Uloga niskotemperaturskih plazmi u proizvodnji integrisanih kola

i gde smo tu mi

Zoran lj. Petrović

U saradnji sa Draganom Marić, Nevenom Puač, Nikolom Škorom, ..., i

Gordanom Malović,

Keio University
Science and Technology


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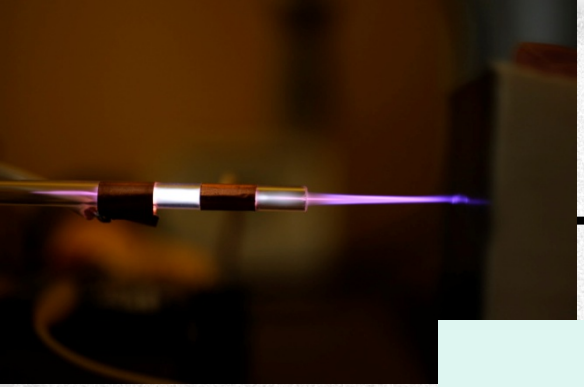
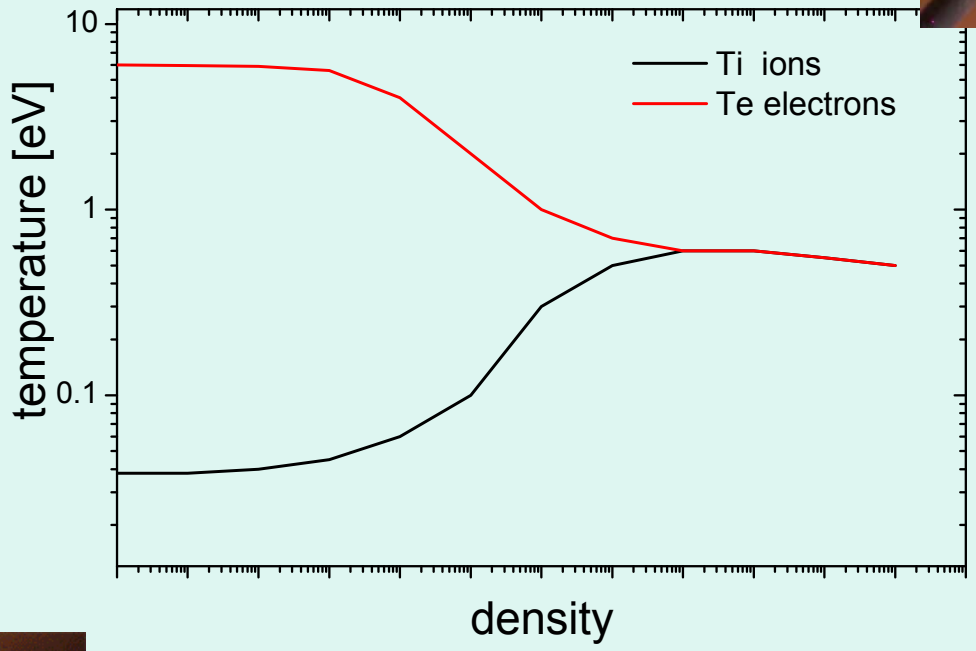
A ima li tu nauke?

A ima li tu tehnike?

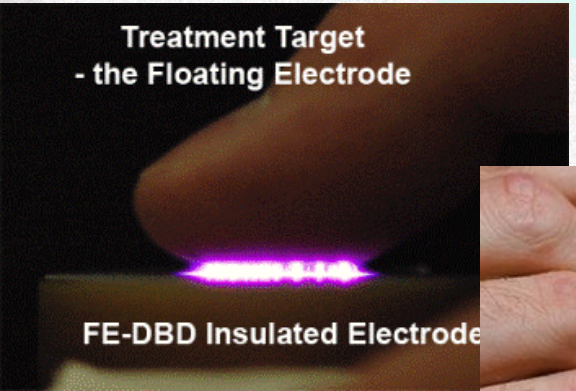
ČEMU SLUŽE NERAVNOTEŽNE PLAZME



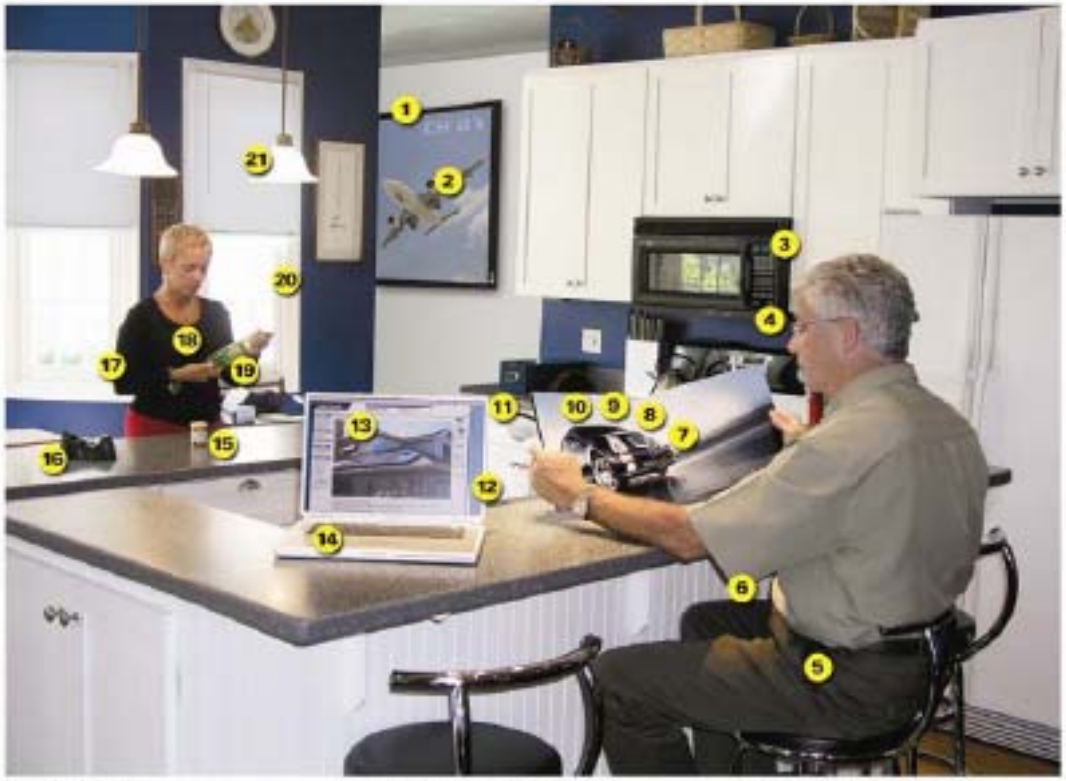
Non-Equilibrium
Cold-
Non-Thermal
Te>>Ti=Tg
293K



Equilibrium
Thermal
Te=Ti=Tg
7000K



LTPSE: ROBUST SCIENCE, SOCIETAL BENEFIT



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

- **Operating premise:**

  LTPSE has a history and future of robust, interdisciplinary science challenges whose resolution provides immediate and long term societal benefit.

Market for Plasma treatment

- Bio-medical
- Sterilization
- Textile
- Plastics
- Solar
- Glass
- Automotive, Aeronautical, …

- Multiple 100Mi$ markets, several growing at more than 20%/year.

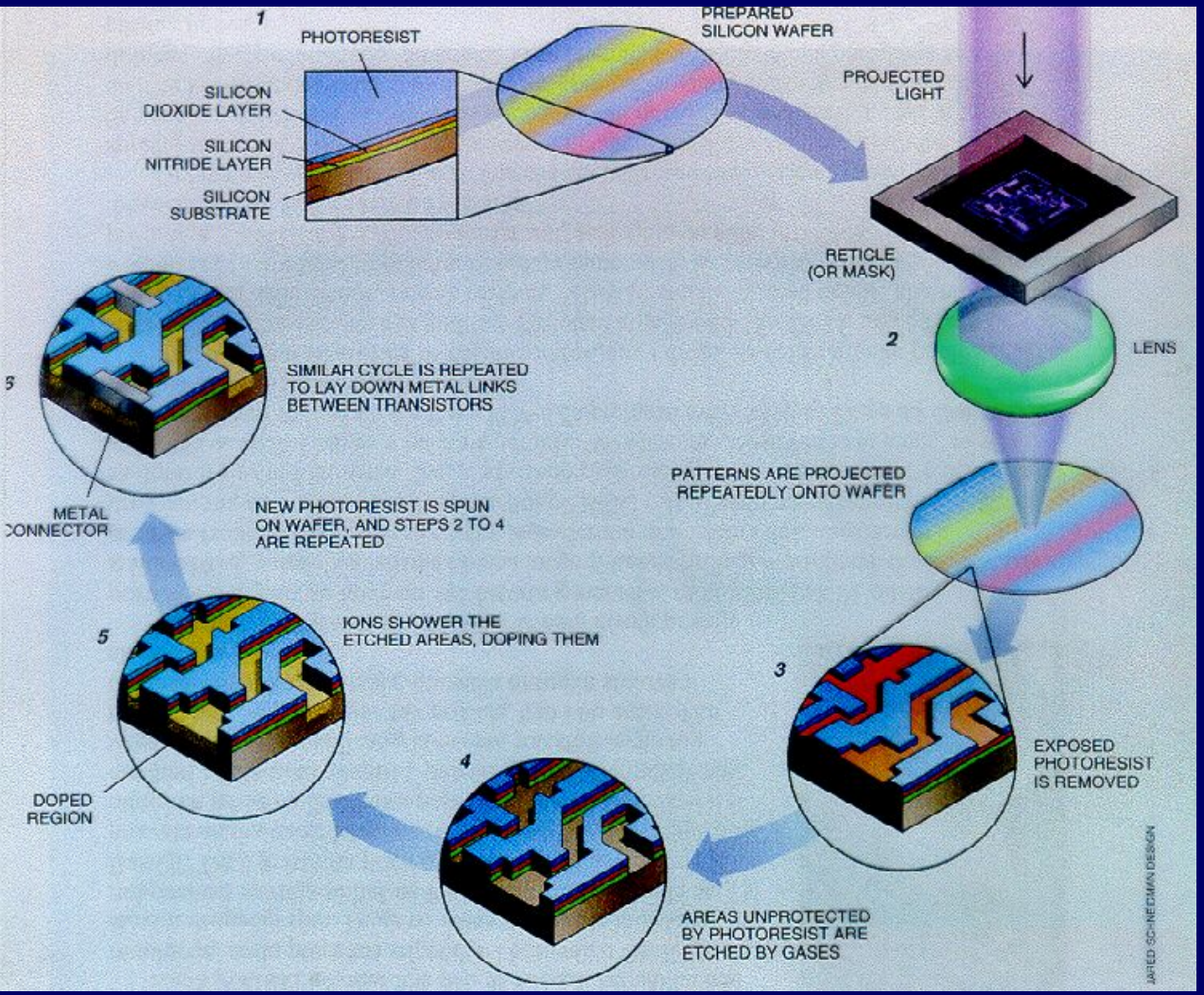
KOJE SU TEHNOLOGIJE NEOPHODNE

KOJE SU TEHNOLOGIJE NA FRONTU MINIJATURIZACIJE

KAKO NAPRAVITI INTEGRISANO KOLO

MOORE OV ZAKON

Proizvodnja integrisanih kola



Nanošenje tankih slojeva

Modifikovanje osobina materijala- implantacija

Uklanjanje foto rezista

Plazma nagrizanje

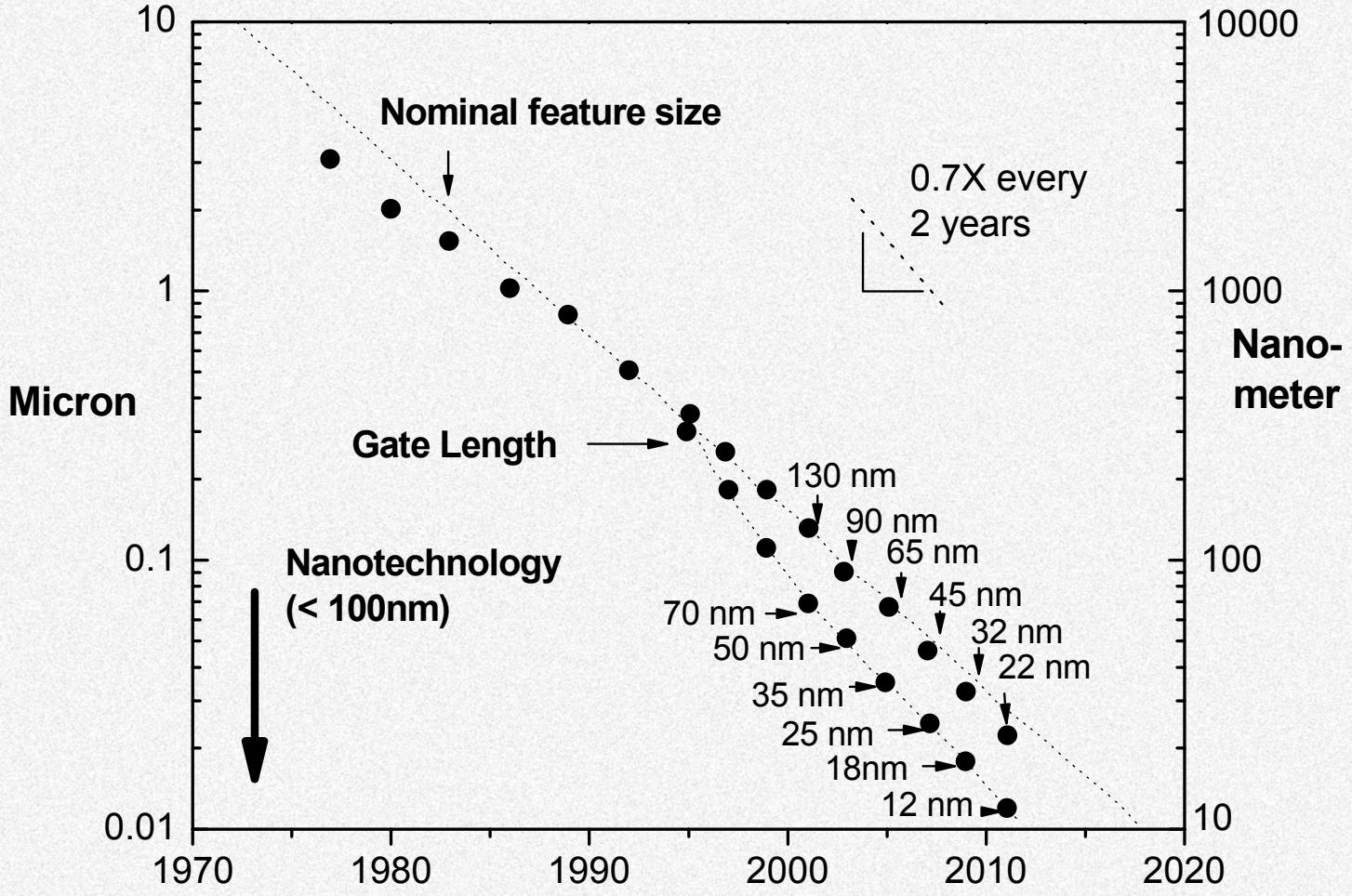
Izvori svetlosti

REMOVABLE STORAGE

5 Megabytes . . . $120,000

65,536 Megabytes . . . $60

Које су границе?



-H. Iwai, Microelectronic Engineering 86, 1520-1528 (2009)

Zašto neravnotežne, Zašto RF plazme

KAKO PROIZVESTI NERAVNOTEŽNU PLAZMU

IZVORI PLAZME

Unique properties of LTP

- **Ion and fast neutral Impact at Surface**
- • Ion current density ~ 10 mA cm^{-2} (10^{17} ions cm^{-2} s^{-1});
- time between impacts on area of ~ 1 nm^2 is about 10-3 s.
- • Energy of single impact dissipates to background heat in ~ 10^{-12} s
- • Conclusion: ion impacts dissipate energy long before another ion hits nearby: *impacts are isolated*
- **Single Ion/Fast Neutral Impact at Surface: Peak and Mean Power Deposited**
- • Ion energy ~ 100 eV, deposited in 1 nm^2 and dissipating in ~ 10^{-12} s
- • Peak power density dissipated by single ion impact: ~ 10^9 W cm^{-2}
- • But for 10^{17} ions cm^{-2} s^{-1} @ 100 eV: average power density ~ 1 W/cm^2
- ***Peak power is large: chemical bonds broken easily at surfaces***
- ***Average power is modest: easily removed, e.g., from wafer backside***
- ***Strong Gradients in time and space near surface***
- **Dramatic surface chemistry at low temperature: First key to LTP uniqueness**

Unique properties of LTP2

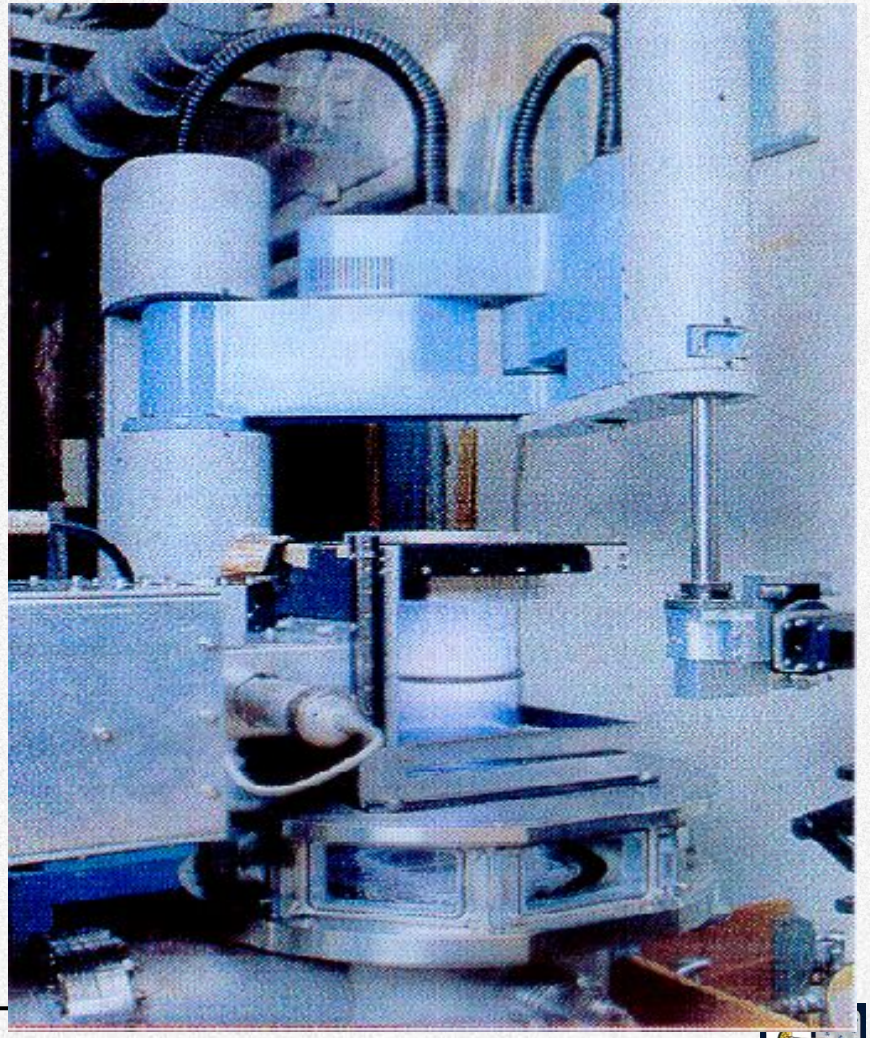
- **Sheaths form near surface naturally due to mass** differences between electrons and ions
- • These high field regions conveniently **accelerateions, often with no collisions, to allow (nearly)** normal incidence impacts at surfaces, converting thepotential energy in sheath into kinetic energy at the surface
- • Collisionless at fairly **high pressure if sheath thickness** < λ_{mfp}
- **Energetic ion impact at normal incidence: Second key to LTP uniqueness**
- • Neutral, chemically active radicals are of coursecreated in large numbers by electron-impact dissociation in molecular gas plasma
- • Surface flux scales with pressure (density) – higher neutral gas pressure allows greater fluxes of radicals, increasing processing rates
- • Well known that individual effects of ions and neutrals can be dramatically altered when both impact surfaces:
- **SYNERGY – *third and perhaps most important key to LTP uniqueness***
- ***Strong fields at the surface, liquid, organic materials, charging of the organelles , ...***

CENTRE FOR NON-EQUILIBRIUM PROCESSES
INSTITUTE OF PHYSICS BELGRADE

Наши ??? Плазма извори- KEIO Uni.

CCP капацитивно спрегнута плазма

ICP индуктивно спрегнута плазма



KOJE SU TEHNOLOGIJE NEOPHODNE

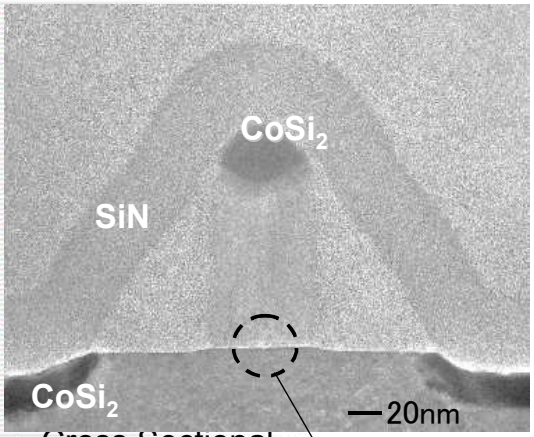
KOJE SU TEHNOLOGIJE NA FRONTU MINIJATURIZACIJE

KAKO NAPRAVITI INTEGRISANO KOLO

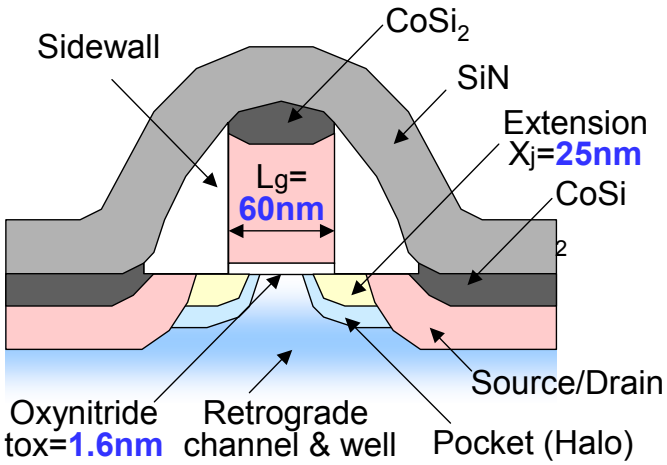
PLASMA ETCHING (PLAZMA NAGRIZANJE)

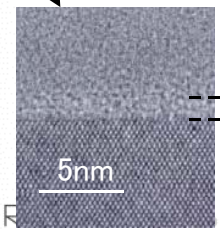
NEC

60nm Gate Transistor



Cross Sectional TEM





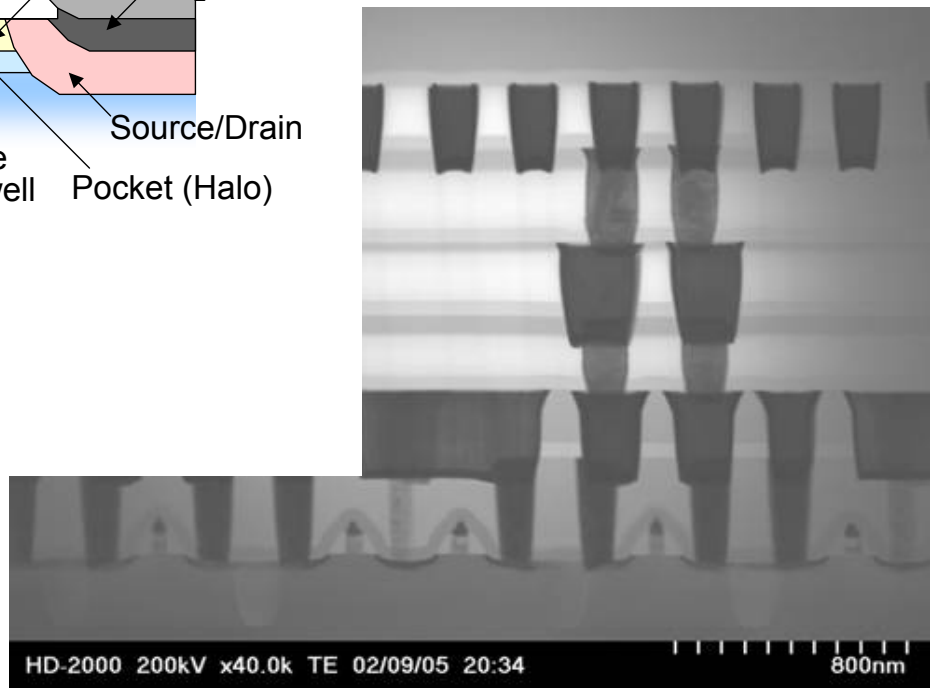
Gate electrode(Poly-Si)

Oxynitride

Si Substrate

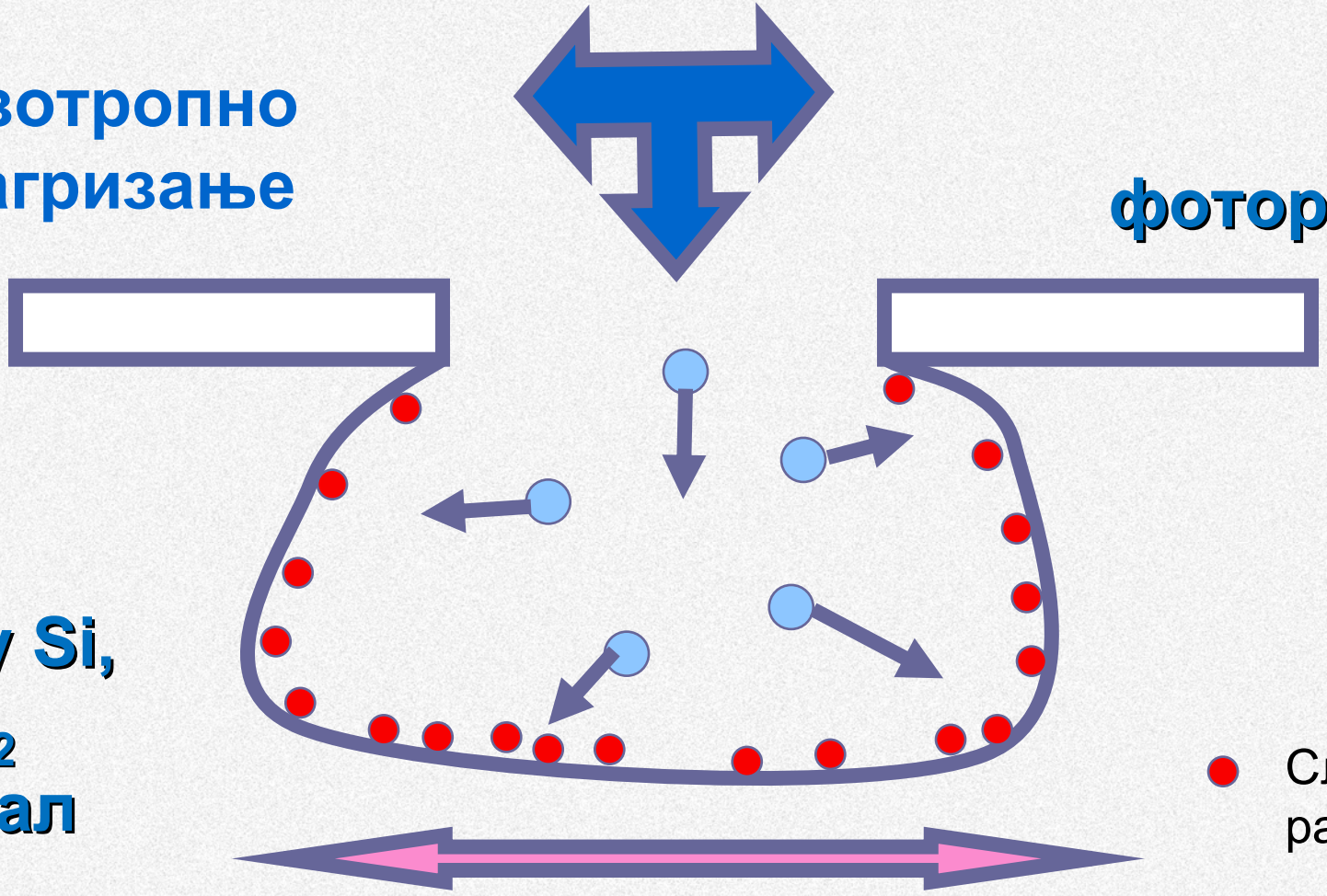
NEC ELECTR

Транзистори
Контактни отвори
виа



Термалне плазме- течности

Изотропно нагризање



CENTRE FOR NON-EQUILIBRIUM PROCESSES
INSTITUTE OF PHYSICS BELGRADE

Неравнотежне плазме

$T_e >> T_i = T$

presheath

Јако поље

фоторезист

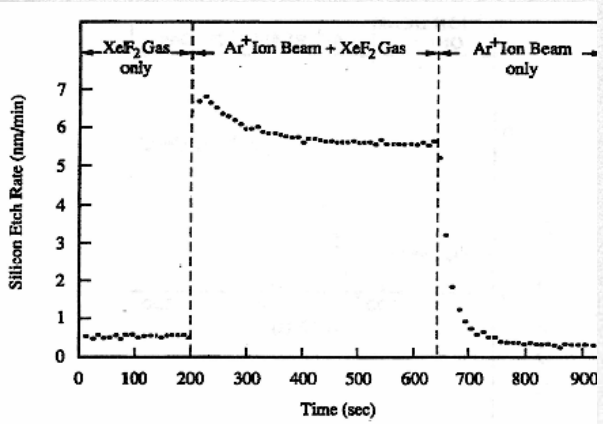
силицијум

анизотропија

радикали

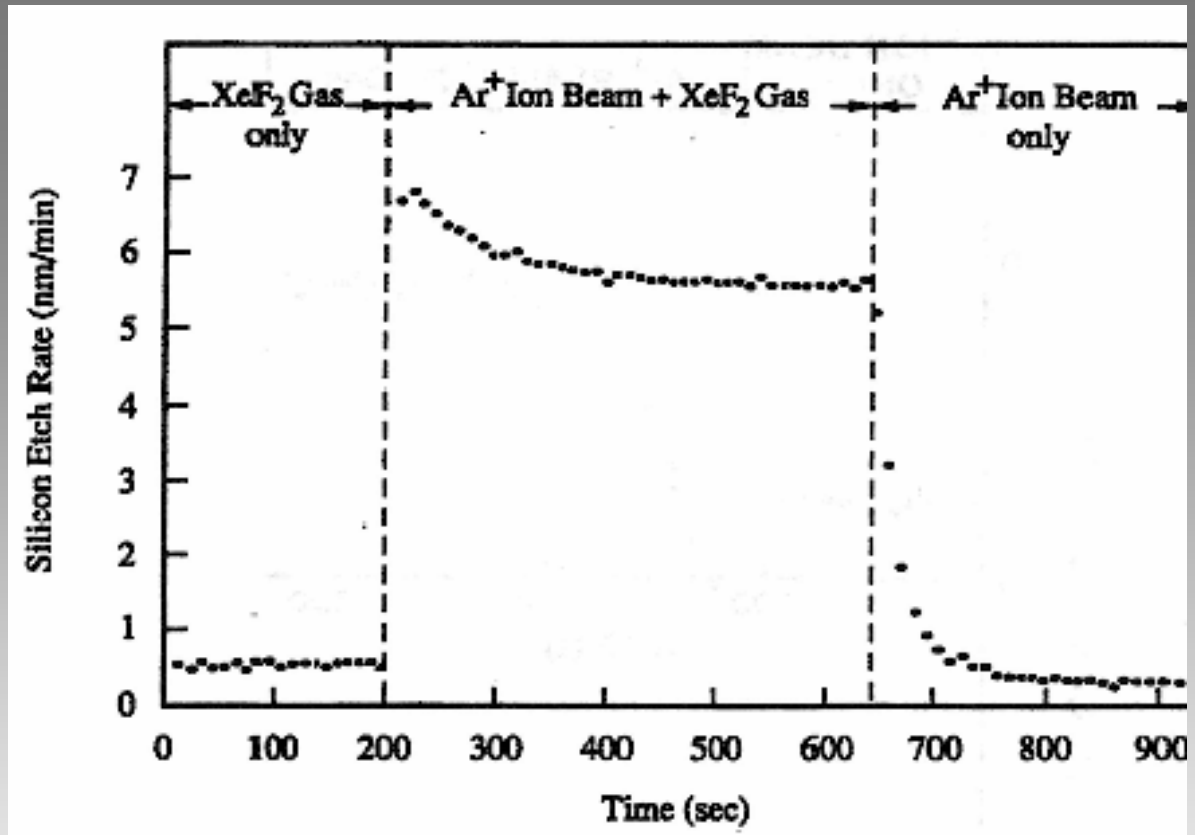
електрони

јони



Боља резолуција

• Ion and neutral synergism is



- Ion and neutral synergism is critically important in plasma enhanced etching surface reactions

Anisotropic etching
Japan 1970s
Hasekawa

John Coburn
Harold Winter:
mechanism

Semiconductor Mfg Market

Plasma Etch: 3-5 Bi$ / year

- Oxide -- Growing with metal layers
- Silicon -- Const, but increasing value

Plasma CVD: 5-10 Bi$ / year

- Low-K ILD -- Growing with metal layers
- …

So, how do we get our cut?

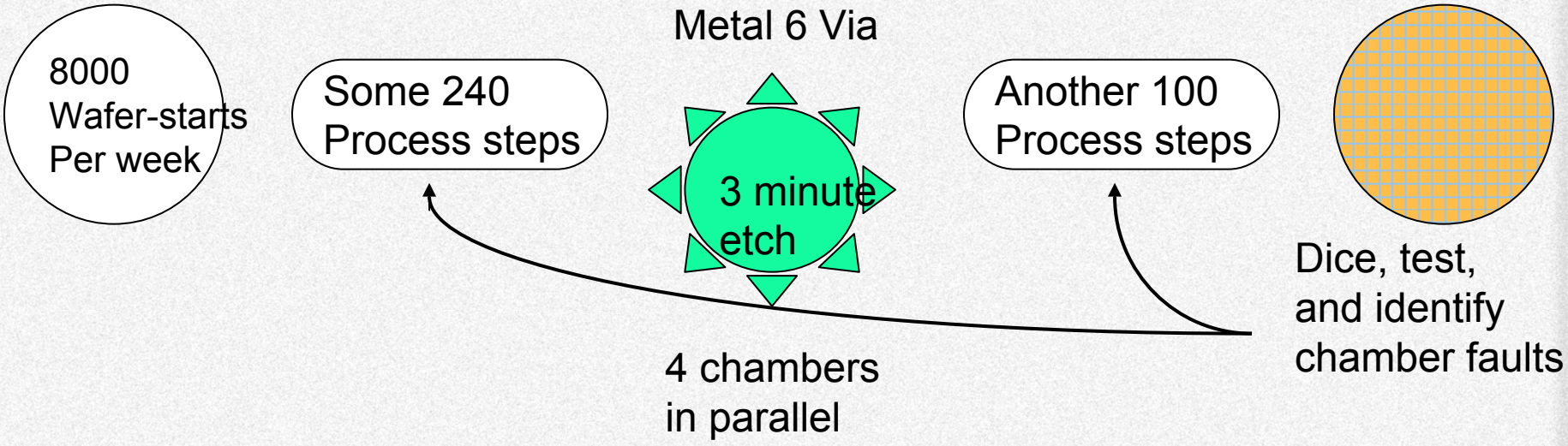
- 1% is 80 Mi$ / year
- Wealth-Generation-Company

SOA: 2006

- Largely, existing products based on 15–year–old technology
- …

Minimum Entry Requirements

- Chamber matching
- Process repeatability



Da li smo mi tu nešto doprineli???

KAKO OBEZBEDITI KONTROLU UZ MODELOVANJE, KAKO KONRTROLISATI PLAZMU

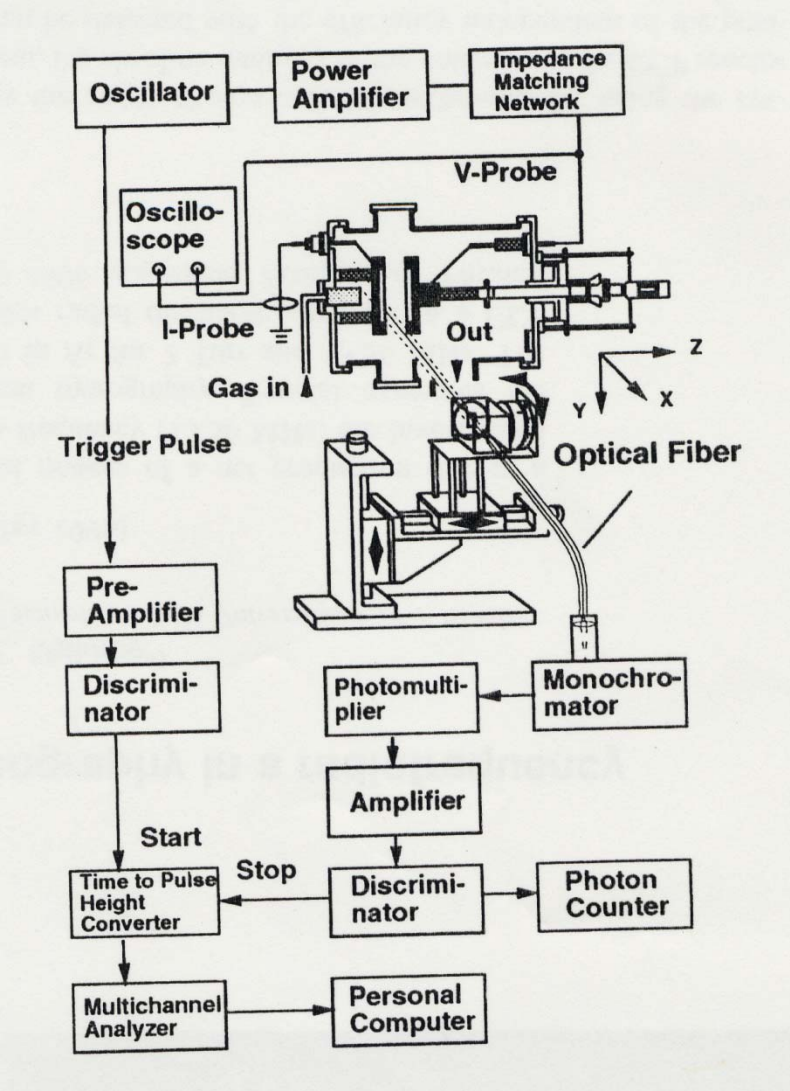
KAKO SMANJITI BROJ GREŠAKA

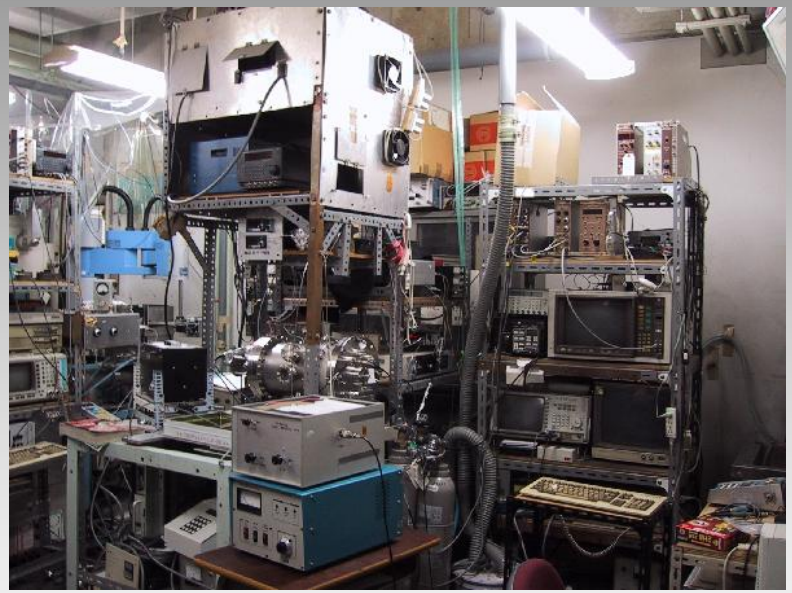
ZAHTEVI PRED PLAZMA FIZIKOM

ISTRAŽIVANJE

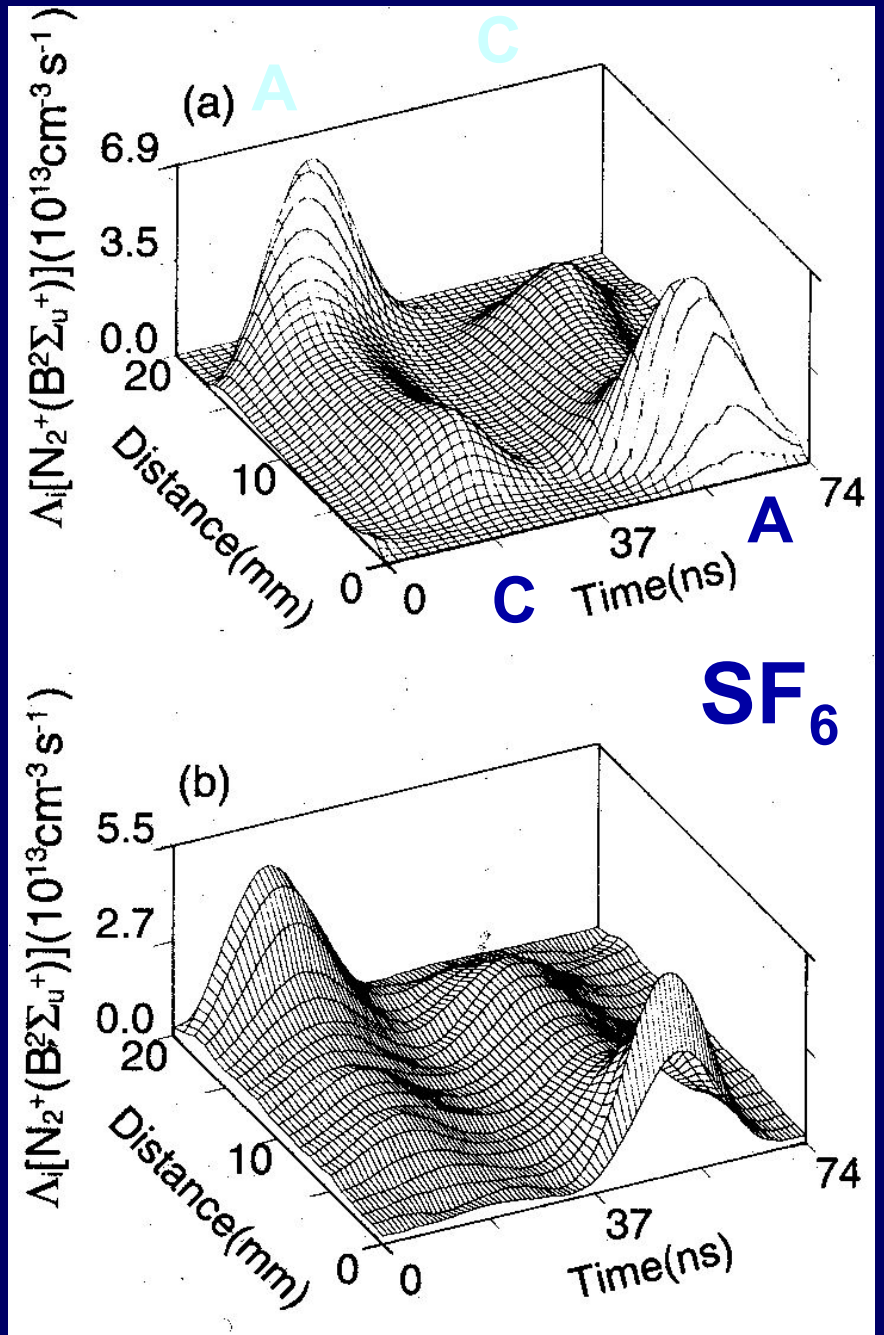
PROIZVODNJA

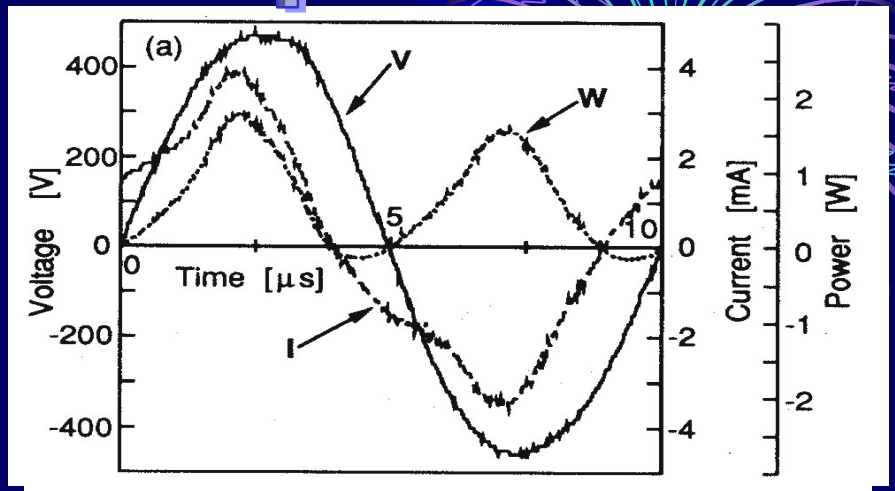
CCP-experiment for 2D-t OES CT

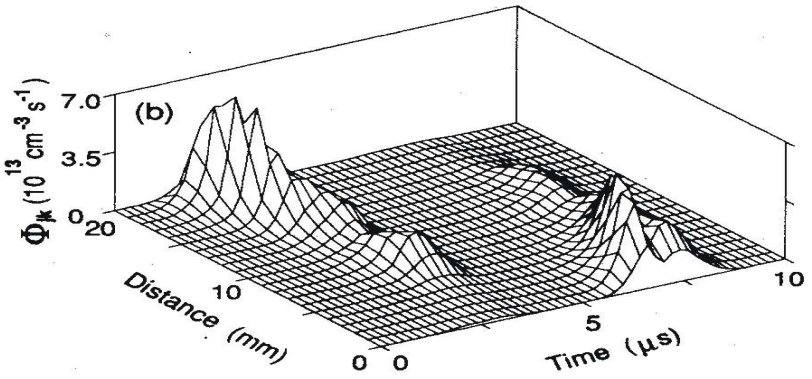


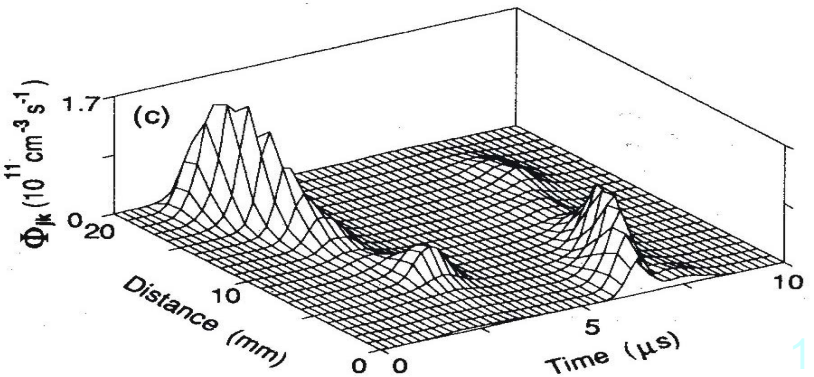


CCP: models and experiments



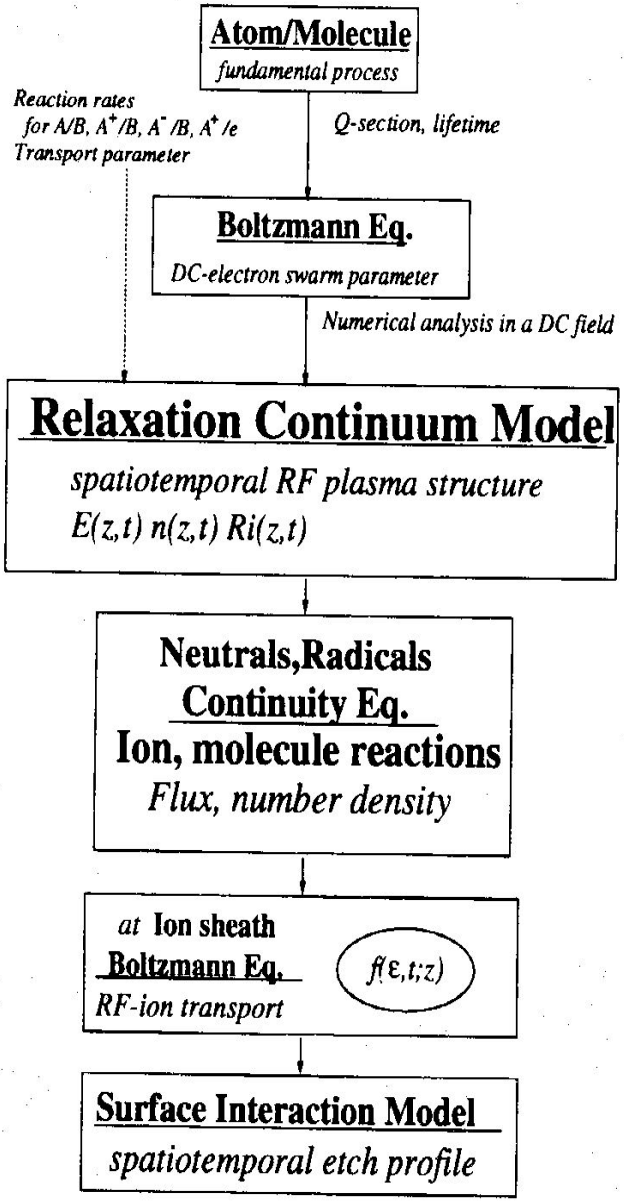






N. Nakano, N.Shimura, **Z.Lj.Petrović** and T.MakabePhys. Rev. E. **49** (1994) 4455

CCP: models and experiments



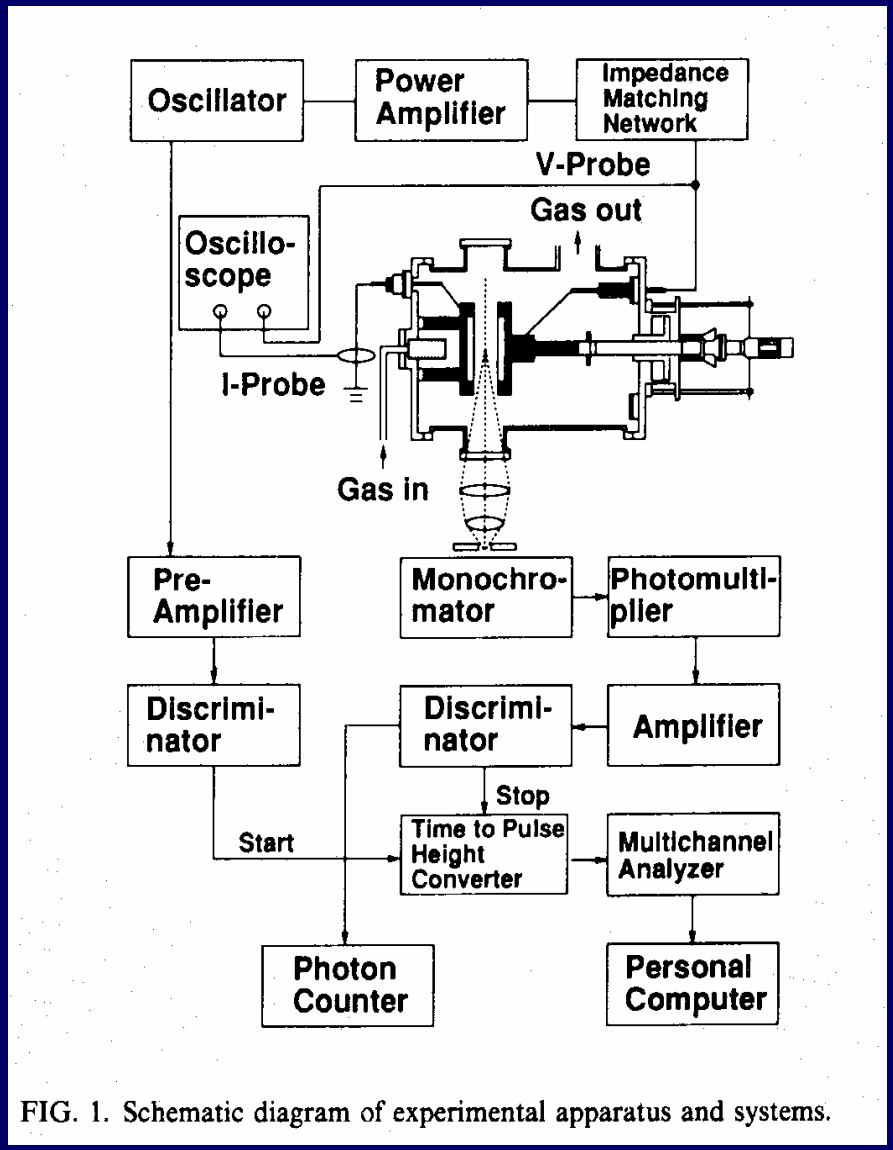
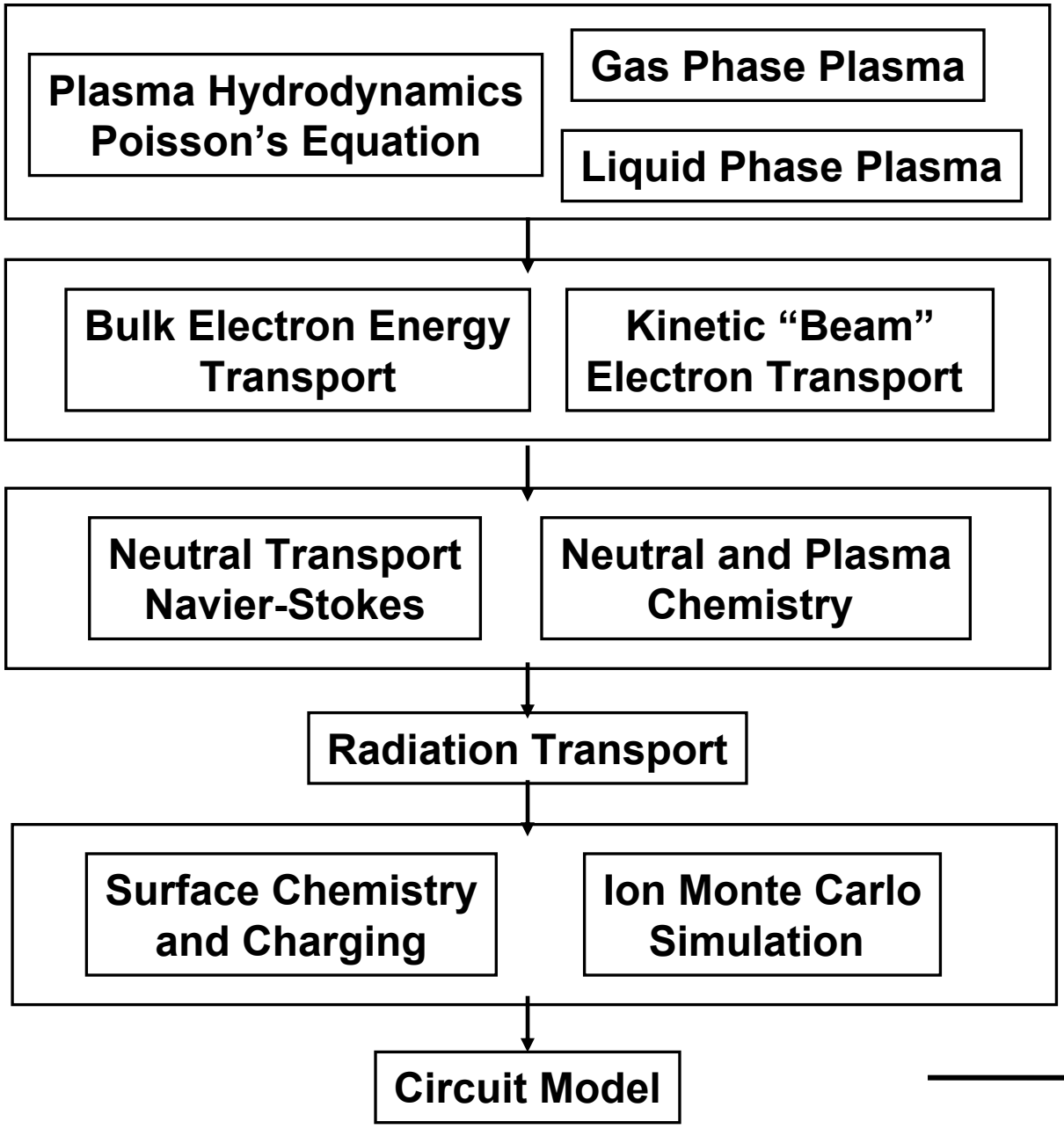


FIG. 1. Schematic diagram of experimental apparatus and systems.

N. Nakano, N.Shimura, **Z.Lj.Petrović** and T.MakabePhys. Rev. E. **49** (1994) 4455

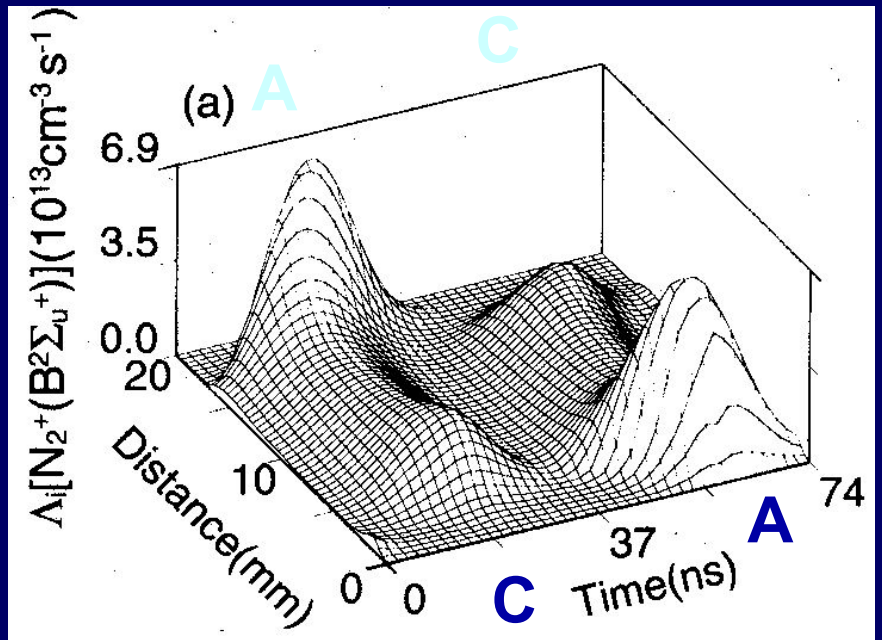


MODEL: nonPDPSIM

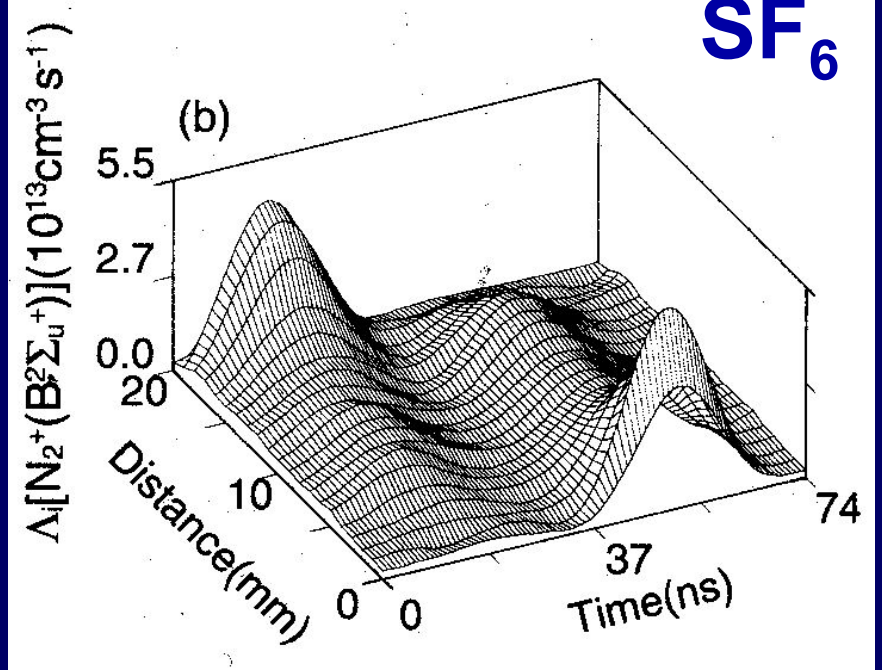
- 2-unstructured mesh with spatial dynamic range of 10^4.
- Fully implicit plasma transport.
- Time slicing algorithms between plasma and fluid timescales.

University of Michigan
Institute for Plasma Science & Engr.

CCP: models and experiments



SF_6



Uloga dvostrukih slojeva

Hemija SF6 plazme

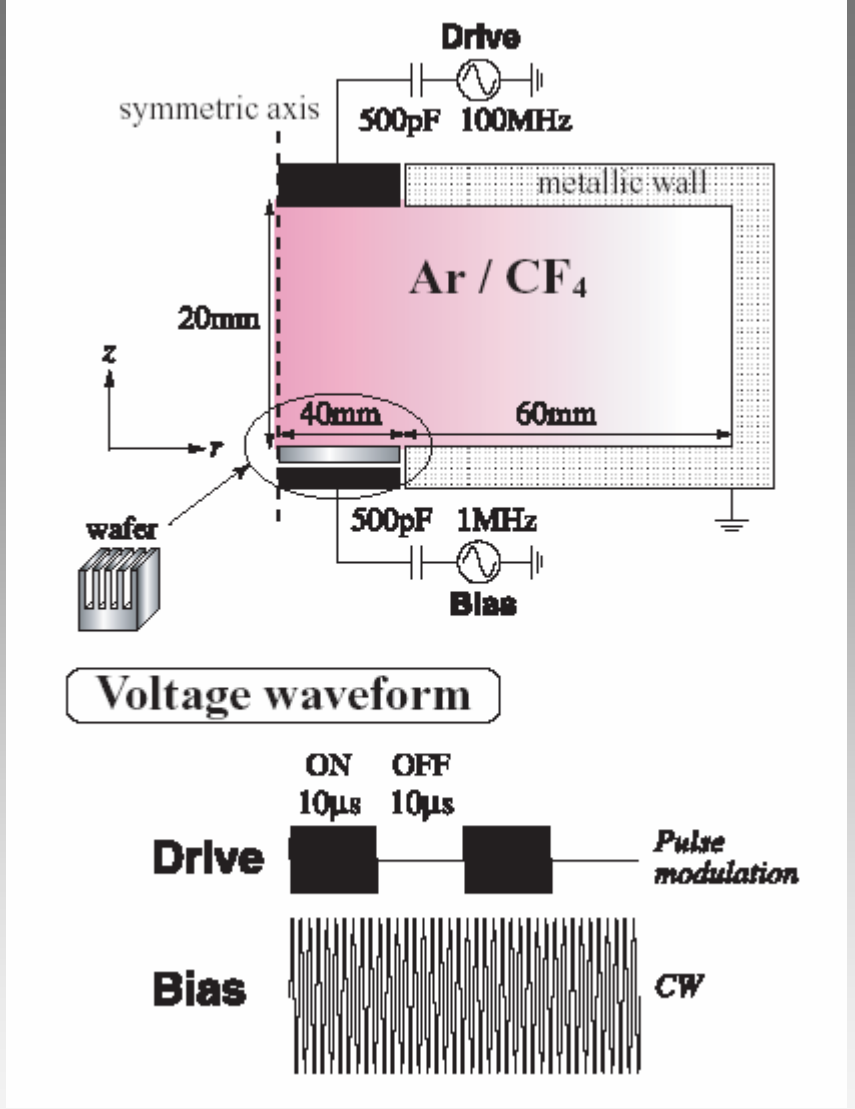
Uloga metastabila Ar

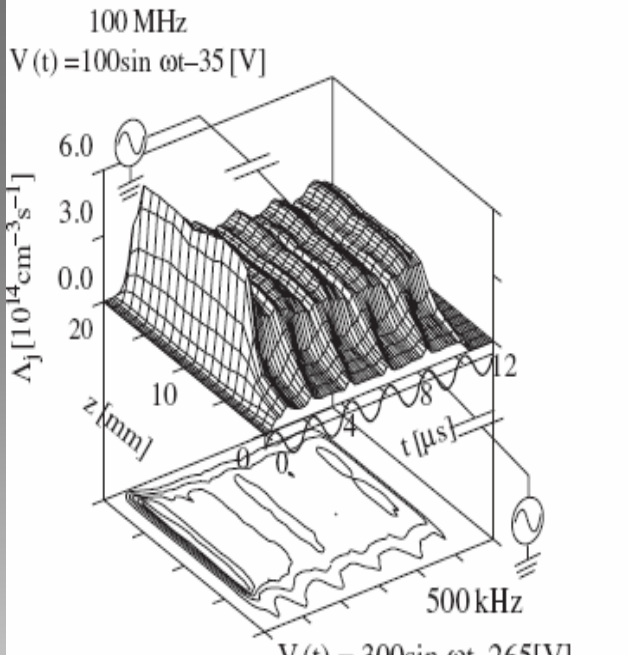
Absolutna optička Emisiona spektroskopija

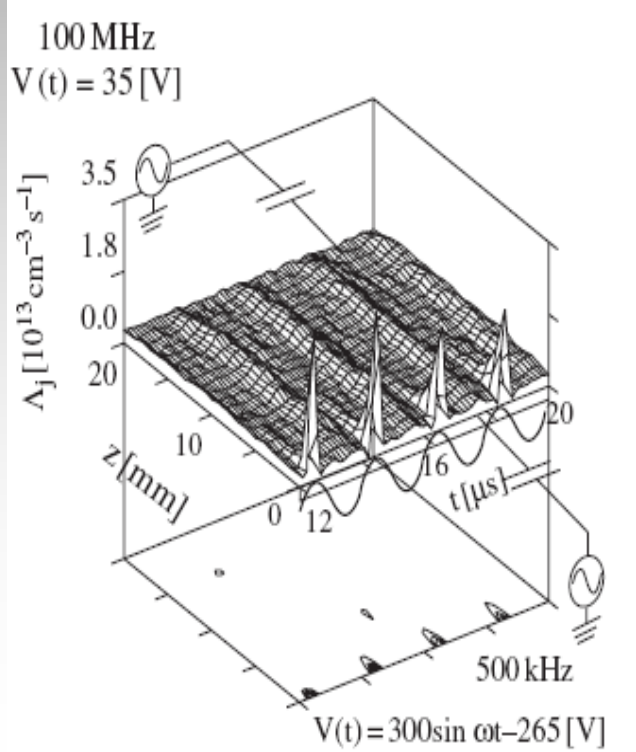
Kompleksni RC model

Impulsni rad

N. Nakano, N.Shimura, **Z.Lj.Petrović** and T.MakabePhys. Rev. E. **49** (1994) 4455

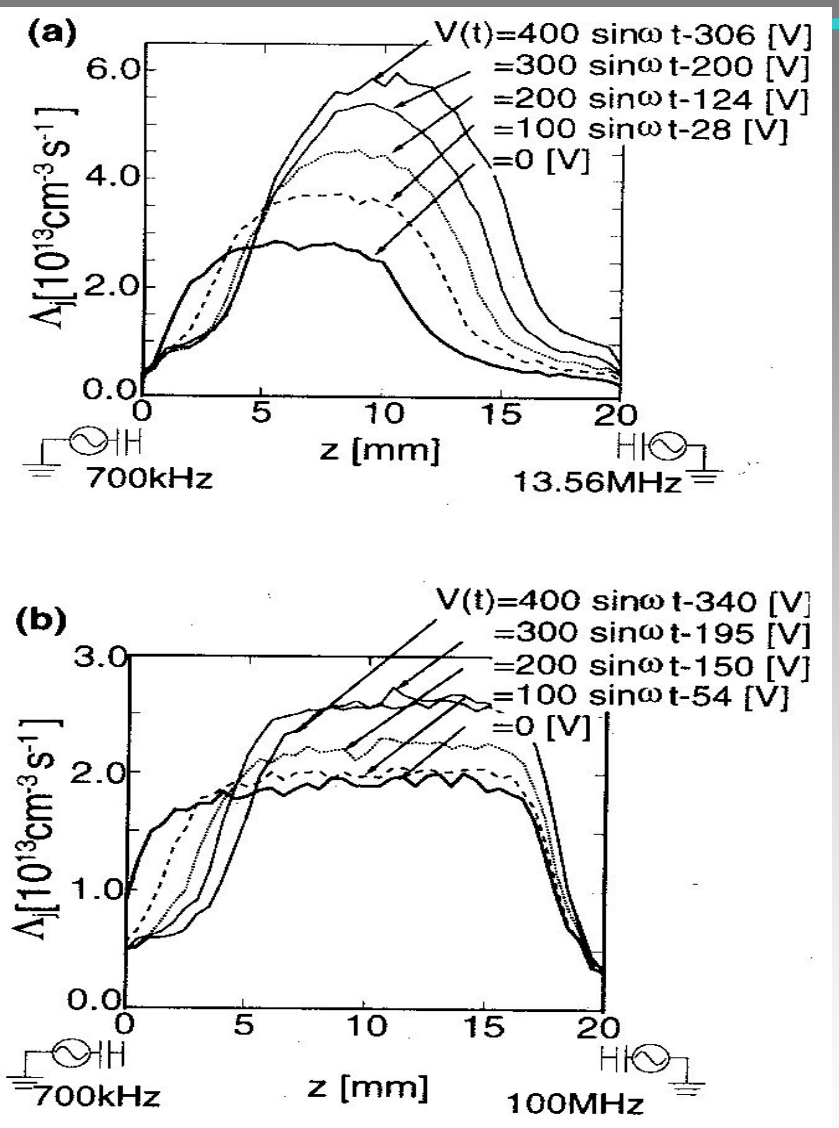


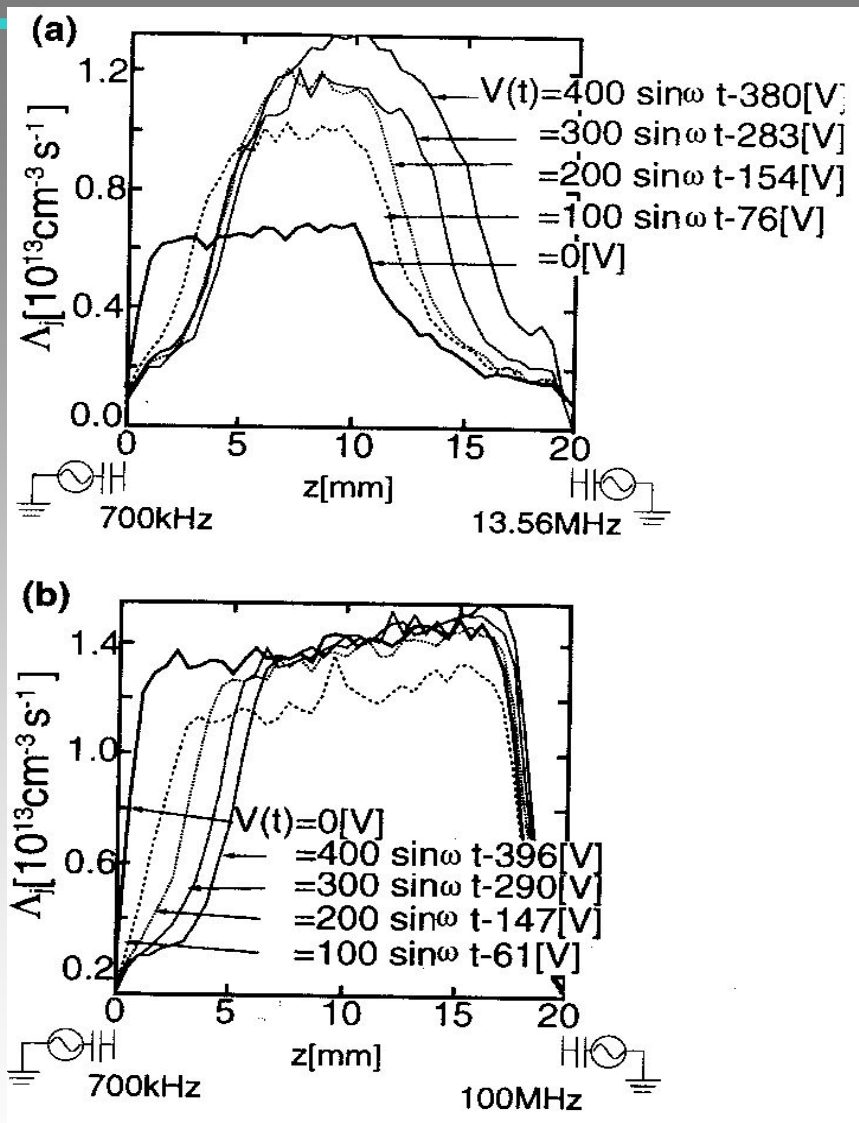




Schematic diagram of the pulsed two-frequency capacitively coupled plasma source developed to reduce charging defects

Dvo frekventni rad CCP_functional separation !!!!!!





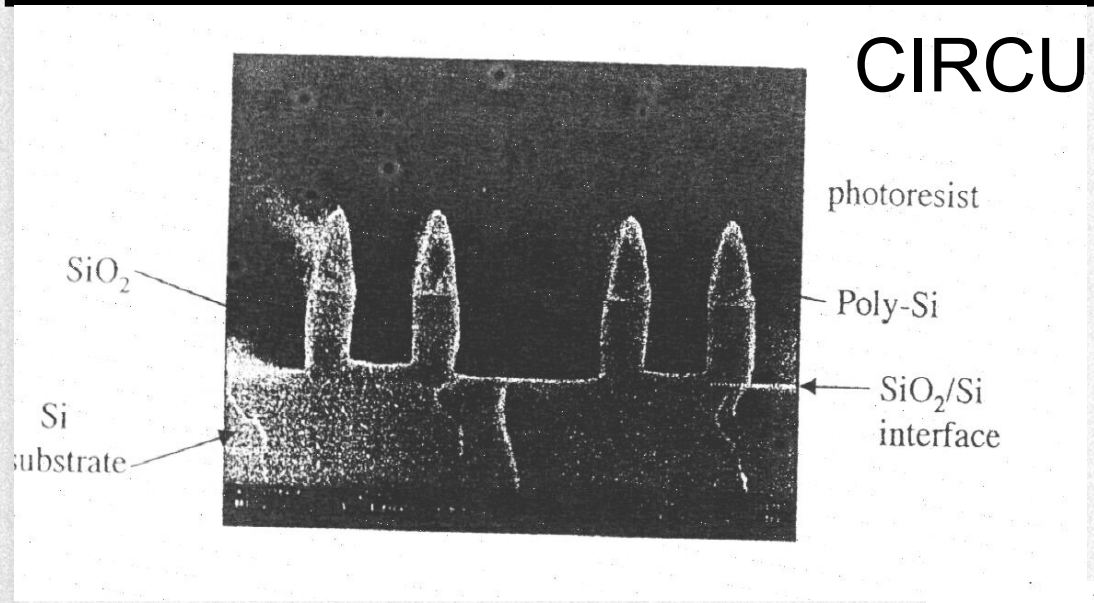
Pure Ar

Ar-CF_4 mixture (5%)

T.Kitajima, Y.Takeo, **Z.Lj.Petrović** and T.Makabe

Appl.Phys.Lett. **77** (2000) 489-491

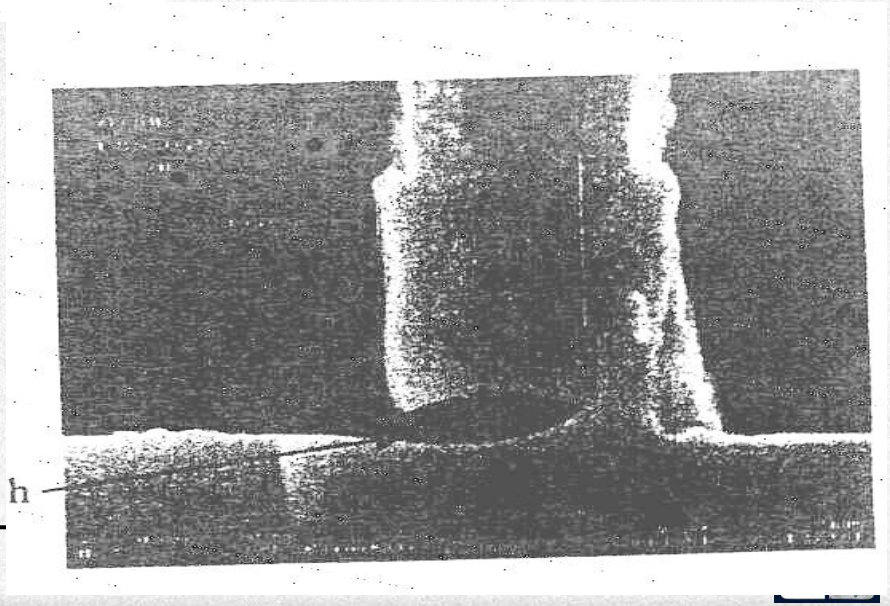
Plasma related problems: CHARGING AND ASPECT RATIO INDUCED DAMAGE IN ULSI CIRCUITS



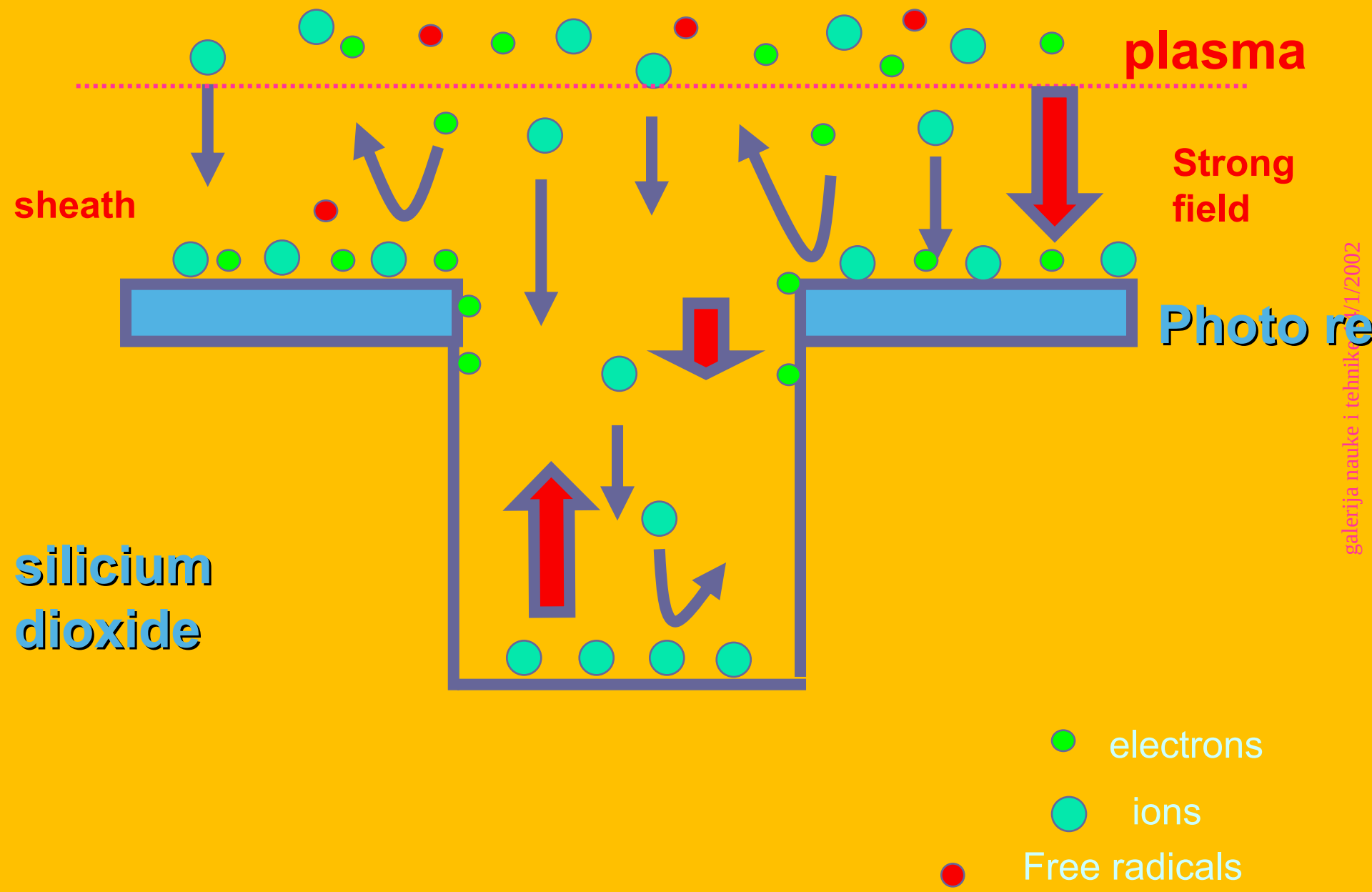
NOTCHING

aspect ratio dependent etching

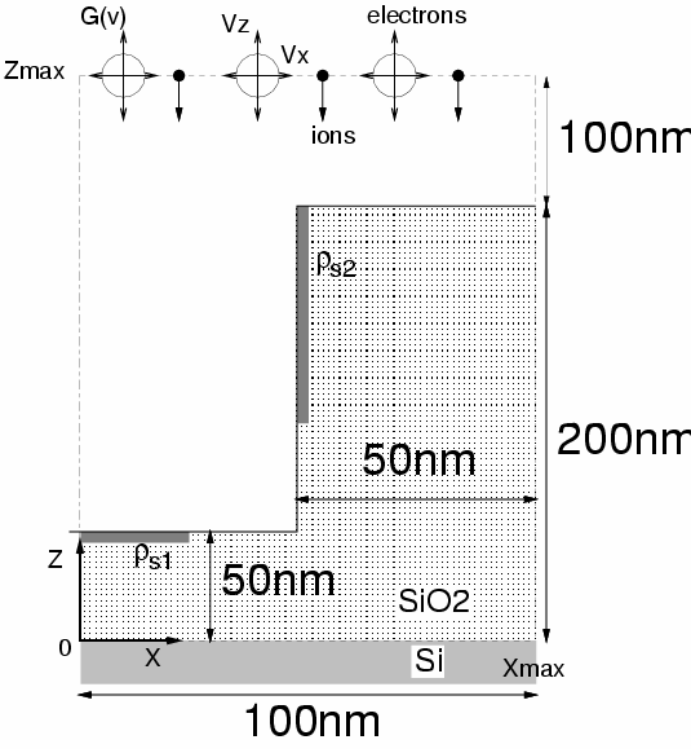
Topography dependent plasma etching: notching, aspect ratio dependent etching, etch stop!!.

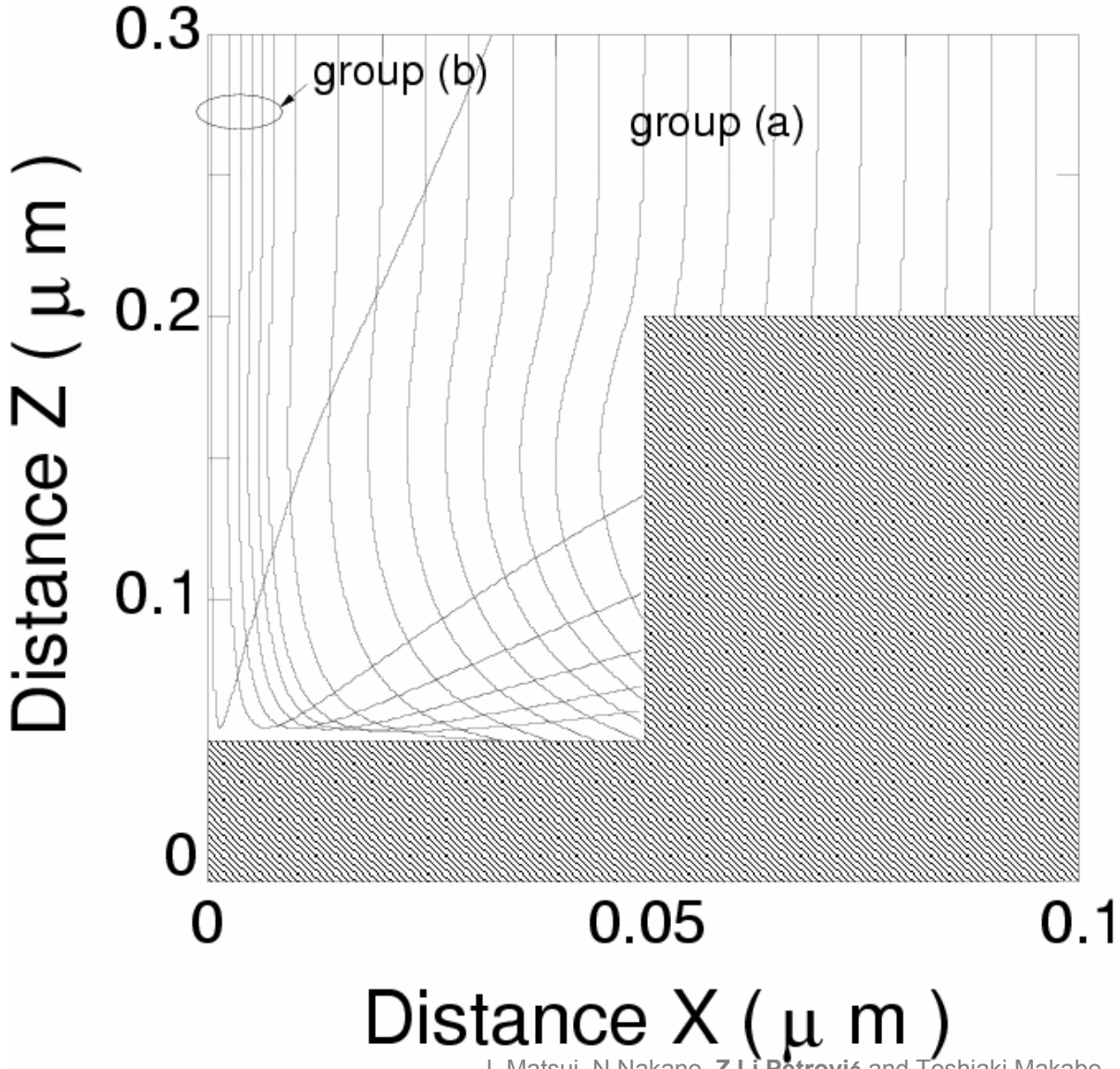


Naelektrisavanje dielektrika kao uzrok g



charging of high aspect ratio nano-trenches



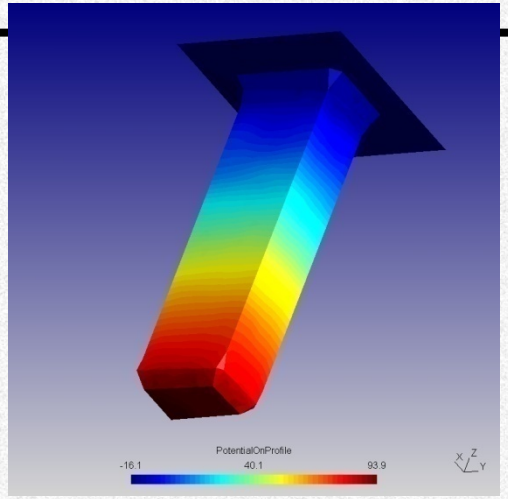


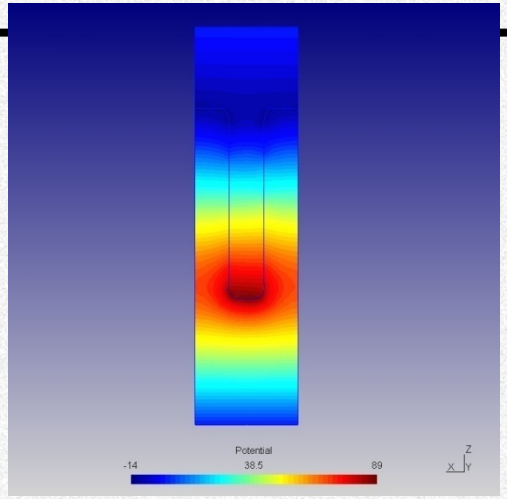
J. Matsui, N.Nakano, **Z.Lj.Petrović** and Toshiaki Makabe
Appl.Phys. Lett. **78** (7) (2001) 883-885.

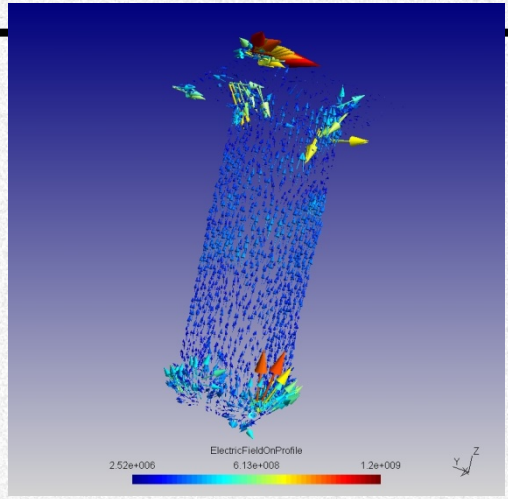
Potential on profile

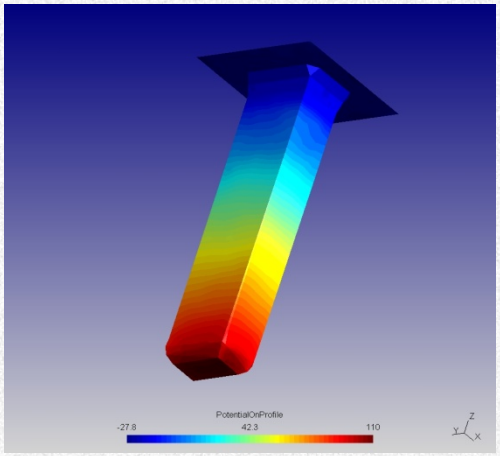
Electric field on profile

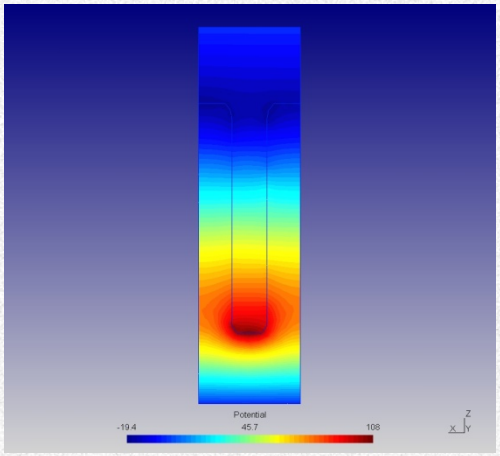
AR =4.5

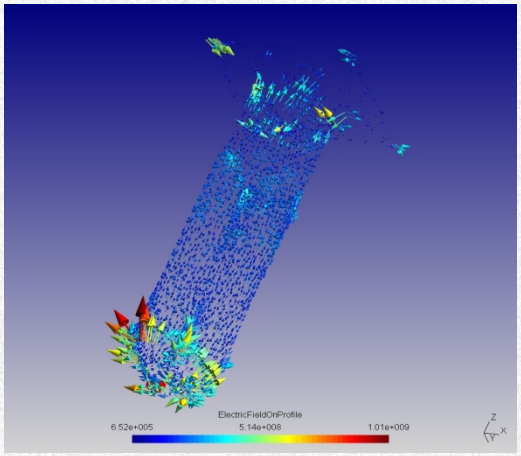








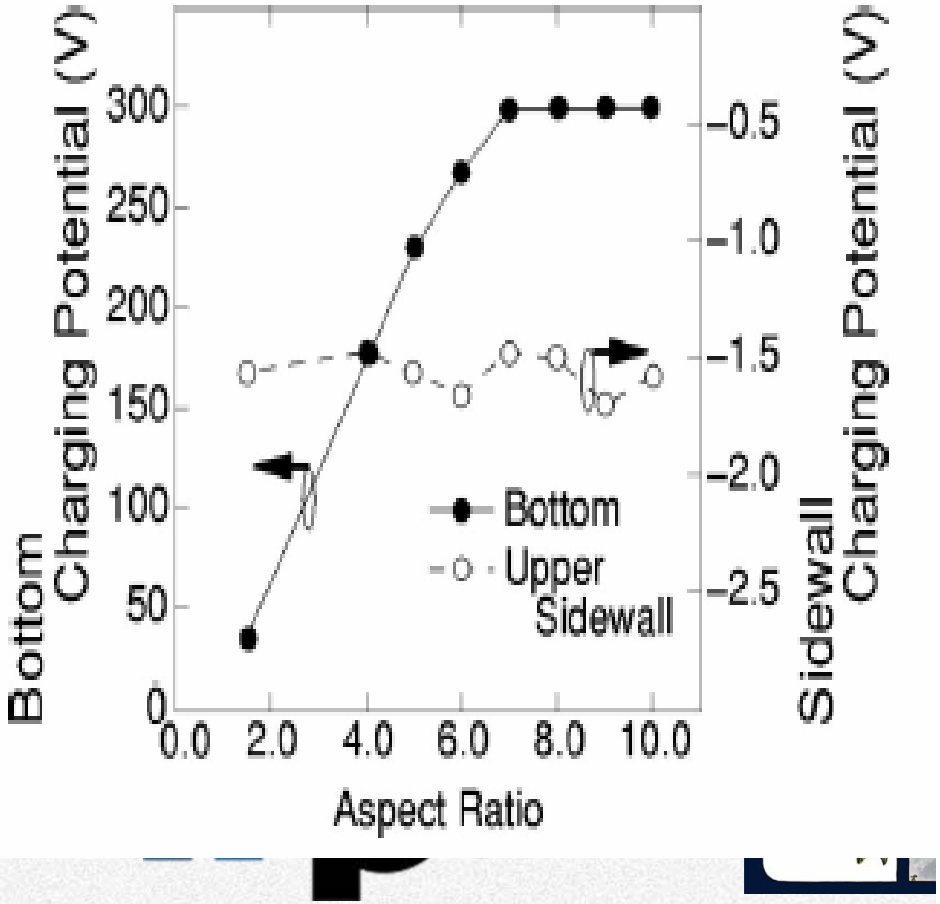


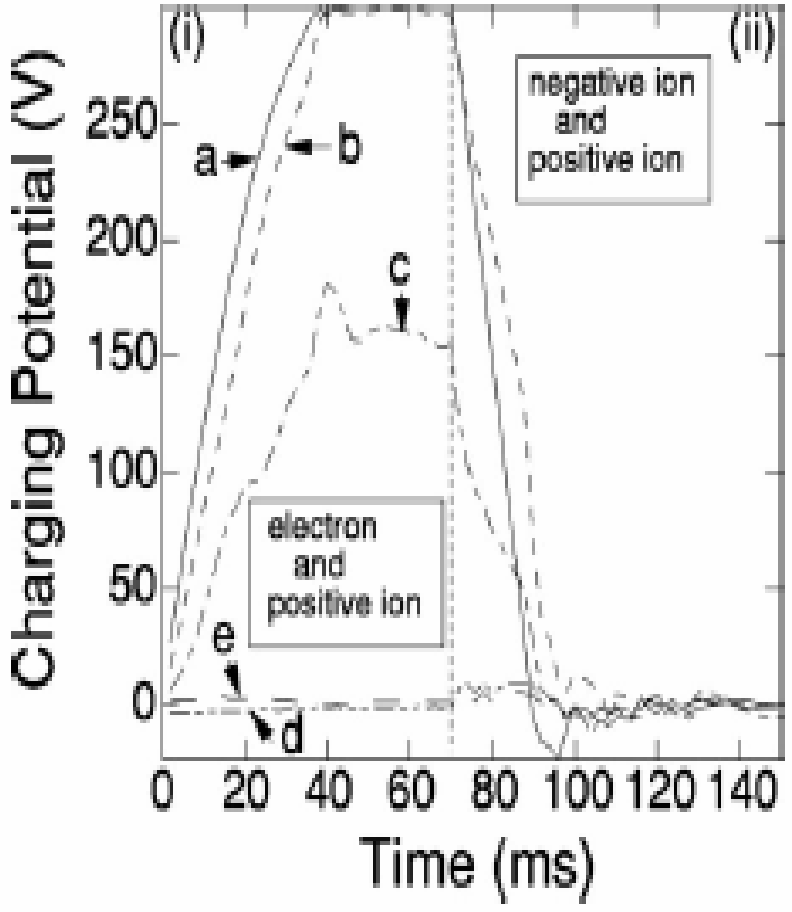


AR =6

Potential cut

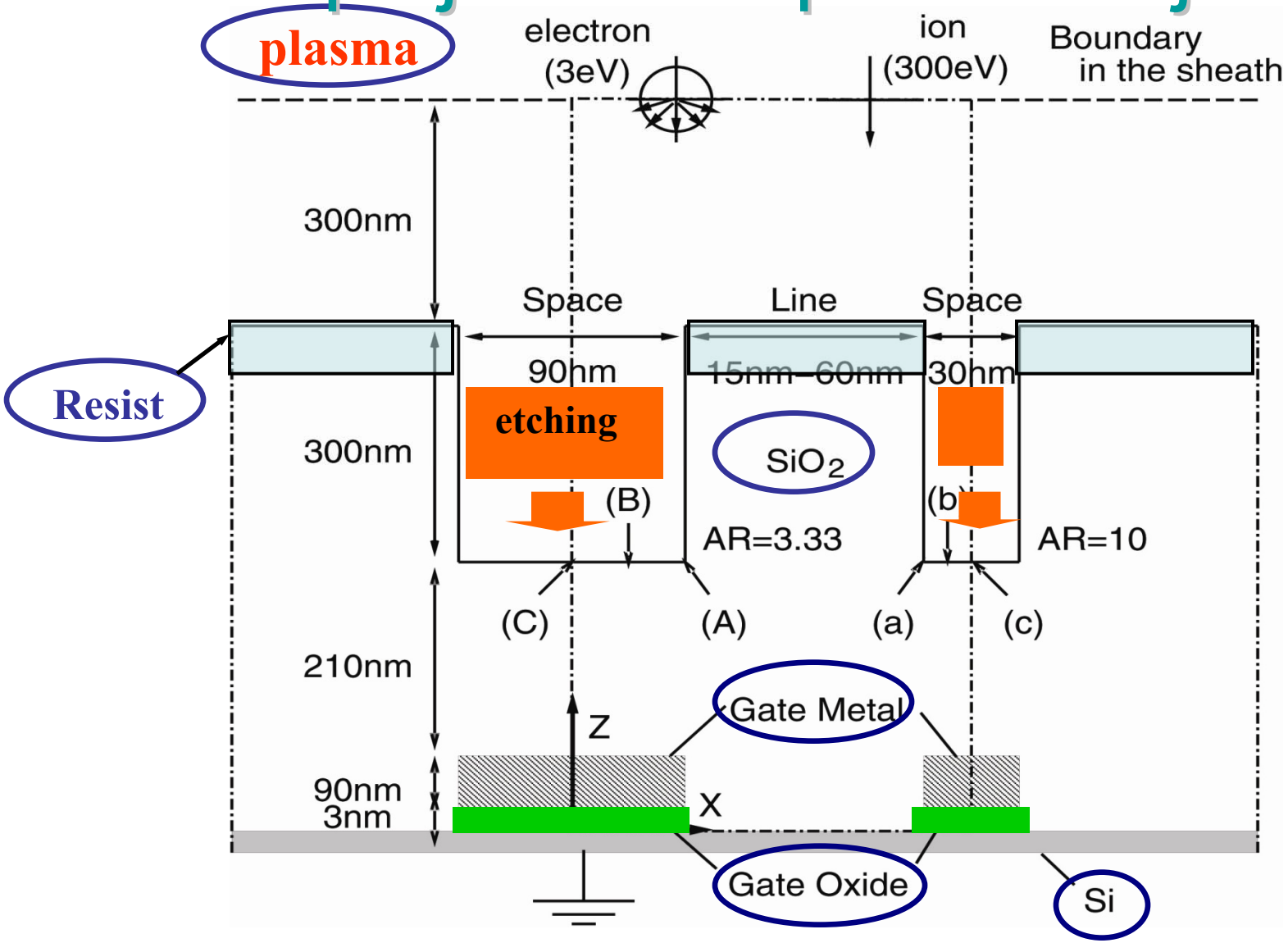
CHARGING OF HIGH ASPECT RATIO NANO-TRENCHIS





- J. Matsui, N.Nakano, Z.Lj.Petrović and Toshiaki Makabe, *Appl. Phys. Lett.* (2001);

Naelektrisavanje dielektrika kao uzrok gr
Proračun polja u toku proizvodnje



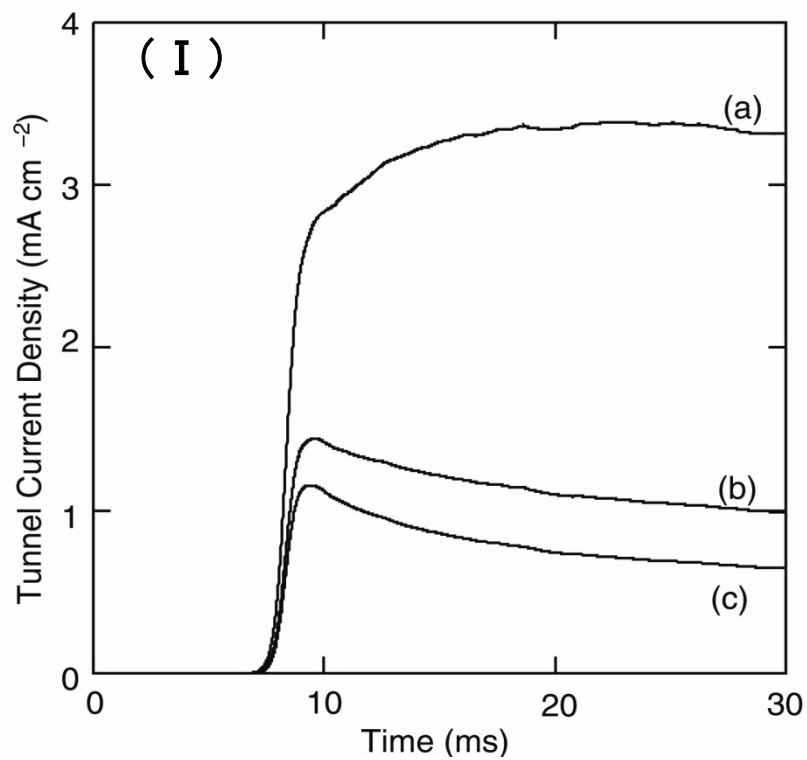
Oštećenja tokom proizvodnje

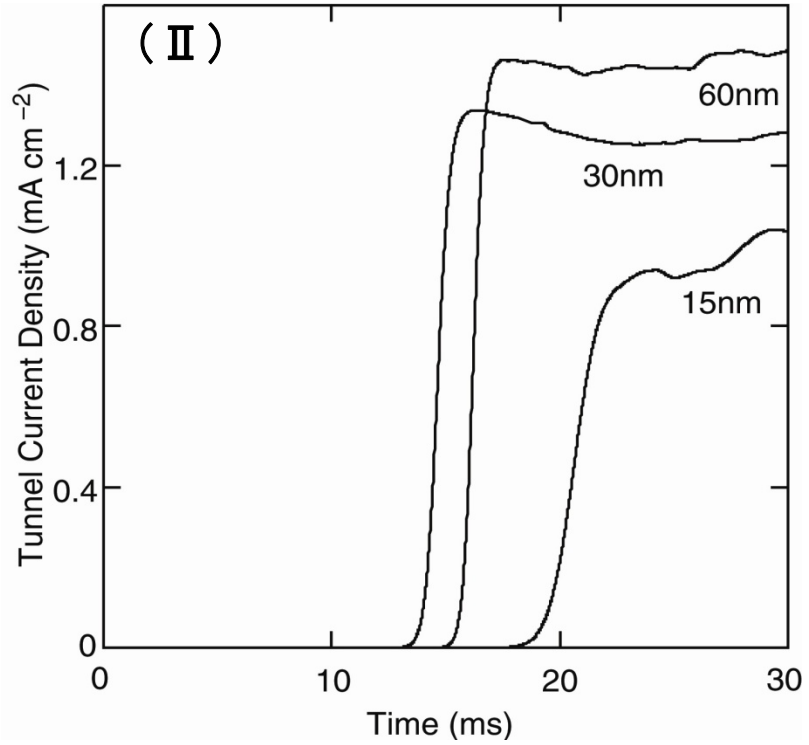
Breakdown condition:

$$Q = \int J_t \cdot S \, dt > Q_{bd}$$

through Bottom insulator

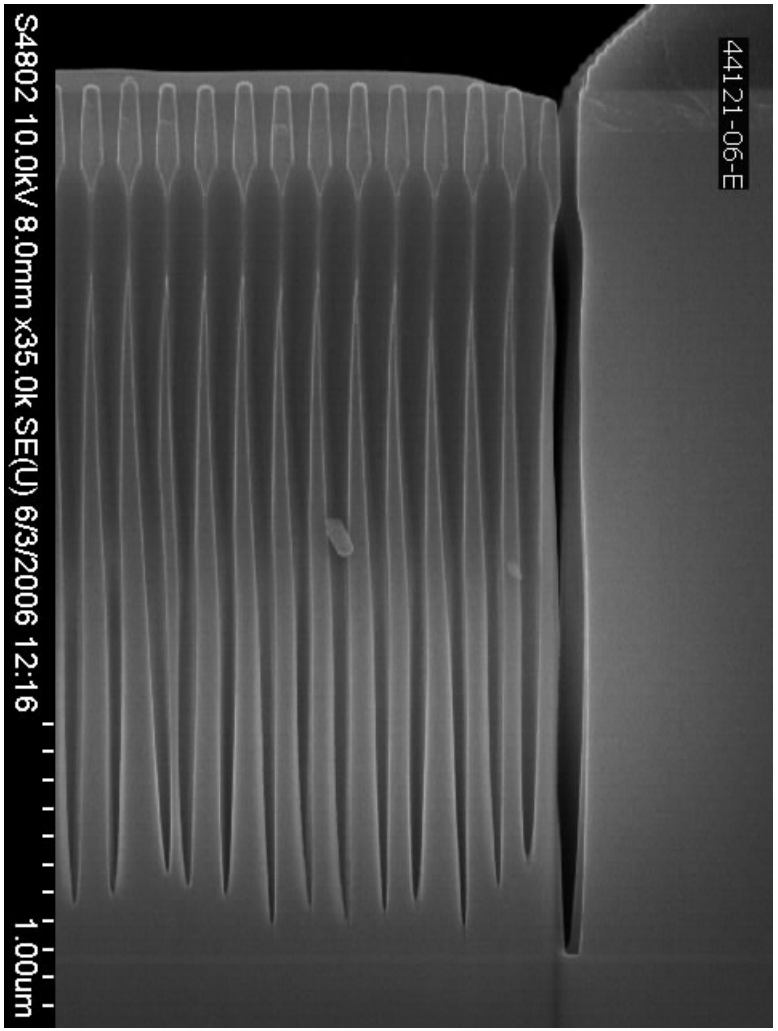
through Gate Oxide

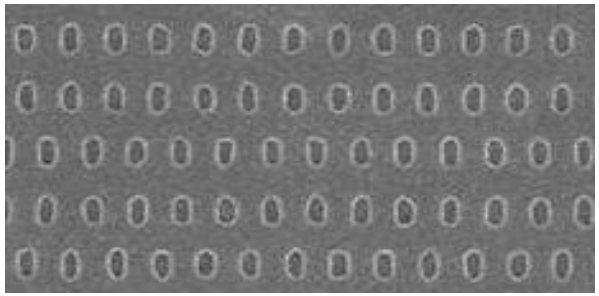




HIGH ASPECT RATIO CONTACT (HARC) ETCHING

- **Processes for HARC etching with aspect ratios > 50-100 are being developed for capacitors and through wafer vias.**





- **Twisting, bowing and curvature of features is randomly observed.**
- **NOTHING changes in the plasma over the scale of a few microns.**
- **What is the source of twisting and how do you fix it?**

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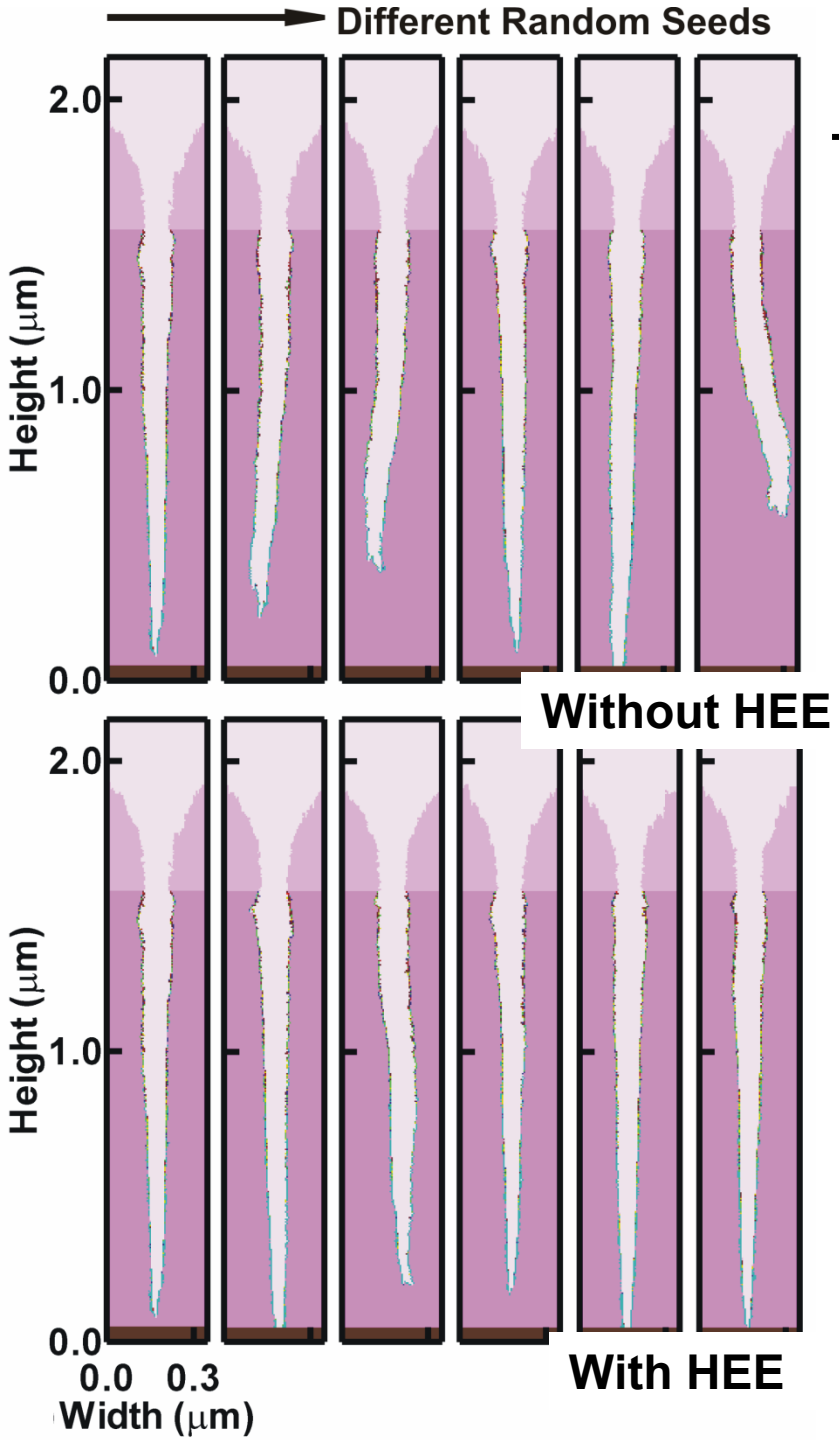
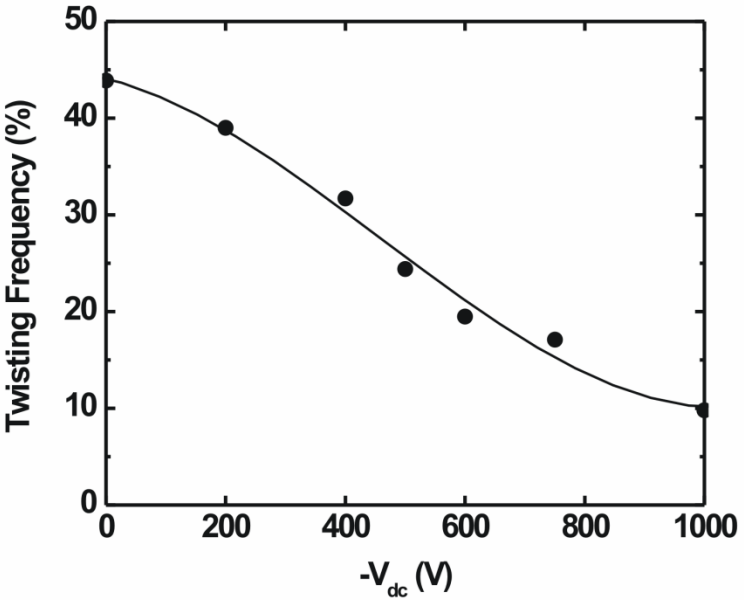
Institute for Plasma Science & Engr.



HEE EFFECTS on TWISTING:

- E-beam current neutralizes sufficient charge to prevent major twisting.
- Difference in etch depth results from randomness of fluxes.
- 40 mTorr, $Ar/C_4F_8/O_2$ = 80/15/5, 300 sccm, RF 5 kW at 10 MHz, DC 200 W.



University of Michigan
Institute for Plasma Science & Engr.

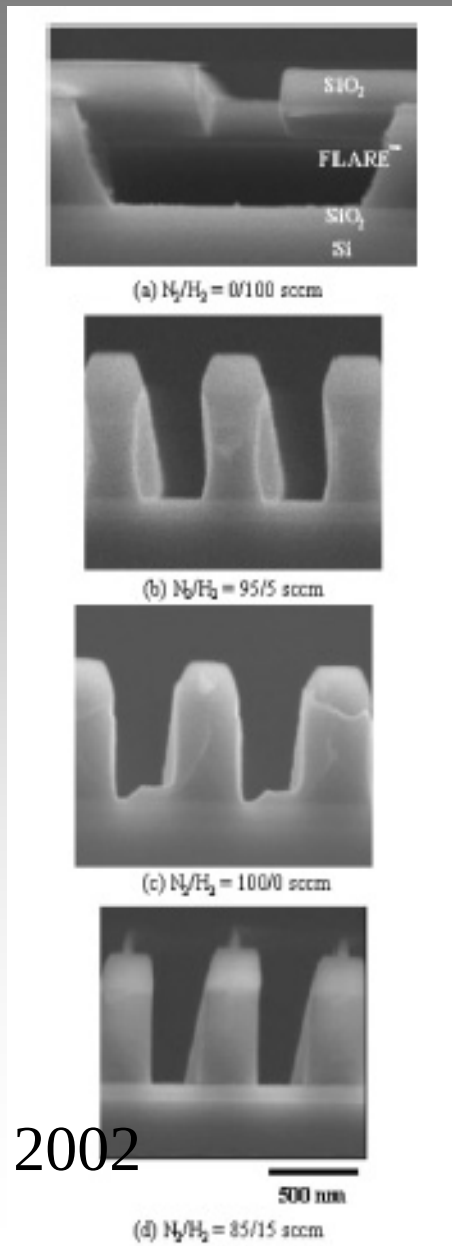
Organski dielektrici nove hemije

Flare-organic polymer

- etching in N_2/H_2,N_2/NH_3 mixtures
  (CF radicals produced in standard CF_4

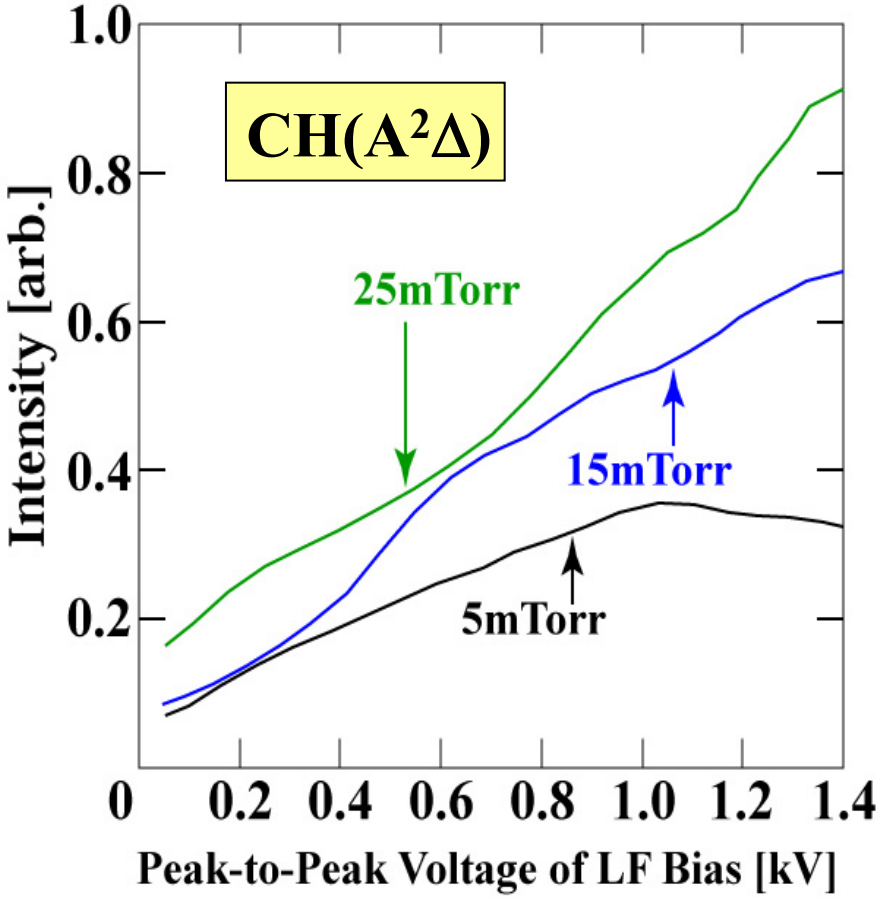
  ▪ N radicals do not etch
  (C-N passivation layer)

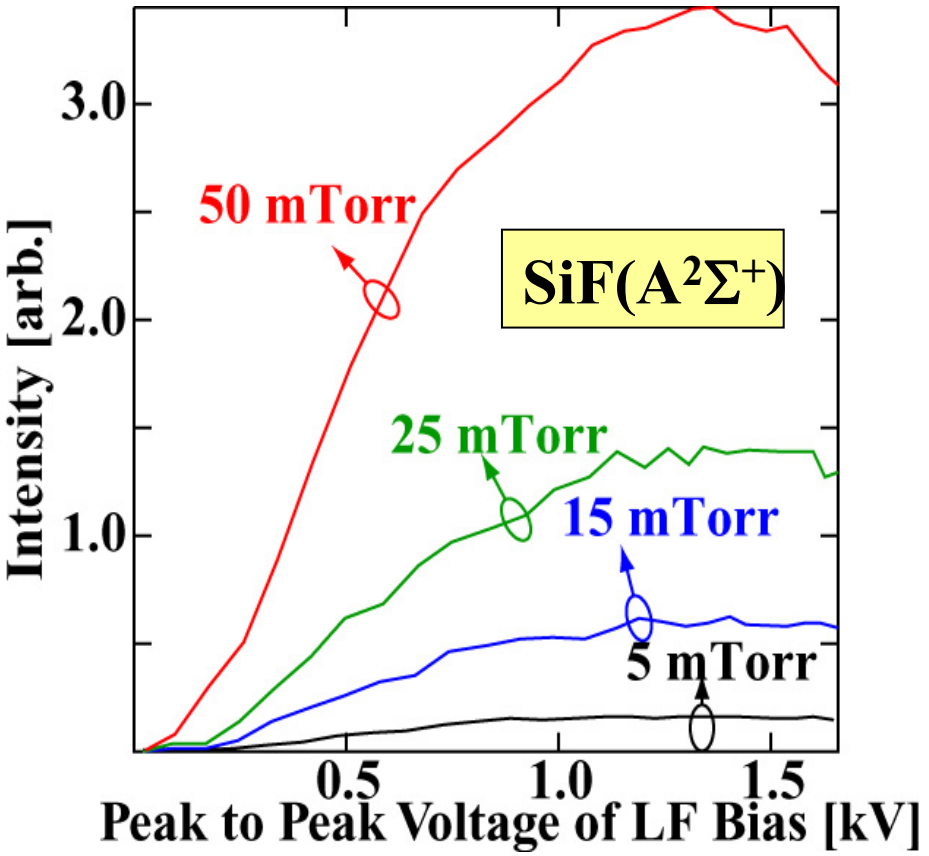
  ▪ H isotropic etching



J. Appl. Phys., Vol. 91, No. 5, 1 March 2002

Ar/CF4etching of SiO2 versus H2/N2 etching of Silk



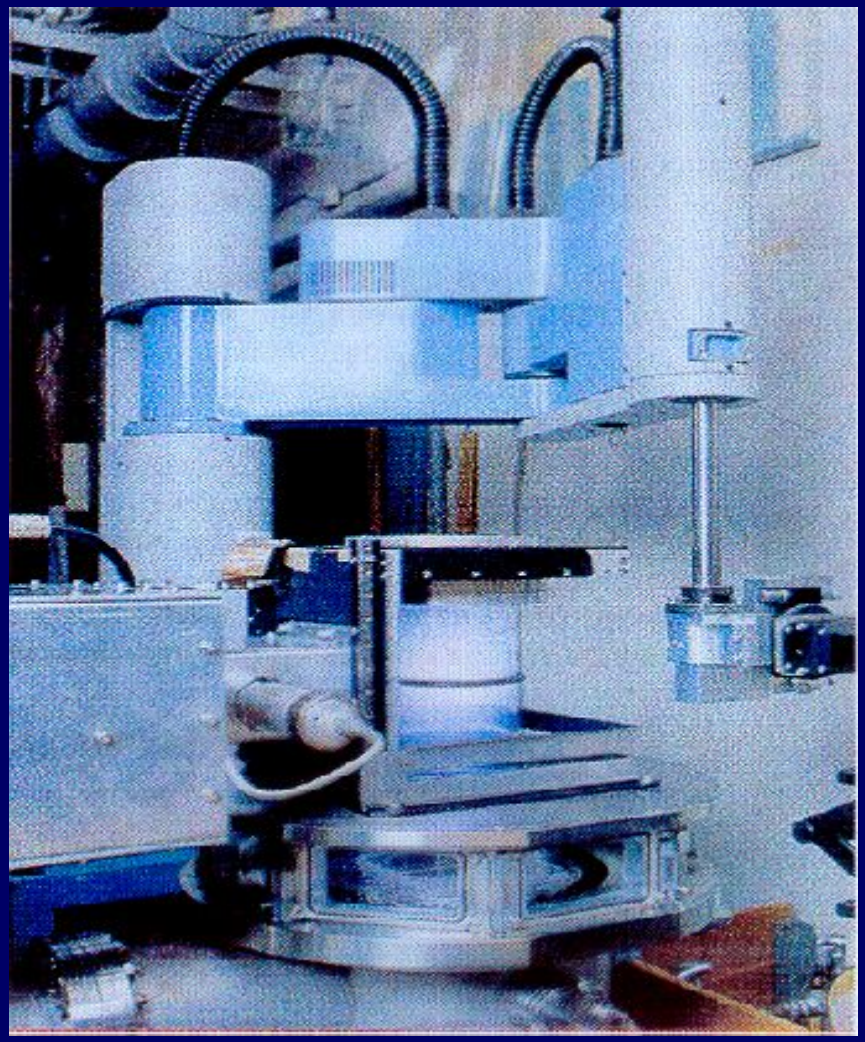


N_2/H_2=25/25sccm, with SiLK

CF_4(5%)/Ar=50sccm, with SiO_2

100 W, コイル上5 mm

Induktivno spregnute plazme dijagnostika konstrukcija ...



Konstrukcija

Kompjuterska tomografija:
Optička emisiona
Laserska apsorpciona

Uloga metastabila (E-H)

Uloga elektrona u gašenju
Pobuđenih stanja

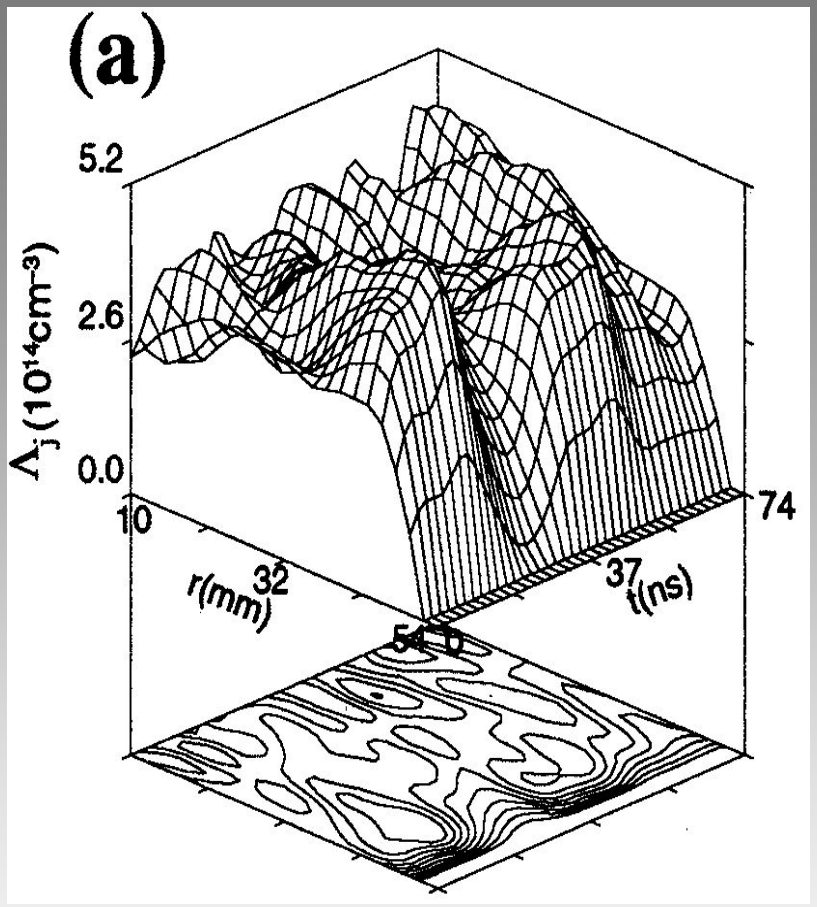
Impulsni rad

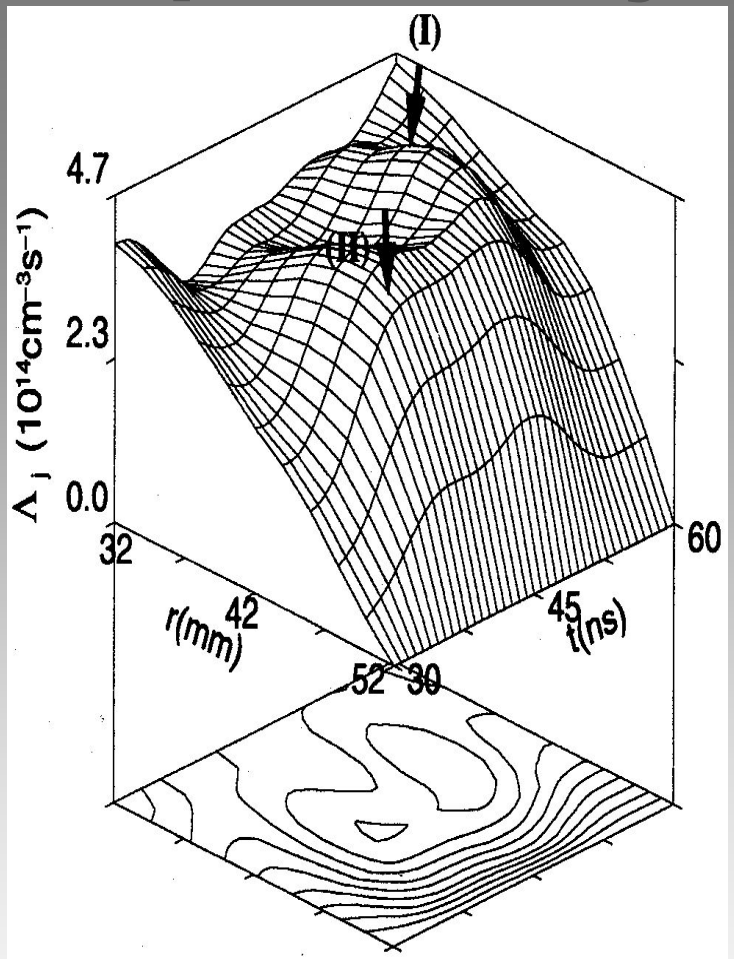
Dvofrekventni rad

Plazma čišćenje
Organski dielektrici

pressures 20-500 mTorr

ExB drift као извор снаге у ICP





3a-temp

I $E_\theta(t)$

II $E_r x B_z(t)$

$$P_\theta(t;\mathrm{I}) = -en_e(r)V_{d\theta}(t,r)E_\theta(t,r) \propto E_\theta(t,r)^2$$

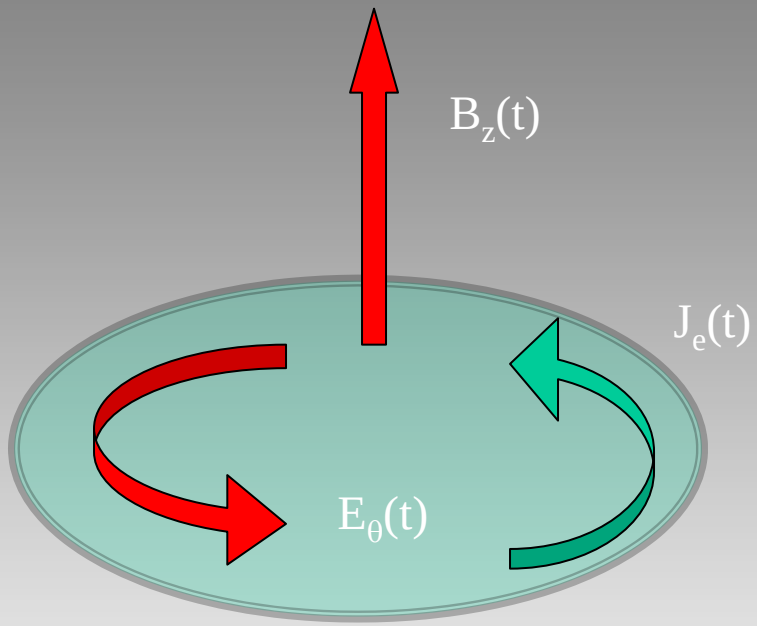
$$\propto \frac{1+\cos(2\omega t)}{2}, \qquad (1)$$

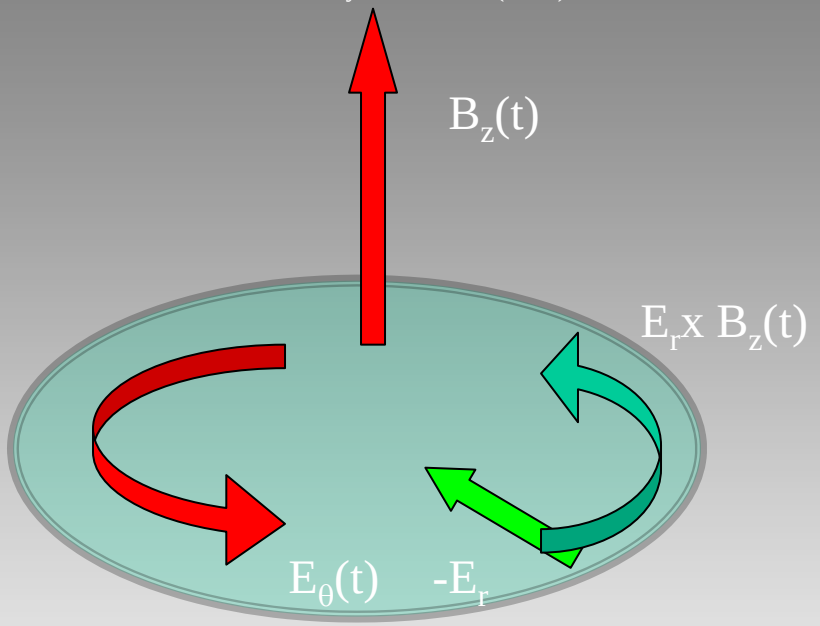
$$P_\theta(t;\mathrm{II}) = -en_e(r)V_{d\mathbf{E}_r\times\mathbf{B}_z}(t,r)E_\theta(r,t) \propto B_z(t)E_\theta(t)$$

$$\propto -\sin(2\omega t). \qquad (2)$$

ExB drift као извор снаге у ICP

M.Tadokoro, H.Hirata, N.Nakano, **Z.Lj.Petrović** and T.Makabe, Phys. Rev. E **57** (1998) R43-R46.





3a-temp

I $E_\theta(t)\ E_\theta(t)$

$$P_\theta(t;\mathrm{I}) = -en_e(r)V_{d\theta}(t,r)E_\theta(t,r) \propto E_\theta(t,r)^2$$

$$\propto \frac{1+\cos(2\omega t)}{2}, \qquad (1)$$

II $E_r x B_z\ (t)$

$$P_\theta(t;\mathrm{II}) = -en_e(r)V_{d\mathbf{E}_r\times\mathbf{B}_z}(t,r)E_\theta(r,t) \propto B_z(t)E_\theta(t)$$

$$\propto -\sin(2\omega t). \qquad (2)$$

Apart from the known and the unknown, what else is there H. Pinter

Direktno povezane plazma tehnologije

IMPLANTACIJA
PLAZMA ČIŠĆENJE
PLAZMA ASHING (SPALJIVANJE)
NANOŠENJE TANKIH SLOJEVA
IZVORI SVETLOSTI

A Gde smo tu mi???

DA LI SU NAŠI (PLAZMA FIZIČARI) STRUČNJACI POTREBNI, GDE I KAKO

LOKALNA RADNA SNAGA PROFIL I ZAHTEVI:

JEFTINI-PRODUKTIVNI-OBRAZOVANI-NEZAHTEVNI

A Gde smo tu mi??? PITAJU SE POLITIČKE PARTIJE

DA LI MI IMAMO PERSPEKTIVE

PERSPEKTIVE

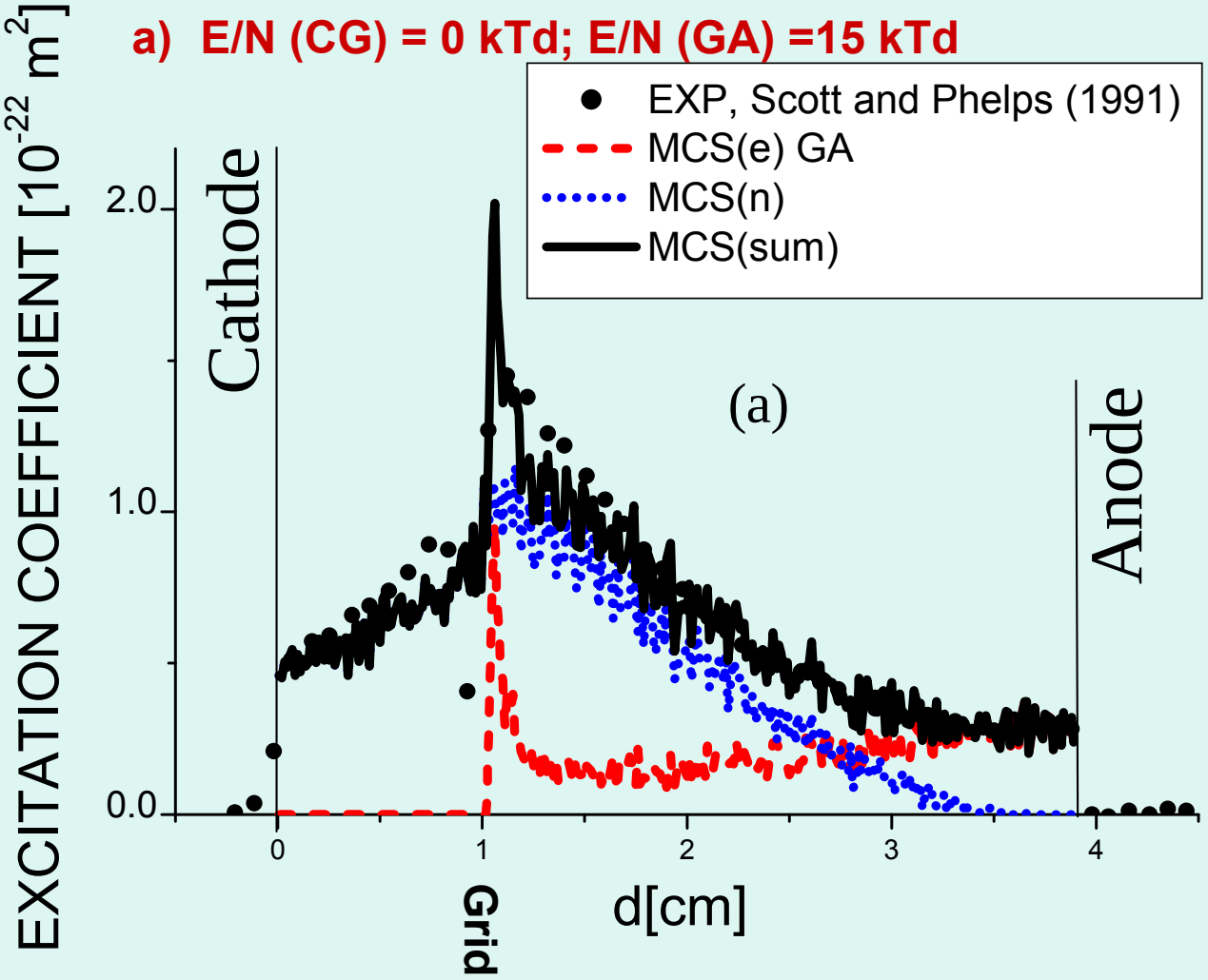
fast neutral etching

no charging damage,
smoother surfaces less than 1 nm roughness

massively parallel, organized manufacture
compatible with industrial processes
possibly a missing link for merged technologies

Scott – Phelps experiment: proof that fast neutrals are doing the excitation

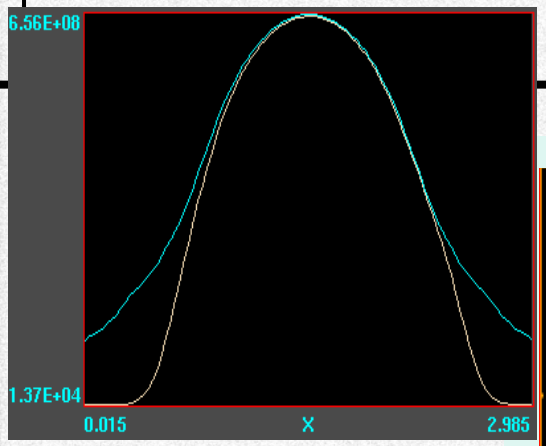
Fast neutrals may also contribute to secondary electron production,[25] sputtering,[26] and etching.[27] Being more efficient in producing excitation, fast neutrals may be more easily diagnosed than ions, including their velocity distribution function.[6] In addition etching by fast neutrals may not suffer from limitations due to charging of the surface.[28]



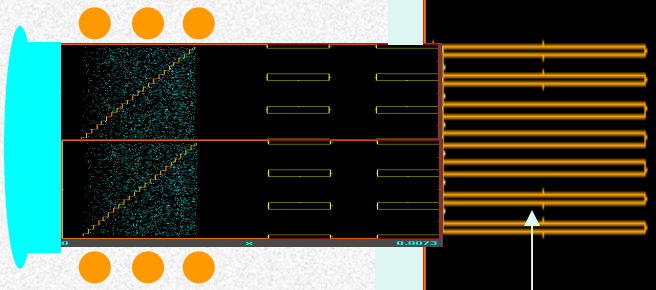
On the role of heavy particles in high current charges and plasma surface interactions

BORATORY
R GASEOUS
CTRONICS
TUTE OF PHYSICS
BELGRADE

Neutral beam source



Density of the particles in the plasma

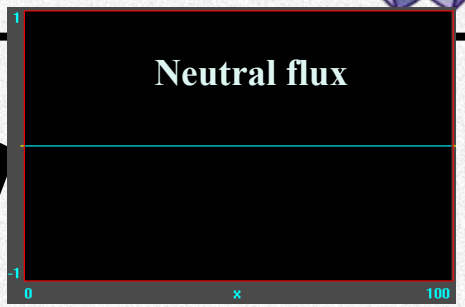


Source

Neutral beam source

Ions

Neutrals



Neutral energy

Neutral angle

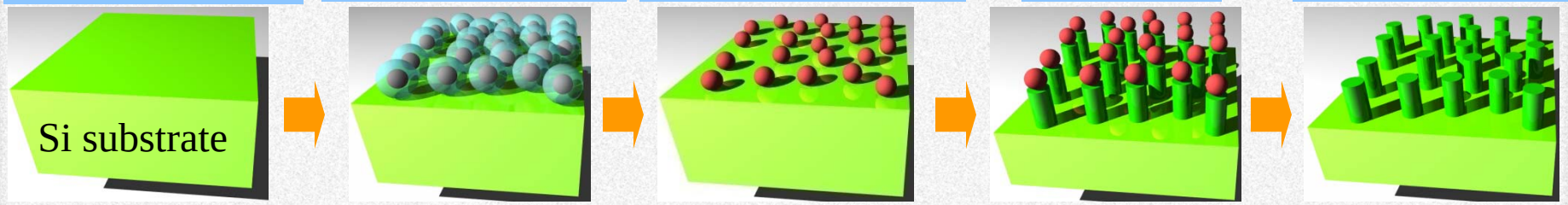
M. Radmilović-Radjenović , Z. Lj. Petrović et al., **Particle-in-cell Modeling of a Neutral Beam Source for Material Processing In Nanoscale Structures Fabrication,** *Material Science Forum* **555** (2007) 47-52.

Nanocolumn and Nanodisk using BIO-NANO PROCESS

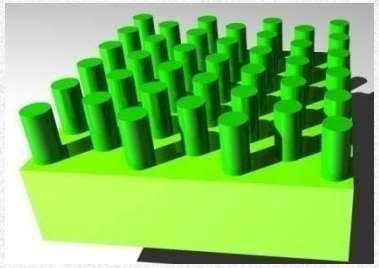
S.Samukawa, Tohoku University

Process Flow

1. Pre-treatment → **2. Ferritin coating** → **3. Remove protein** → **4. Etching** → **5. Remove iron**

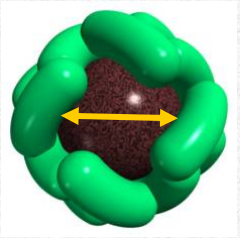


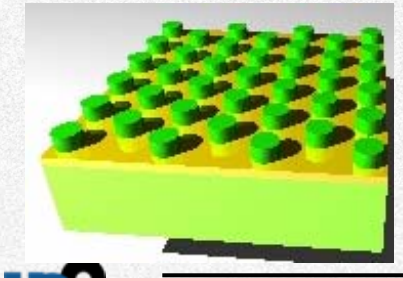
Possible Applications



High Aspect Nanocolumns:
Vertical Surrounding Gate MOSFET,...

ferritin iron core: 7nm





Thin Nanodisks:
Floating gate memory, Single electron transistor,...

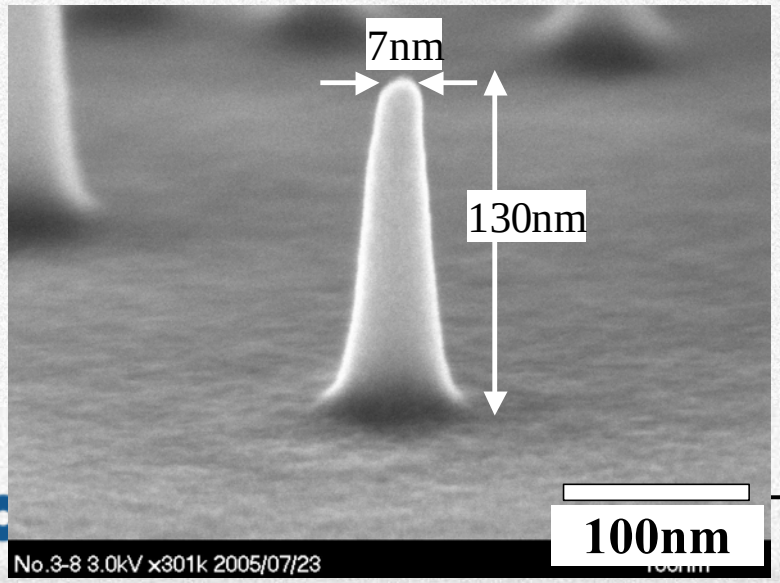
Purpose: fabricating uniform and defect-free nanostructure.

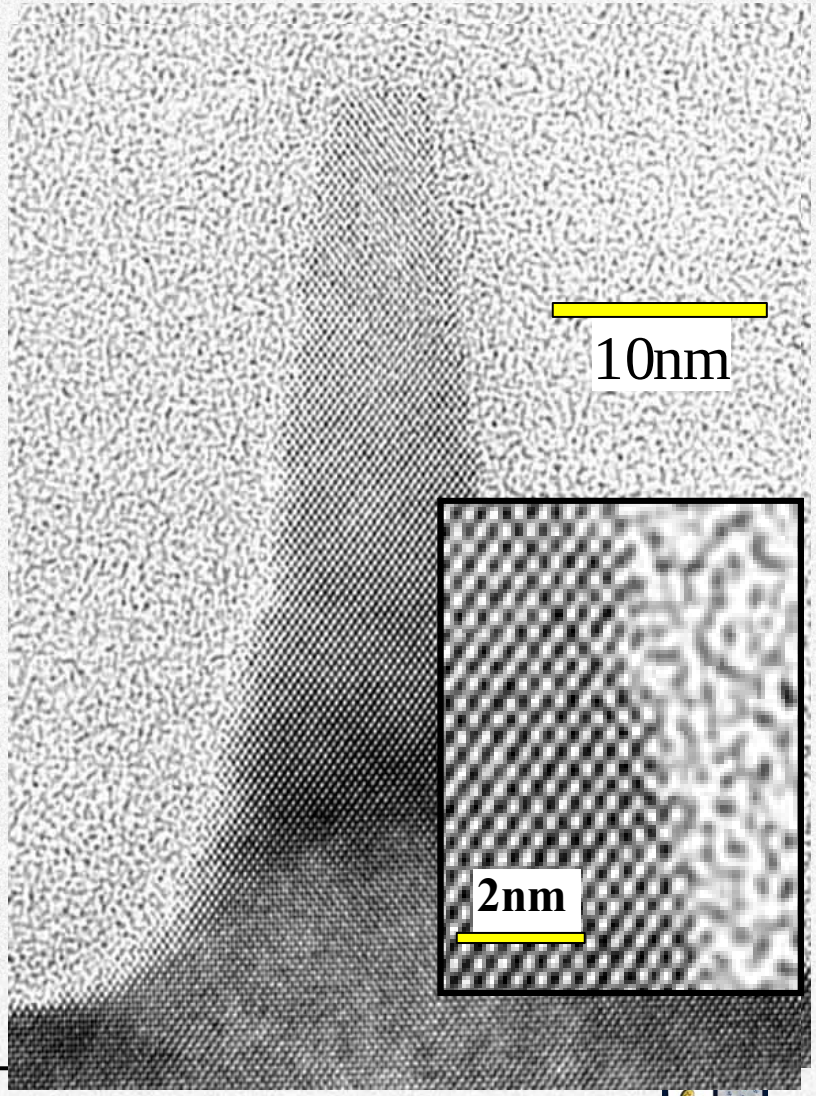
High Aspect Nanocolumns

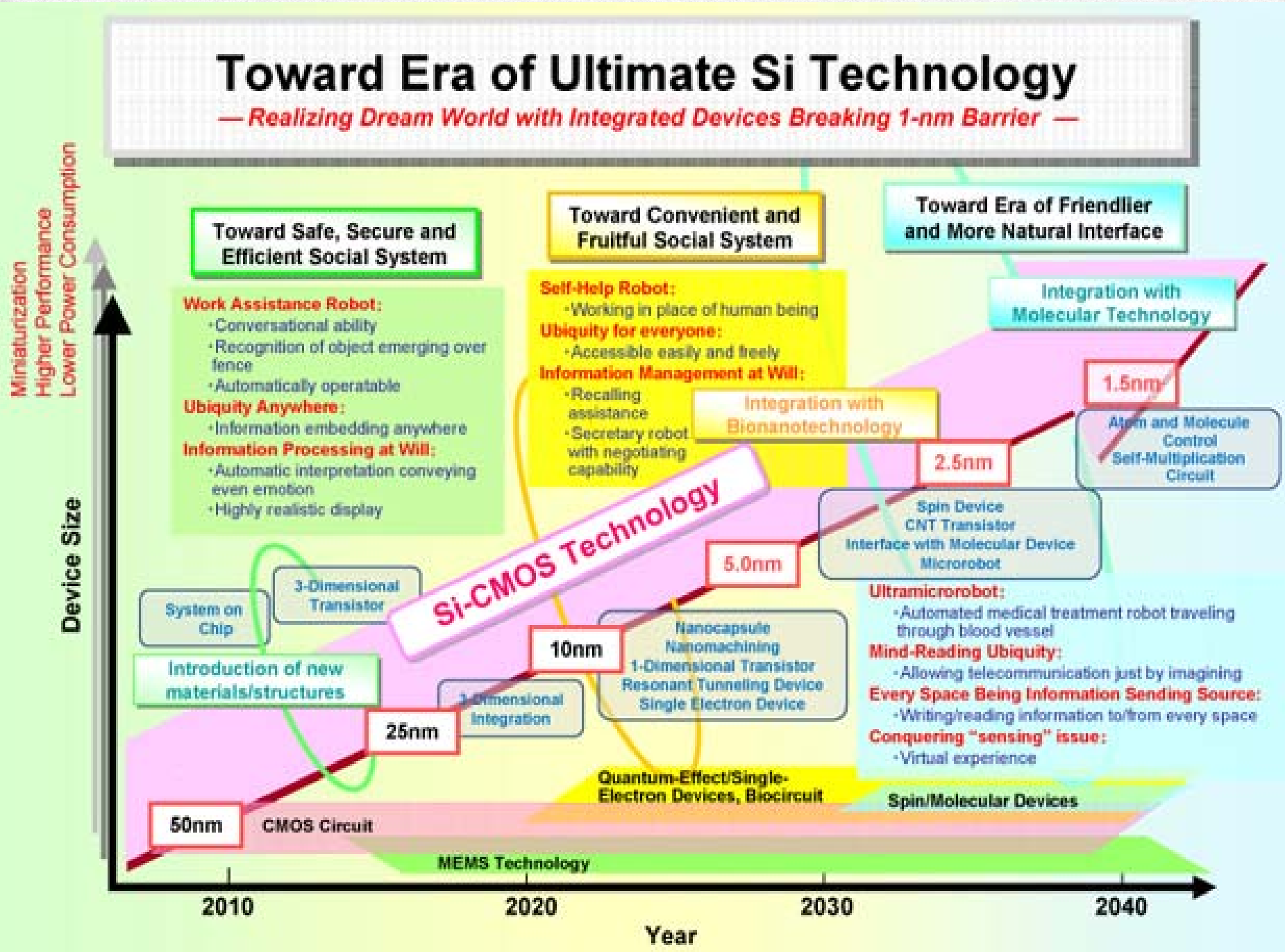
High aspect nanocolumn can be fabricated by simple one-step etching.

Etching condition:

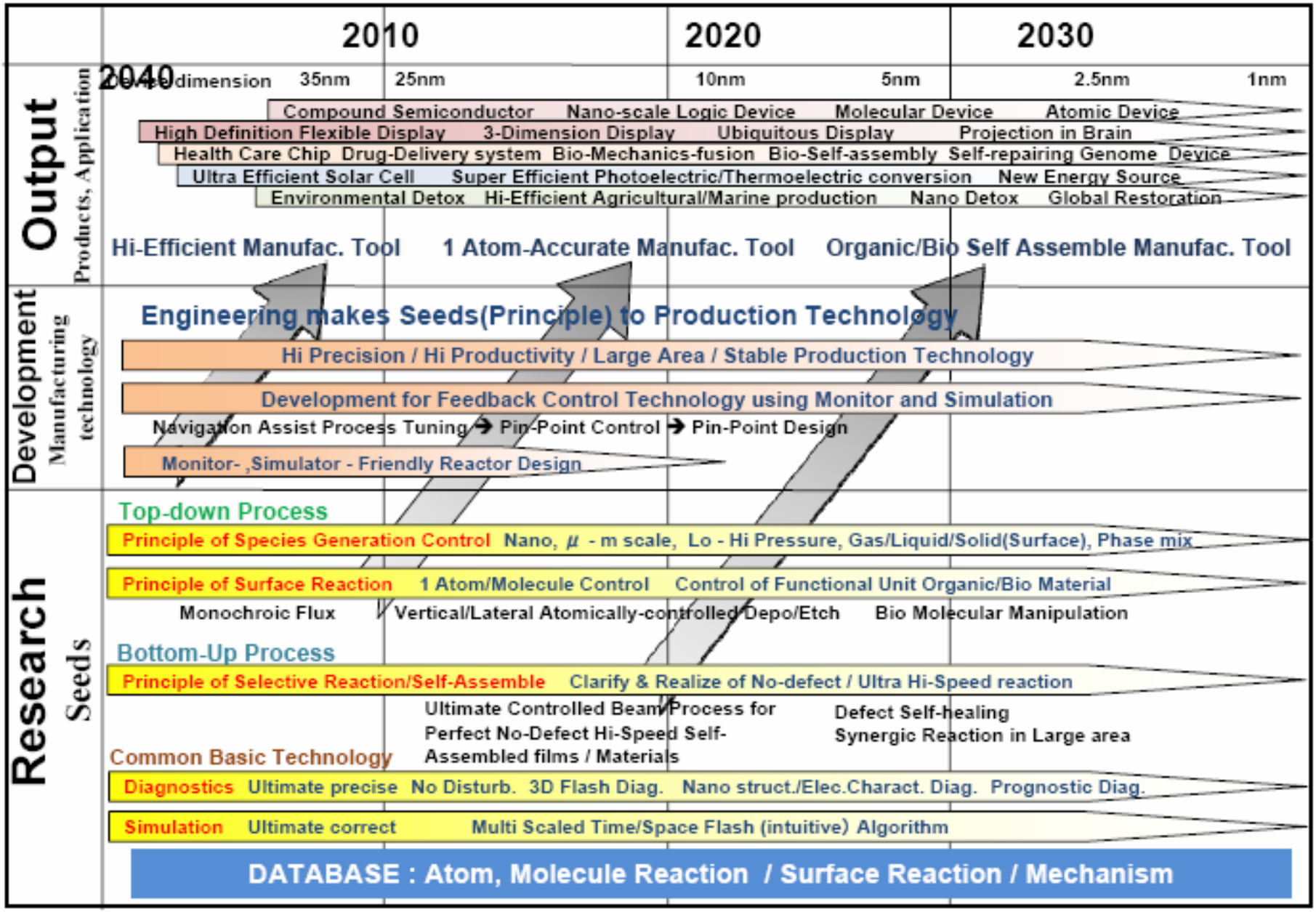
Gas: Cl_2 ~10mTorr in plasma chamber
Cooled to –20° C
ICP power 800W, pulse modulation 50 μs/50 μs






Toward Era of Ultimate Si Technology
— Realizing Dream World with Integrated Devices Breaking 1-nm Barrier —
Miniaturization
Higher Performance
Lower Power Consumption
Device Size
Toward Safe, Secure and Efficient Social System
Work Assistance Robot:
·Conversational ability
·Recognition of object emerging over fence
·Automatically operatable
Ubiquity Anywhere:
·Information embedding anywhere
Infomation Processing at Will:
·Automatic interpretation conveying even emotion
·Highly realistic display
Toward Convenient and Fruitful Social System
Self-Help Robot:
·Working in place of human being
Ubiquity for everyone:
·Accessible easily and freely
Information Management at Will:
·Recalling assistance
·Secretary robot with negotiating capability
Toward Era of Friendlier and More Natural Interface
Integration with Molecular Technology
Integration with Bionanotechnology
Si-CMOS Technology
50nm
25nm
10nm
5.0nm
2.5nm
1.5nm
CMOS Circuit
System on Chip
3-Dimensional Transistor
Introduction of new materials/structures
3-Dimensional Integration
Nanocapsule
Nanomachining
1-Dimensional Transistor
Resonant Tunneling Device
Single Electron Device
Spin Device
CNT Transistor
Interface with Molecular Device
Microrobot
Atom and Molecule Control
Self-Multiplication Circuit
Ultramicrorobot:
·Automated medical treatment robot traveling through blood vessel
Mind-Reading Ubiquity:
·Allowing telecommunication just by imagining
Every Space Being Information Sending Source:
·Writing/reading information to/from every space
Conquering "sensing" issue:
·Virtual experience
Quantum-Effect/Single-Electron Devices, Biocircuit
Spin/Molecular Devices
MEMS Technology
2010
2020
2030
2040
Year

Plasma · Process Technology



Plasma Electronics Division, JSAP

Evolution in Nano-Structure Technology

Dimension

10 nm → 1 nm → sub nm

Ubiquitous Highly Safe Society

Top-Down

Devices Process
Electron Beam
VUV

Nano-lithography
Nano-excitation

Ultra-high speed devices
Ultra-low power devices
Fusion

Bottom-Up

Self-organization
Super integration
Petabit Storage
Single electron and photon
Quantum Communication
Molecular machine

Wafer-Scale Processing

Nano-Analysis
Structure and Elements
TEM SPM

NEMS
Nano material properties
Compatible
Atomic and molecular manipulation

Atomic-Scale Resolution

Quantum-state controlled Devices
Bio-Devices

High-Quality Semiconductors

Nano-Materials
CNT

Quantum structures
Organic molecules
Bio-molecules
Complementary

Specific Functionality, Bio molecules

Nano-molecular Science

Highly Reliable Devices
Ubiquitous
Wearable Computers
Cryptographic Communication
Security
Environment and Energy
Highly Efficient Power Generation
Ultra-Low Power Devices
Welfare and Medicine
Bio-Compatible Devices
In-Vivo Medical Devices

Innovation in Nano-Science and Evolution in Technology Networks

New Properties, New Materials, and New Functionality

2005 2010 2015 2020 2025 2030 2035 2040