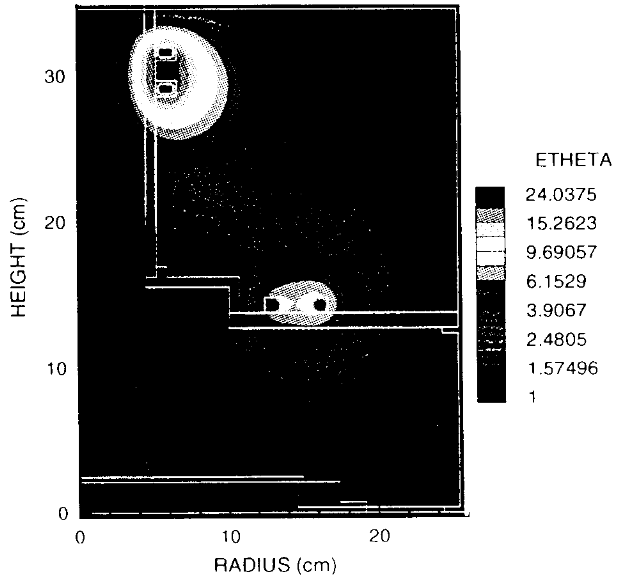
- Conceptual designs of 30 cm etching tools are being performed.
- Example: The goal of this design is to separately control production of radicals and ion flux to the wafer.



Kushner

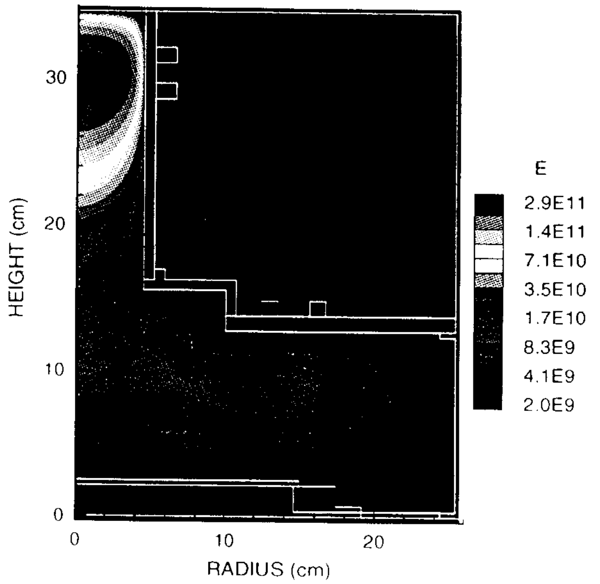
---

30 cm PLASMA ASSISTED DOWN STREAM ETCHING TOOL: INDUCTIVE ELECTRIC FIELD



- The azimuthal electric field is separately produced in the radical and ion flux production zones.
- The electric fields are isolated by distance and intervening metals.
- Ar/Cl2=70/30, 10 mTorr, 800W

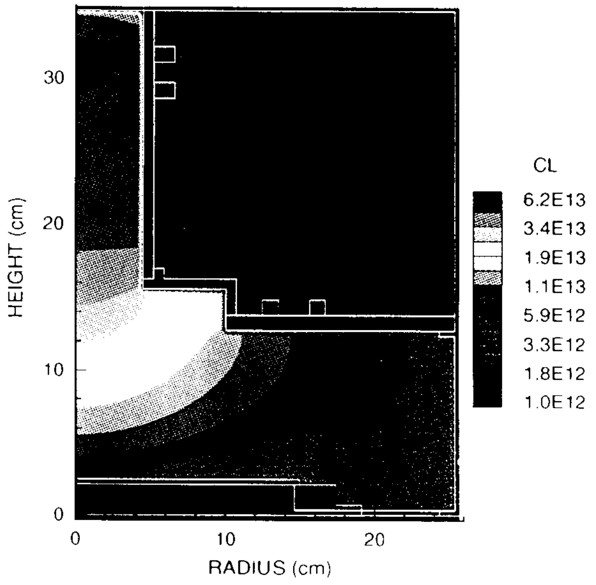
30 cm PLASMA ASSISTED DOWN STREAM ETCHING TOOL: PLASMA DENSITY



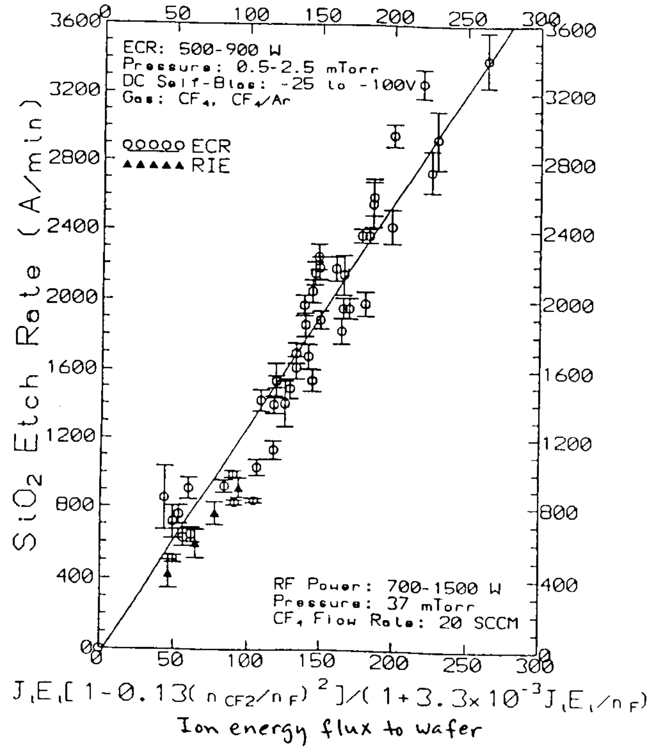
- The plasma (electron) density is 10-50 times larger in the radical production zone.
- Ar/Cl2=70/30, 10 mTorr, 800W

---

30 cm PLASMA ASSISTED DOWN STREAM ETCHING TOOL: Cl ATOM DENSITY



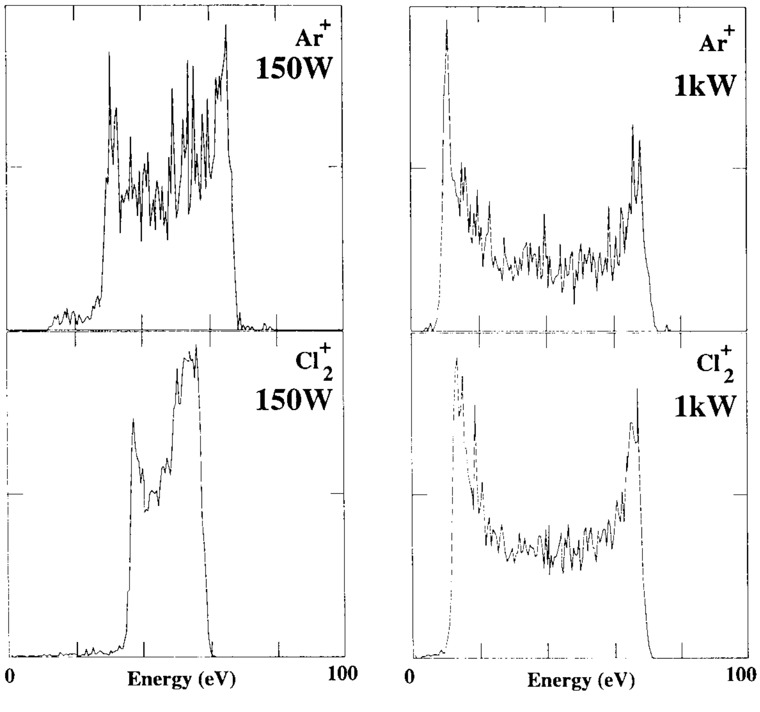
- Due to its low sticking coefficient on walls, the Cl radicals produced in the upstream zone are uniformly distributed in the etch chamber.
- Ar/Cl2=70/30, 10 mTorr, 800W



Ji and Hershkowitz
U. Wisconsin

Plasma ERC

POWER EFFECT ON ION ENERGY DISTRIBUTIONS



- As power is increased the sheath narrows allowing the heavier ions to see the instantaneous sheath potential.

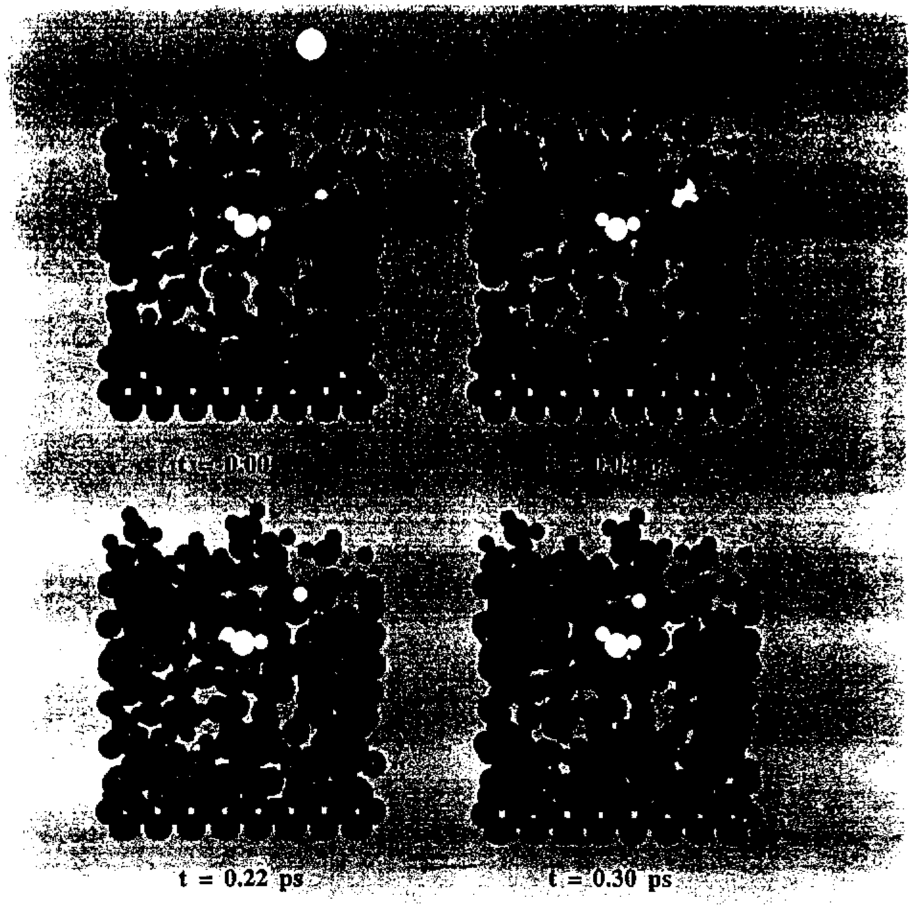
power	150W	1kW
sheath thickness	0.877 mm	0.345 mm

- The lighter Ar^+ "sees" the instantaneous potential at low power while the Cl_2^+ is affected much less.

Ar/Cl_2 10mTorr, 100V

SPUTTERING OF FLUORINATED SILICON

M.F. [illegible]



Argon

Fluorine

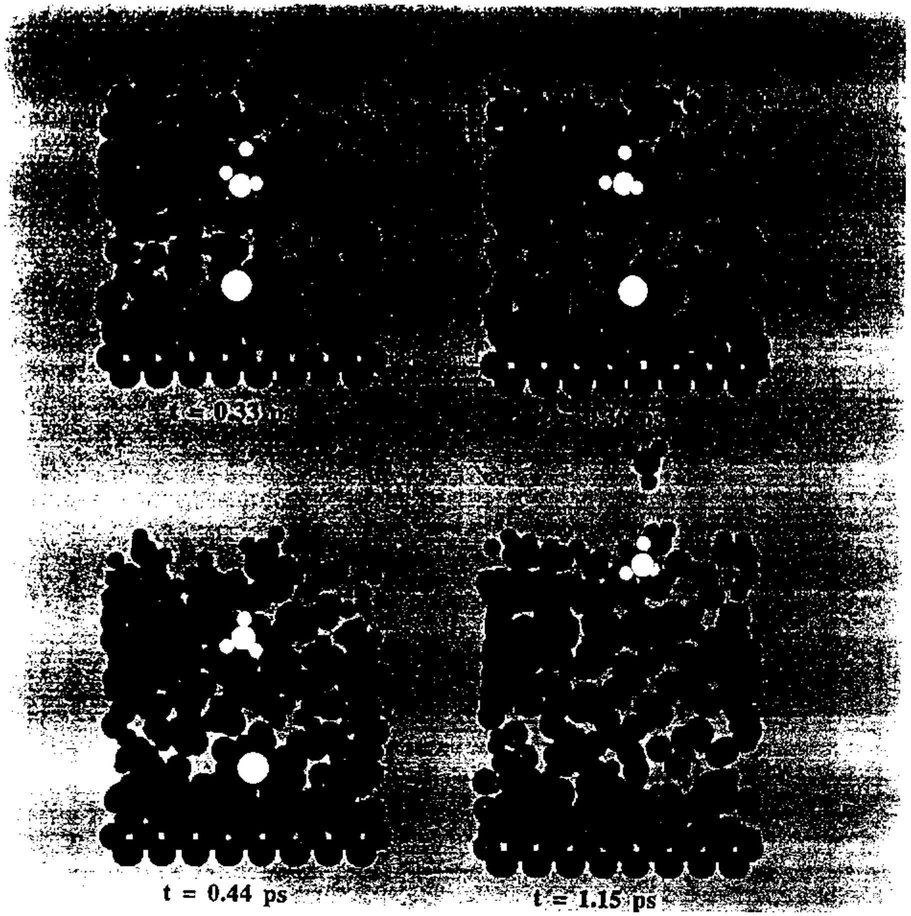
Silicon

200 eV Ar, F/Si = 0.58

SiF_2 + [illegible]

SiF_3

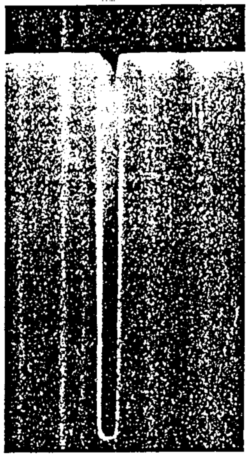
SPUTTERING OF FLUORINATED SILICON



Forefront topics: VLSI etch

- Dense plasma sources
- ⟹ Micro-loading
- Particulates (dust)
- Device damage
- Electrostatic chucks
- Neutral beam etching
- Low ε dielectrics

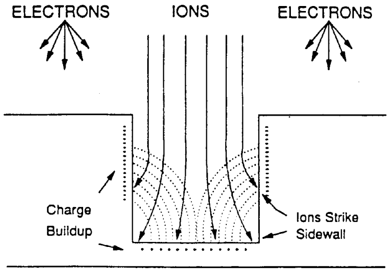
RIE lag and microloading

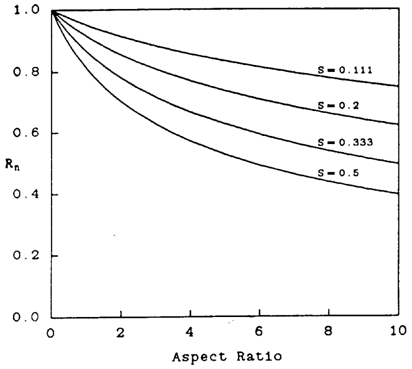


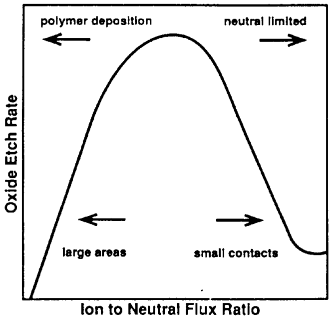
RIE lag: function of aspect ratio. Here, 20-1 trench, AT&T

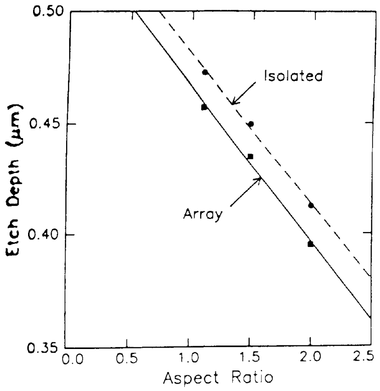
Microloading: function of nearby features (Gottscho et al.)

RIE lag and microloading 2









Lag

Loading

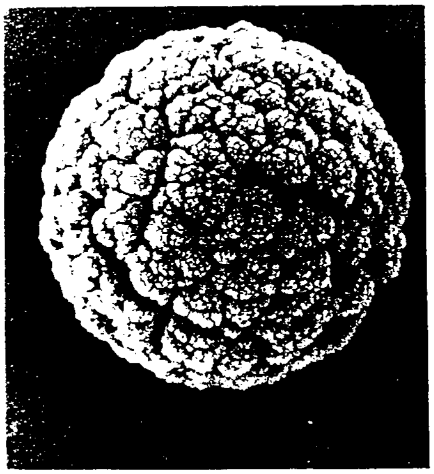
R.A. Gottscho, C.W. Jurgensen, and D.J. Vitkavage, JVSTB 10, 2133 (1992).

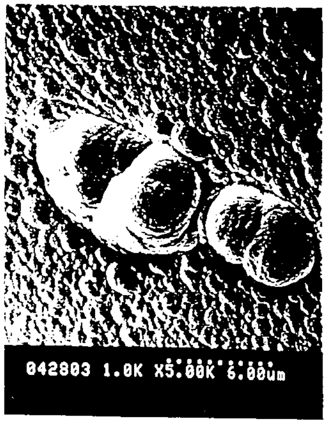
Forefront topics: VLSI etch

- Dense plasma sources
- Micro-loading
- Particulates (dust)
- Device damage
- Electrostatic chucks
- Neutral beam etching
- Low ε dielectrics

Particulates in plasmas

Dust particles are floating probes with a charge $Q = CV_f$.





A.Garscadden, B.N. Ganguly, P.D. Haaland,
and J. Williams, PSST **3**, 239 (1994).

H.M. Anderson, S. Radovanov, J.L. Mock,
and P.J. Resnick, PSST **3**, 302 (1994).

The negative dust is trapped in regions of positive potential. Other forces are dominated by neutral drag. Gravity is negligible.

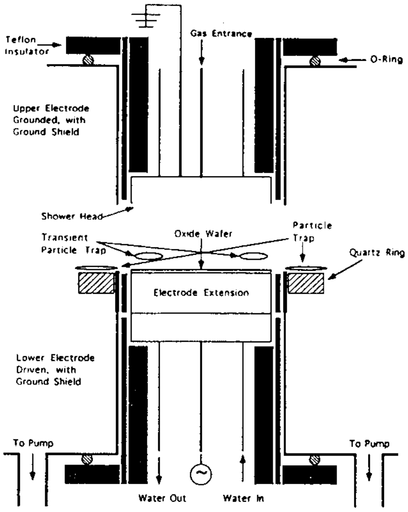


Figure 2. Schematic of the GEC reference cell, showing modifications and particle traps.

H.M. Anderson, S. Radovanov, J.L. Mock,
and P.J. Resnick, PSST **3**, 302 (1994).

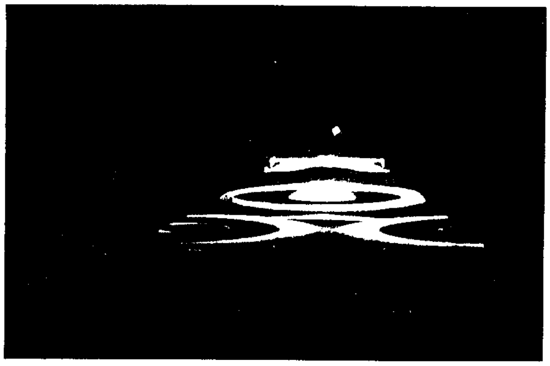
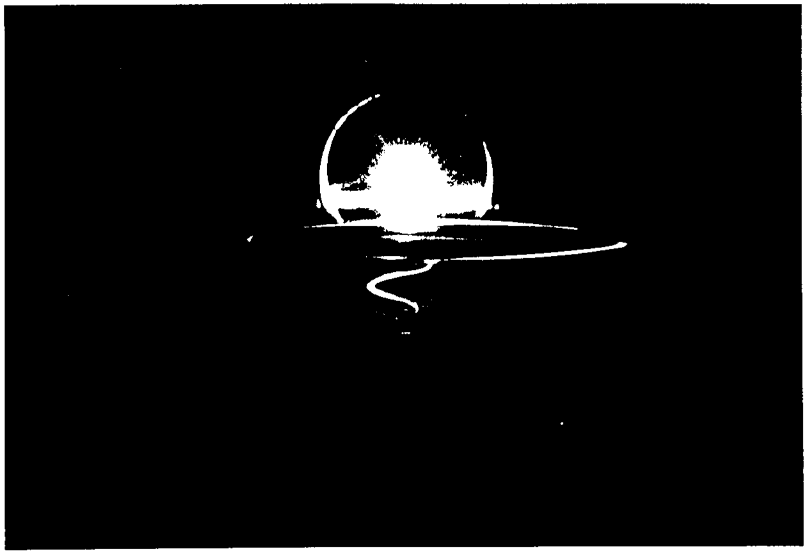


Figure 2. A photograph of the rastered laser light scattering image showing trapped particle clouds over three closely packed Si wafers on a graphite electrode.

G.S. Selwyn, PSST **3**, 340 (1994).

Gary Selwyn, Los Alamos National Laboratory



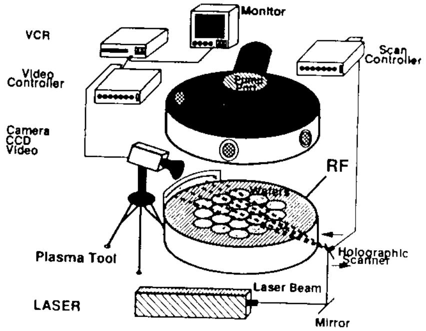
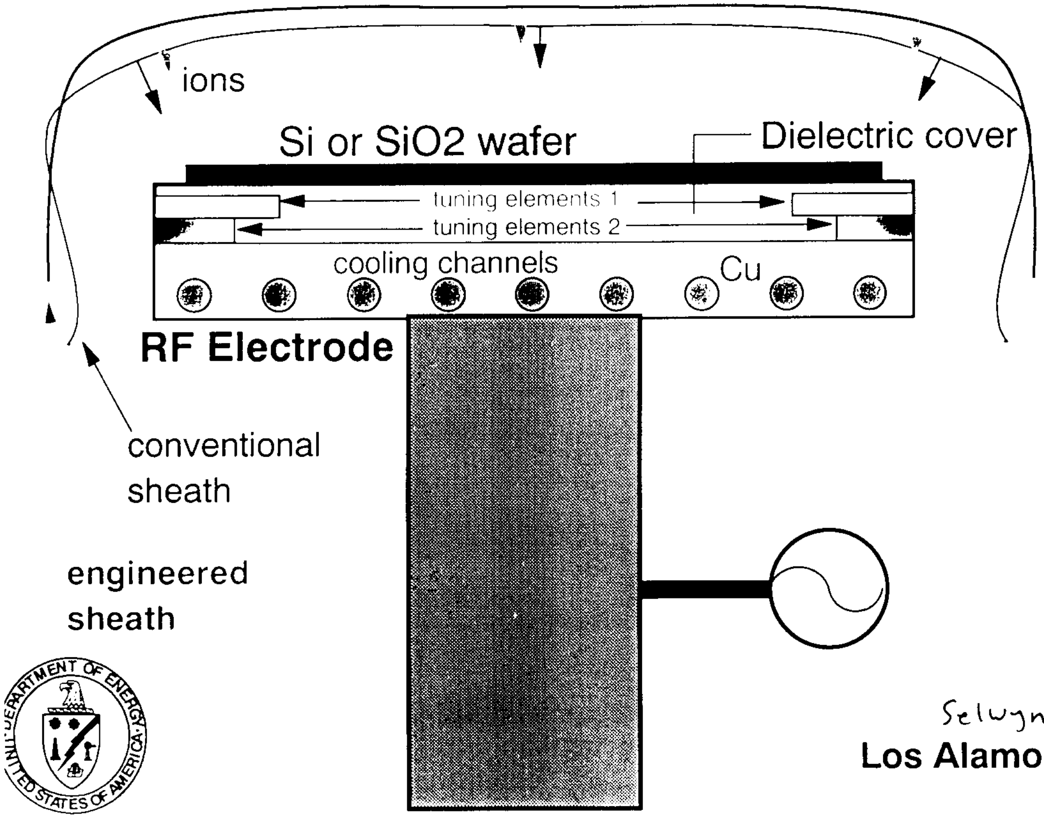


Figure 1. The rastered laser light scattering experimental set-up, showing the position of the laser, video detection system and the plasma tool.

Electrode Engineering: Buried Elements Design



ions

Si or SiO2 wafer

Dielectric cover

tuning elements 1

tuning elements 2

cooling channels

Cu

RF Electrode

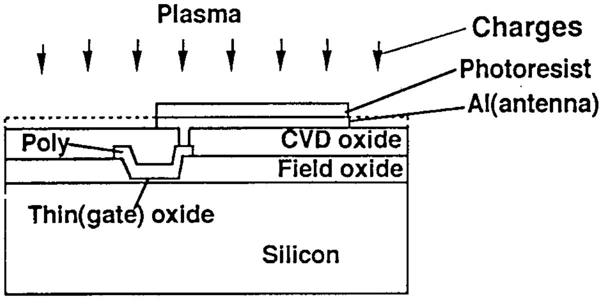
conventional sheath

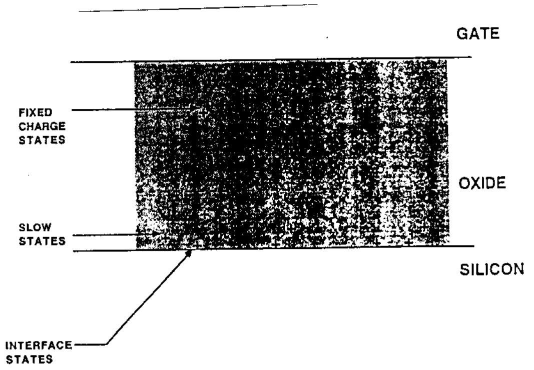
engineered sheath

Selwyn

Los Alamos

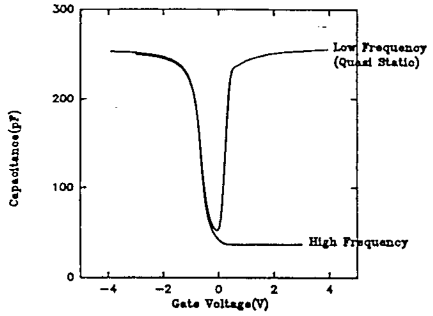
Charges are imbedded in thin (>20 Å) oxide gates during plasma processing

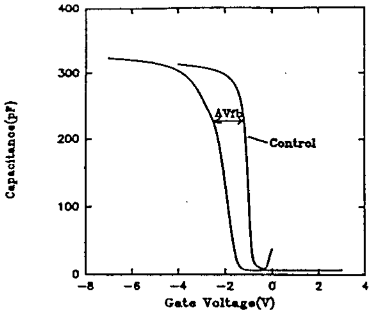


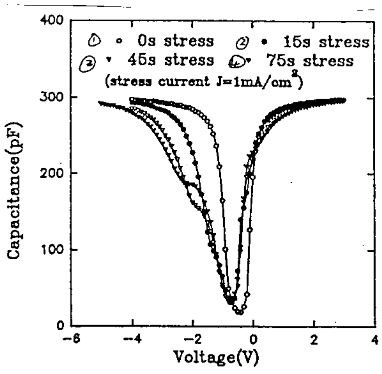


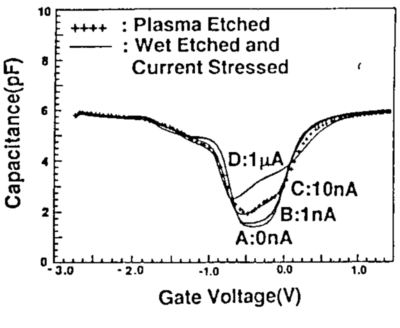
Source: C.R. Viswanathan, lecture notes

Damage can be detected by shifts in the capacitance vs. bias voltage (CV) curve



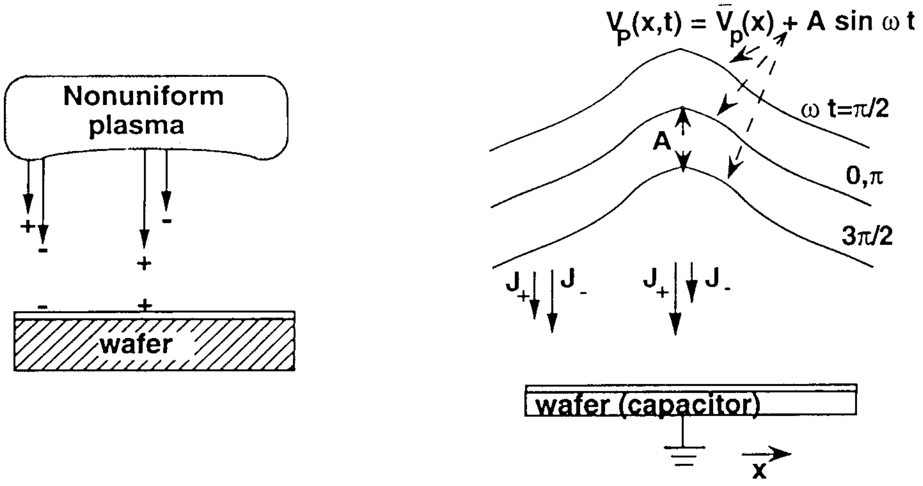






Source: C.R. Viswanathan, lecture notes

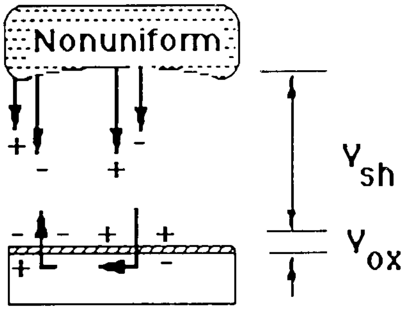
Charging Caused By Plasma Non-uniformity



- $J_- \propto \exp -qV_{sh}/kT_-$
- $J_+ \propto n_+$

J.P. McVittie, Stanford Univ.

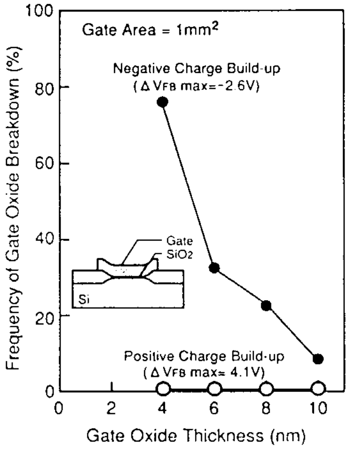
Nonuniform Plasma -- Thin Oxide

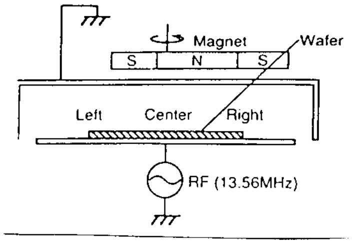


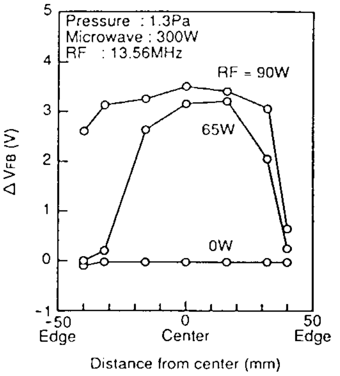
- Surface charges until $J_{ox} = J_+ - J_-$
- Substrate current balances charging across wafer.

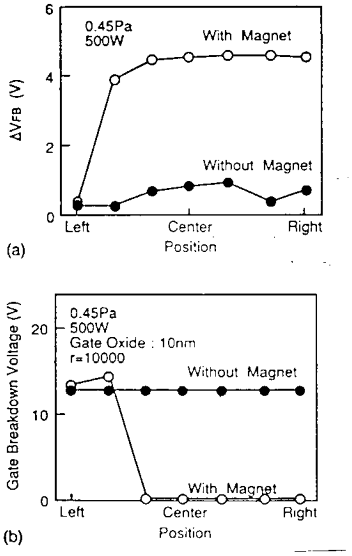
J. McVittie, Stanford Univ.

Damage depends on gate thickness, bias power, magnetic fields, etc.





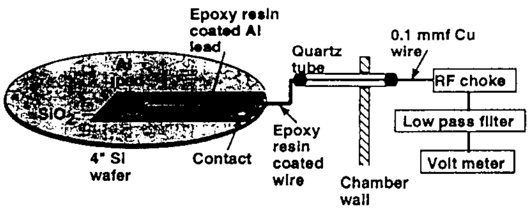


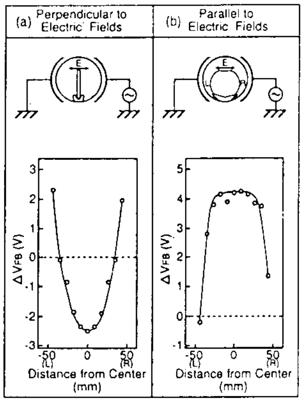


K. Nojiri and K.T. Tsunokuni,
JVSTB **11**, 1819 (1993).

Damage depends on the directions of E and B (and E x B)

Direct measurements of surface potential across a wafer are possible

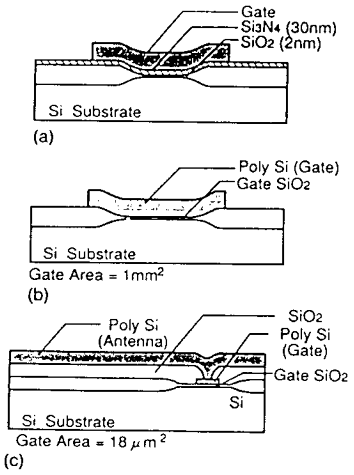


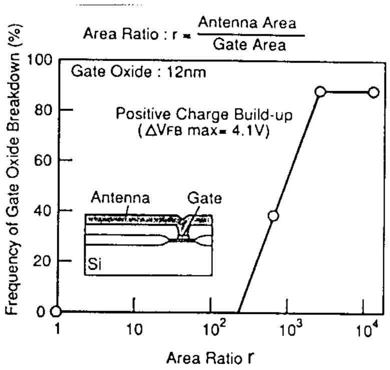


Condition of Plasma Treatment
Gas : O2 , RF Power : 400W , Pressure : 330Pa ,
Time : 20min

J. P. Mc Vittie, Stanford
T.J. Dalton and H.H. Sawin, MIT
K. Nojiri and K.T. Tsunokuni, JVSTB **11**, 1819 (1993).

The antenna effect makes it worse

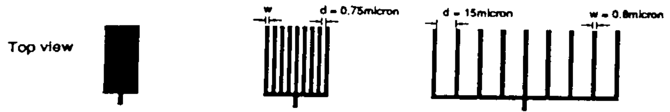




K. Nojiri and K.T. Tsunokuni, JVSTB **11**, 1819 (1993).

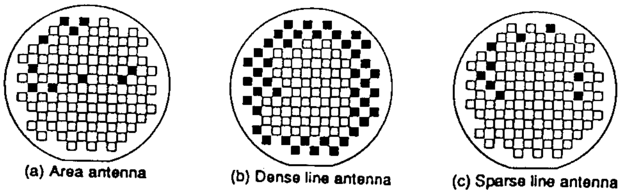
Effect of Aspect Ratio on Charging Damage

From: Hasimoto, Dry Process Symposium1993
Poly Si etching inHCl/O2 in ECR



(a) Area antenna (b) Dense line antenna (c) Sparse line antenna

Fig. 1 Schematic shapes of the antennas

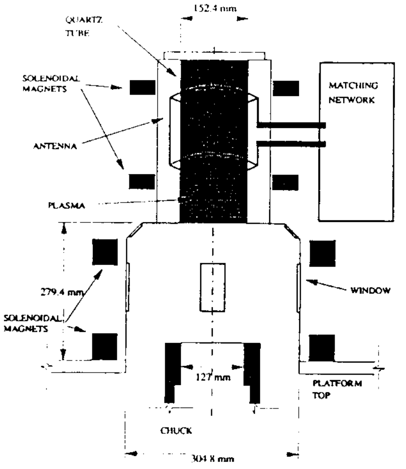


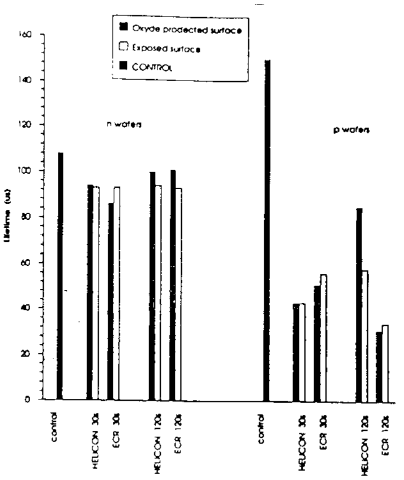
(a) Area antenna (b) Dense line antenna (c) Sparse line antenna

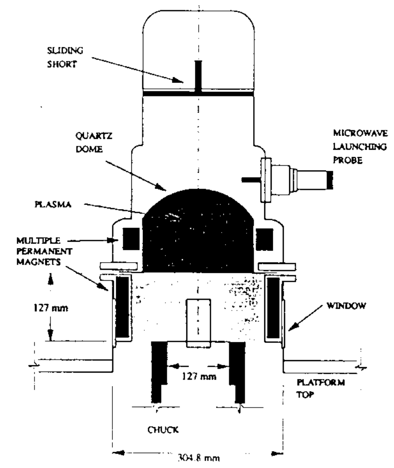
Fig. 2 Breakdown failure patterns of MOS capacitors. Each antenna's area ratio is 10000.

- **Poly Si in narrow spaces clears last and offers collection path for charging current.**

Helicon and ECR sources produce 10X less damage than RIE







N. Blayo, I. Tepermeister, J.L. Benton, G.S. Higashi, T. Boone, A Onuoha, F.P. Klemens, D.E. Ibbotson, and J.T.C. Lee, JVSTB **12**, 1340 (1994).

Semiconductor Processing

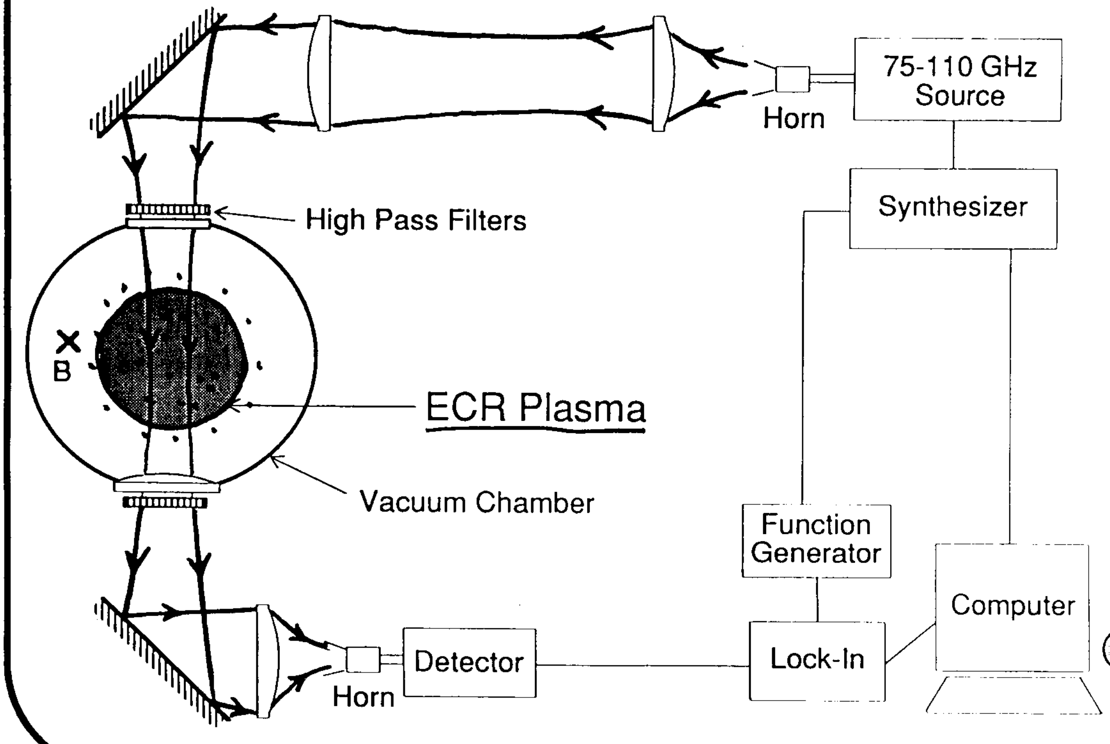
- Physical mechanisms in etching
- Plasma sources
- Modeling
- Problems at the forefront
- Diagnostics and sensors
- PECVD, PVD, cleaning, stripping

--Dry processing preferred for environment!

The alphabet soup of diagnostic techniques

- OES: Optical emission and absorption spectroscopy (VUV, UV, visible, infrared)
- FTIR: Fourier transform infrared absorption spectroscopy
- LIF: Laser-induced fluorescence
- REMPI: Resonance-enhanced multiphoton ionization spectroscopy
- HREELS: High resolution electron energy loss spectroscopy
- MS: Mass spectrometry
- LEEDS: Low energy electron diffraction spectroscopy
- XPS: X-ray photoelectron spectroscopy
- AES: Auger electron spectroscopy
- CARS: Coherent anti-Stokes Raman scattering
- IR:Infrared diode laser absorption
- ESCA: Electron Spectroscopy for Chemical Analysis
- Micro-Raman scattering
- Attenuated total internal reflection
- Film interference measurements

Microwave Spectroscopy Diagnostic for ECR Plasma Deposition



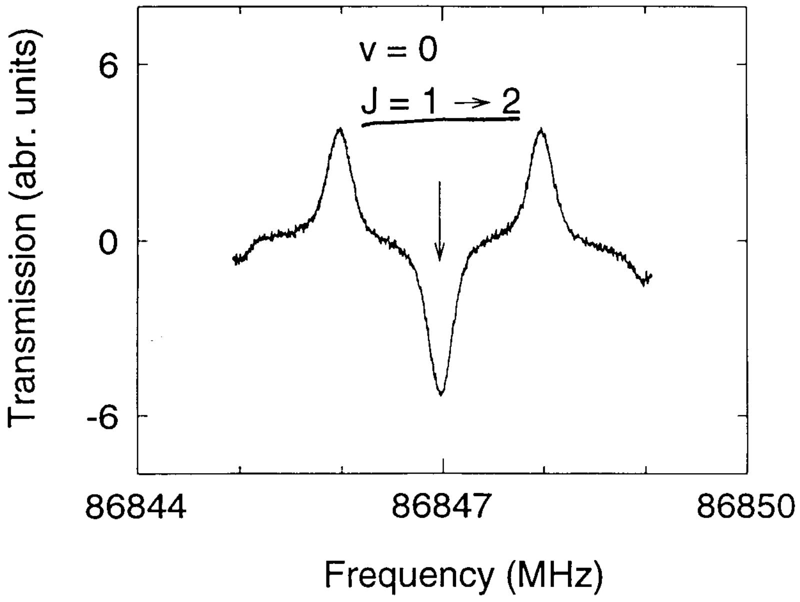
Claude Woods

Plasma ERC

Flat panel displays

- General principles
- AMLCDs (Active Matrix Liquid Crystal)
- Plasma-addressed LCDs (PALC)
- TFELs (Thin Film ElectroLuminescent)
- Plasma displays
- Field Emission displays

Microwave Spectra of SiO in ECR Plasma of O_2 and SiH_4



ECR power 50W, 10 mTorr

Flow rate O_2= 30, SiH_4= 18 sccm

Translational temperature 550 K

Column density of SiO N dL= $9 \times 10^{12} cm^{-2}$

Average density of SiO $2 \times 10^{11} cm^{-3}$

SiO abundance 0.1%

The potential market for FPDs

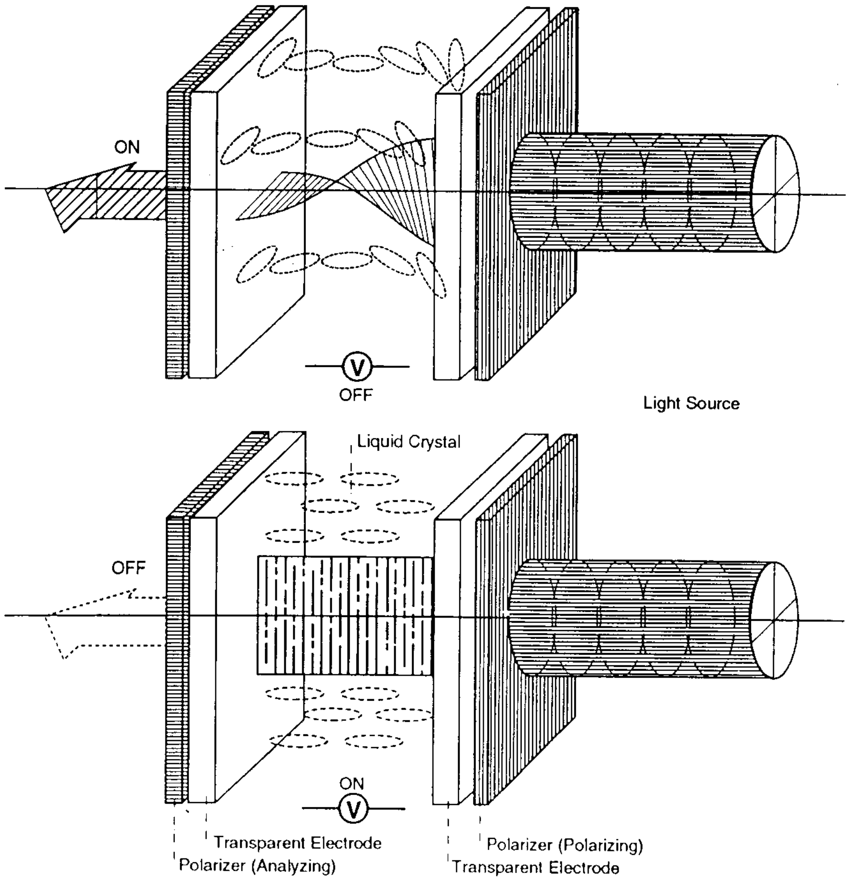
- More compact and efficient than CRTs
- Aircraft cockpits
- Portable computers
- Viewfinders (e.g. camcorders)
- Desk computer monitors
- Flat-screen TV, projection TV
- Automobile dashboards

Plasmas and display technology

THE BOTTOM LINE

- Because of low required resolution (1280 x 1024 pixels x 3 colors), wet processing can be used, BUT...
- Plasma processing is needed for speed (60 plates/hr/fab line), AND
- Plasma processing avoids liquid wastes and is better for the environment.

Figure 1-6 *Principle of operation of a twisted nematic liquid crystal display*



Transparent conductors are made of ITO (indium tin oxide).

W.C. O'Mara, Liquid Crystal Flat Panel Displays (Van Nostrand, 1993).

Passive Matrix

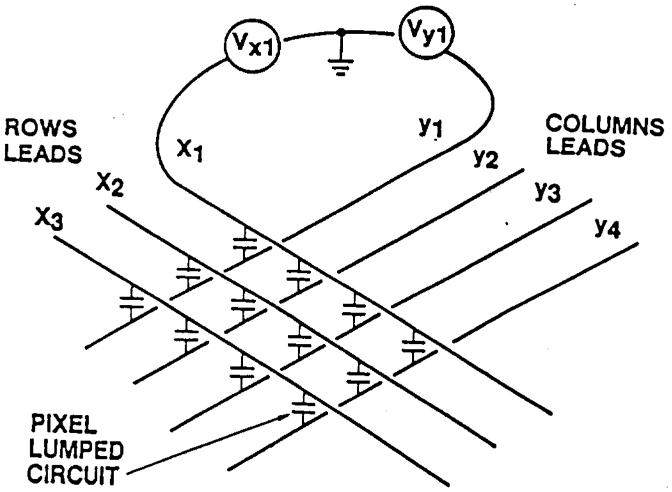
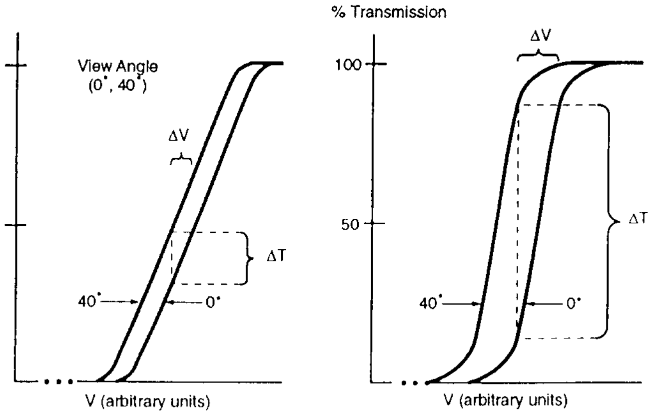
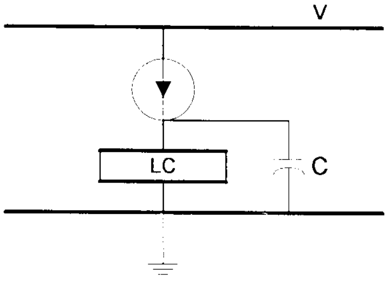


Figure 1-7 *Transmission versus voltage curves for TN and STN materials.*

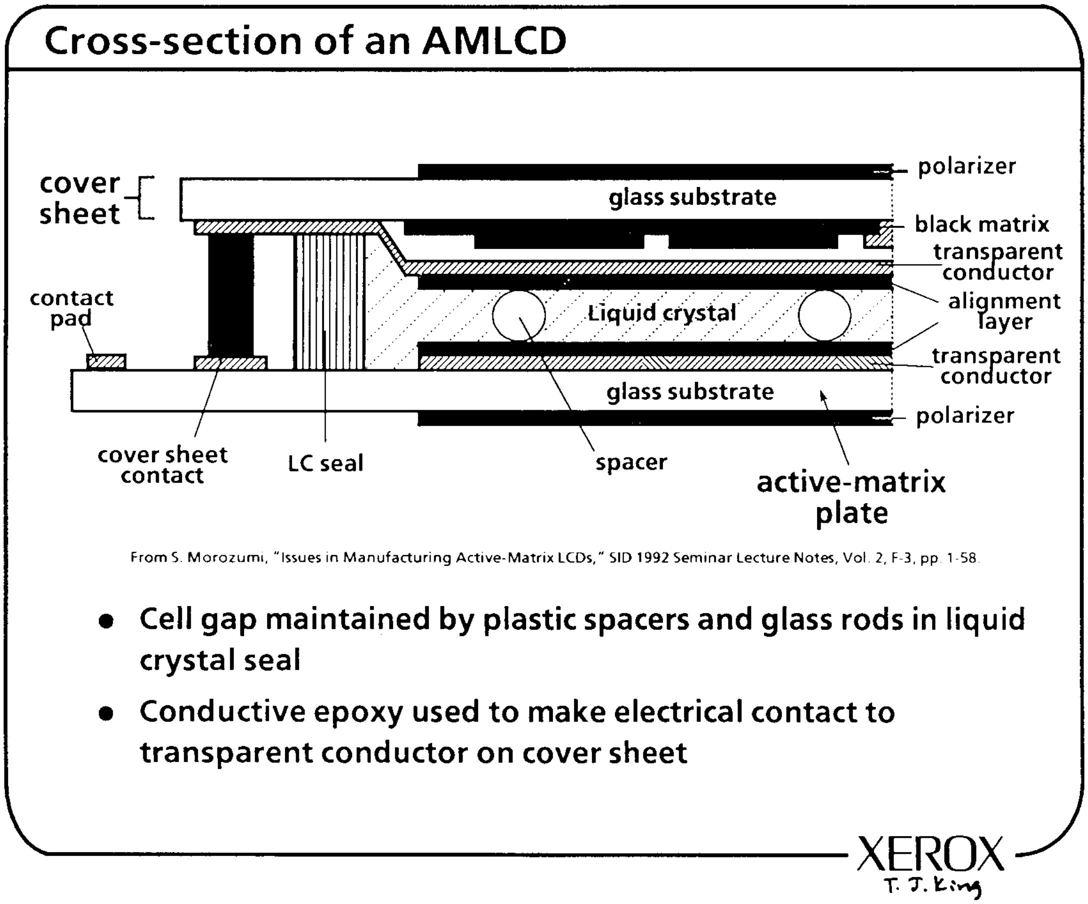


Two-terminal switches

e.g. MIM or PIN diode, can give definite threshold for better multiplexibility, but require a storage capacitor between plates:



Hence, one uses a three-terminal Thin FilmTransistor (TFT). One plate can be grounded, and the other has all the circuitry etched and deposited on it.



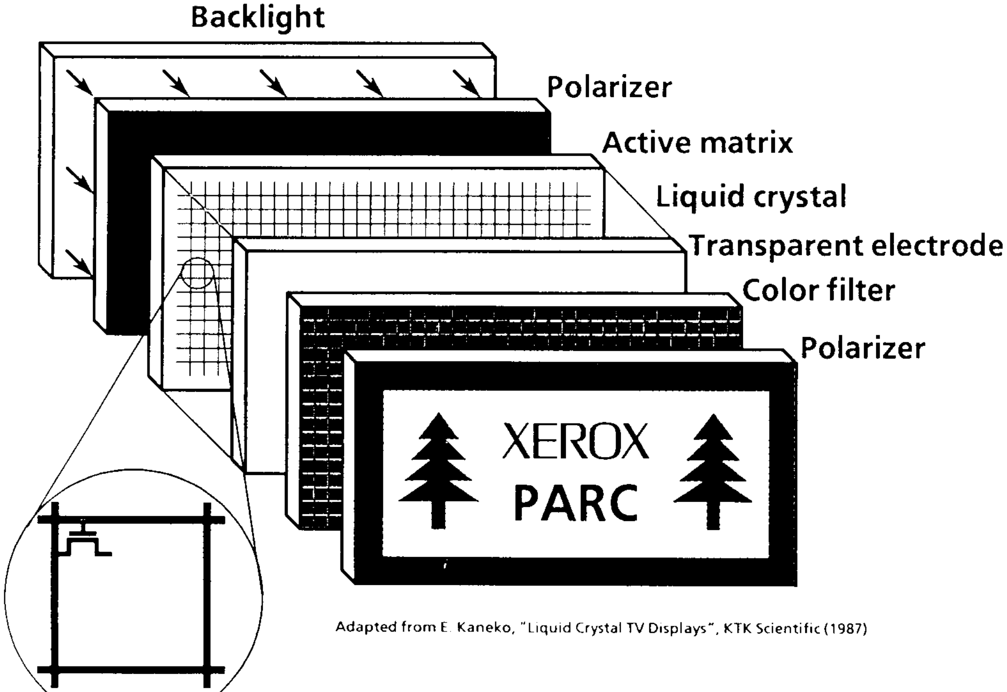
Cross-section of an AMLCD

From S. Morozumi, "Issues in Manufacturing Active-Matrix LCDs," SID 1992 Seminar Lecture Notes, Vol. 2, F-3, pp. 1-58

- **Cell gap maintained by plastic spacers and glass rods in liquid crystal seal**
- **Conductive epoxy used to make electrical contact to transparent conductor on cover sheet**

XEROX
T. J. King

Components of a TFT-AMLCD



Backlight

Polarizer

Active matrix

Liquid crystal

Transparent electrode

Color filter

Polarizer

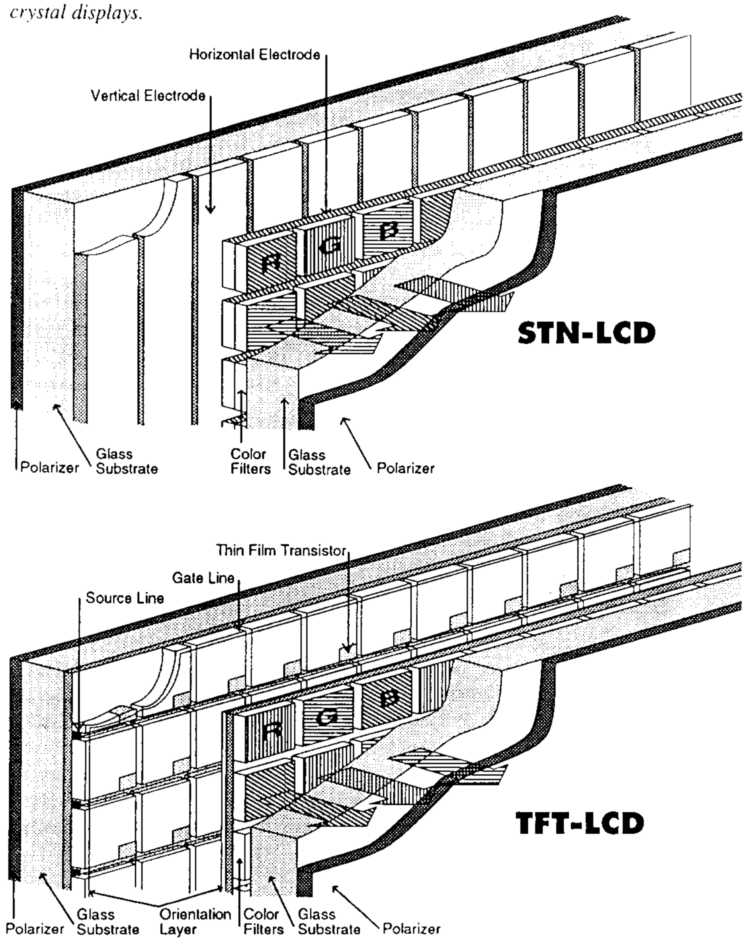
Adapted from E. Kaneko, "Liquid Crystal TV Displays", KTK Scientific (1987)

(TFT used as switch to store charge on LC capacitor)

XEROX

T. J. King

Figure 1-8 *Schematic representation of passive and active matrix color liquid crystal displays.*



W. C. O'Mara, Liquid Crystal Flat Panel Displays (Van Nostrand, 1993).

Amorphous-Si TFT fabrication process

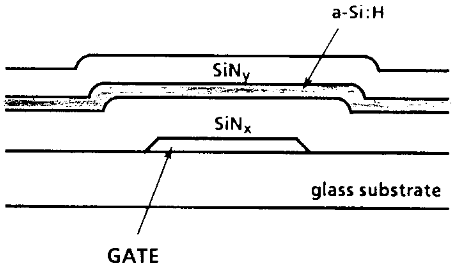
Gate metal deposition (RF sputter)

Gate mask

Gate metal etch (wet)

"NSN" deposition (PECVD)

- **gate nitride deposition**
  gases: NH_3, SiH_4 (N_2 or He dilution)
  temperature: 350°C
  thickness: ~3000Å
  rate: < 200 Å/min for in-line system;
  ~2000 Å/min for cluster tool
- **a-Si:H deposition**
  gases: SiH_4, H_2
  temperature: 250 - 300°C
  thickness: 500Å
  rate: < 200 Å/min for in-line system;
  ~2000 Å/min for cluster tool
- **top nitride deposition**
  temperature: 250°C
  thickness: ~1500Å

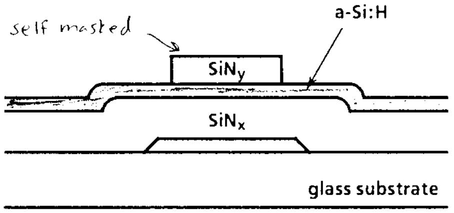


Schematic cross-sectional view of
a-Si TFT structure after NSN deposition

Amorphous-Si TFT fabrication process (cont.)

Backside flood exposure

Top nitride etch (wet)

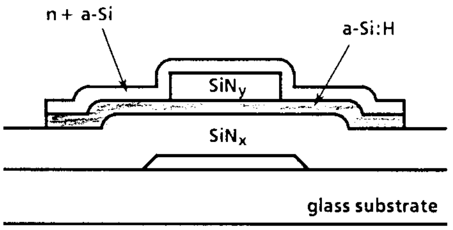


Schematic cross-sectional view of
a-Si TFT structure after top nitride etch

n+ a-Si deposition (PECVD)
gases: SiH_4, PH_3, H_2
temperature: < 250°C
thickness: 1000Å
rate: <200 Å/min for in-line system;
~2000 Å/min for cluster tool

n+ mask

a-Si etch (RIE)
gases: SF_6, $CFCl_3$
pressure: 100 mT
rate: 1000 Å/min



Schematic cross-sectional view of
a-Si TFT structure after n + etch

Amorphous-Si TFT fabrication process (cont.)

S/D metal deposition (RF sputter)

Top metal mask

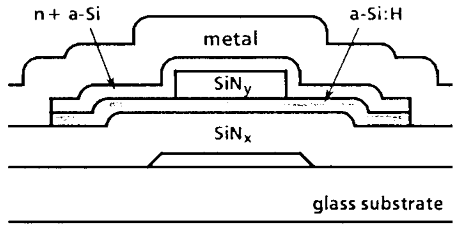
Top metal etch (wet)

"slot" mask

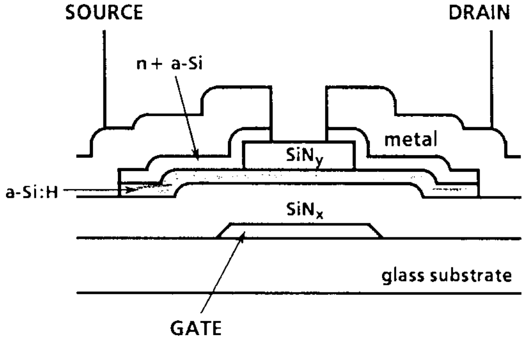
Top metal etch (wet)

n+ etch (RIE)
  gases: SF_6, $CFCl_3$
  pressure: 100 mT
  rate: 1000 Å/min

Passivation SiO_xN_y deposition (PECVD)
  gases: SiH_4, NH_3, N_2O, He
  temperature: < 200°C
  thickness: 6000Å
  rate: < 200 Å/min for in-line system;
    > 1000 Å/min for cluster tool

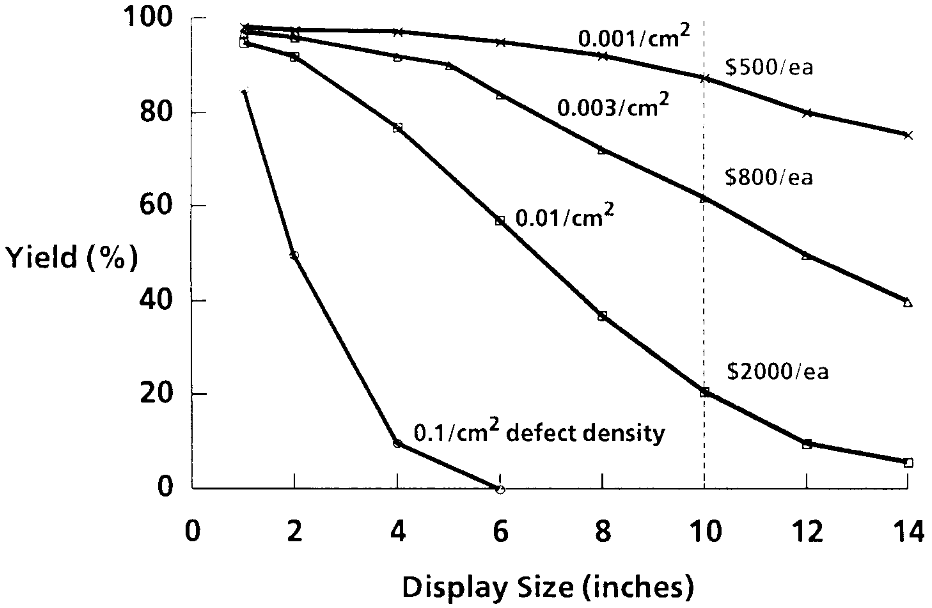


Schematic cross-sectional view of
a-Si TFT structure after top metal deposition



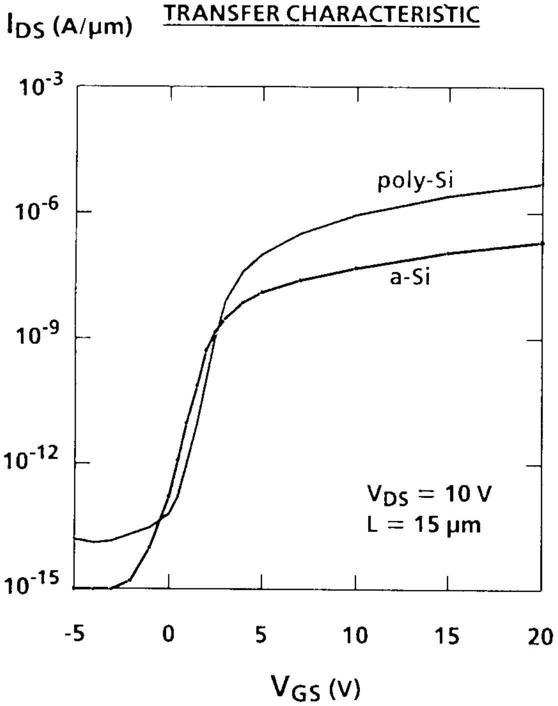
Active Matrix Yield vs. Defect Density

Simulated Yields for Color TFT-AMLCDs



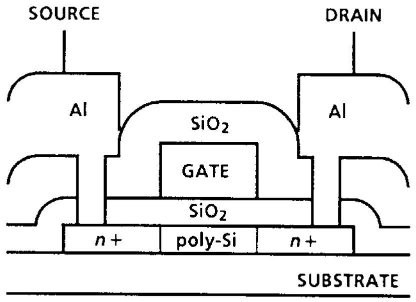
Y. Yamamura, Nikkei Microdevices 1993

Polycrystalline-Si Thin-Film Transistor



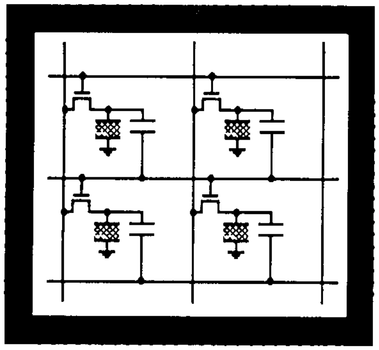
SCHEMATIC CROSS-SECTIONAL VIEW

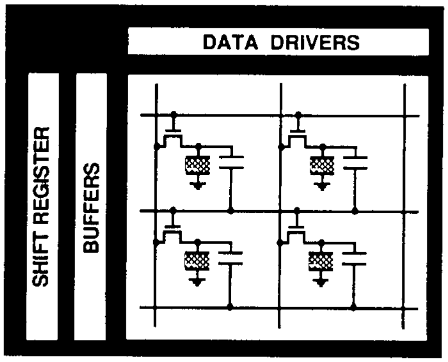
(top-gate coplanar structure)



XEROX

TECHNOLOGY COMPARISON: a-Si vs. poly-Si





AMORPHOUS SILICON

- low TFT mobility (1 cm^2/V s)
  - → separate LSI drivers required
- low-temperature (350°C) process
  - → glass substrates

POLYCRYSTALLINE SILICON

- higher TFT mobility (μ_n=50 cm^2/Vs; μ_p=30 cm^2/Vs)
  - → smaller pixel TFTs (higher aperture ratio)
  - → integration of driver circuitry
    - ◆ fewer external connections
      - → improved reliability
    - ◆ reduced system cost
- high-temperature (>550°C) process
  - → high strain-point glass or quartz substrates

Summary: Plasma processes for AMLCD technologies

APPLICATION	CHALLENGES
FILM DEPOSITION (a-Si, n+ a-Si, SiN_x, SiO_xN_y, SiO_2)	IMPROVED FILM PROPERTIES HIGH PROCESS THROUGHPUT
FILM ETCH (Si, SiN_x)	METAL ETCH PROCESS DEV. SiO_2 ETCH PROCESS DEV.
ION DOPING	(SUBSTRATE HEATING, CHARGING)
HYDROGENATION	HIGH PROCESS THROUGHPUT

Challenges enhanced by use of large glass substrates:

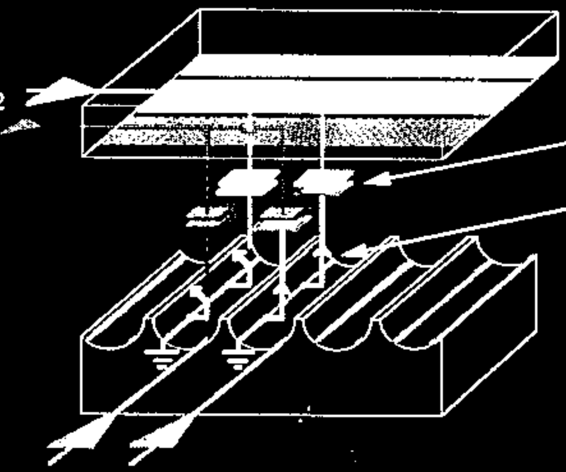
- process uniformity
- substrate cooling/heating
- process throughput
- particulate control

XEROX

FPD design considerations

- Backlight and circuit efficiency
- Contrast and grayscale; bright light visibility
- Resolution and speed for HDTV
- Signal storage between sweeps
- Visible angle
- Simplicity, ruggedness, cost

PALC Equivalent Circuit



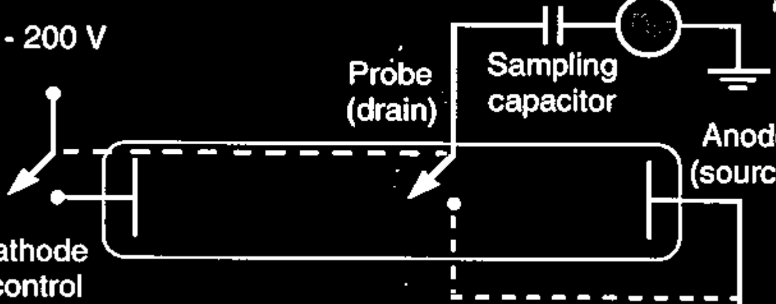
Data 2
Data 1

Equivalent Pixel Capacitance

Plasma Switching Action

Strobe 1 (off)
Strobe 2 (on)

Plasma Switch



Analog signal source

- 200 V

Probe (drain)

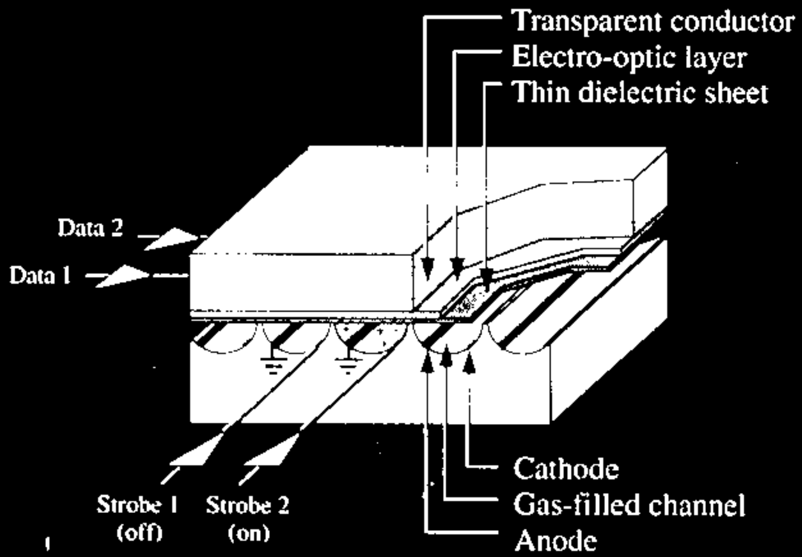
Sampling capacitor

Anode (source)

Cathode (control or gate)

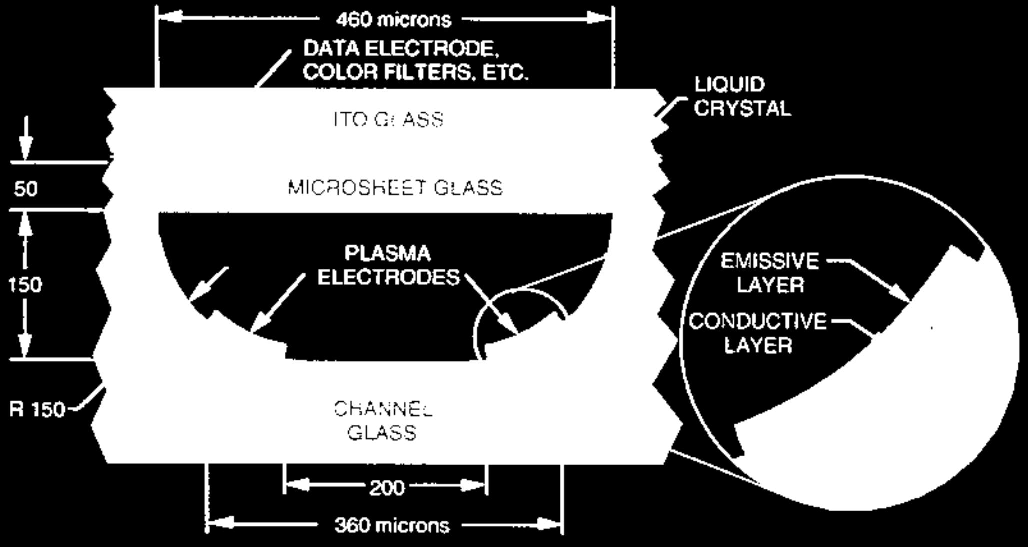
Virtual connection

PALC Cross Section



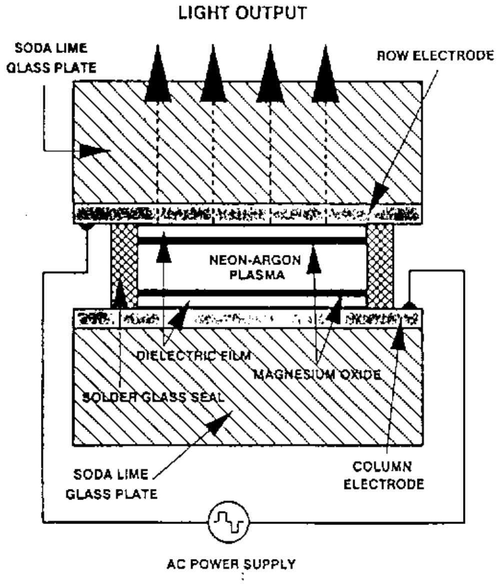
PALC Channel Cross-Section

Detail

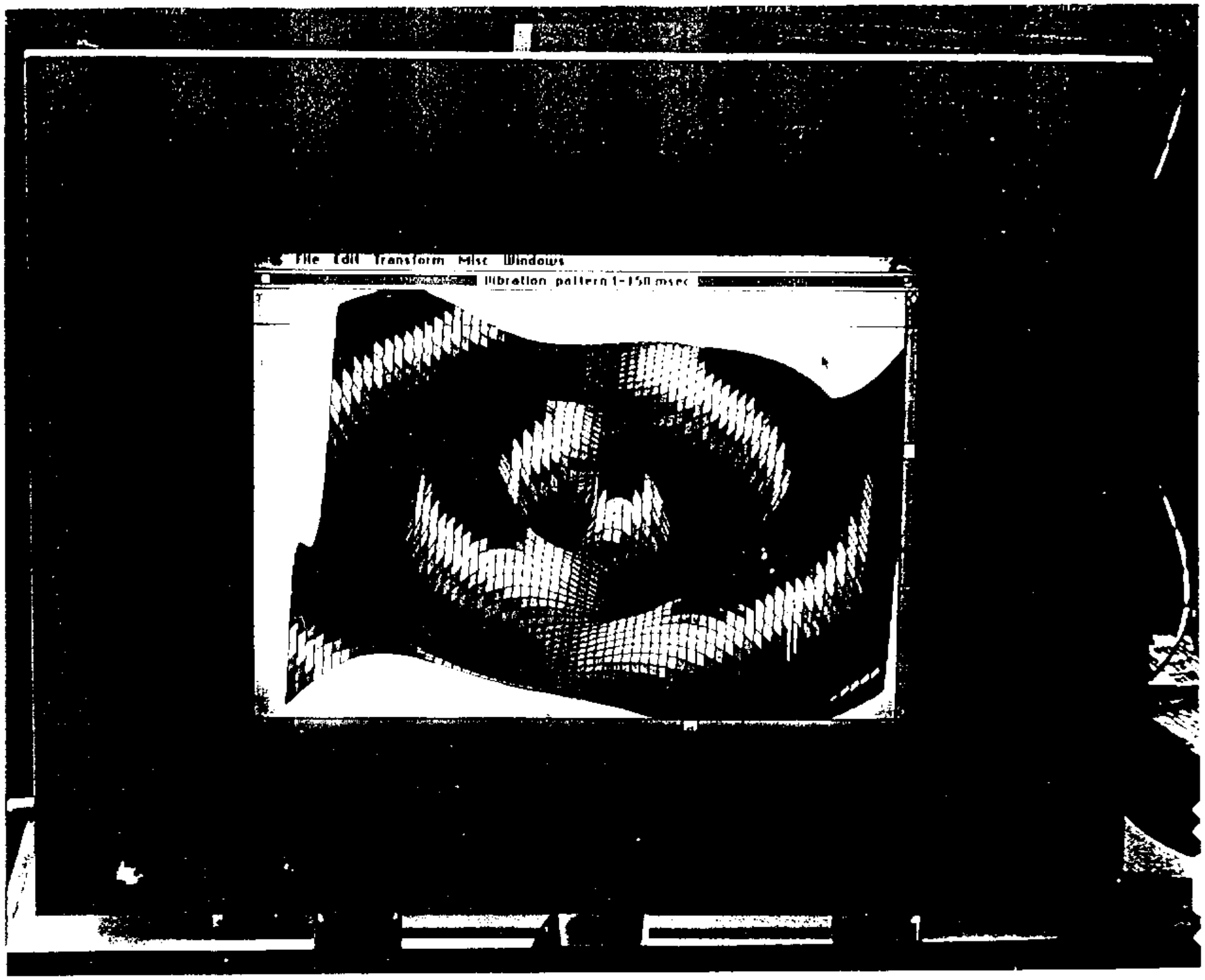


DISPLAY TECHNOLOGY

AC Plasma Displays



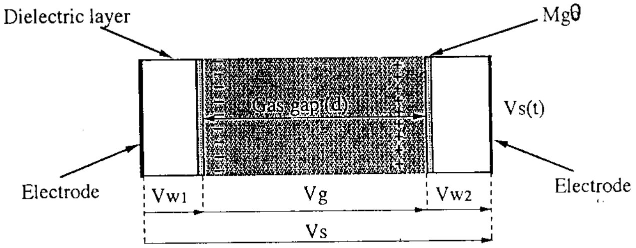
Very large (~60") ac plasma displays have been made.

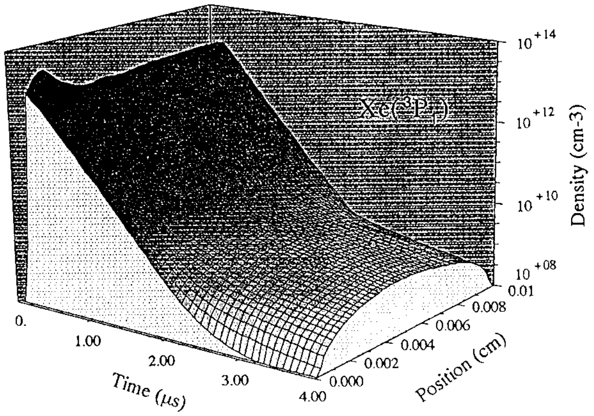


J. Meunier, Ph. Belenguer, and J.P. Boeuf (Toulouse)

Gas mixture: Ne-Xe(10%)
Gas pressure: p=560 torr
Gap length: d=100μm
Dielectric capacitor: 460 pF cm^{-2}

Sustaining Voltage: Vs(t)
Wall Voltage: Vw=Vw1+Vw2
Gap voltage: Vg





Color Plasma Displays: Where Are We Now?

Plasma fever has infected both the U.S. and Japan because plasma displays can be big – really big.

by Shigeo Mikoshiba

At the SID '94 symposium in San Jose last June, I saw standing-room-only audiences at the plasma display sessions for the first time in 20 years. Similar plasma fever can be found in Japan, where "plasma display technical meetings" are being held three times a year to informally discuss the technological issues of plasma display panels (PDPs) in detail. The last meeting in Tokyo attracted some 230 participants from 73 organizations. Support came from infrastructure industries dealing with a variety of components, including glasses, phosphors, thick-film print screens, pastes, and fabrication technologies.

Plasma fever is spreading, I presume, not because plasma developers have recently made magnificent technical breakthroughs, but rather because people have realized that TFT liquid-crystal techniques are not adequate for large displays – at least for the near future. Other technologies, such as electroluminescence (EL) and field-emission display (FED) technology, are demonstrating color and appear capable of producing small displays. In small sizes, these displays might have to compete directly with LCDs. If this were the case, they would have to compete under a handicap: the promoters of these technologies, although serious, do not have access to huge R&D budgets as LCD manufacturers do.

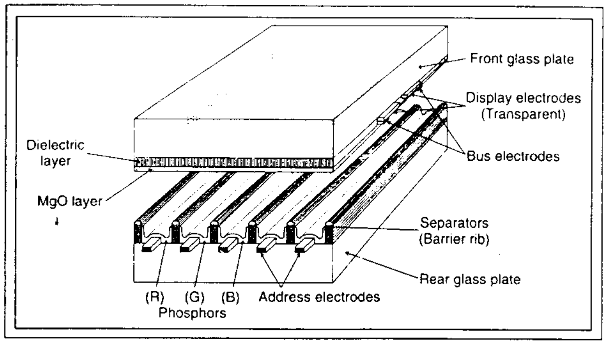


Fig. 1: Fujitsu's epoch-making 21-in. plasma-display monitor uses a three-electrode surface-discharge structure. (Figure courtesy of Fujitsu, Ltd.)

Another thing that impressed me at the SID meeting was that the statement "plasma is large and in full color" seemed to be commonly accepted, especially on the exhibition floor.

How They Operate

A PDP is a collection of miniature gas-discharge lamps working on the same principle as ordinary household fluorescent lamps. Images can be reproduced by controlling the intensity or duration of the discharge current at each lamp. The vacuum ultraviolet radiation emitted by the gas discharge excites the phosphor deposited on the inner wall of the lamp. The lamp's color can be determined by choosing an appropriate phosphor.

PDPs are categorized mainly by whether the voltages applied to their discharge electrodes are ac or dc, although there are also hybrid types such as ac-dc and dc-CRT. The electrodes of dc panels are exposed to the discharge gas; those of ac panels are insulated by thin-film dielectric layers.

A well-designed PDP has an extremely attractive set of features. First, it is thin, with a total panel thickness of 6 mm or less. The overall thickness of the final device is design-dependent. Electronic drivers are usually mounted at the back of the panel, but they can be attached to the panel's periphery to reduce thickness.

PDP is the only direct-view technology that can display an image having a diagonal mea-

---

Dr. Shigeo Mikoshiba is Professor of Electronic Engineering at The University of Electro-Communications, Tokyo, Japan, and Associate Editor of Information Display.

[illegible] ent of 40 in. or more. Photonics of Northwood, Ohio, introduced a 60 in. diagonal fully populated monochrome display in 19[illegible]. Dr. Peter Friedman of Photonics says [illegible] be able to double the diagonal of the company's current 30 in. color plasma display without much difficulty.

PDP is rugged and safe. In the unlikely event that a blow or fall accidentally breaks a panel, there is no danger of glass fragment [illegible]. Neon atoms are more stable than [illegible] of the rare gases that are commonly used in existing panels. The basic structure and materials are extremely durable, so system durability at ambient temperature is typically determined by the electronics. Users of [illegible] production units of ac monochrome PDPs expect a lifetime of 100,000 hours.

PDP viewing angles are wide — comparable to that of CRTs. Panels offer full color, 8 bit gray scale capability, high contrast ratio (CR), and speeds high enough for HDTV displays.

Because of the strong current voltage nonlinearity that produces a sharp "knee" in the current voltage curve, plasma panels permit the addressing of many electrodes with a time multiplexing technique. This eliminates the need for the complicated active-matrix addressing techniques used in some LCDs.

If you need a high-resolution display, LCD might be a better answer than PDP. The ability to put PDP pixels close together is limited because of the need to deal with relatively high voltages. What's more serious is that luminous efficiency is reduced as the discharge dimensions become smaller because more energy is wasted by the increased diffusion loss of charged particles to the cell walls.

Low luminance is another problem. Gas discharges do not produce ultraviolet radiation exclusively, and a lot of energy is wasted in simply heating the gas and cathodes. The luminous efficiency of the typical plasma display is [illegible] lm/W for white, which corresponds to an energy conversion efficiency of only about [illegible].

Display Update

The epoch-making Fujitsu/Fujitsu General 21 in. [illegible] plasma TV and monitor are now on the market under the name "Plasma Vision." The initial price of the monitor [illegible] is now down to ¥780,000. Mr. Tsutae Shinoda, Project Manager, Display [illegible] Ltd., Japan, said that he has received many more requests for price quotes than he had expected. The display resolution of 640 × 480 pixels is designed to be compatible with IBM's Video Graphic Array (VGA) standard. The overall size of the set is 490 mm wide, 440 mm high, and 60 mm deep.

The structure of the Fujitsu panel incorporates a pixel pitch of 0.66 mm, consisting of three (RGB) discharge cells (Fig. 1). The panel is an ac type filled with a gas mixture of xenon and neon. Each single cell has three electrodes. Surface discharge takes place between the two transparent display electrodes, which are on the front glass plate. The electrical conductivity of these electrodes is enhanced by overlaid thin film Cr-Cu-Cr bus electrodes.

The electrodes are coated with dielectric and magnesium oxide (MgO) layers. The MgO's low sputtering rate assures a longer panel life, and its high coefficient of secondary electron emission provides a lower operating voltage — but at the expense of a tedious thin film process. The third electrode, which addresses the discharge cell, is on the rear glass plate. Separators — or barrier ribs — are 50 μm wide, 100 μm high, and are on a 0.22 mm pitch. They are made by a multiple printing technique of thick-film pastes. The separators prevent electrical and optical crosstalk between neighboring cells.

Phosphors are deposited on the address electrodes as well as on the side walls. This increases the phosphor deposition area and improves the white peak luminance to 150 cd/m², the luminous efficiency to 0.7 lm/W, and the viewing angle to 140°. The CR is 50:1 in a dark room. The panel can display 64 gray shades and 260,000 colors. The highest voltage for the IC drivers is 180 V p-p. The monitor, including the high voltage drive electronics and their control circuits, consumes 100 W and weighs 4.8 kg. The panel life is in excess of 10,000 hours. Fujitsu's goal is to upgrade the size to 40 in. within [illegible] years.

At SID '94, NHK (Japan Broadcasting Corp.) Science and Technical Research Laboratories, in collaboration with Dai Nippon Printing Co., Ltd., reported on the development of an experimental 40 in. diagonal full color dc display (Fig. 2). Its active area is 87[illegible] mm horizontally and 520 mm vertically, with an aspect ratio of 16:9. A pixel is composed of four (RGBG) discharge cells. The number

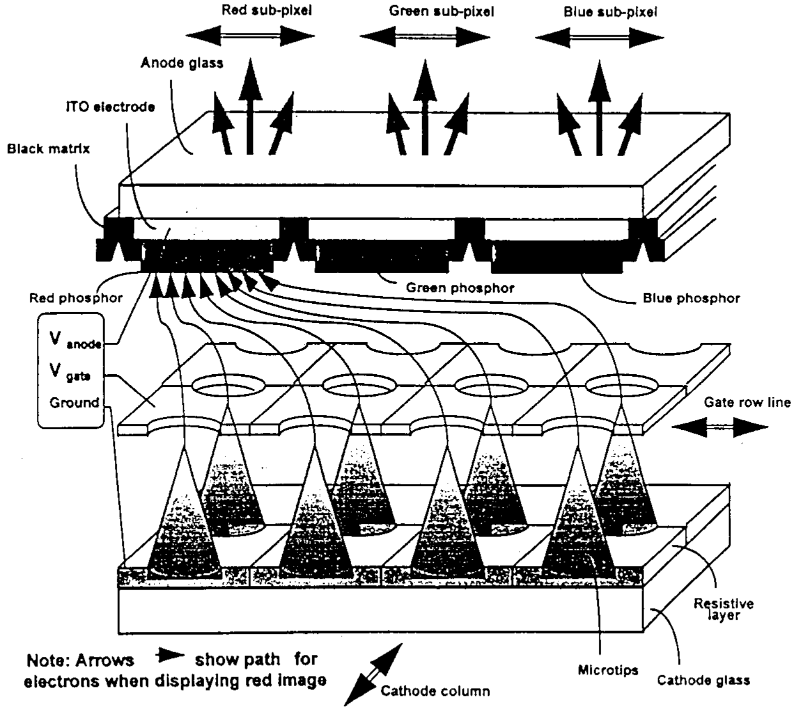
NHK Science and Technical Research Laboratories

Fig. 2: NHK and Dai Nippon Printing Company have produced an impressive 40 in. diagonal plasma display.

DISPLAY TECHNOLOGY

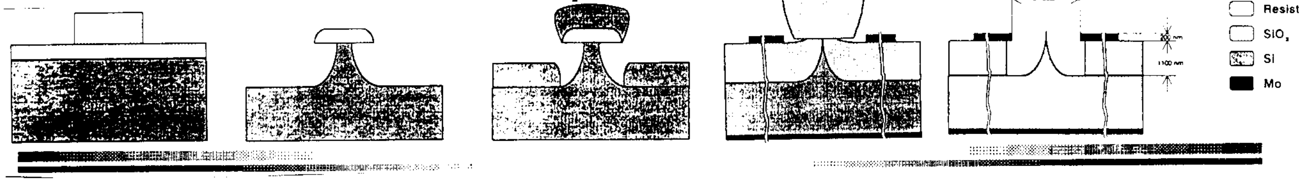
Field Emission Displays

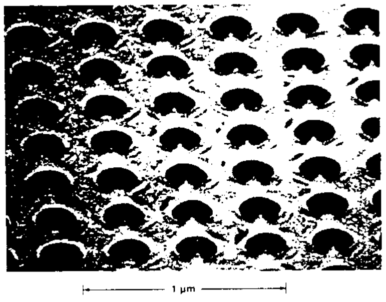
FED Pixel Structure



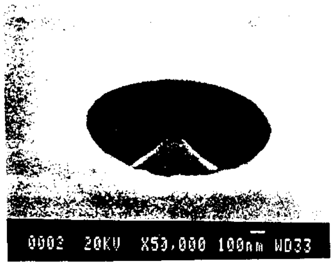
Note: Arrows show path for electrons when displaying red image

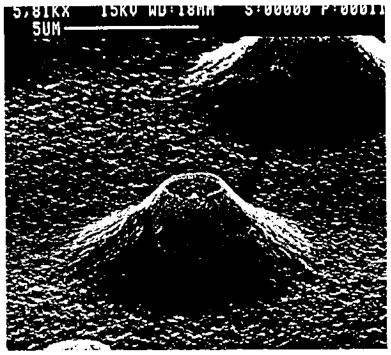
Fabrication of microtips

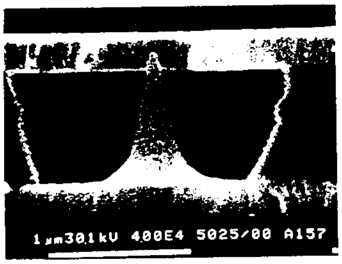


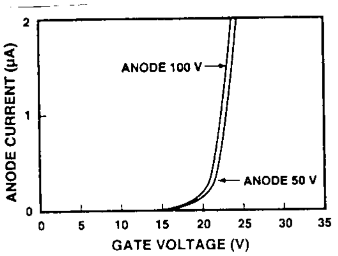


DENSITY = 10^9 CONES/cm^2
GATE-TIP SPACING = 0.08 µm
TIP-TIP SPACING = 0.32 µm









D.Peters, I. Paulus, and D. Stephani, JVSTB **12**, 652 (1994).
C.O. Bozler, C.T. Harris, S. Rabe, D.D. Rathman, M.A. Hollis, and H.I. Smith, *ibid.*, p. 629.
J.E. Pogemiller, H.H. Busta, and B.J. Zimmerman, *ibid.*, p. 680.
G.N.A. van Veen, *ibid.*, p. 655.

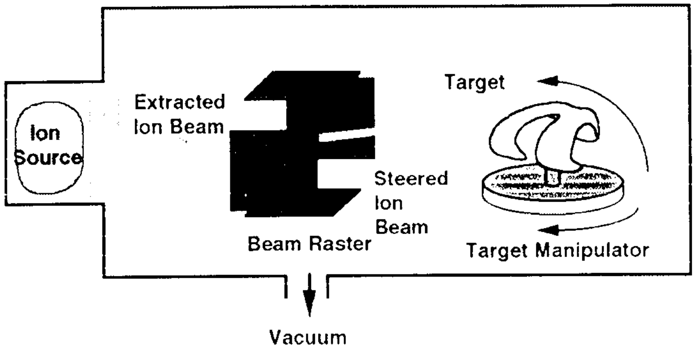
Ion implantation

- Ion beam implantation (mostly of nitrogen)
  - Object rotates for coverage
  - IBED: ion beam enhanced deposition
- Plasma source ion implantation (PSII)
  - Plasma surrounds object
- For hardness, wear, friction, corrosion, etc.
- Metals: e.g. steel rebars, tools
- Non-metals: plastics, glass, hard disks, Si

Comparison of Conventional Beamline Ion Implantation and Plasma Source Ion Implantation

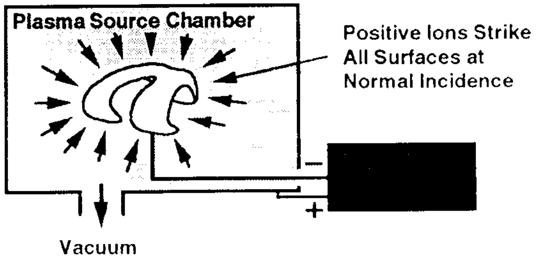
Conventional Beamline Implantation

- Line of sight process
- Beamline rastering and target manipulation are required to achieve uniform implantation



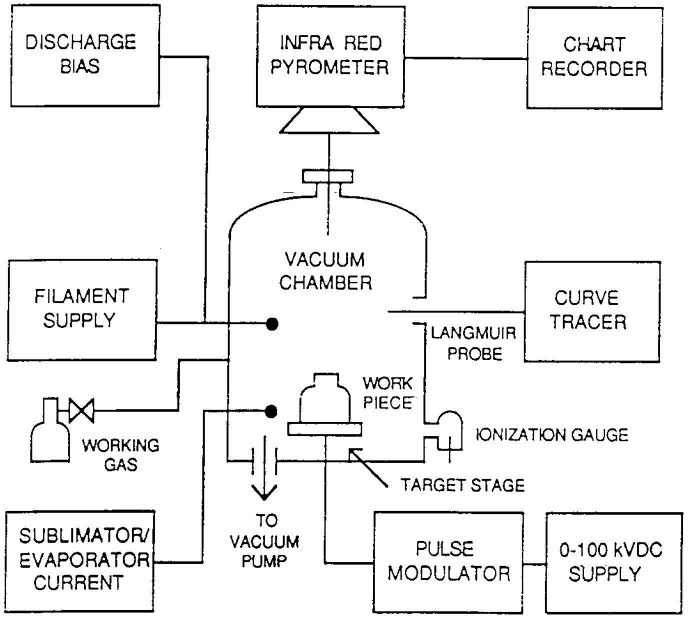
Plasma Source Ion Implantation

- Plasma sheath surrounds target
- Ions bombard all surfaces of target without beam rastering or target manipulation



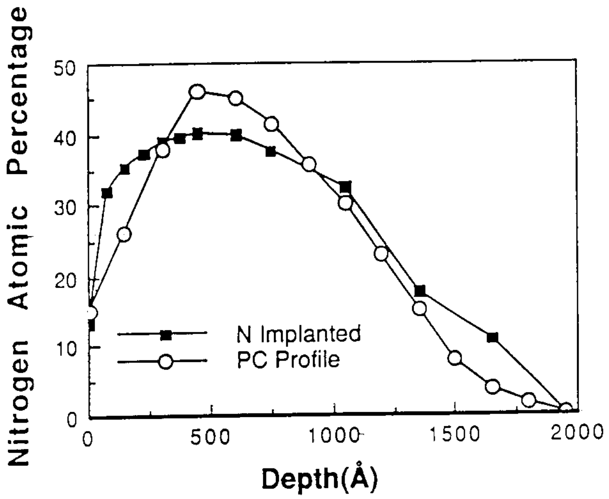
Plasma ERC

PSII achieves accelerator-physics surface modification in a bell jar-like environment



John Conrad, U.Wisc.

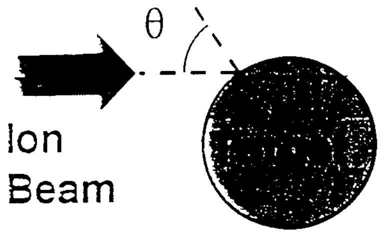
PSII provides the deposition profile characteristic of beamline implantation, but in a much simpler system

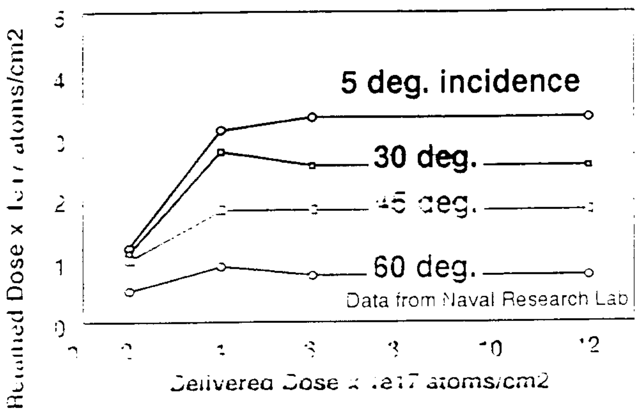


Auger depth profile data of the concentration of nitrogen ions implanted at 50 keV in Ti-6Al-4V alloy to a dose of 3×10^{17} atoms/cm^2. Also shown is the prediction of the PC Profile Code.

Retained Dose Problem

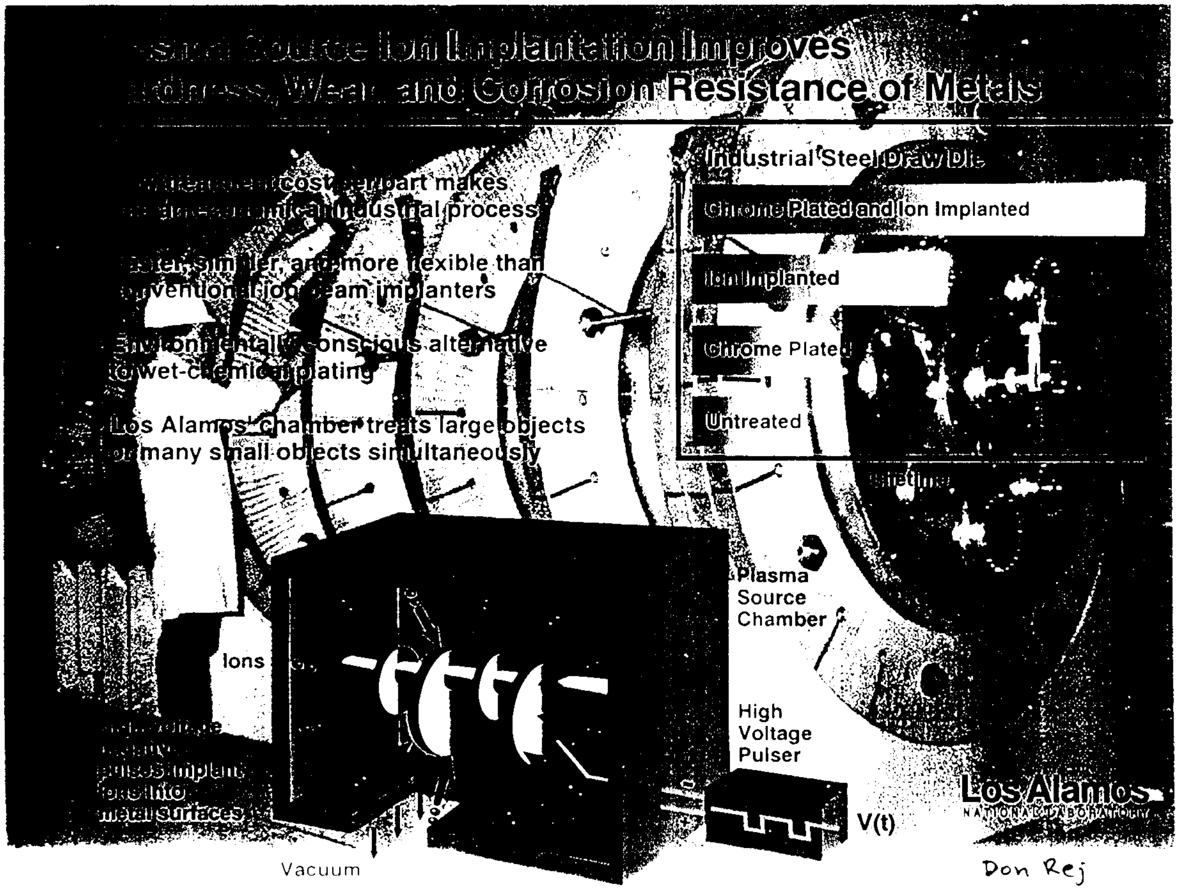
- In ion implantation, the maximum dose which can be achieved (the retained dose) is limited by sputtering of the target due to bombardment of the incident ions.
- In conventional beamline ion implantation, the sputtering rate increases rapidly with the angle ofincidence for non-normal bombardment, and as aresult, the retained dose suffers for non-normal bombardment.





Data from Naval Research Lab

In contrast, with PSII, the retained dose problem is minimized because to lowest order, the ions trajectories are everywhere perpendicular to the target.



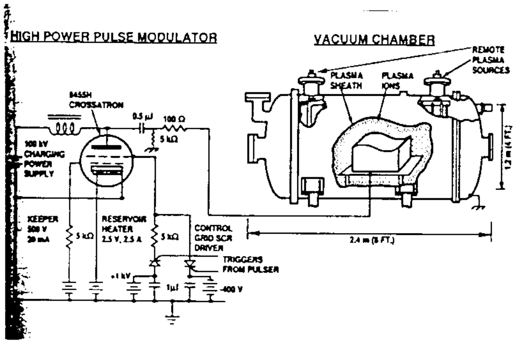
Plasma Source Ion Implantation Improves Hardness, Wear and Corrosion Resistance of Metals

- Low treatment cost per part makes it an economical industrial process
- Faster, simpler, and more flexible than conventional ion beam implanters
- Environmentally conscious alternative to wet-chemical plating
- Los Alamos' chamber treats large objects or many small objects simultaneously

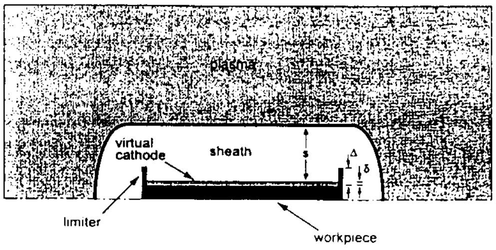
Don Rej

PSII Problems

- Huge power supplies: >50kV, 50A, 2kHz
- Secondary electron emission
- Thin sheaths: dense plasmas



J.N. Matossian, JVSTB **12**, 850 (1994)



D. Rej, B. Wood, R. Faehl, and
H. Fleishmann, JVSTB **12**, 861 (1994)

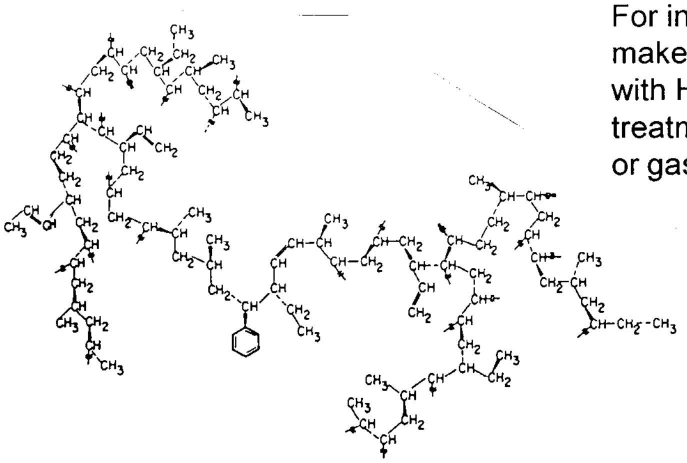
Plasma surfacing and polymerization

- Barrier coatings
  - Gas tanks, potato chip bags, Coke bottles
- Fibrous materials
  - Paper, wood, textiles
- Optical coatings, optical fibers
- Integrated optics (optical computing)
- Cleaning and sterilization of biomedical surfaces
- Plasma polymerization

Plasma polymerization

- Many materials can be synthesized:
  - organics, fluorocarbons, organosilicones, organometallics, polymer-metal composites
- Usually, monomers are turned into oligomers or polymers that are linear and weak.
- In a plasma, the electrons break bonds easily and the polymers formed are cross-linked, and the films are strong and without pinholes.
- How this happens is not known in detail.

Tailoring the polymers



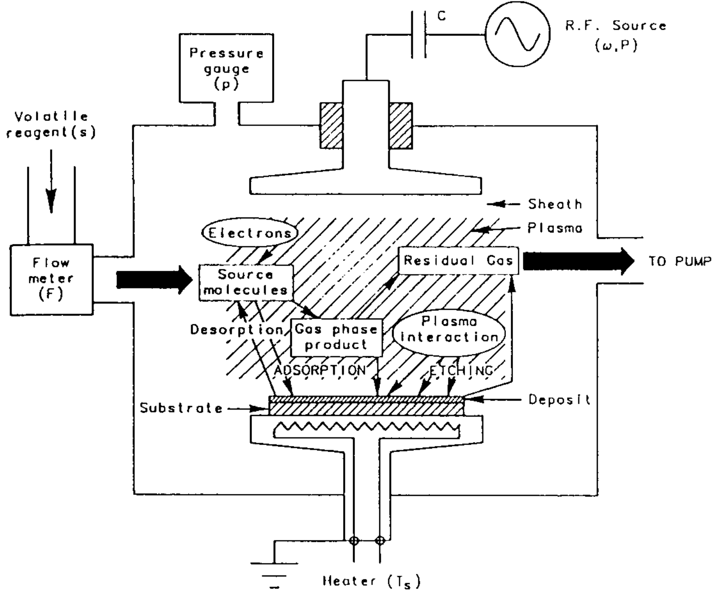
Properties of the films can be changed by attaching radicals to the ends of the chain. For instance, adding an NH_3 group will make a film will adhere well; an OH group with HMDSO will improve wettability; treatment with CF_4 forms a barrier for O_2 or gasoline.

The most common polymer is PPMMA: plasma polymerized methyl methacrylate (plexiglas).

N. Morosoff, in *Plasma Deposition, Treatment and Etching of polymers*, ed. by R. d'Agostino (Academic, 1990).

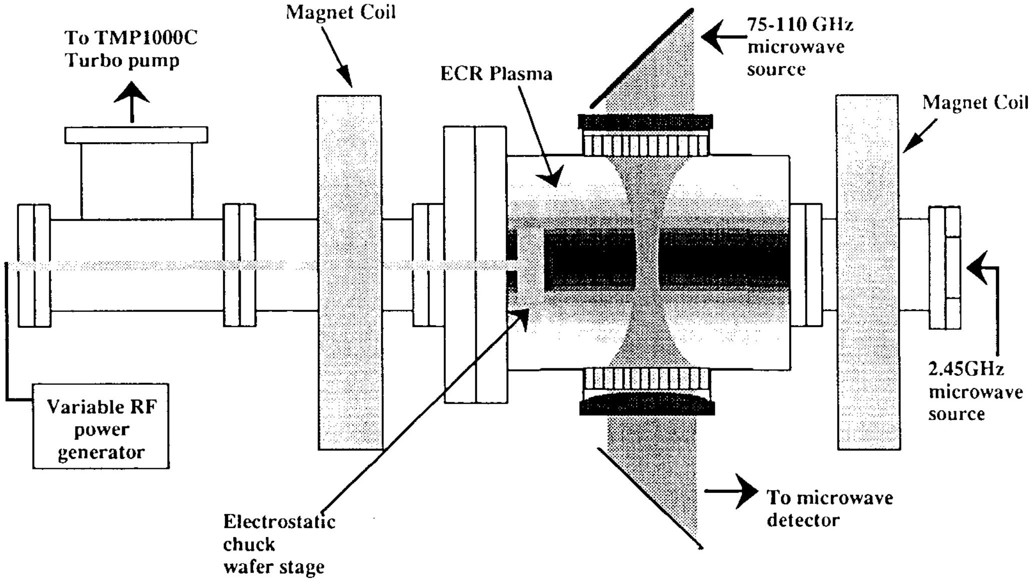
Plasma sources for PP

Simple glow discharges have been used, but the new high-density sources are being developed to give higher deposition rates.



A.M. Wrobel and M.R. Wertheimer, in *Plasma Deposition, Treatment and Etching of polymers*, ed. by R. d'Agostino (Academic, 1990).

ECR DEPOSITION SYSTEM AND MICROWAVE SPECTROMETER



Denice Denton, Wisconsin

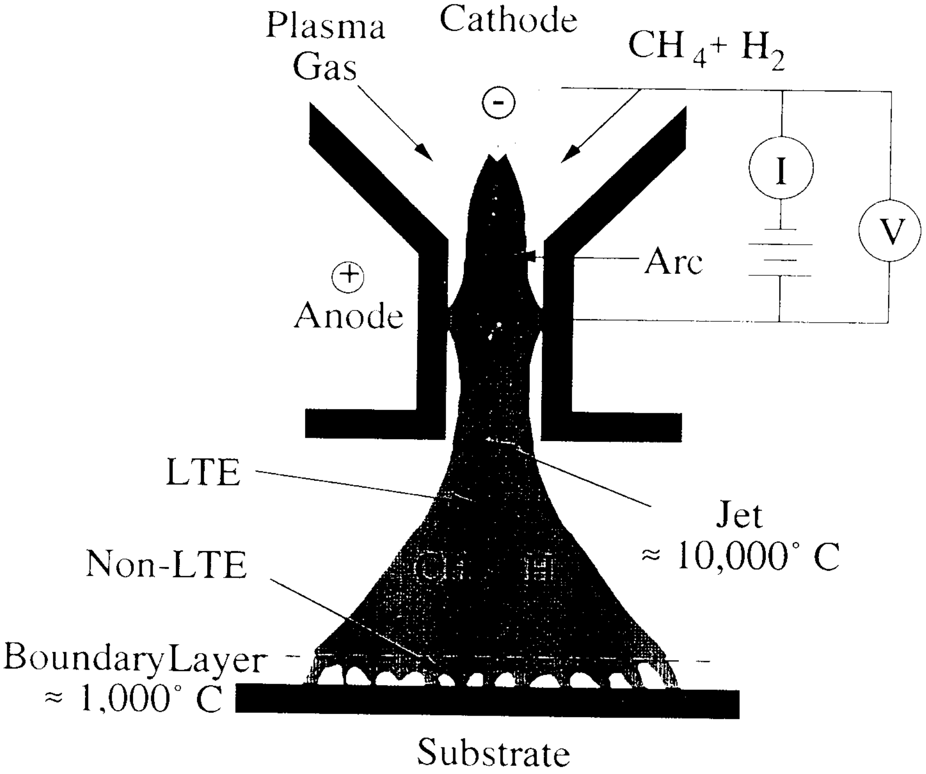
Plasma ERC

Research areas in Plasma polymerization

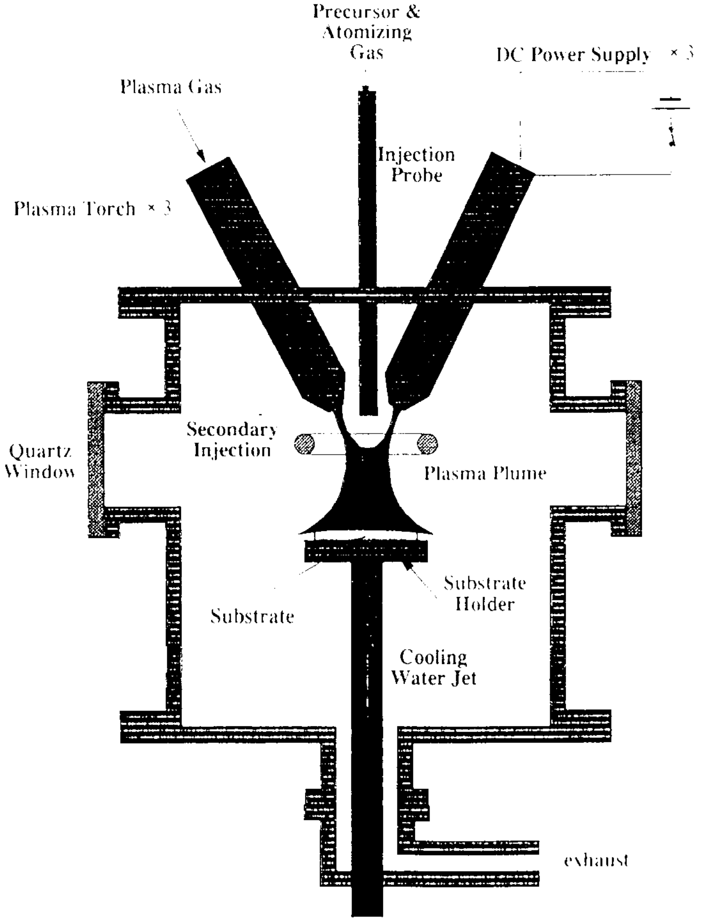
- Detect precursors and try to understand mechanism of cross-linking
- Understand the roles of the many variables:
  - » density, electron temperature, pressure, frequency
  - » gases, flow rate, substrate temperature
- Make devices to treat inside and convoluted surfaces
- Make devices to treat continuous webs of material
- Find new substances that can make plastics more recyclable

Thermal plasmas

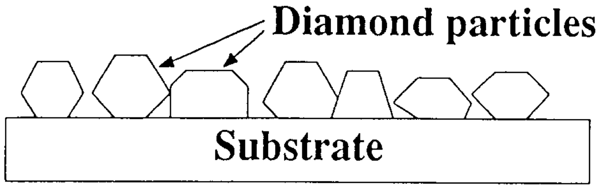
- Spray treatment of turbine blades, etc.
- Diamond deposition
  - hard, heat conductor, electrical insulator
- Synthesis of new materials
  - β-C_3N_4, cBN (cubic boron nitride)
- Waste treatment
- Metallurgy



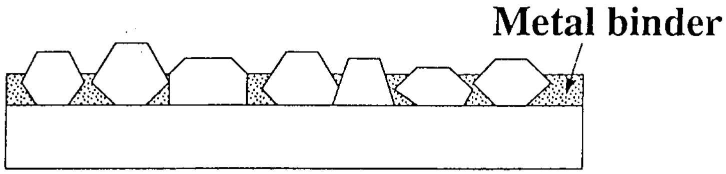
Emil Pfender, U. Minn.



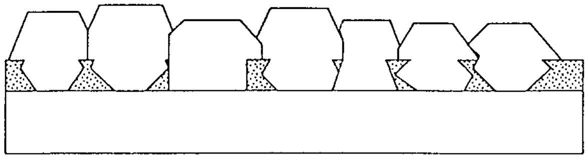
Schematic drawing of the triple torch plasma reactor



Step 1: diamond deposition on substrates by plasma CVD



Step 2: electroplating of metal binder



Step 3: re-growth of diamonds

examples of topics in

Low-Temp Plasma Physics

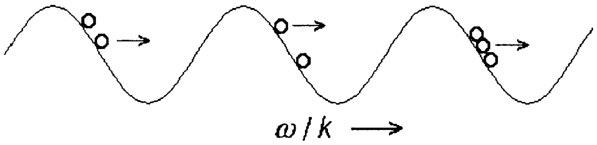
- Landau damping in partially ionized gases
- Radiation transport in high pressure discharges
- Multi-step ionization processes; Penning mixes
- Transit-time heating in sheaths
- Electron runaway in rf discharges
- Rf and mwave discharges for lighting
- Use of instabilities in e-beam sources, PALC displays, laser isotope separation
- Isotope separation by ICRH


(a) Diamond crystals are deposited by RF thermal plasma CVD

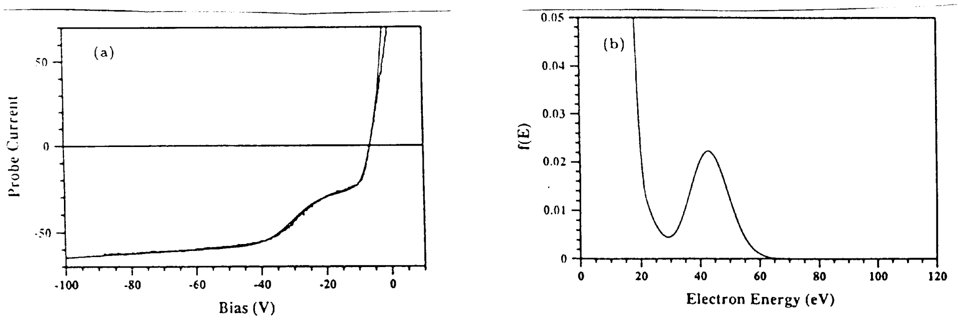

(b) Diamond crystals are partially embedded in the binder after electroplating


(c) Diamond growth is continued to produce a continuous overlayer of diamond

Kinetic effects in low-temp plasmas



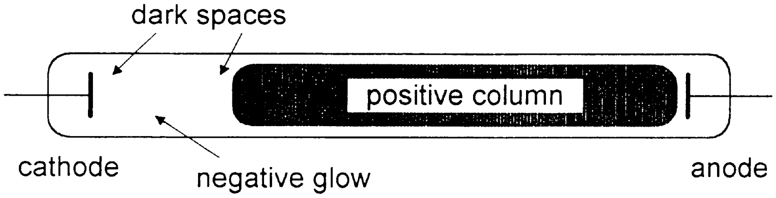
Electrons can be accelerated to ionizing energy by surfing on helicon waves, which happen to have the right phase velocities. After an inelastic collision, they can be picked up and re-accelerated. [F.F. Chen, PP&CF **33**, 339 (1991)]



P. Zhu and R.W. Boswell, Phys. Fluids B **3**, 869 (1991).

Radiation transport

TYPICAL HIGH PRESSURE DISCHARGE


dark spaces

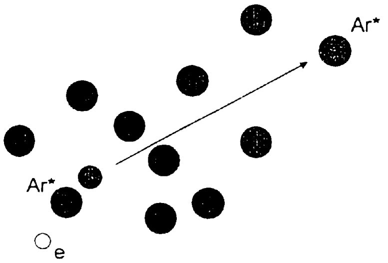
positive column

cathode

negative glow

anode

The region near the cathode has a) non-Maxwellian electrons and b) resonant photons

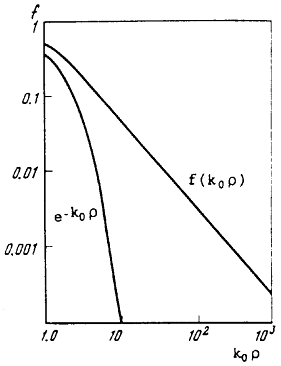


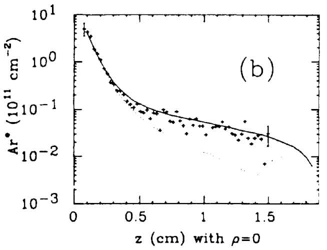
Excitation energy travels faster by photon transport than by electron collisional transport. However, a spectrum of frequencies is involved, and a simple diffusion equation cannot be used.

This problem is amenable to treatment by powerful analytical and computational tools.

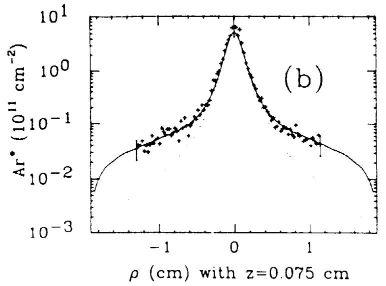
Modeling of radiation transport

The density of excited atoms falls off much more slowly than exponentially, as in diffusion. [L.M. Biberman, V.S. Vorob'ev, and I.T. Yakubov, *Kinetics of Nonequilibrium Low-Temperature Plasmas* (Consultants Bureau, 1987)].

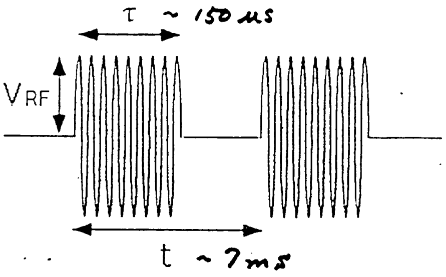




Using a propagator method which treats the photon spectrum approximately, Lawler et al. have been able to fit the measured Ar* density profiles in r and z for a Hg-Ar mixture such as is used in fluorescent lights. [R.C. Wamsley, K. Mitsuhashi, and J.E. Lawler, Phys. Rev. E **47**, 3540 (1993)].

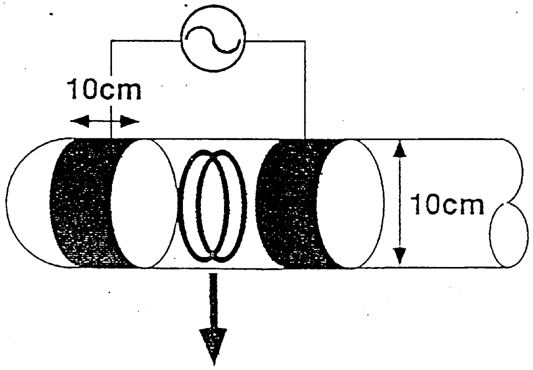


RF Ring Experiment (Y. Sakawa, Nagoya Univ.)



Pulse modulated RF Voltage

V_{RF}=1.0kV
f =1.5MHz
P_{RF}=1.0kW

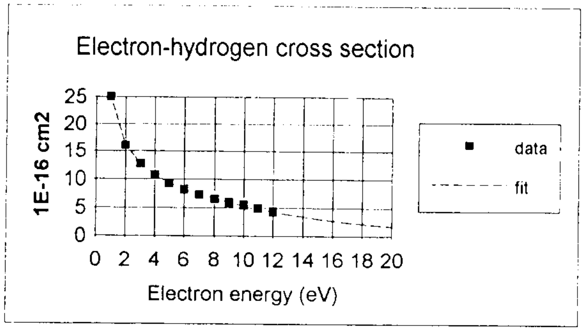


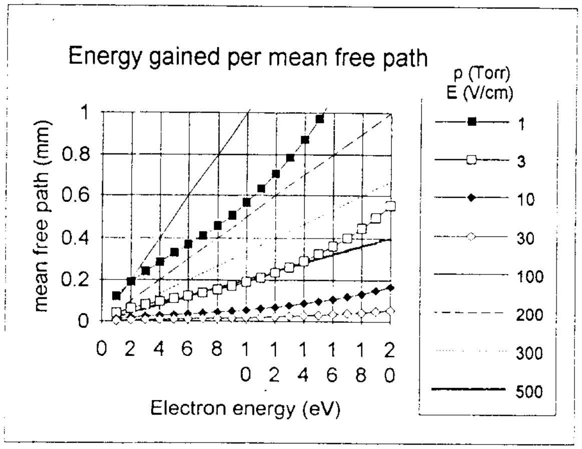
Plasma Parameters

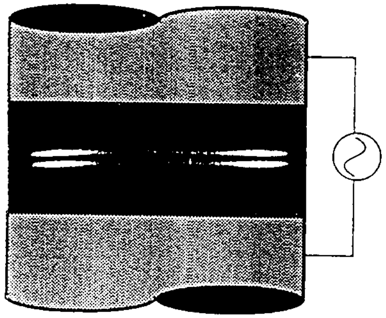
n_e~10^8-10^{10} cm^{-3}
T_e~5 eV
p_{H_2}=1-30 Torr

Scanning diode-array Camera (SDAC)

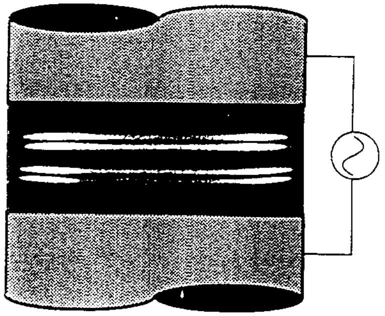
ELECTRON RUNAWAY IN ATOMIC HYDROGEN



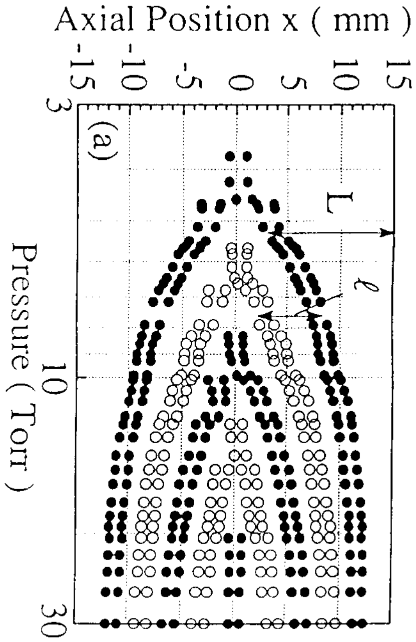




(a)



(b)



Plasmas in the lighting industry

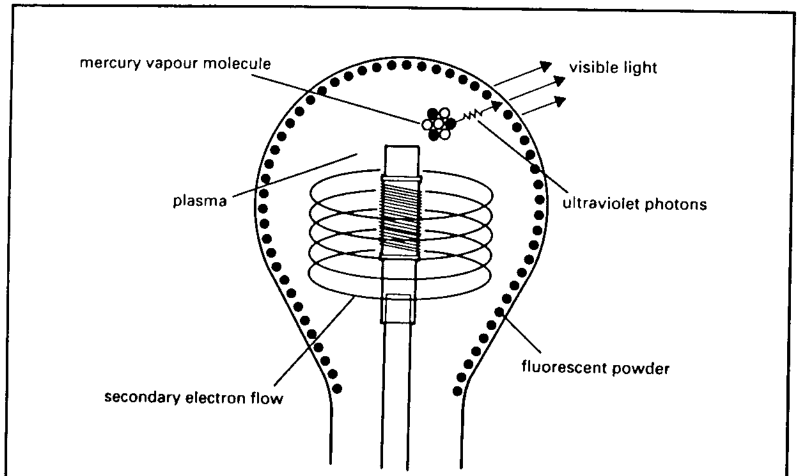
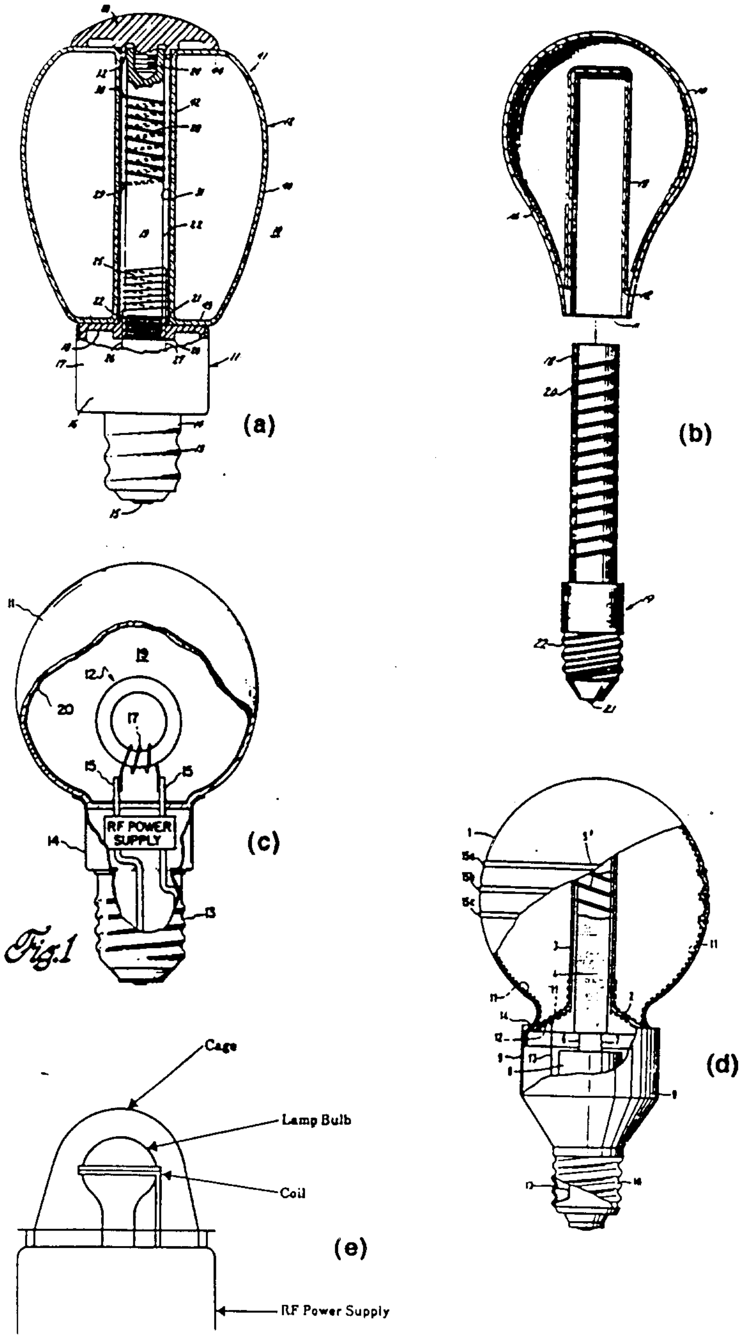


Fig. 2.3 Operation of gas discharge

The Phillips QL-lamp: 65-80W @ 2.65 MHz

Source: Bob Piejak, Osram Sylvania

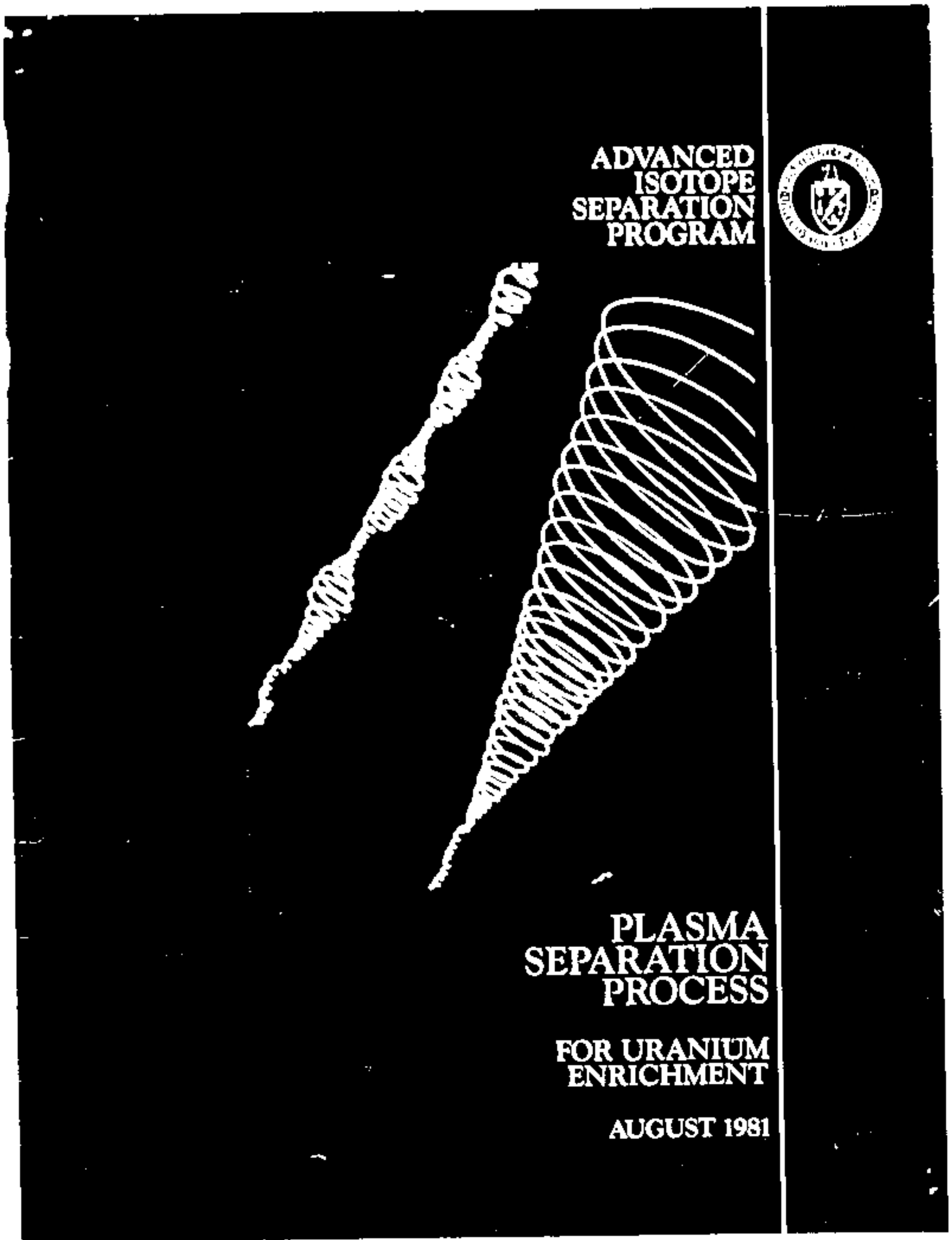


Isotope separation

- PSP (Plasma Separation Process, ICRH)
- AVLIS (Atomic Vapor Laser Isotope Separation)

Peaceful uses:

- Medical isotopes
- Fusion wall materials
- Spacecraft power sources



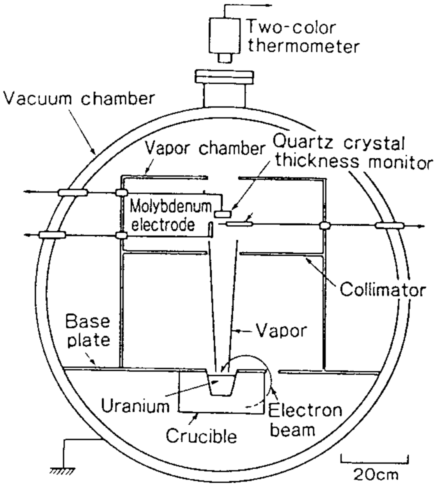
ADVANCED
ISOTOPE
SEPARATION
PROGRAM

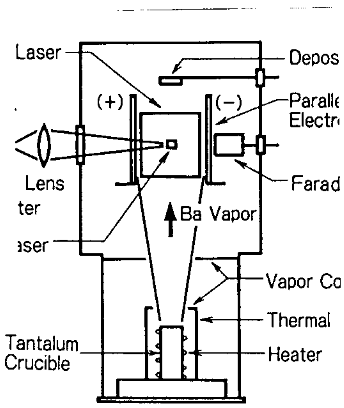
PLASMA
SEPARATION
PROCESS

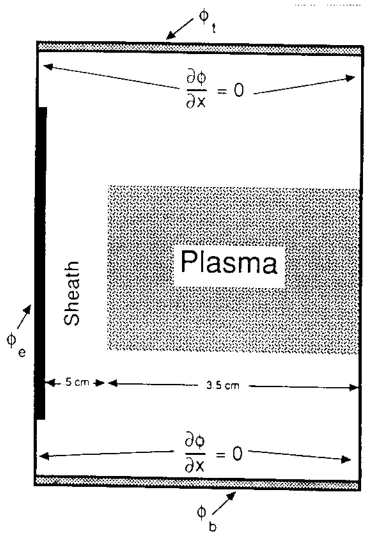
FOR URANIUM
ENRICHMENT

AUGUST 1981

Possible use of instabilities to extract plasma

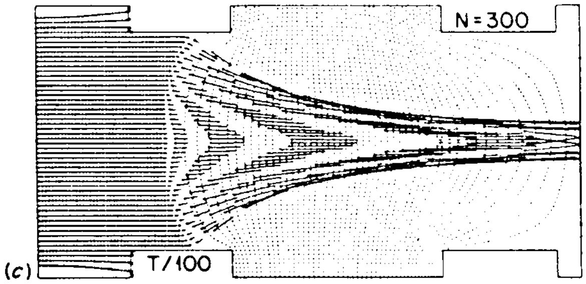






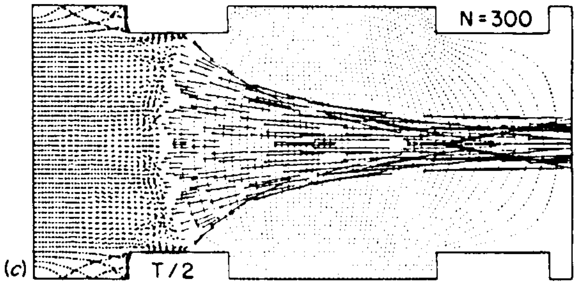
a) R. Nishio, K. Tuchida, M. Tooma, and K. Suzuki, J. Appl. Phys. **67**, 6734 (1990).
b) K. Yamada, T. Tetsuka, and Y. Deguchi, J. Appl. Phys. **67**, 6734 (1990).
c) P. Vitello, C. Cerjan, and D. Braun

Ion acoustic instability in an expanding sheath



V →

$V \geq V_{Bohm}$

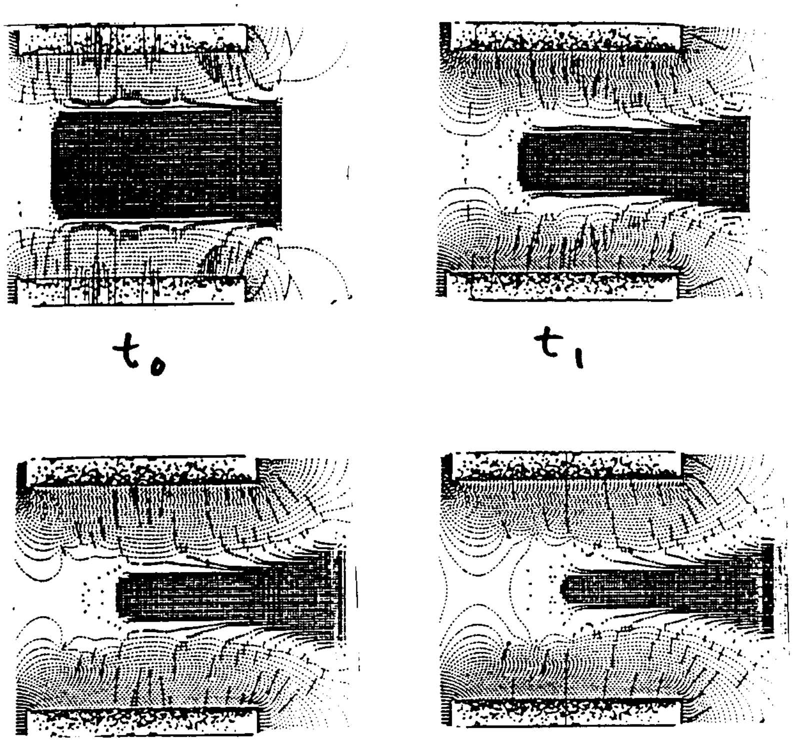


V →

$V < V_{Bohm}$

PLASMA JET

$\xrightarrow[v_0]{}$



t_0 t_1

t_2 t_3

Figure 5

John Whealton, ORNL