Magnetron Sputtering Technology

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Outline

1. Historical timeline of sputtering technology
2. Overview on industrial application of magnetron sputtering
3. Basics for magnetron sputtering
4. Sputtering Systems
5. Sputtering processes
6. Thin film design and control by plasma diagnostics
7. Recent progress and perspective of magnetron sputtering technology

History of Sputtering

- The verb to *SPUTTER* originates from Latin *SPUTARE* (To emit saliva with noise).
- Phenomenon first described 150 years ago…
- *Grove* (1852) and *Plücker* (1858) first reported vaporization and film formation of metal films by sputtering.
- Key for understanding discovery of electrons and positive ions in low pressure gas discharges and atom structure (J.J. Thomson, Rutherford), 1897—
- Other names for SPUTTERING were SPLUTTERING and CATHODE DESINTEGRATION.

History of Sputtering

- Cylindrical-hollow cathode discharge : *by Penning in 1936*
- Cylindrical-post cathode discharge : *by Penning & Moubis in 1939*
- Magnetron ion gauge : *by Penning in 1939*
- Sputter erosion pattern : *by Helmer & Jepson in 1961*
- Conical / Circular / Planar magnetron devices : *in 1970`s*
- Unbalanced magnetron device : *by Window in 1984*
- Closed-field unbalanced magnetron device : *by Teer in 1989*
- Pulsed magnetron device : *by Schiller etc. in 1993*
- Variable field magnetron device : *by Colligon etc. in 1995*
- High Power Pulse Magnetron Sputtering : *by Kouznetsov in late 1990s*

Overview on industrial application of magnetron sputtering

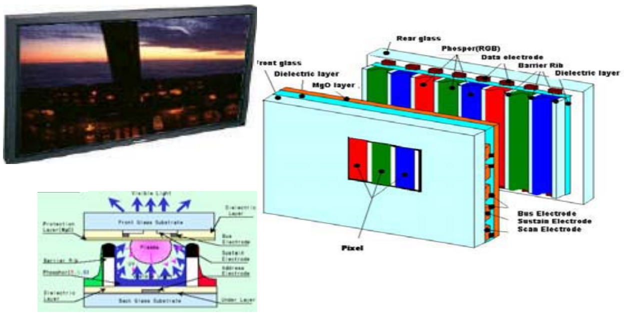
- ☐ Electronics
- ☐ Automobile and machinery
- ☐ Decorative and Packaging etc.

Thin films synthesized by magnetron sputtering

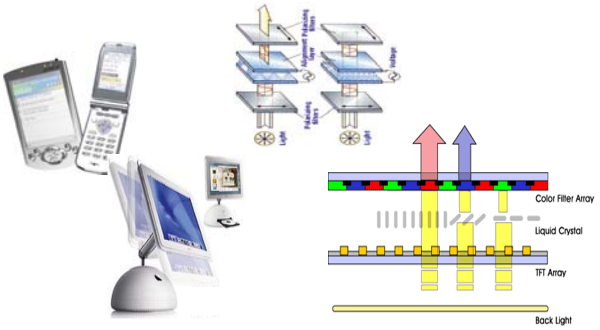
1. Metals – Cu, Ti, Al, W, Mo, Cr, Si etc.
2. Oxides – ITO, $A1_2O_3$, In_2O_3, SnO_2, SiO_2, Ta_2O_5.
3. Nitrides - TaN, TIN, A1N, Si_3N_4, CNX
4. Carbides - TiC, WC, SiC
5. Sulfides - CdS, CuS, ZnS
6. Oxycarbides and oxynitrides of Ti, Ta, Al, and Si

Flat Panel Display

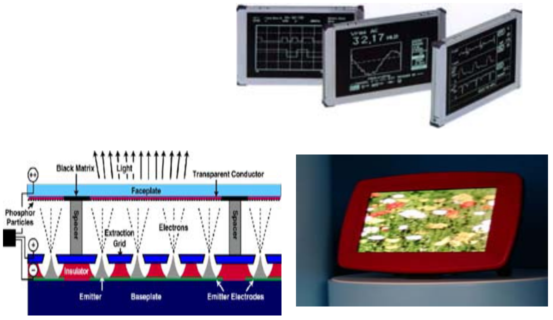
Plasma Display Panel



Organic Light-Emitting Display

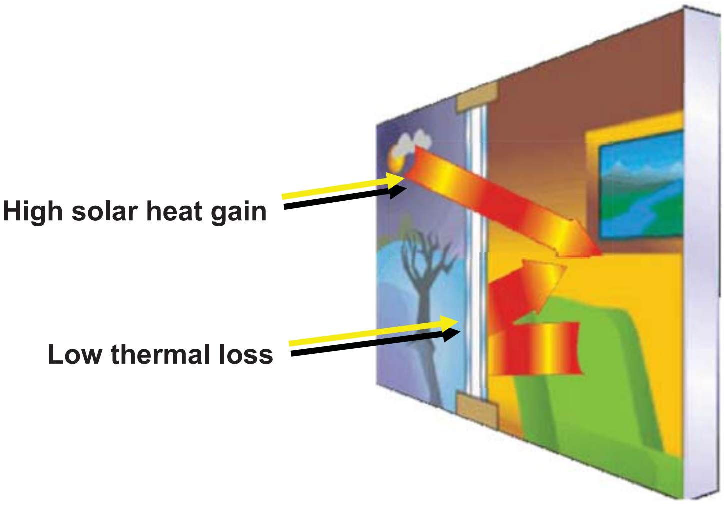


Liquid Crystal Display



Field Emission Display

Glass & Energy



Application fields

❑ Low E glass
❑ Reflective glass
❑ Decorative glass
❑ Light valve glass
❑ Electrochromic glass

Low E glass?

Low-E = Low-Emissivity

- Redirects (reflects) radiant heat (long wave radiant energy) back toward the source
- Reduces heating costs in the winter
- Reduces cooling costs in the summer
- Various combinations work with the direct sun (SHGC) and re-radiated heat U-factor

Sputter coating process

Automobile, Tool & machinery industry

Properties of tribological coatings

Film	Color	Hardness (GPa)	Friction coeff.
TiN	Gold	22 – 25	0.45
ZrN	White gold	18 – 21	0.45
CrN	Silver gray	18 – 23	0.35
TiCN	Violet – gray	28 – 34	0.2
CrCN	Gray	20 – 30	0.2
TiAlN	Violet – black	25 – 35	0.4
CrAlN	Gray	24 – 30	0.35
Al_2O_3	Gray	20 – 24	0.2
DLC	Black	20 – 60	< 0.1

Applications for automobile industry

Applications for Machinery parts

Applications of various tools & molds

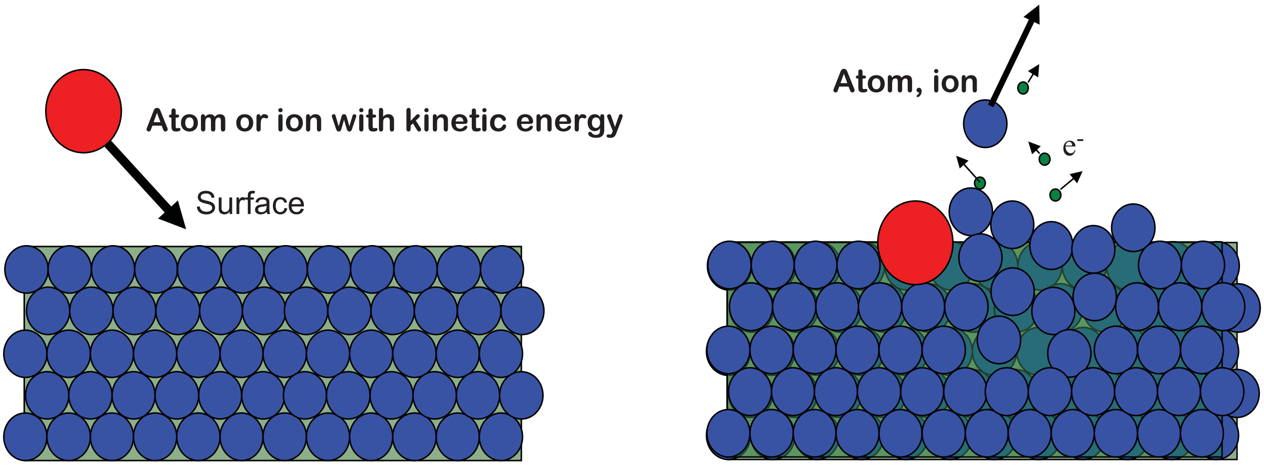
Basics for magnetron sputtering

- ❑ Ion-surface interaction
- ❑ Principle of magnetron discharge
- ❑ Sputtering yield (species, energy, incident angle etc)

What is sputtering?

- "Sputtering" is a term used to describe the mechanism in which atoms are ejected from the surface of a material when that surface is struck by sufficient energetic particles.
- Alternative to evaporation.
- First discovered in 1852, and developed as a thin film deposition technique by Langmuir in 1920.
- Depostion of various metallic films and compounds films.

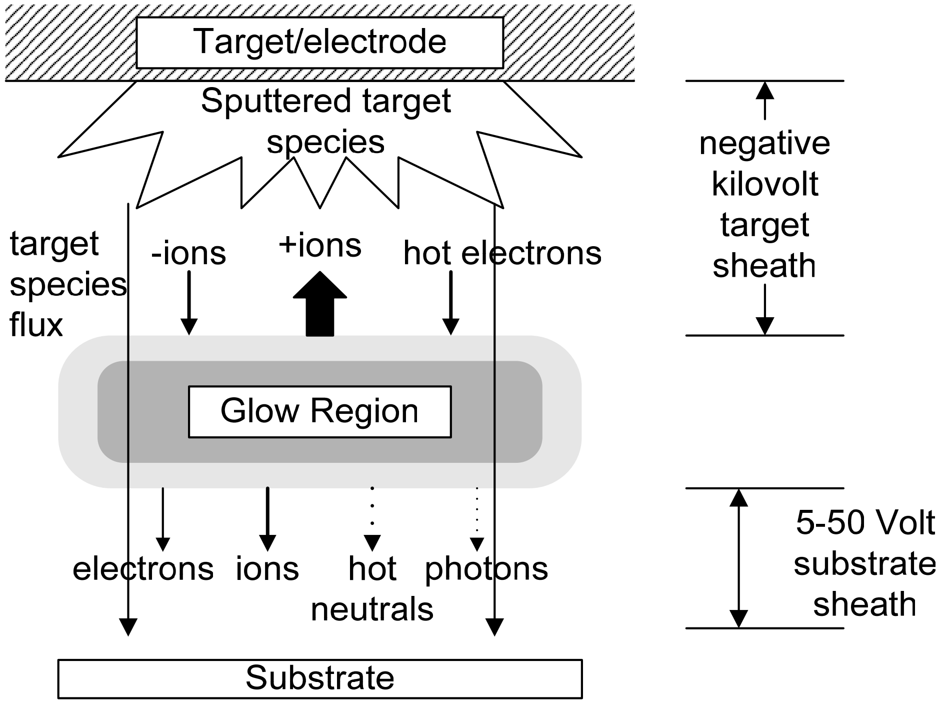
What is sputtering?



The impact of an atom or ion on a surface produces sputtering from the surface as a result of the momentum transfer from the in-coming particle.

Unlike many other vapor phase techniques there is no melting of the material.

Sputtering process for thin film deposition



Sputtering steps

1st : Ions are generated in plasma and directed at a target.

2nd : The ions sputter targets atoms .

3rd : The ejected atoms are transported to the substrate.

4th : Atoms condense and form a thin film on the substrate

Plasma

- Plasma is weakly ionized quasi-neutral gas made up of ions, electrons atomic and molecular species →ne = ni = n0
- Processing plasmas have plasma densities between $10^8 \sim 10^{13}/cm^3$
- In magnetically confined plasma (magnetrons), plasma densities as high as $10^{15}/cm^3$ can be realized
- Plasma species : Electron (ne), Ions (ni), Neutrals (n0)
- Electron velocities are much higher than that of ions

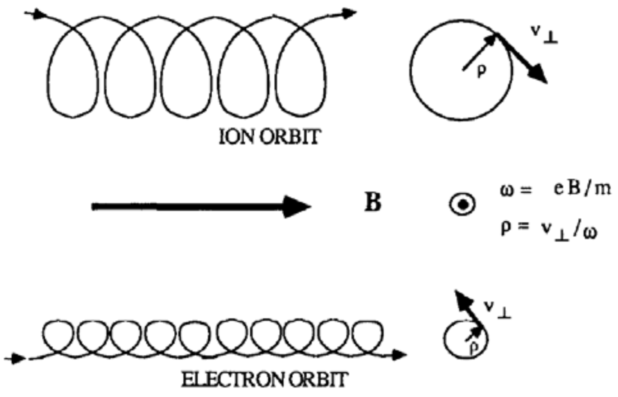
❖ Plasma generation

- Plasma generation regions → collision between high velocity electron (thermal or high energy electron) and neutrals
- Applying power sources for discharge;
  - DC source : Continuous DC, Pulsed DC
  - AC source : LF (~ 100 Hz), MF (~100 - ~ 1MHz), RF (> ~1 MHz)

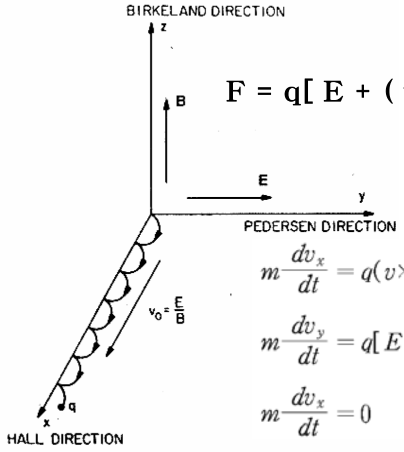
Charged particle motion
in a static electric and magnetic fields

J. Roth - Industrial Plasma Engineering Volume 2 ;
Applications To Nonthermal Plasma processing

- Orbits of ion and electron in a homogeneous static magnetic field



- Lorentz equation



F = q[E + (v × B)]

$$m\frac{dv_x}{dt} = q(v\times B)_x = qv_yB$$

$$m\frac{dv_y}{dt} = q[E+(v\times B)]_y = qE - qv_xB$$

$$m\frac{dv_x}{dt} = 0$$

$$v_x = v_d = \frac{E}{B}$$

- Without electric field

  → electron orbits in plane of the page

- With electric field

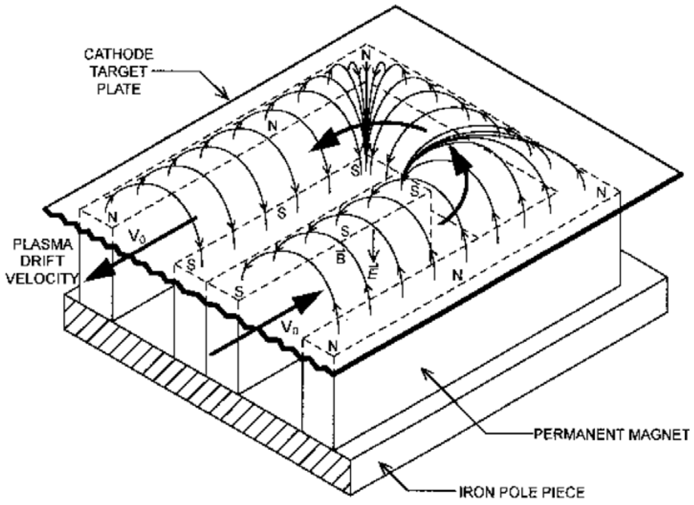
  → Electron experiences constant force

  → Cyclical motion with net movement to *x* direction

Magnetron discharge

➢ Electron motion

in a combined electric and magnetic field



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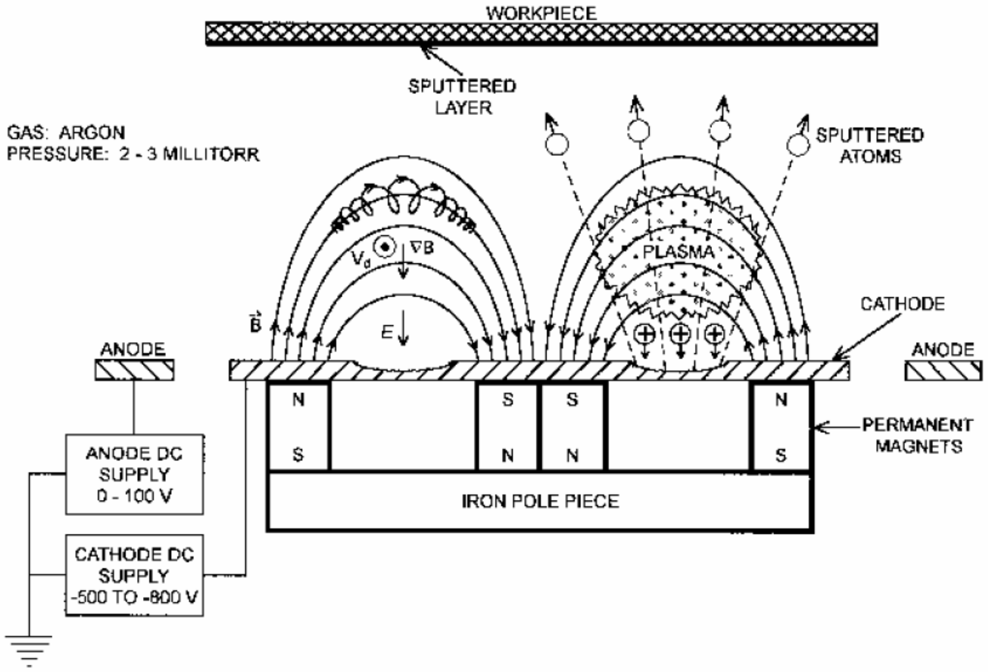
__Magnetron discharges__ :

are characterized by crossed electric and magnetic fields, with the sheath electric field at right angles to a confining magnetic mirror field. The E/B 'magnetron' drift velocity is perpendicular to both the electric and magnetic fields, thus making the plasma itself and its effects on a workpiece more uniform in the E × B/B^2 drift direction.

- ● Static B field perpendicular to plane of cathode
  - electrons move in spiral path
  - ionization increase, voltage decrease

- ● Static B field parallel to plane of cathode
  - electrons constrained near cathode
  - high level of ionization , voltage decrease
  - *EXB* drift cause electrons to drift to one side

Magnetron configurations



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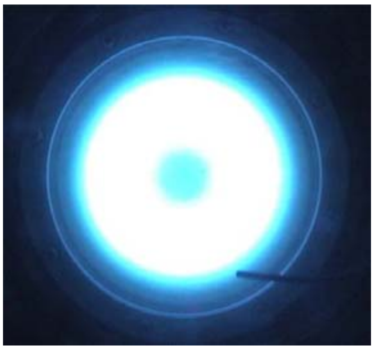
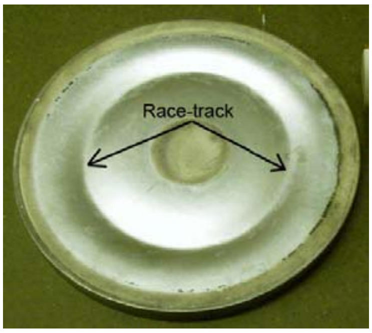
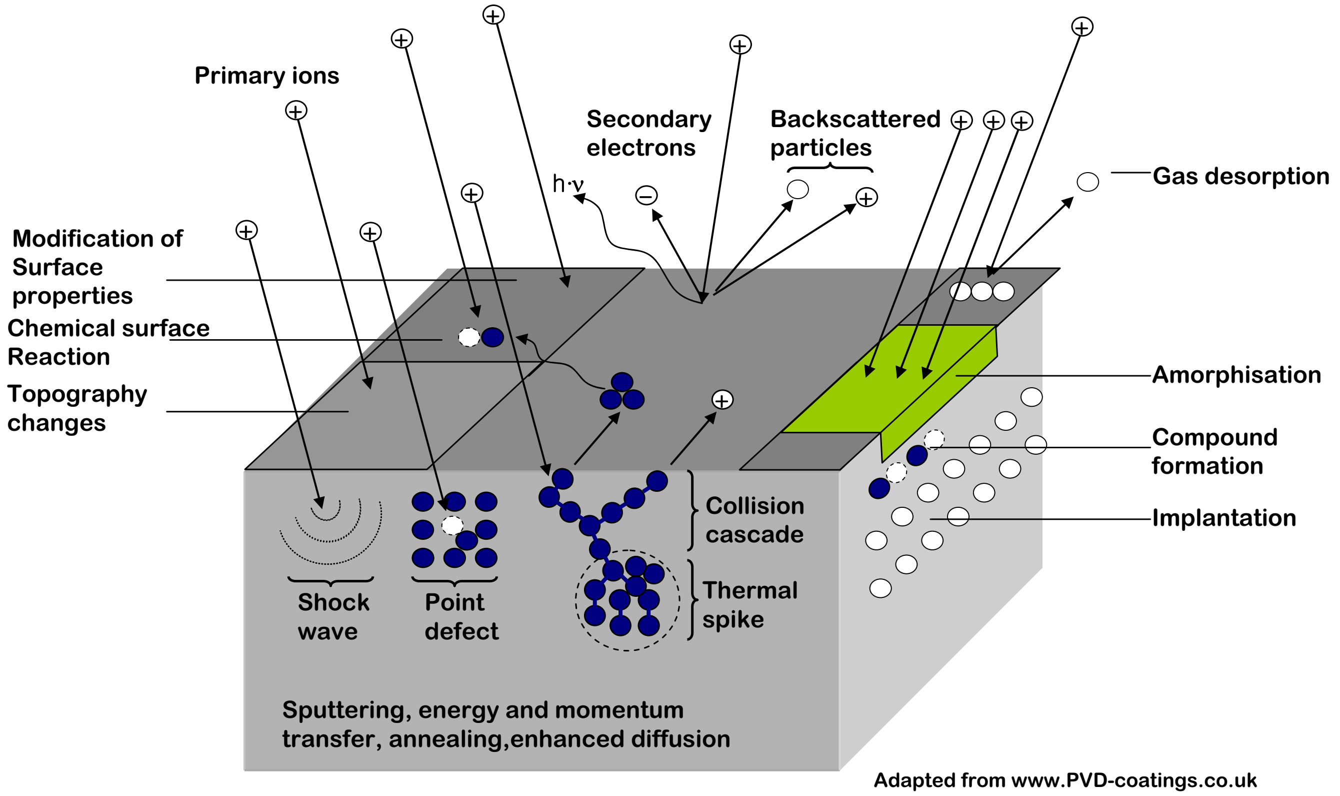
magnetron sputtering plasma



Sputter target

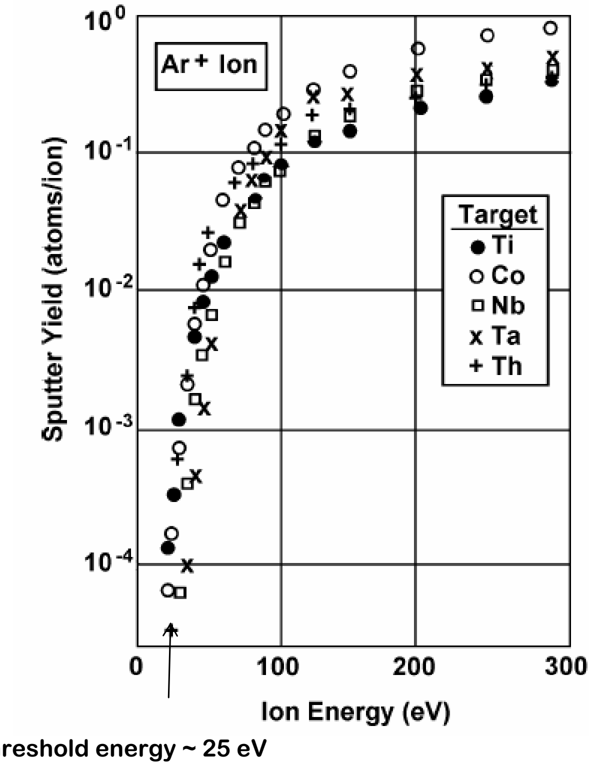


Collision cascade sputtering mechanism and energetic particles involved in the sputtering process

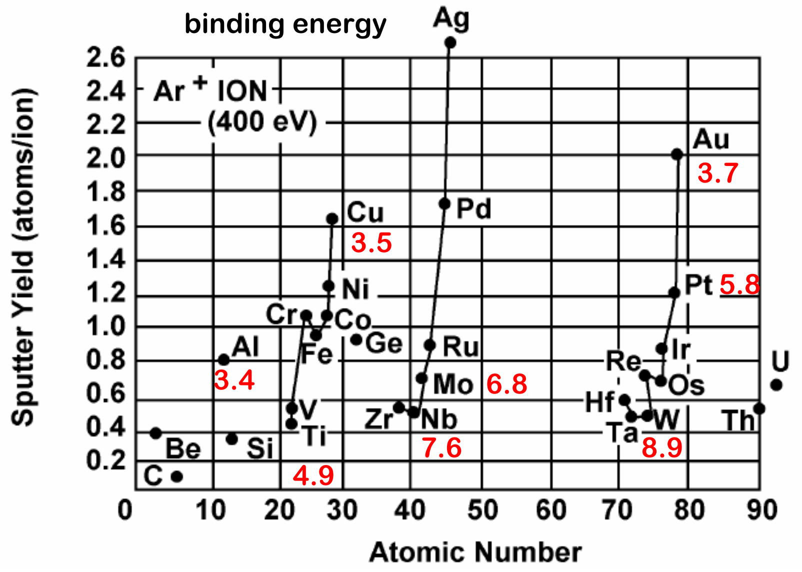


Adapted from www.PVD-coatings.co.uk

Sputtering Yields
incident ion energy and target atom mass



- Effect of target atom mass and surface binding energy

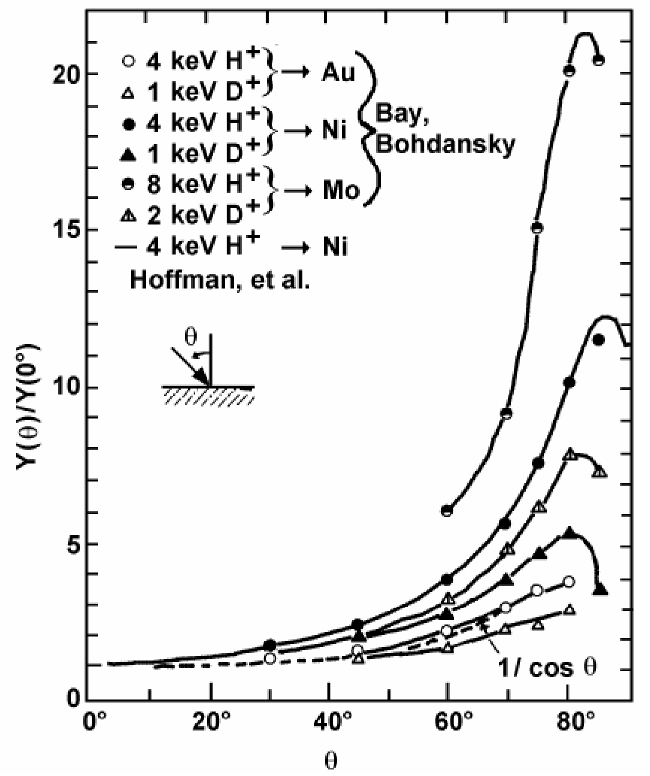


- Sputtering yield, S

$$S \propto \left(\frac{m_i m_t}{(m_i+m_t)^2}\right)\left(\frac{E_i}{U}\right)$$

K. Wasa *et.al* THIN FILM MATERIALS TECHNOLOGY, William Andrew, Inc

Sputtering Yields
effect of incident ion angle



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- Sputtering yield increases with ion incidence angle *θ* up to approx 80° due to the decrease in the scan depth of incident ions.
- Sputtering yield, S ∝ 1/cosθ
- At higher angles, sputtering yield decrease as more ions are reflected in initial collisions

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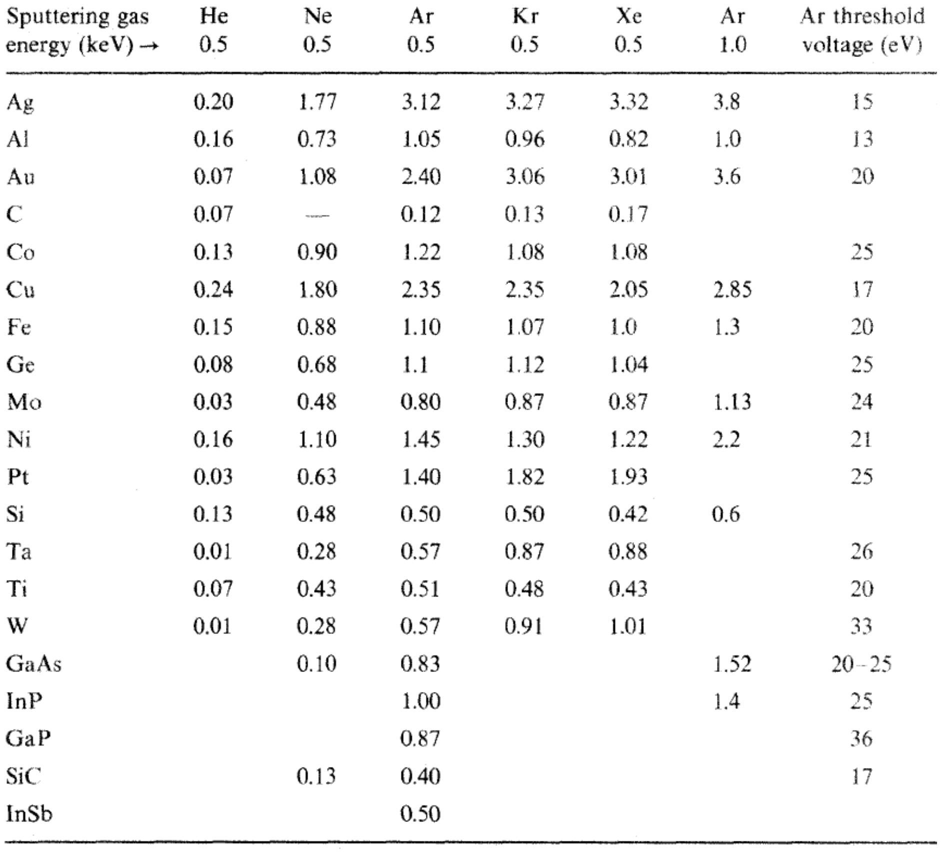
Sputtering yield data for metals and semiconductors



Sputtering gas energy (keV) →	He 0.5	Ne 0.5	Ar 0.5	Kr 0.5	Xe 0.5	Ar 1.0	Ar threshold voltage (eV)
Ag	0.20	1.77	3.12	3.27	3.32	3.8	15
Al	0.16	0.73	1.05	0.96	0.82	1.0	13
Au	0.07	1.08	2.40	3.06	3.01	3.6	20
C	0.07	—	0.12	0.13	0.17		
Co	0.13	0.90	1.22	1.08	1.08		25
Cu	0.24	1.80	2.35	2.35	2.05	2.85	17
Fe	0.15	0.88	1.10	1.07	1.0	1.3	20
Ge	0.08	0.68	1.1	1.12	1.04		25
Mo	0.03	0.48	0.80	0.87	0.87	1.13	24
Ni	0.16	1.10	1.45	1.30	1.22	2.2	21
Pt	0.03	0.63	1.40	1.82	1.93		25
Si	0.13	0.48	0.50	0.50	0.42	0.6	
Ta	0.01	0.28	0.57	0.87	0.88		26
Ti	0.07	0.43	0.51	0.48	0.43		20
W	0.01	0.28	0.57	0.91	1.01		33
GaAs		0.10	0.83			1.52	20–25
InP			1.00			1.4	25
GaP			0.87				36
SiC		0.13	0.40				17
InSb			0.50				

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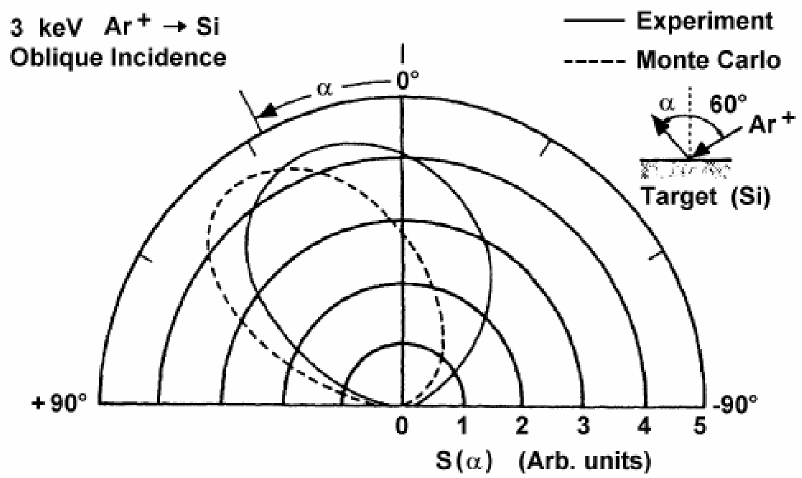
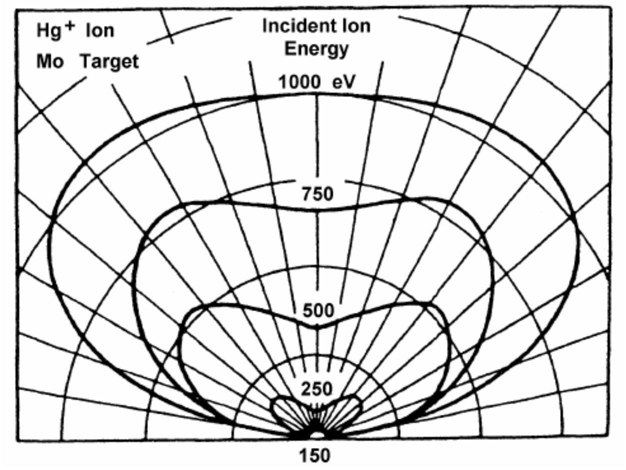
Angular dependence of the sputtered flux



Angular distributions of sputtered Si atoms for 3 keV Ar$^+$ ion bombardment at an incident angle of 60°



Angular distributions of sputtered particles from a polycrystalline target

The distribution of sputtered particles depends primarily on the energy incidence angle of the ion and the relative masses of the collision partners

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Energy of the Sputtered Atoms

- bombarding ion energy: typically 100 ~ 1000eV
- average ejection energy of the sputtered atoms: 1 ~ 10eV

: This relatively high energy of the deposited atoms is partially responsible for the better adhesion for sputtered films than for evaporated films.

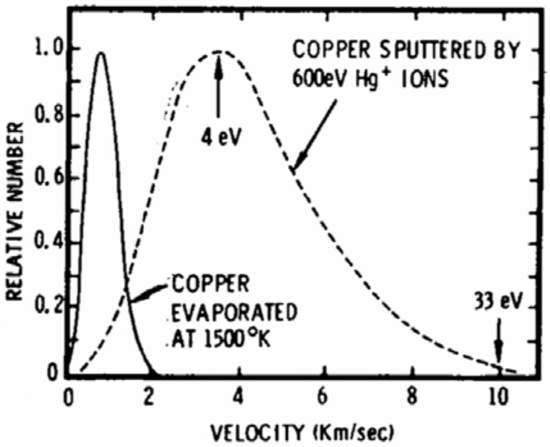
(cf.) average E of the evaporated atoms: ~ kT(0.1 ~ 0.3 eV)

bonding E of chemisorbed atoms: 1 ~ 10eV

bonding E of physisorbed atoms: < 0.5eV

- velocity of sputtered atoms: 4 ~ 9 km/sec for most materials

(cf.) velocity of evaporated atoms: ~ 1 km/sec



- **Comparison of velocity distributions of sputtered and evaporated Cu atoms**

Typical magnetron sputtering conditions

- **Magnetic field : 200 ~ 500 Gauss**
- **Working pressure : 1 ~ 10 mTorr**
- **Discharge voltage : 300 ~ 700 V**
- **Target thickness ; 3 ~ 20 mm**
- **Rate is proportional to power density**
- **Rate is limited by target cooling efficiency**

Features in Magnetron sputtering

● Advantages

- wide range of coating materials including alloys and compounds
- good adhesion due to high energy of depositing atoms
- high film density and uniformity
- easy process control and scale-up capability
- synthesize new materials- metastable compositions/structures
- reactive sputtering of insulator films

● Disadvantages

- relatively low deposition rate
- low energy efficiency and ionization (a few %)
- limited sputtering for insulator target
- magnetic film synthesis requires special process
- intrinsic stress is often high
- limitation of uniformity control for complex shapes

Evaporation Vs. Sputtering

	Vacuum/evaporation	Plasma/sputtering
A. Source attributes		
1. Phase	Melt or solid	Solid target
2. Mechanism of atom removal	Thermal evaporation (hot source)	Ion bombardment and collisional momentum transfer (cool target)
3. Energy supplied to source	Thermal energy ~0.1 to 0.2 eV/atom + ΔH_v	> 20 eV/atom
4. Atom removal rate	~ 1.3×10^{17} atoms/cm^2-s for $M = 50$, $T = 1500$ K, $P_e = 10^{-3}$ torr (Eq. 3-2)	~ 10^{16} atoms/cm^2-s at 1 mA/cm^2 and $S = 2$
5. Atom emission geometry	$\cos\phi$ and $\cos^n\phi$	$\cos\phi$ as well as directional according to crystallography
6. Applicability, availability	All materials, generally high purity	Targets of all materials, variable purity

	Vacuum/evaporation	Plasma/sputtering
B. Gas phase attributes		
1. Composition	Evaporant atoms, associated and dissociated compound fragments, residual gases	Sputtered atoms, assorted metastable ionized and excited species, sputtering gas, ions, electrons, residual gases
2. Pressure	High to ultrahigh (~ 10^{-5} to 10^{-10} torr)	~1–100 mtorr discharge
3. Species energy	~0.1–0.2 eV for evaporants	3–10 eV for sputtered atoms 2–5 eV for electrons
4. Atomic mean free path	Larger than evaporant–substrate spacing. No gas collisions in vacuum	Less than target–substrate spacing. Many gas collisions in the discharge
C. Condensed film attributes		
1. Energy of condensing atoms	Low (0.1 to 0.2 eV)	High (~a few eV); higher with substrate bias
2. Gas incorporation	None	Some
3. Adhesion to substrate	—	Generally good
4. Film stoichiometry	Generally different from multicomponent alloy and compound sources	Same as the target composition

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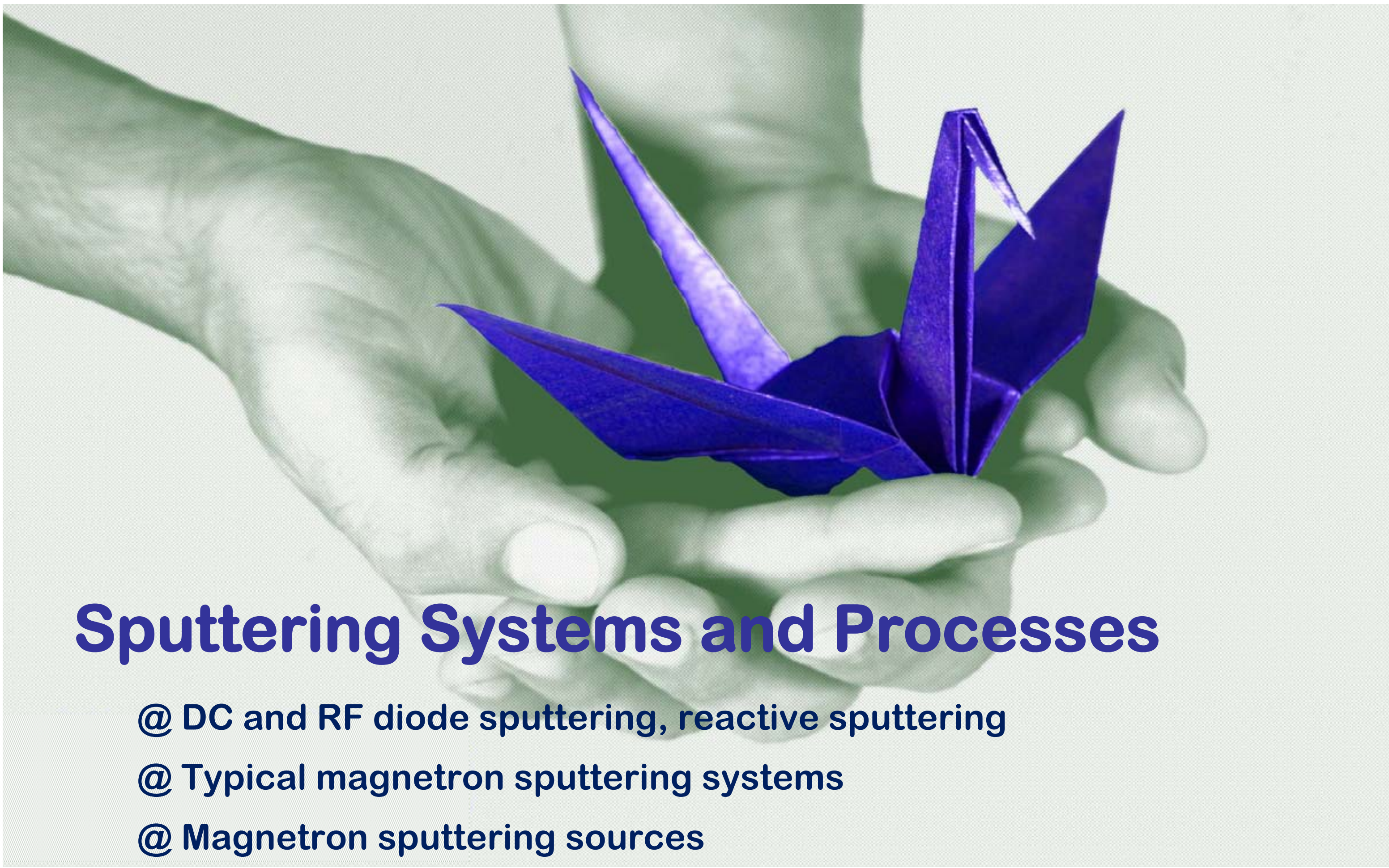


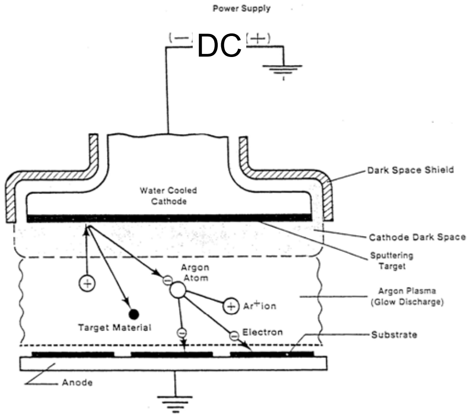
Sputtering Systems and Processes

@ DC and RF diode sputtering, reactive sputtering

@ Typical magnetron sputtering systems

@ Magnetron sputtering sources

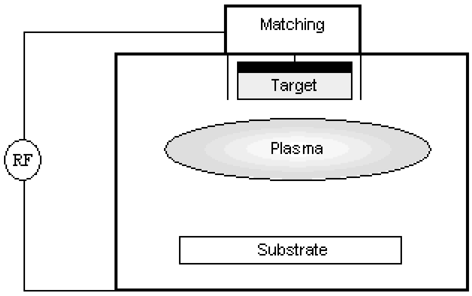
DC and RF diode sputtering process



- main usage: metal sputter coating
- configuration: target(cathode) + substrate(anode)
- operating pressure range in the DC sputtering system
- operating voltage and current

  V: 500 ~ 5000 V (typically 2 ~ 5 kV)

  J: 0.1~ 2.0mA/cm^2 (typically ~ 0.5mA/cm^2)
- deposition rate: 10 ~ 40 nm/min
- Working pressure : 30 mTorr~ 100 mTorr



- An RF sputtering can be used to deposit not only conductive and semiconductor films but also insulating films.

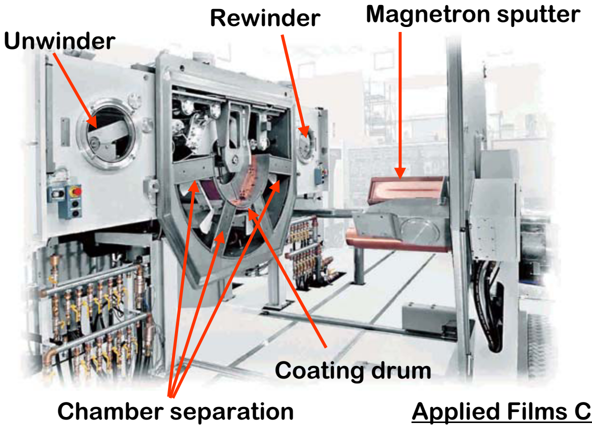
  (cf.) DC methods cannot be used to sputter non-conducting targets because of charge accumulation on the target surface.
- Arcs are less likely to form in RF discharge.
- Good reproducibility
- The substrate mounting electrode is made larger than the target electrode to control unwanted sputtering (for RF diode type).

Typical sputtering systems

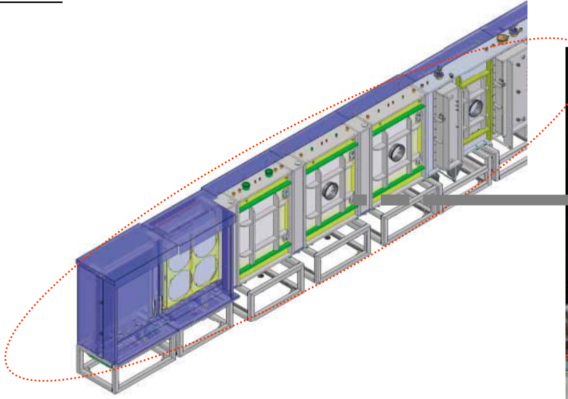
- Batch type system

Institute for Plasma Advanced Materials

- Roll-to-Roll Web system



Applied Films Co., Ltd

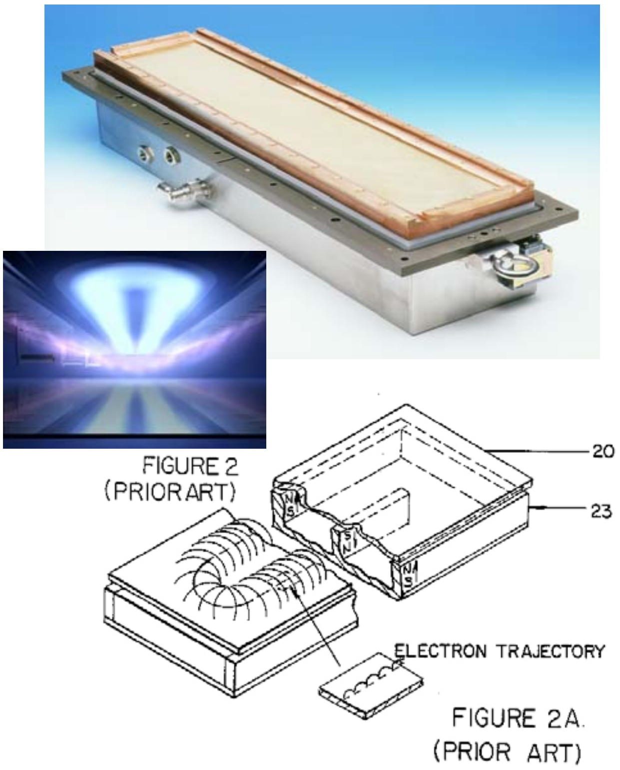


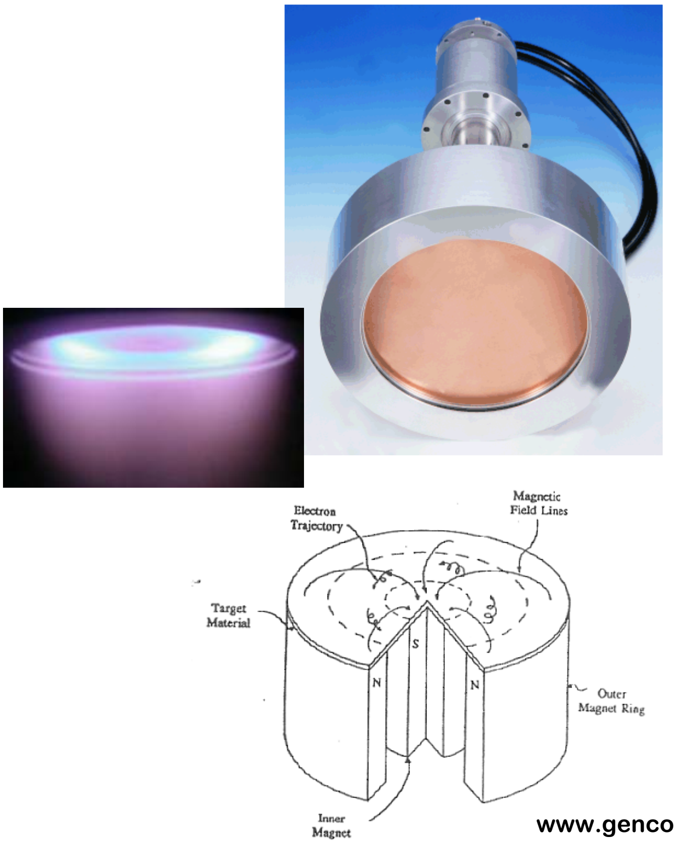
- In-Line system

Leybold Optics GmbH

Conventional magnetron sources

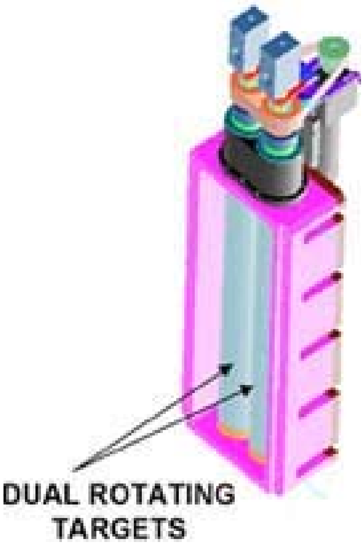
Rectangular and circular magnetron

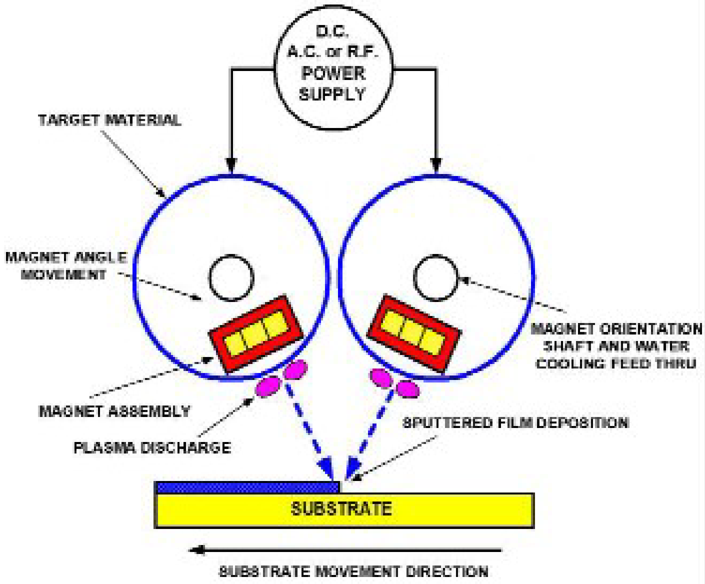




www.gencoa.com

Cylindrical Magnetron Source with Rotational Magnet



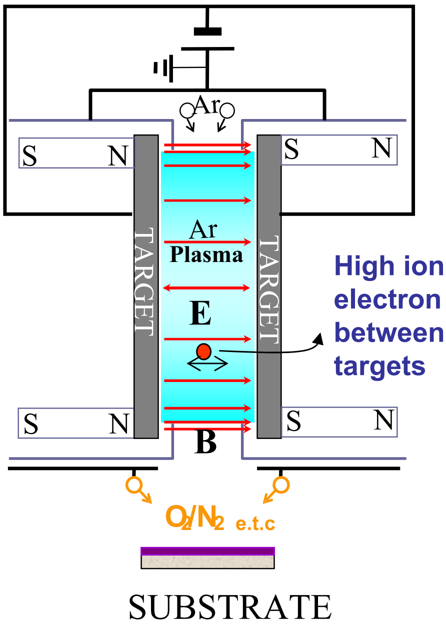


www.angstromsciences.com

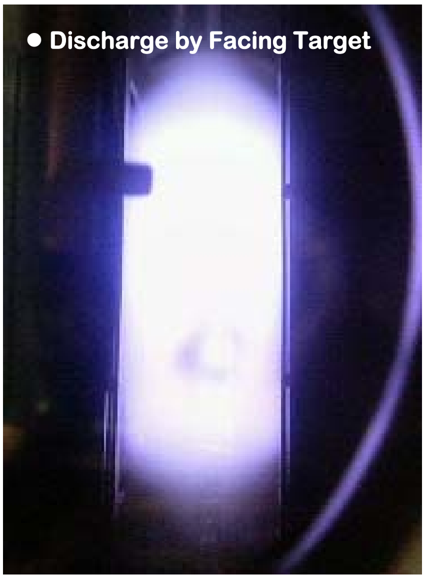
- **Advantage : High efficiency of target utilization (up to 90 %)**
  Longer target life time, higher stability, less arcing

- **Disadvantage : Target materials are limited in cylindrical shape and high cost**

Facing Target Sputtering Source



High ionization by electron oscillation between confined two targets



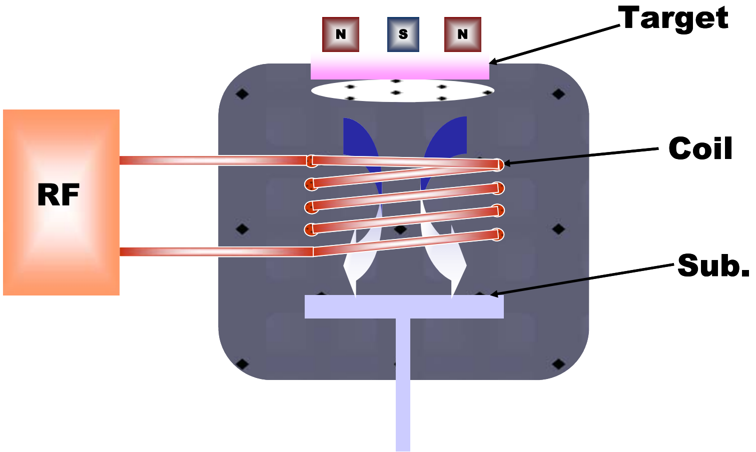
- Discharge by Facing Target

- **Target erosion shape**

- **Advantage :**
  - High target utilization,
  - Low temperature process by suppression of surface damage by direct ion bombardment from target to substrate
  - Low plasma impedance and low pressure discharge

ICP Magnetron Source

- The ICP coil highly ionizes sputtered atoms moving to substrate.



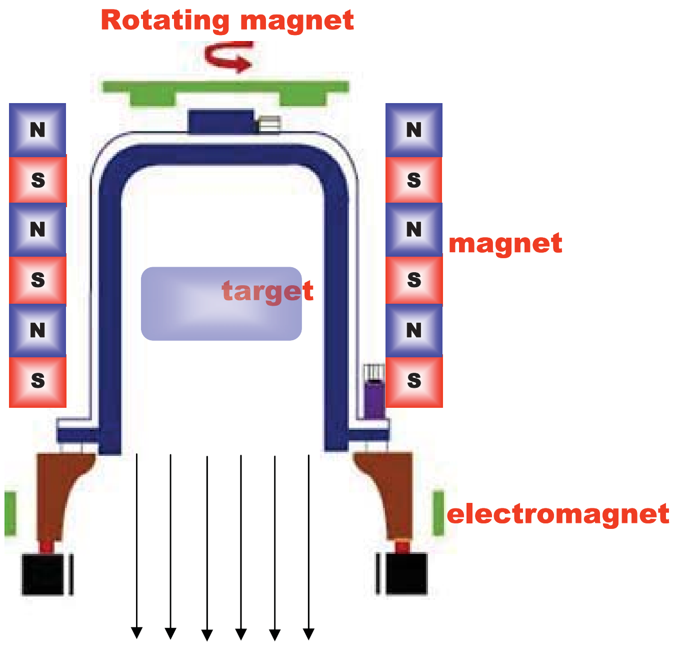
- **Advantage : Generation of high density plasma**

  High ion-to-neutral ratio at substrate

  High ionization; approx. 80 %

  High deposition rate by high neutral flux

Hollow Cathode Magnetron Source



- Intense glow discharge is formed in a cup shaped cathode or between two parallel plates.

- High ion density plasma > $10^{13}cm^{-3}$

- The electrons captured in the geometry are between two "electrostatic mirrors", and therefore the probability for ionization of sputtered neutrals drastically can be enhanced.

Reactive sputtering

- Definition
  - The sputtering of element targets in the presence of chemically reactive gases that actively react with both the ejected target atoms and target surface
  - Reactive sputtering provides an easy technique to deposit high quality compound films
  - For example, for oxide deposition the sputtering gas is a mixture of argon and oxygen. The argon ions in the plasma sputter the metallic target to provide the metal flux. This flux is then deposited on the substrate through reaction with oxygen to formed the oxide film.
  - Reactive sputtering is commonly used to deposit thin films of ceramic compounds such as Al_2O_3, SiO_2, TiO_2, TiN, TiC, etc.

Reactive sputtering

● Advantages

- Easy control of film composition
- High deposition rate of various compound films
- Cost effective & high purity compound film formation due to high purity of target
- Process capability of high target power density due to high cooling efficiency of metallic target

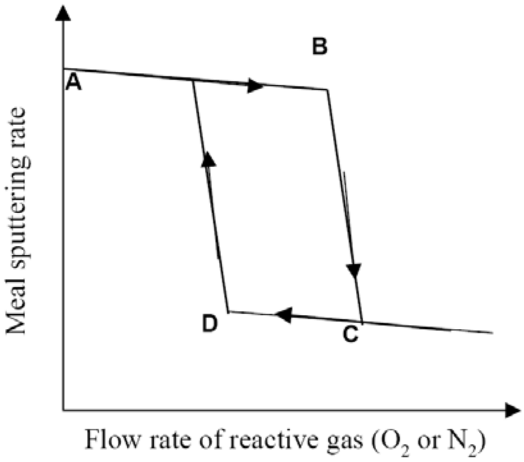
● Disadvantages

- Target poisoning : the build-up of insulating layers on target surface
- Arcing problem and breakdown of insulating layer on target surface
- Pure compound films are often hard to be formed because of reactive species
- concentration is not sufficient to react will all the sputtered atoms

---

Reactive sputtering

Poisoning effect



● With increasing flow rate of reactive gas

A: metal target is sputtered in pure Ar

B: the reactive gas adsorption rate on the target begins to exceed the sputtering rate →transition from metallic mode to compound mode

C: compound layer formation on the target surface →target becomes "poisoned"

● With decreasing flow rate of reactive gas

D: the sputtering rate begins to exceed the reactive gas adsorption rate →transition from compound mode to metallic mode

● <u>Hysteresis effect in discharge voltage</u>

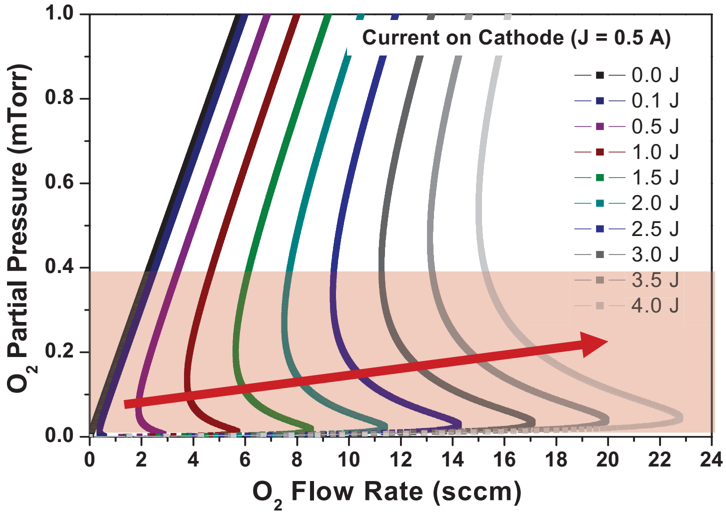
- compounds formed on the poisoned target have higher secondary electron emission coefficients compared with metals.

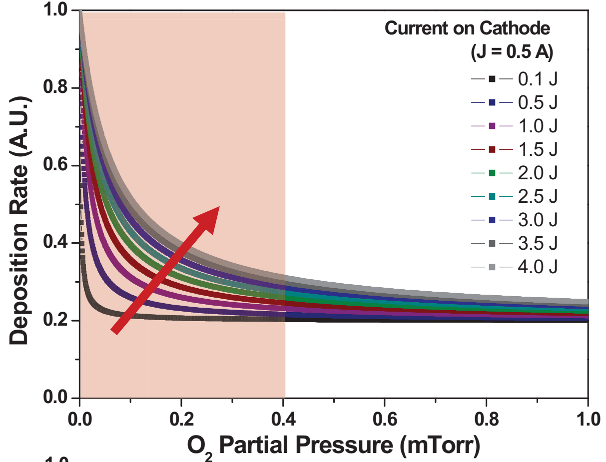
→ leads to a reduction in discharge voltage

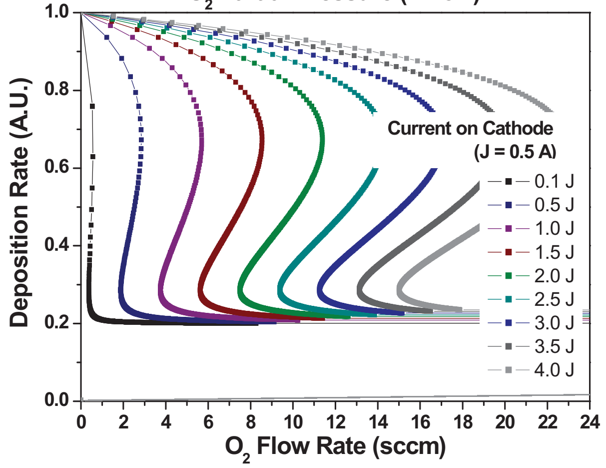
● <u>Hysteresis effect in deposition rate</u>

- the drastic decrease in deposition rate in compound mode

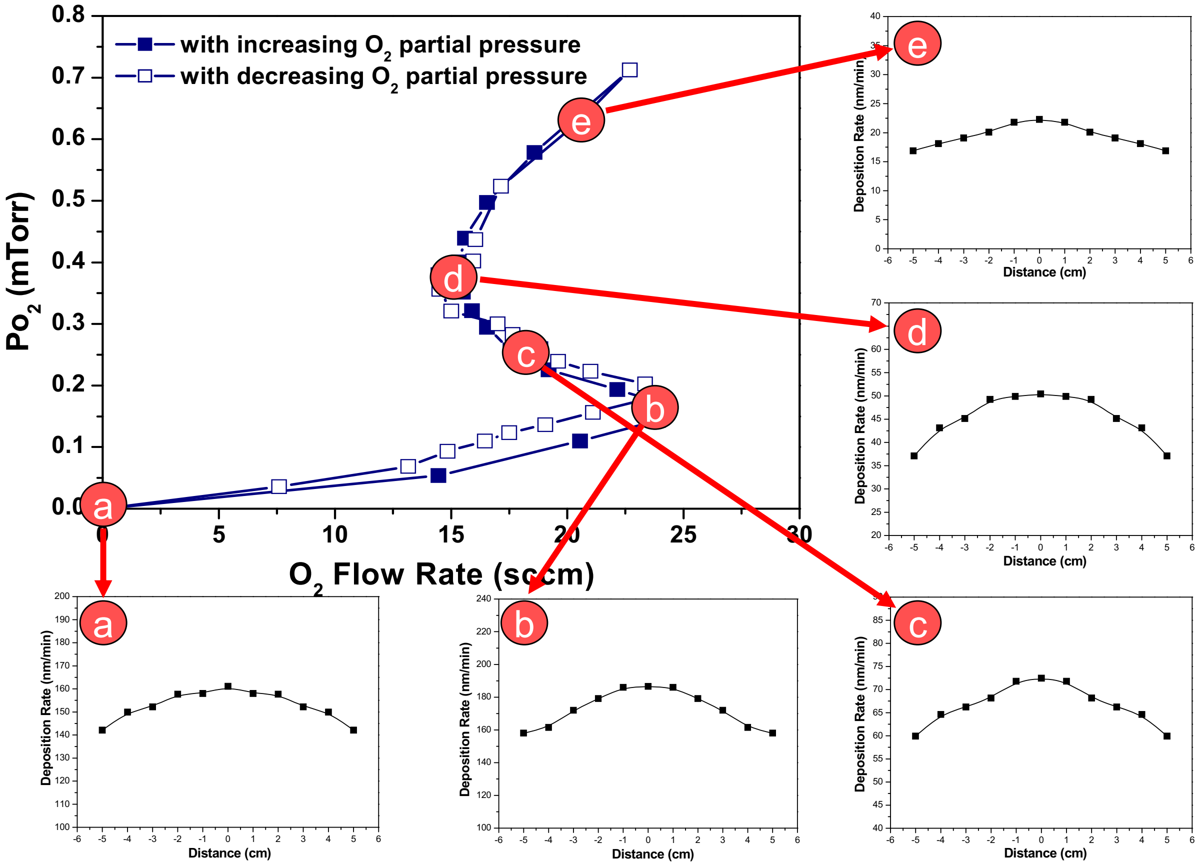
The Simulations of target current effects on poisoning & deposition rate







Film Uniformity as a function of S-Curve



Pulsed magnetron sputtering

in reactive magnetron sputtering

- **Pulsed reactive gas flow**

-. The reactive gas flow switches on & off periodically for short time

-. Not easy control of process

- **Pulsed DC magnetron**

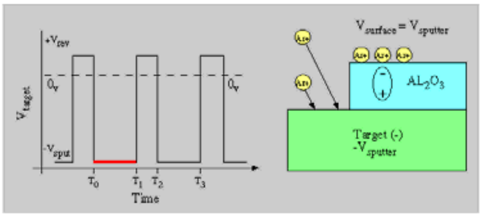
-. Unipolar and Bipolar pulsed DC

-. Single or Dual target system

-. Effective control of plasma density by modulation of duty ratio and frequency

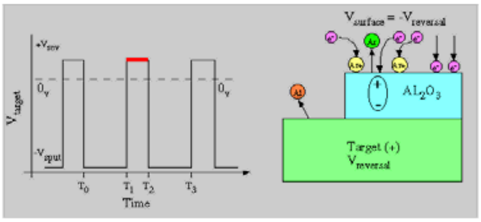
-. High rate reactive sputtering capability by bipolar pulsed DC

Normal sputter mode



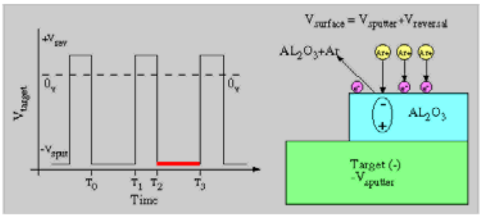
$V_{surface} = V_{sputter}$

Reversal mode



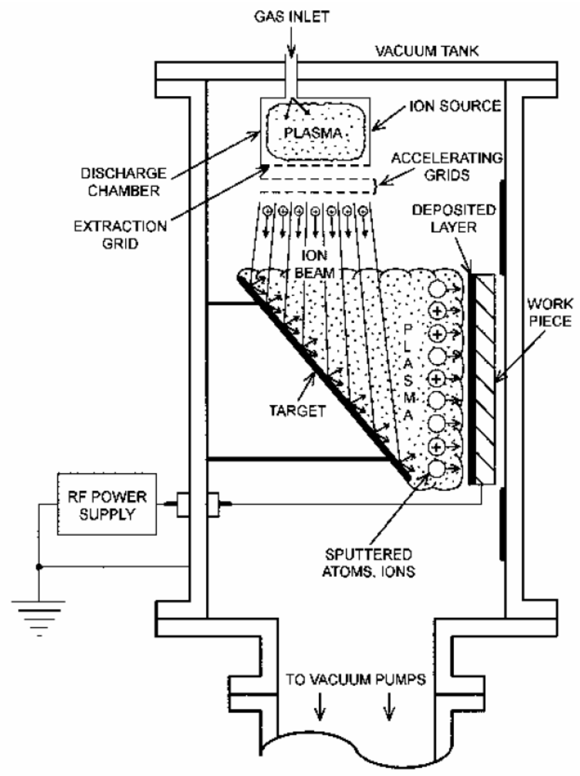
$V_{surface} = -V_{reversal}$

Return to sputter mode



$V_{surface} = V_{sputter} + V_{reversal}$

Ion beam sputtering process



➢ Advantages

- independent control of target current density and voltage
- low pressure operation (≤0.1 mTorr)

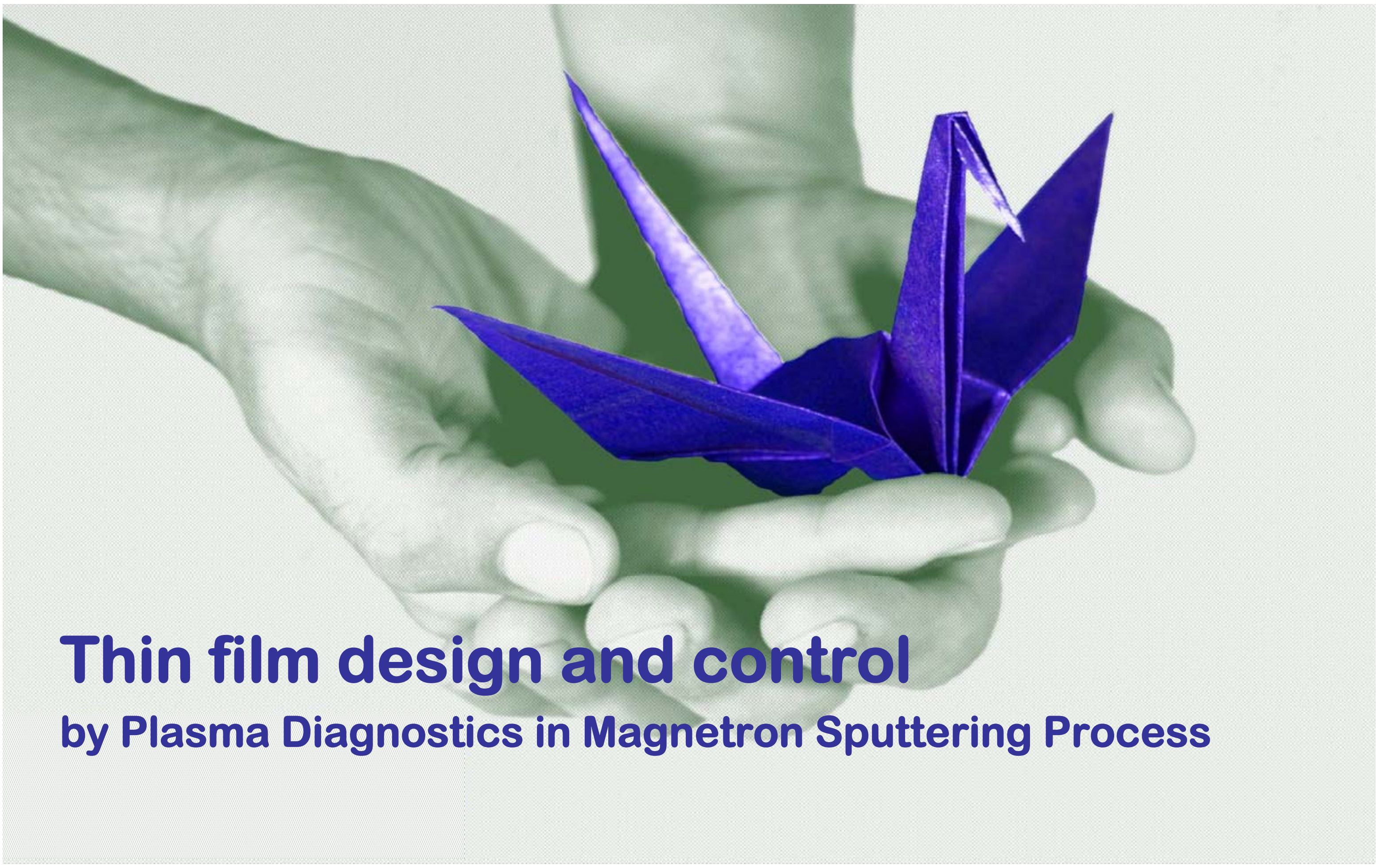
  and contamination can be reduced.
- the deposited atoms have high kinetic energy

  and thus high reactivity.
- negative ion effect (re-sputtering effect) can be avoided.
- sputtering of magnetic material target

➢ Disadvantages

- difficulty in large area deposition
- low sputtering rate (a few ~ several hundred Å/min)
- ion source is expensive.

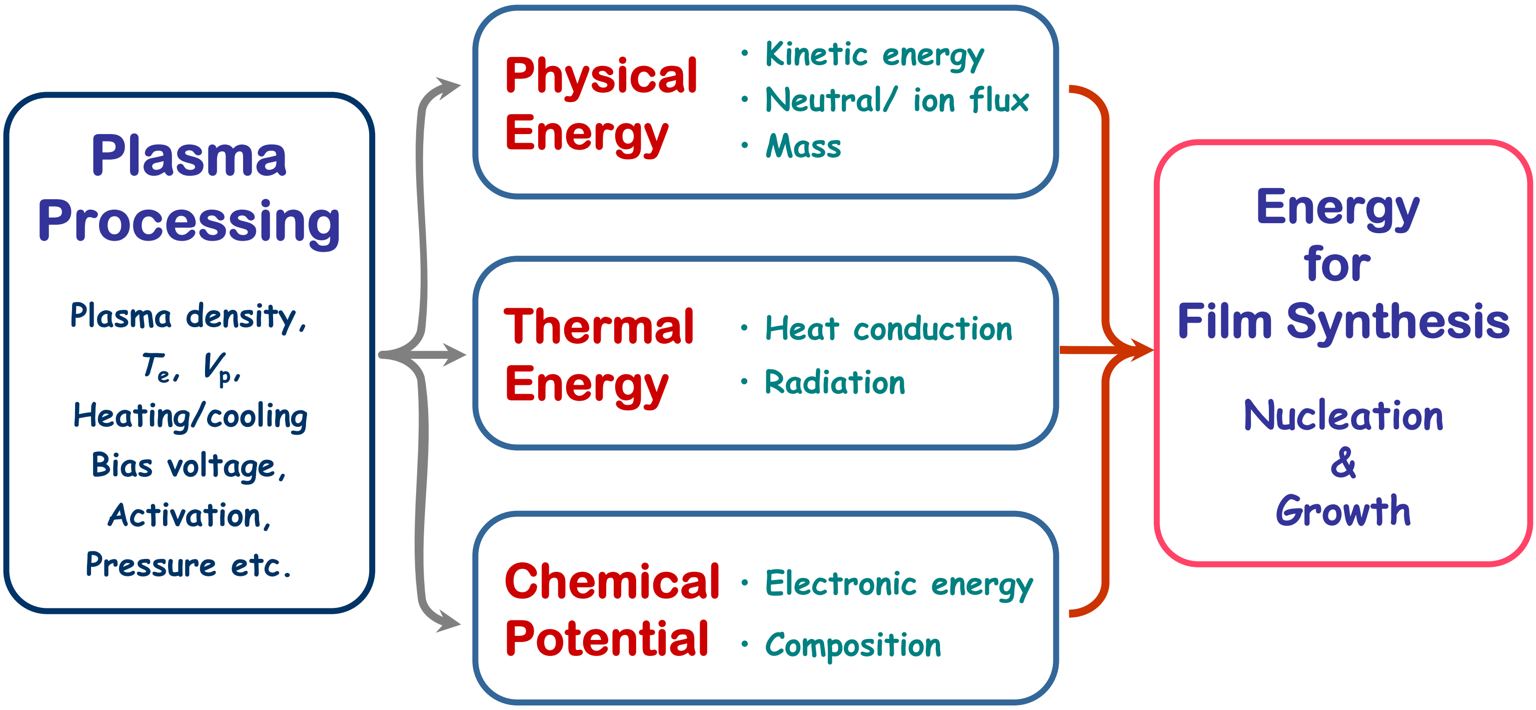
J. Roth - Industrial Plasma Engineering Volume 2 ; Applications To Nonthermal Plasma processing



Thin film design and control

by Plasma Diagnostics in Magnetron Sputtering Process

Design and Synthesis of Thin Film



Plasma Processing

Plasma density,
T_e, V_p,
Heating/cooling
Bias voltage,
Activation,
Pressure etc.

Physical Energy
- Kinetic energy
- Neutral/ ion flux
- Mass

Thermal Energy
- Heat conduction
- Radiation

Chemical Potential
- Electronic energy
- Composition

Energy for Film Synthesis

Nucleation
&
Growth

How to design and synthesize for functional film?

Design of Film Structure and Plasma Parameters for Film Synthesis

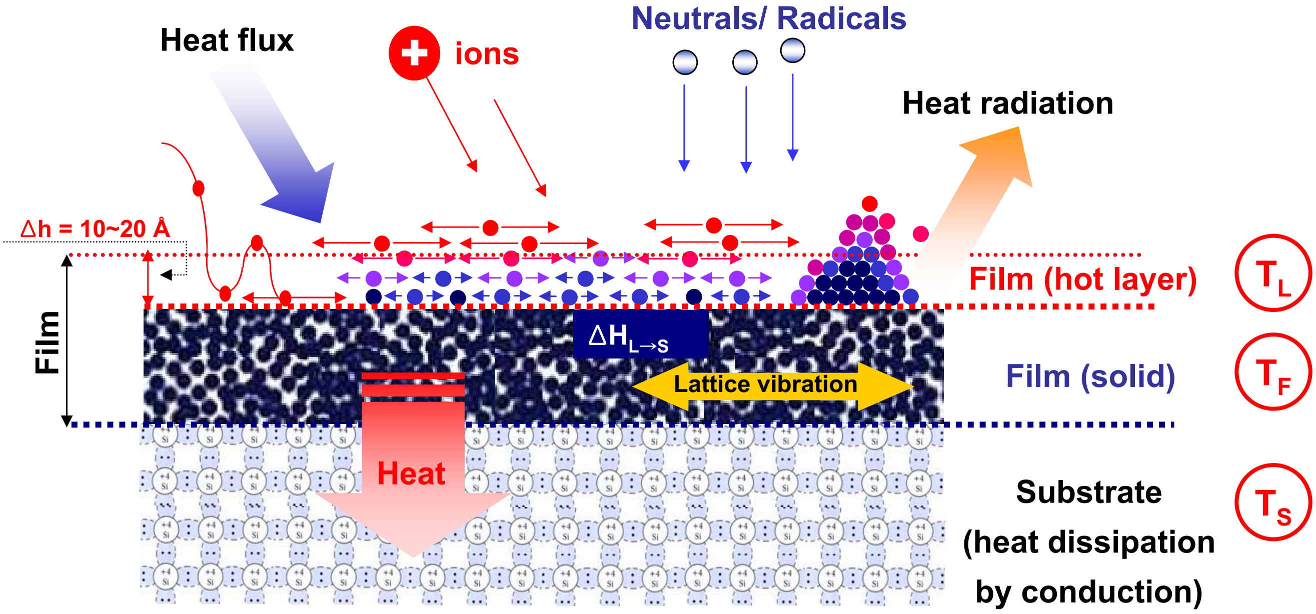
Design of film nucleation and growth

- Heat of formation (ΔH_f) for film materials
- Physical energy + Thermal energy + Chemical potential

Design and control of plasma parameters

- Plasma parameter design and processing
  - → Depositing energy control on surface
  - → Micro structure control
- Process design for film structure control

New film growth model in magnetron sputtering



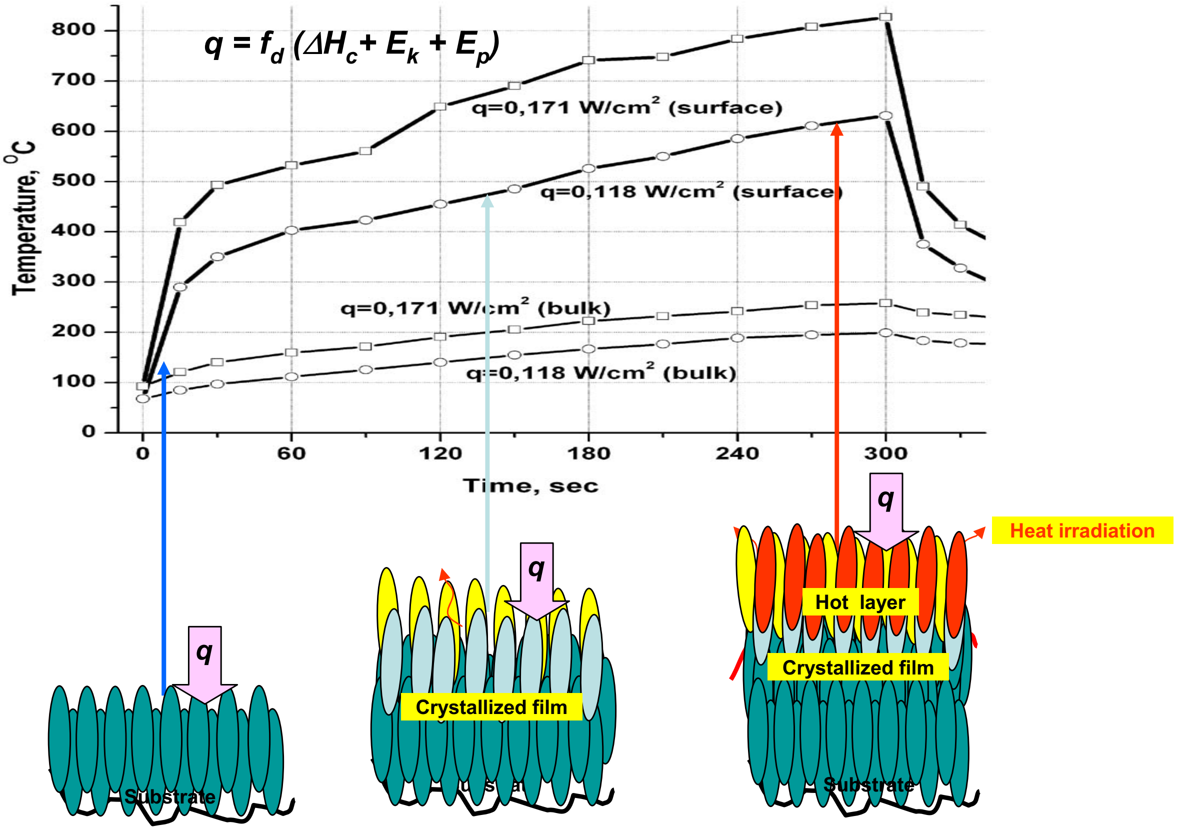
$T_L > T_F \approx T_S$

$\Delta T = T_F - T_L \approx q\,\Delta h$

J. G. Han, *et.al.*,
J. Vac. Sci. Technol., 24 (2006)

Model of the film growth

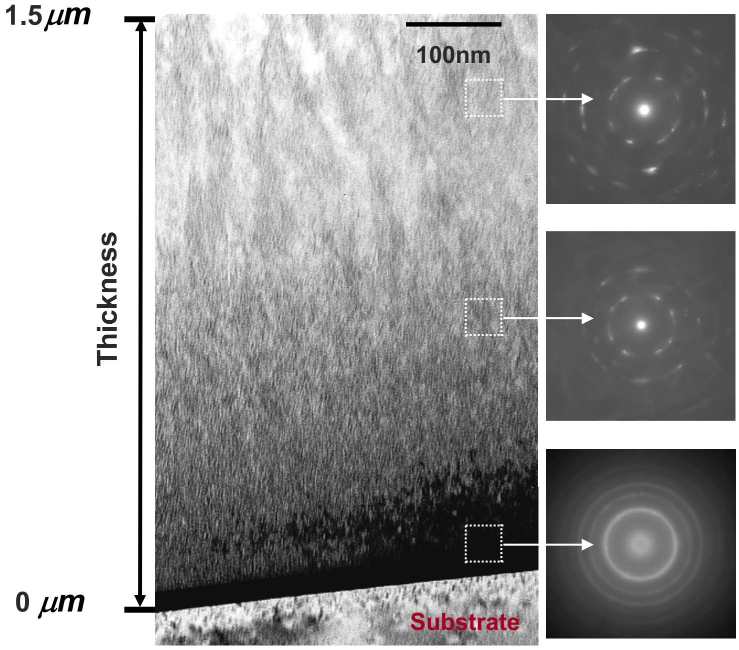
J. G. Han, *et.al.*,
J. Vac. Sci. Technol., 24 (2006)

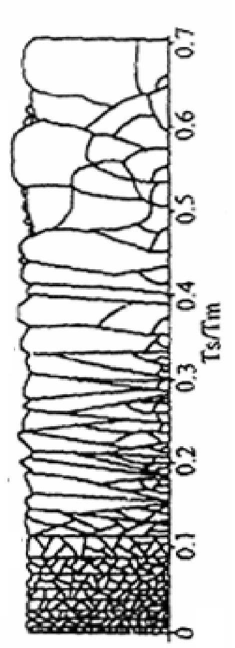


Film structure change during film growth

Kinetic energy of condensing atoms is ~8eV

$$T_l(x) = \frac{q}{k_a}(L-x) + T_s$$





800K

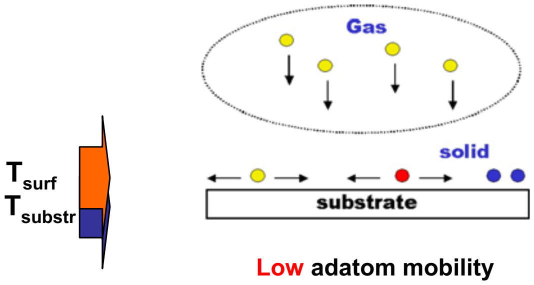
Increasing temp.

R.T

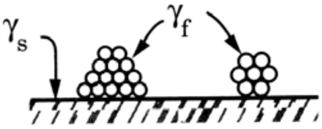
J. G. Han, *et.al.*,
Vacuum, 80 (2006)

Effect of physical energy and flux

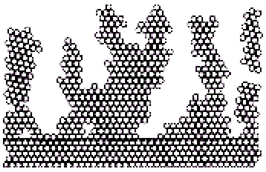
Low kinetic energy and flux (E_k ~ 0.1eV)



Low adatom mobility

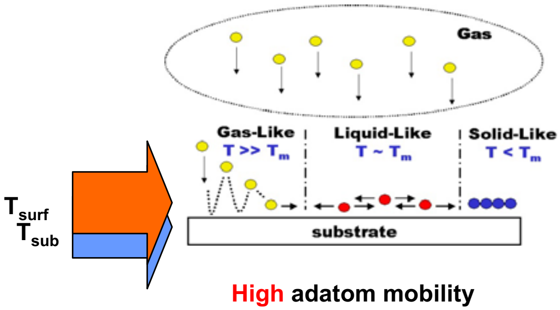


Island (Volmer-Weber) growth mode

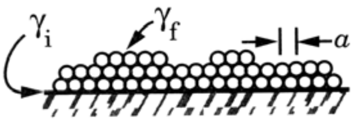


Columnar film structure

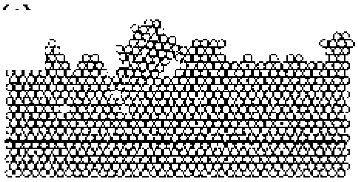
High kinetic energy and flux (E_k ~ 10eV)



High adatom mobility



Frank-van der Merve layer growth mode



Dense film structure

Plasma diagnostics

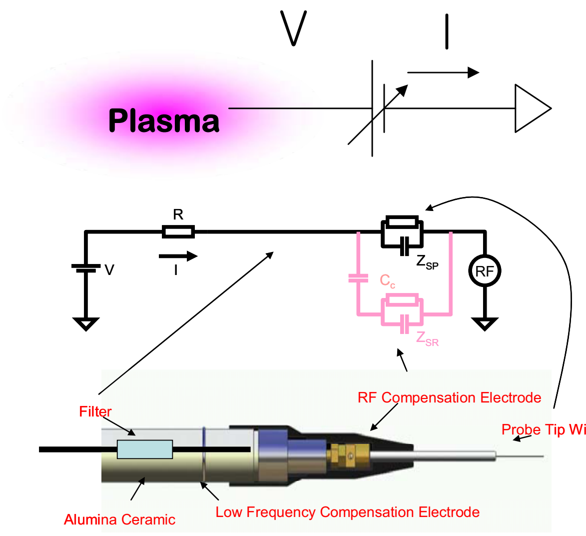
of processing plasma during magnetron sputtering

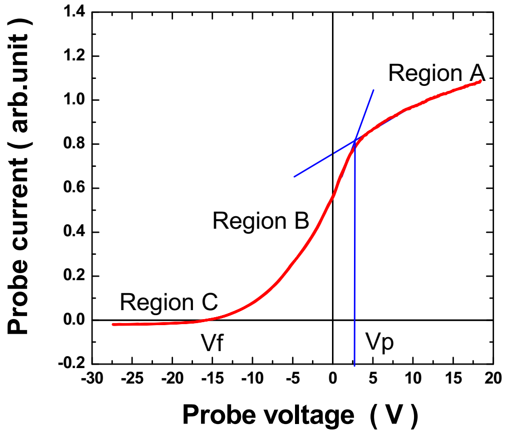
Plasma diagnostics tools:

- ❑ Langmuir probe
  - electron temperature(Te), electron density
- ❑ Fabry-Perot Confocal Interferometry
  - energy of neutral particles
- ❑ Laser Induced Fluorescence (LIF)
  - neutral and ion density
- ❑ Optical emission spectroscopy
  - radical and ion species
- ❑ Time resolved OES with high resolution CCD
  - neutrals, radicals and ions distribution

Plasma diagnostics

Electrostatic probe (Langmuir probe)





Region A : Electron saturation region
Region B : Transition region
Region C : Ion saturation region

$$I = I_{es}\exp\left(\frac{V-V_p}{T_e}\right) - I_{is}$$

➢ Measurement of plasma parameters

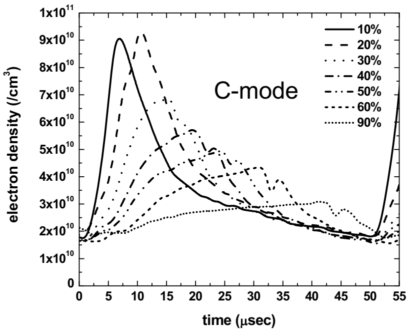
- **Plasma density**
- **Plasma potential**
- **Electron temperature**
- **EEDF(Electron Energy Distribution Function)**

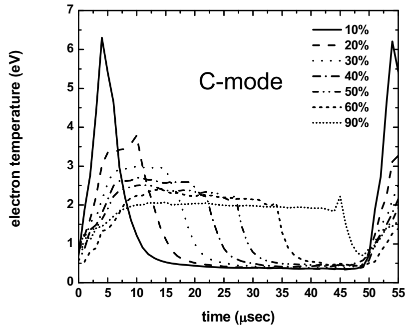
Plasma diagnostics

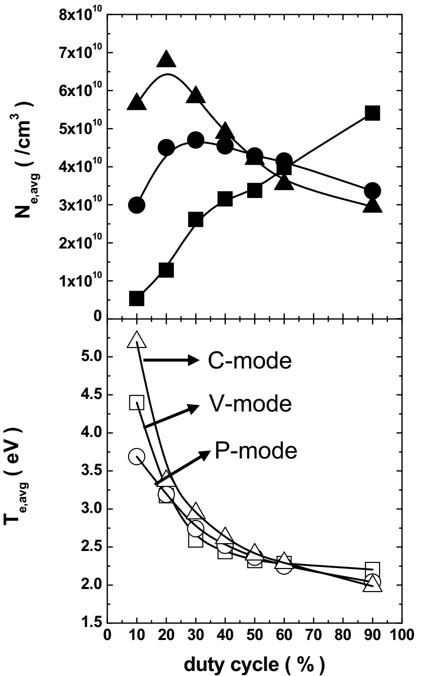
Electrostatic probe (Langmuir probe)

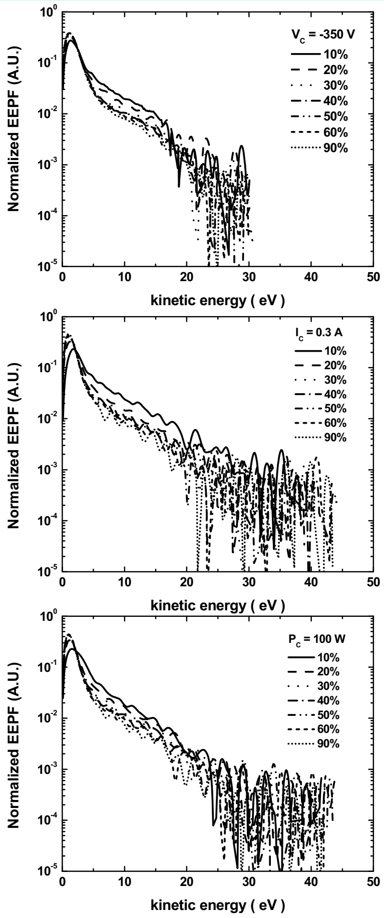
➢ N_e and T_e vs duty cycle in pulsed DC magnetron discharge

Time-resolved probe measurement









Plasma diagnostics

Fabry-Perot Confocal Interferometer

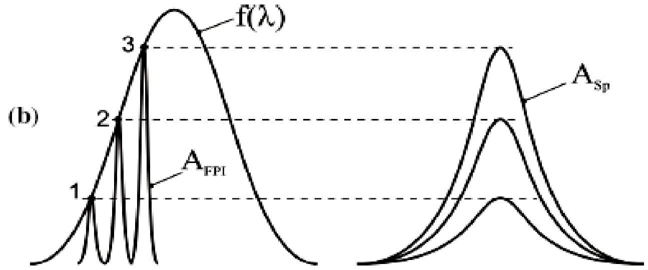
FPI principle

Signal after FPI: $g(\lambda) = \int d\lambda' A(\lambda - \lambda') f(\lambda')$

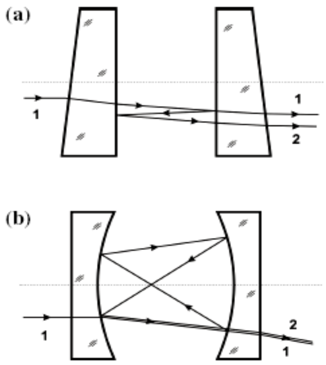
Signal after FPI and spectrometer: $h(\lambda) = \int d\lambda' A_{Sp}(\lambda - \lambda') \int d\lambda'' A_{FPI}(\lambda' - \lambda'') f(\lambda'')$

Combination of a FPI and a spectrometer:

Output intensity for 3 mirror positions:



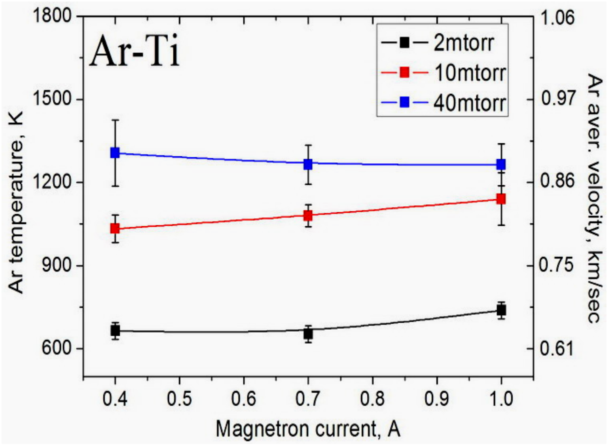
Planar FPI vs. confocal FPI



FPI was combined with an spectrometer to provide a high spectral resolution along with dispersive element.
In a process of FPI mirror movement the different parts of a plasma emission line can be transmitted. In this case a FPI works like a tunable band pass filter with extremely narrow band.

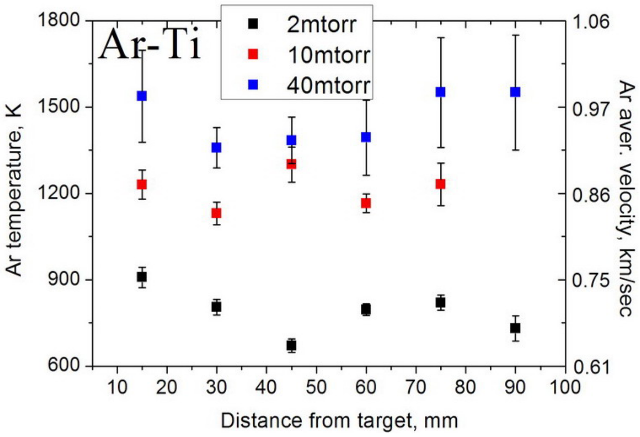
Ar Temperature : power and distance effects

Distance from target = 3cm, 750.4 nm Ar line



Typical Ar temperature measured by FPI illustrates that Ar temperature does not depend much on the magnetron current, ***but strongly depend on the working pressure** in the reactor.*(Data for Ar-Cu, Ar-Cr and Ar-Ti magnetron discharges)

Magnetron current = 0.7A 750.4 nm Ar line



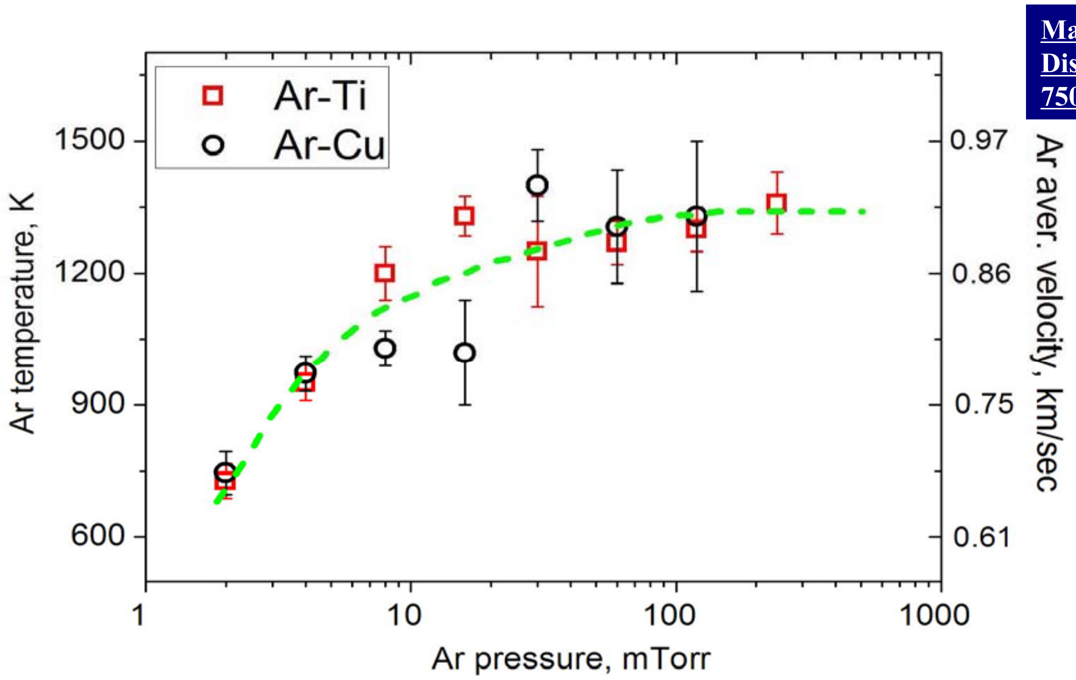
The distance effect on the Ar temperature is minimal (Data for Ar-Cu, Ar-Cr and Ar-Ti magnetron discharges)

J. G. Han, *et.al.*,
Plasma Source Sci. Technol., 15 (2006)

Ar lines: pressure effect*

FPI Ar temperature measurements in an extended working pressure range show the saturation of the temperature after approx. 20 mtorr of pressure. This data was verified by adding 5% of nitrogen into the discharge (see next slide).

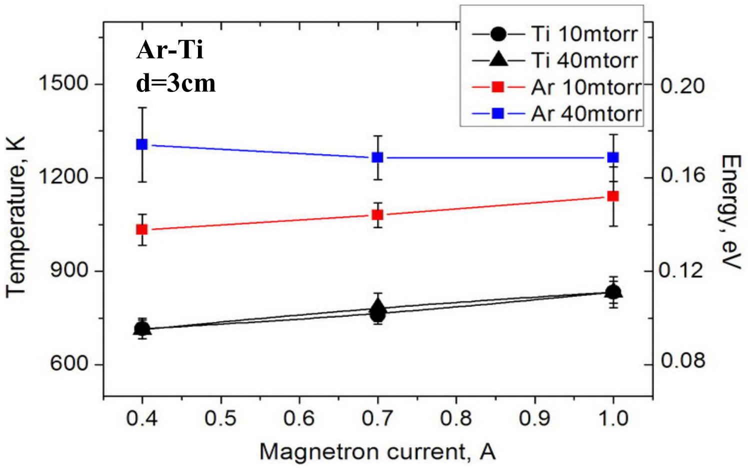
Magnetron current = 0.7A
Distance from target = 3cm
750.4 nm Ar line



J. G. Han *et al.*,
J. Phys.D: Appl. Phys. *Submitted*

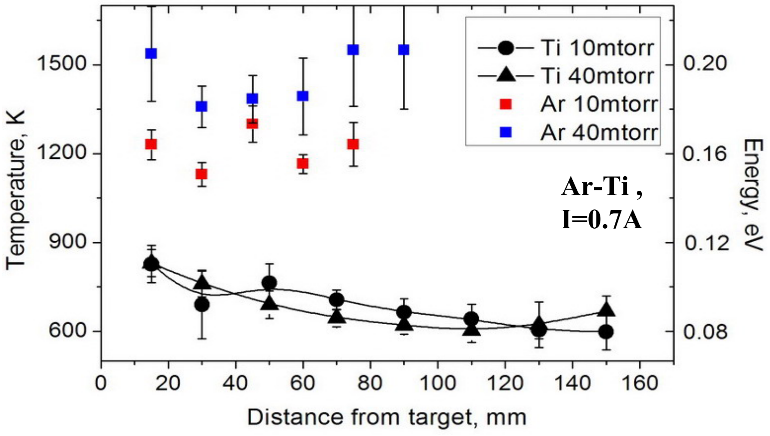
Ti vs. Ar temperature

J. G. Han *et al.*,
J. Phys.D: Appl. Phys. *Submitted*



Here a comparison between Ar and Ti (thermalized) temperatures measured by FPI is presented.

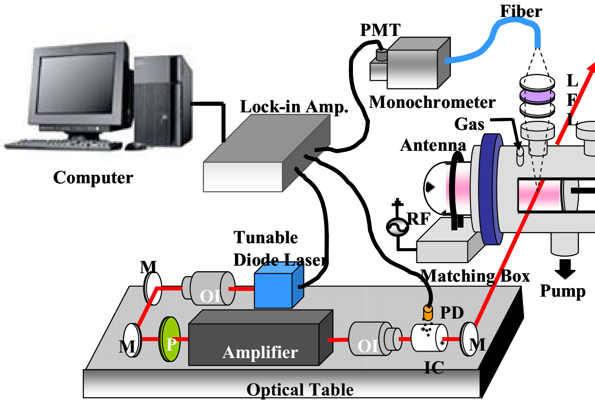
The strong difference between Ar and Ti temperatures can be seen.
The average kinetic energy of thermalized Ti is about 0.1 eV, whereas for Ar it is above 0.15 eV.



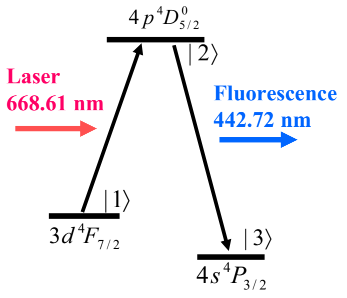
Plasma diagnostics
Laser induced fluorescence (LIF)

This technique employs a laser (usually tunable dye laser) to excite a resonance between a lower state (in most instances a single rotational level or group of rotation levels) ans a level in an excited electronic state.

➢Setup



M : Mirror
L : Lens
F : Filter
P : Polarizer
OI : Optical Isolater
IC : Iodine Cell
PD : Photodiode



<Argon ion metastable>

$$\boxed{I_{LIF} \propto I_{Laser} n_1}$$

I_{LIF} : Intensity of LIF
K : Factor
I_{Laser} : Intensity of Laser beam
n_1 : Ion metastable state density
B_{12} : Einstein absorption coefficients
A_{23}, A_{2n} : Einstein coefficients for spontaneous emission
Q_2 : Collisional depopulation of $|2\rangle$

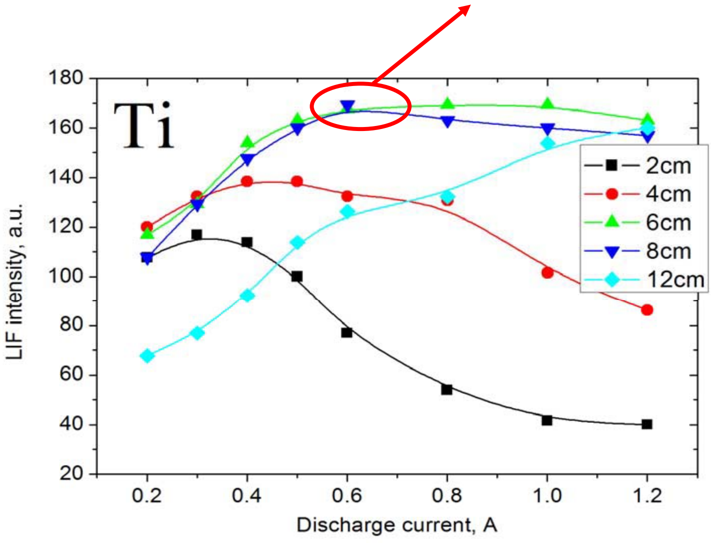
➢Applications of LIF

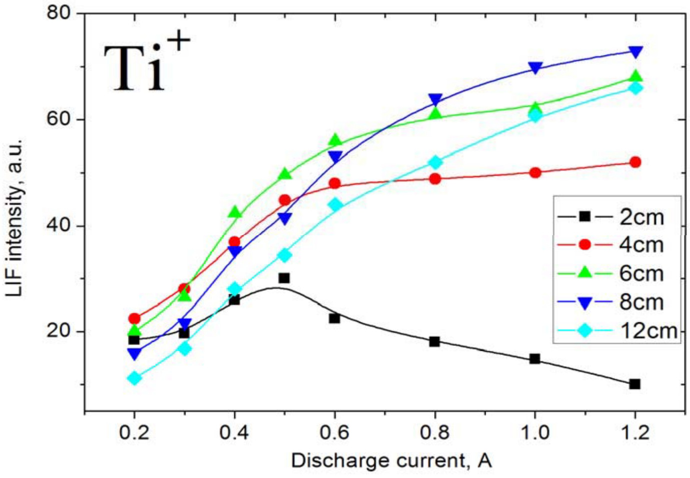
- **Distribution Function :** $f(\vec{x}, \vec{v}, t)$, $f(\vec{x}, \vec{v})$, $f(\vec{v})$
  - **Relative Density, Drift Velocity, Temperature, etc.**
  - **D_{vv}, C_v : Velocity-Space Diffusion & Convection (Fokker-Planck coefficients)**
  - **Electric Field (Stark Effect)**
  - **Magnetic Field (Zeeman Effect)**
  - **Neutral density and temperature measurement**
  - **ion density and temperature measurement**

Plasma diagnostics
Laser induced fluorescence (LIF)

Ti and Ti⁺ density

[Ti] = 2×10^{11} cm^{-3} (OAS data*)



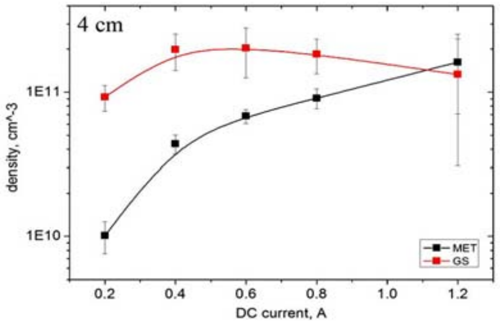


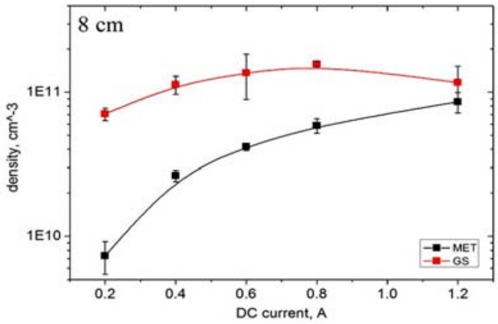
Working pressure = 4 mtorr

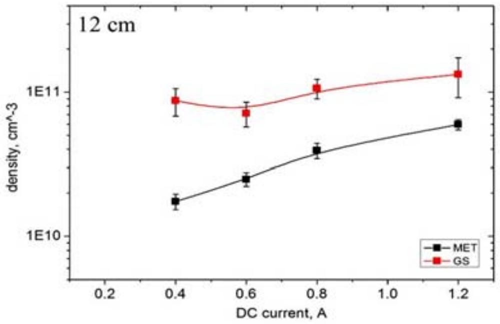
* [N. Britun et al, *Ar-Ti Magnetron Discharge Characterization Using Optical Absorption Spectroscopy,* Metals and Materials International, *In Press*.]

Ti density by OAS*

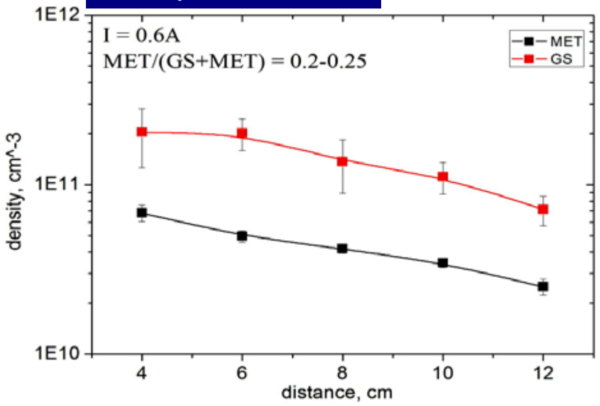
Working pressure = 4 mtorr







Density distance effect



MET – Density of metastables
GS - Density of ground states

J. G. Han, et al.
Metals and Materials International, *In Press*.

Plasma diagnostics

Optical emission spectroscopy (OES)

PLASMA ⇔ mixture of gas species, containing: electrons, ions, molecules, atoms, reactive species

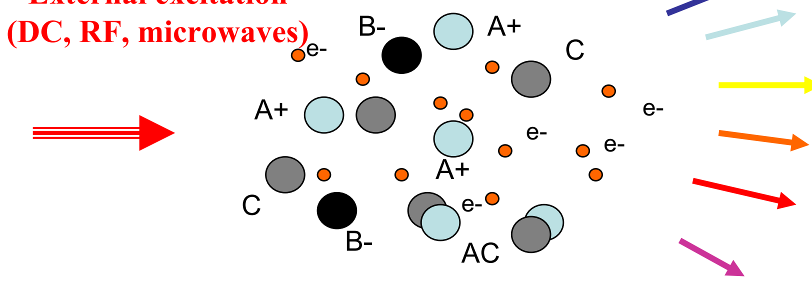
After species collisions:
⇒ *species relaxation*
⇒ *energy released*
⇒ ***Light Emission***

at λ characteristics of physical phenomena inside plasma

Spectral Analysis

OES system

External excitation (DC, RF, microwaves)

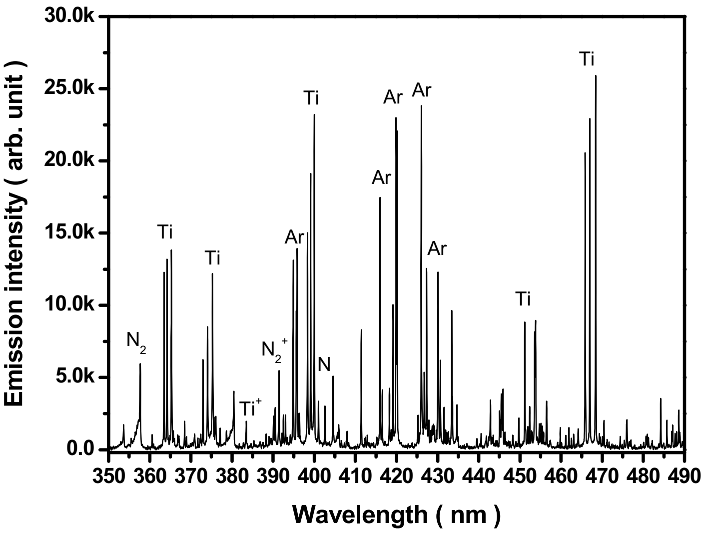


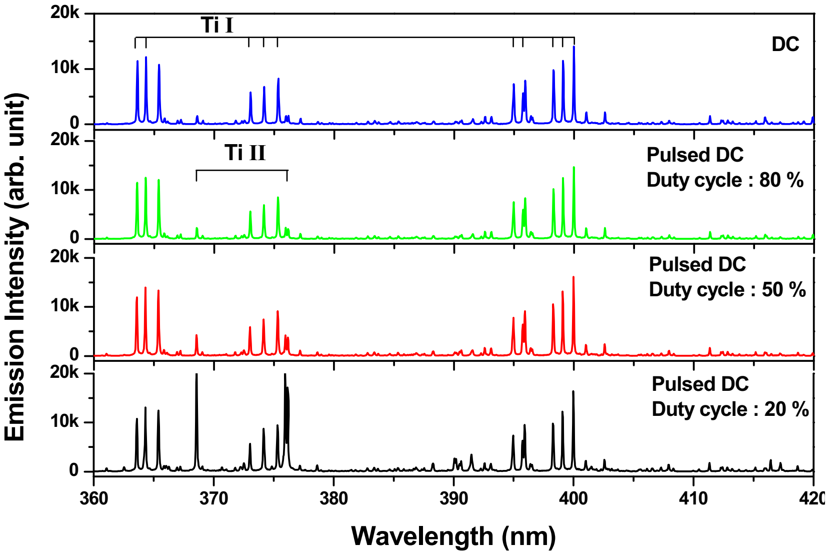
OES: - a non-intrusive plasma diagnostic,
- *simple,*
- *has good sensitivity,*
- *inexpensive.*

☞ ***OES infos:***
- *on gas species in presence,*
- *on their relative concentrations,*
- *appearance or disappearance of species during etching process*

Plasma diagnostics
Optical emission spectroscopy (OES)

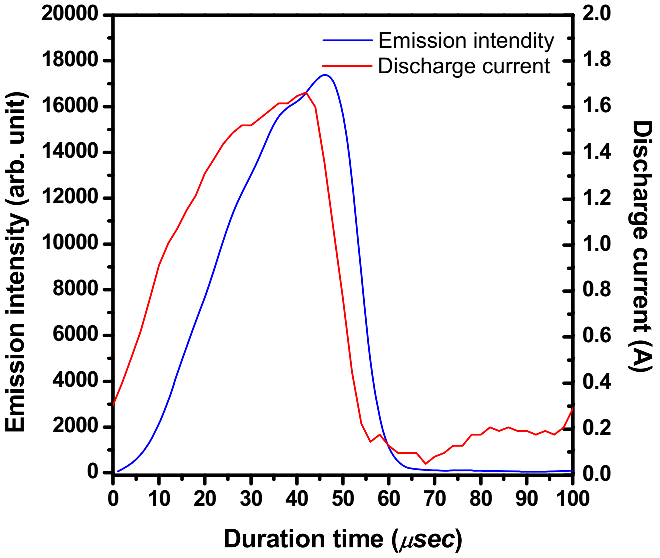
➢ Typical emission spectrum in pulsed magnetron sputtering discharge during TiN deposition

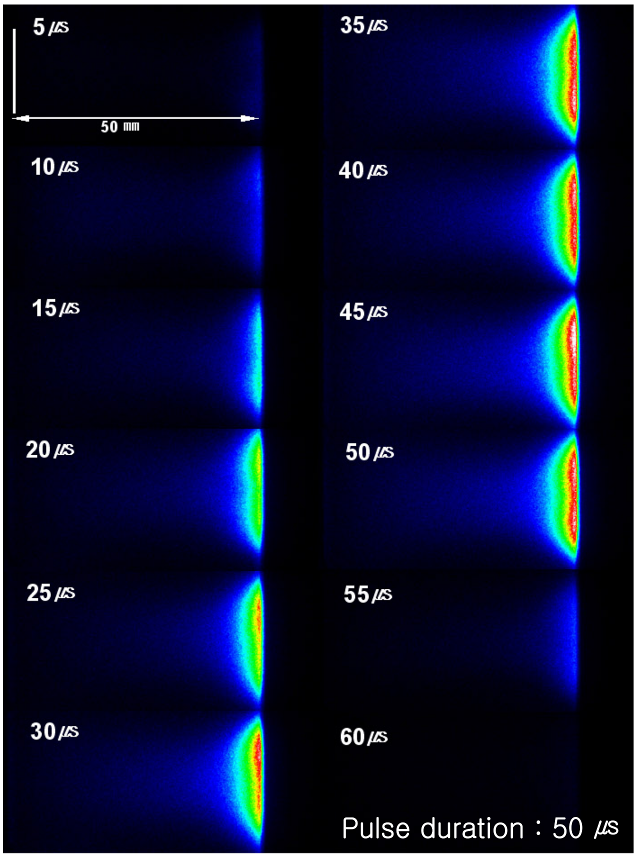


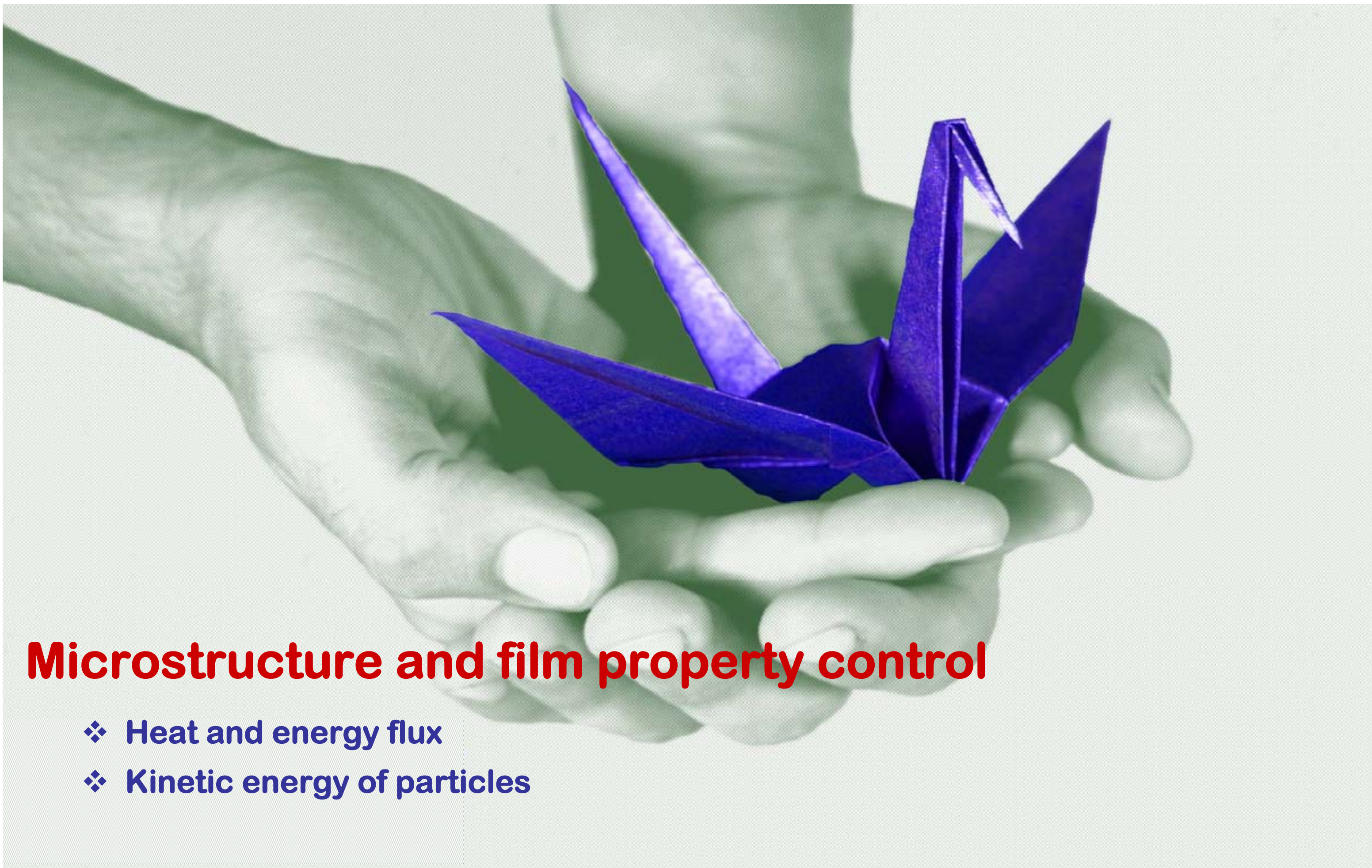


Plasma diagnostics
Optical emission spectroscopy (OES)

Optical Emission Image of Ar ion in pulsed Magnetron discharge



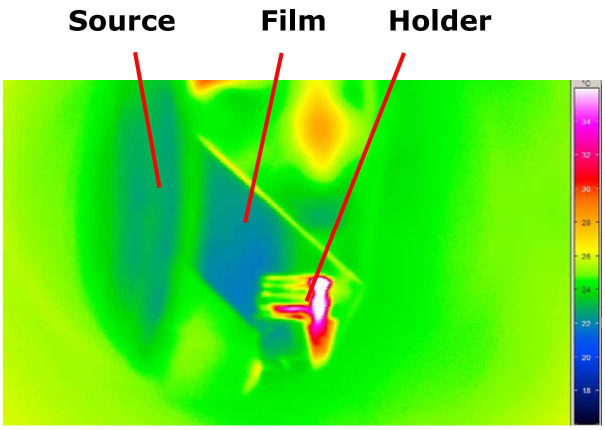


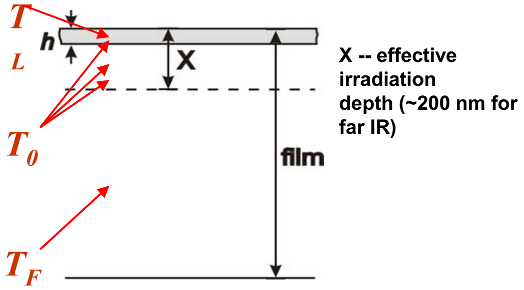


Microstructure and film property control

- Heat and energy flux
- Kinetic energy of particles

Schematic of Substrate Temperature Measurement System using IR Camera





$X = \lambda_0 / 4\pi\kappa$

$\lambda_0 - wavelength$

$\kappa - extinction\ \ coefficien\ t\,(\kappa = 3-5\ for\ metals\ )$

$we\ \ assumed\ \ \varepsilon_L(T) = 3\,\varepsilon_F(T)$

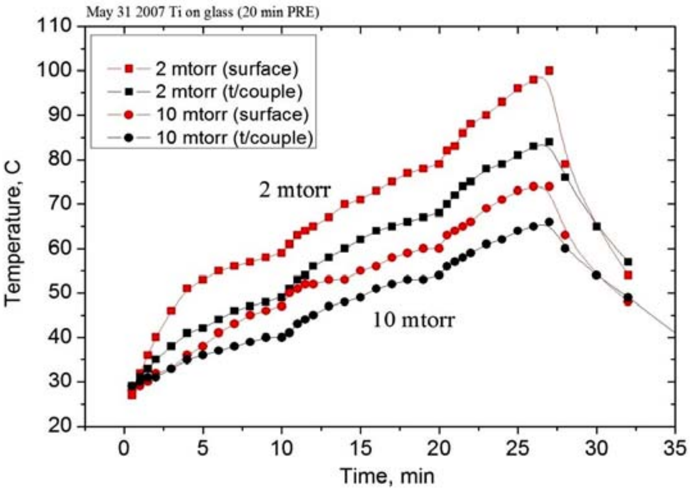
$$P_{\Sigma}(T) = \underbrace{\varepsilon_0 P(T_0)}_{\text{film surface}} + \underbrace{(1-\varepsilon_0)\varepsilon_T P(T_T)}_{\text{target}} + \underbrace{\varepsilon_{eff.} P(T_{eff.})}_{\text{ambient objects}} + \ldots$$

$$where\ \ P(T) = \int_{\lambda 1}^{\lambda 2} I(\lambda, T)\, d\lambda$$

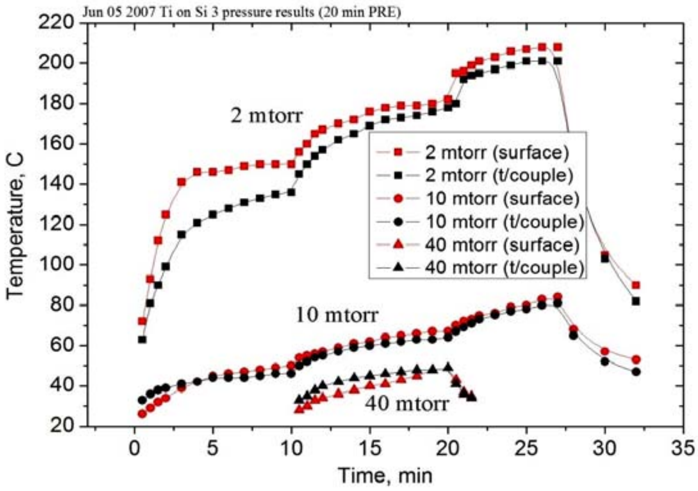
Surface temperature measurement

Depositions done on glass and Si substrates without additional cooling (at 3 different magnetron currents):

Ti on Glass



Ti on Si

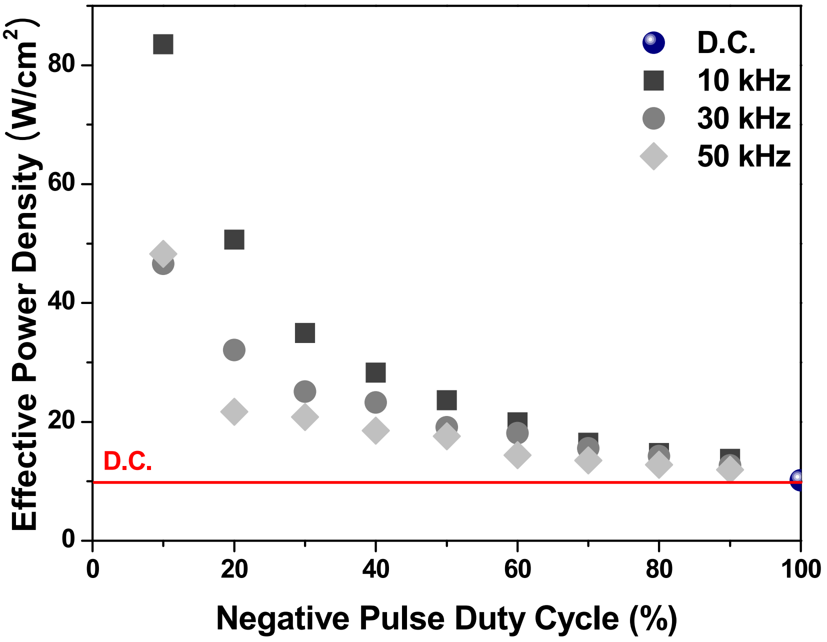


In case of thin substrates without cooling the temperature difference is less than that in the case of cooling substrate but both substrate and surface temperatures cab be much higher .

Effective power density evaluation

in pulsed magnetron discharge

B.P : $3*10^{-5}$ torr
W.P : $3*10^{-3}$ torr
d_{t-s} : 8 cm
Input Power Density : 10.1 W/cm^2



- **Effective power density ; P_{dA}**

τ : variable duration of the voltage pulse (= t_1)

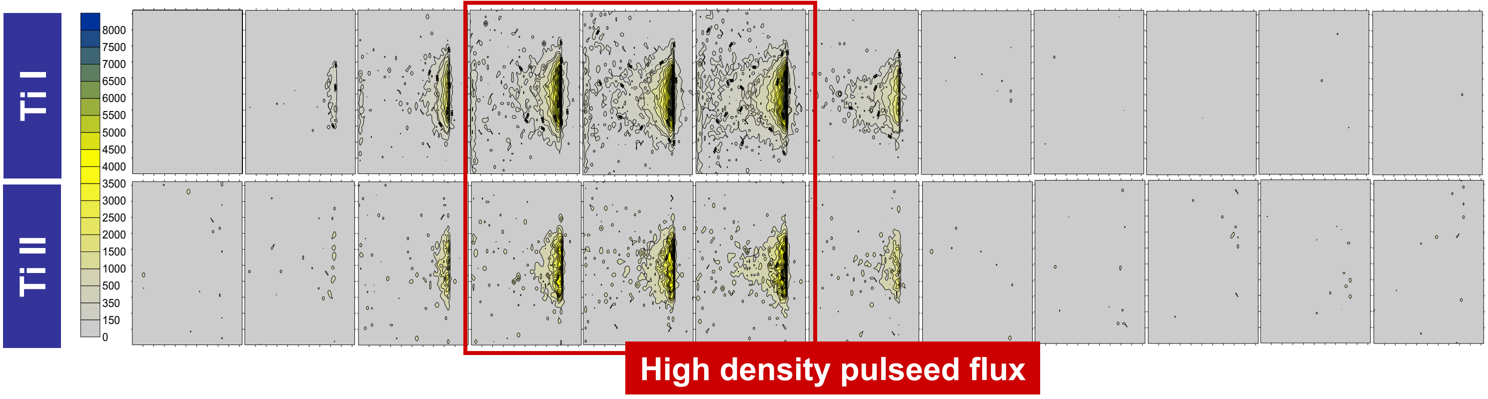
$$P_{dA} = \frac{1}{\tau}\int_0^{\tau} P_d(t)dt$$

Neutral and ion flux with pulse duty cycle

B.P : $3*10^{-5}$ torr
W.P : $3*10^{-3}$ torr
d_{t-s} : 8 cm
Input Power Density : 10.1 W/cm^2

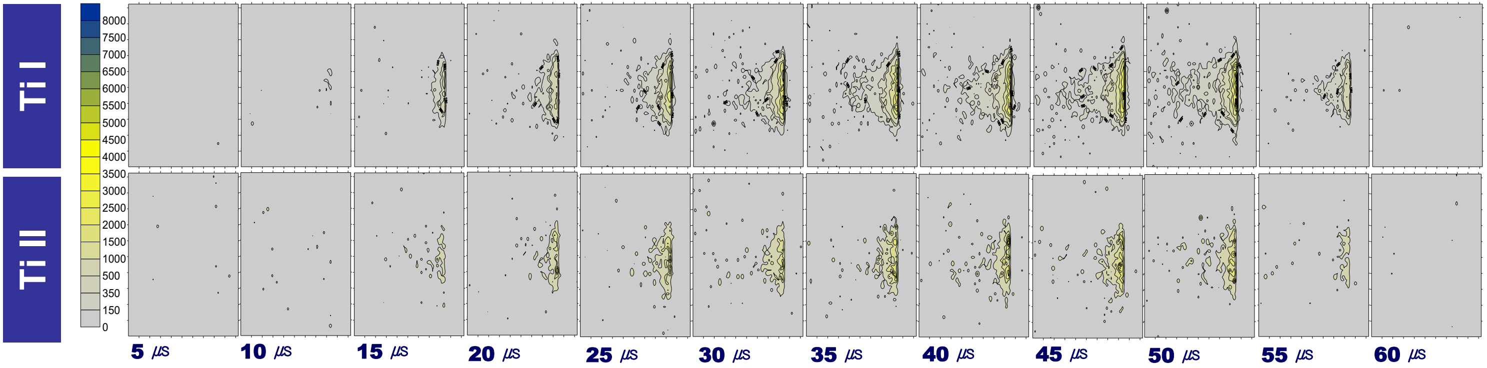
J. G. Han *et al.*,
Thin Solid Films, 475 (2004)

- Pulse duty cycle : 30 %



High density pulseed flux

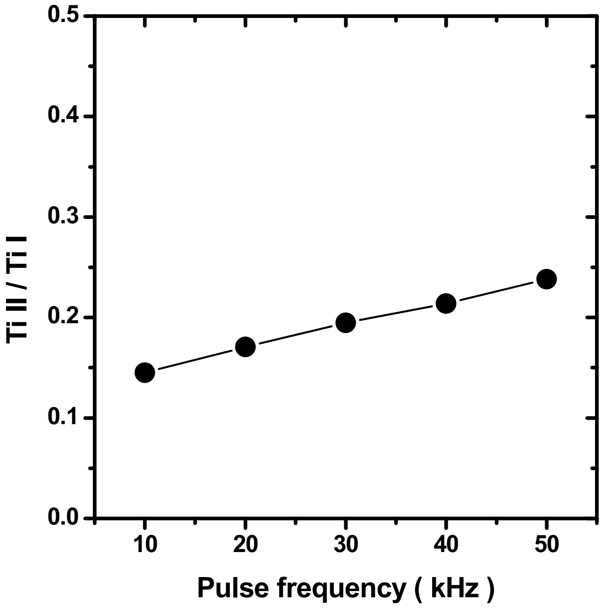
- Pulse duty cycle : 50 %

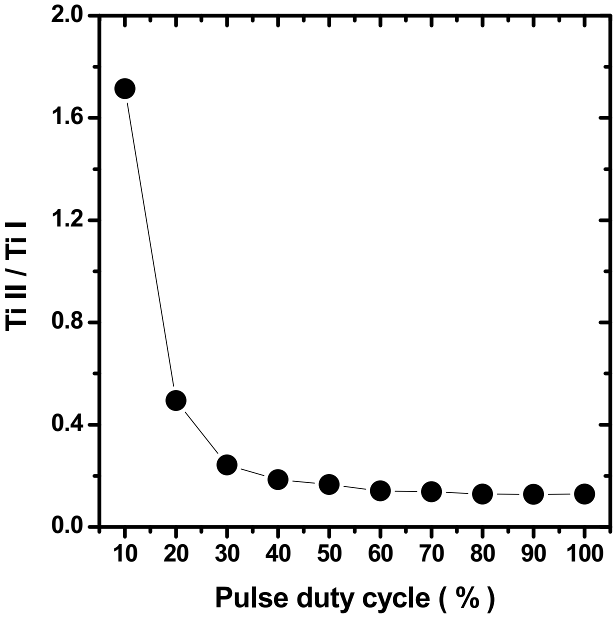


Ion to neutral ratio of Ti

with various pulse parameter

J. G. Han *et al.*,
Thin Solid Films, 475 (2004)





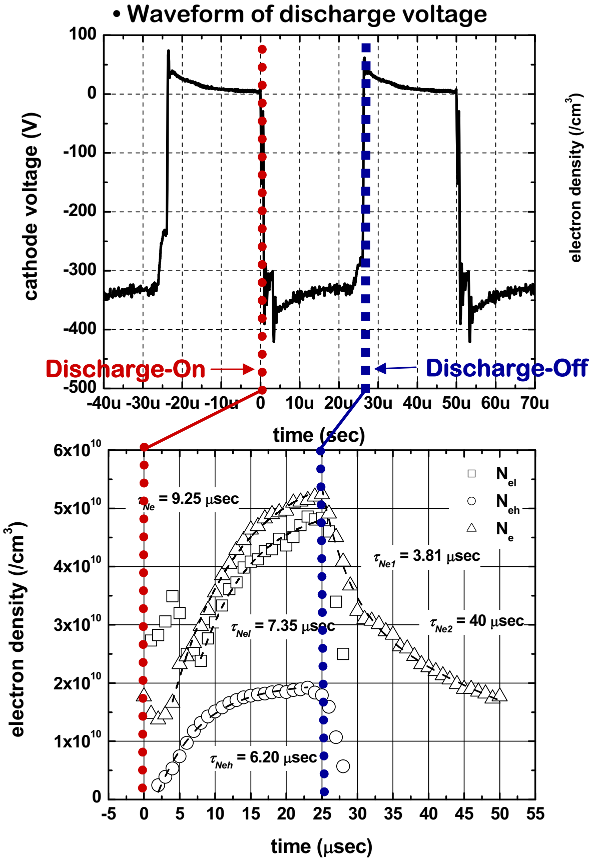
Higher frequency
Lower duty cycle

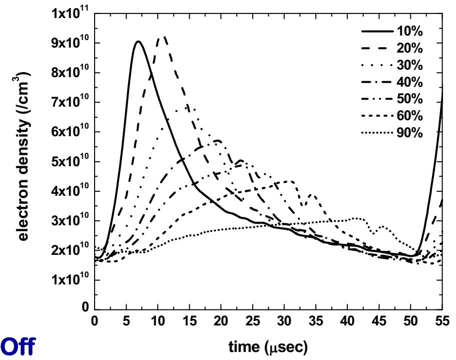
Increase effective power
in the same average power

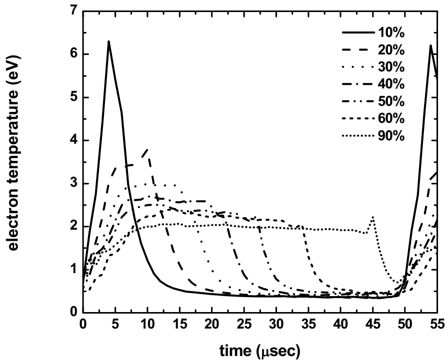
Higher ionization

Time resolved electron density in pulsed plasma

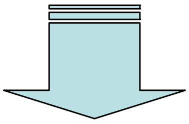
• Waveform of discharge voltage







Lower pulse duty cycle



High electron temp. and density

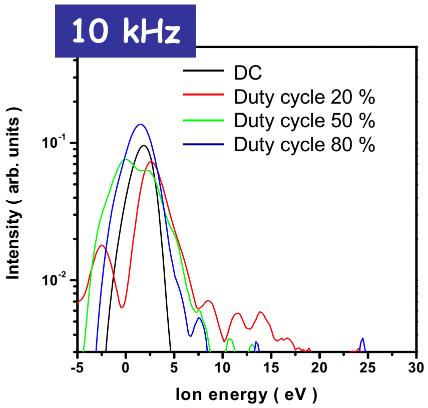
S. H. Seo *et al.*,
Plasma Source Sci. Technol., 15 (2006)

20 kHz, 50% duty cycle, 1 μs time resolution

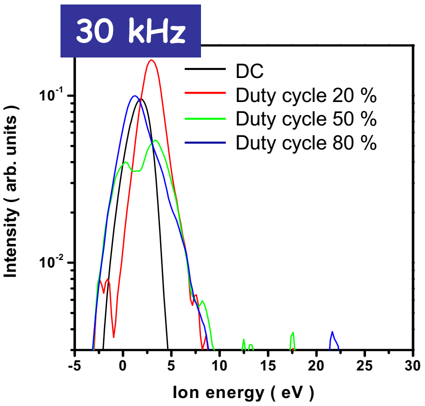
Ion Energy Distribution
with various pulse parameters

J. G. Han *et al.*,
Surf. Coat. Technol., 200 (2005)

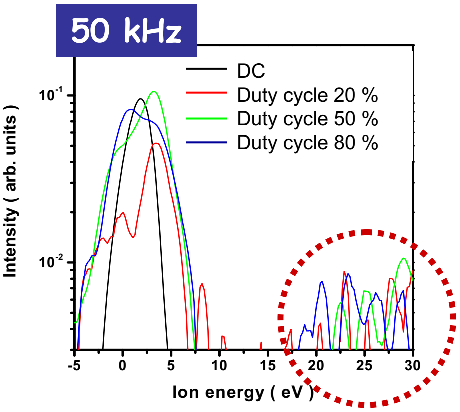
10 kHz



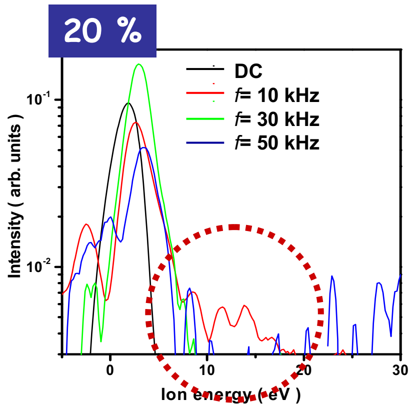
30 kHz



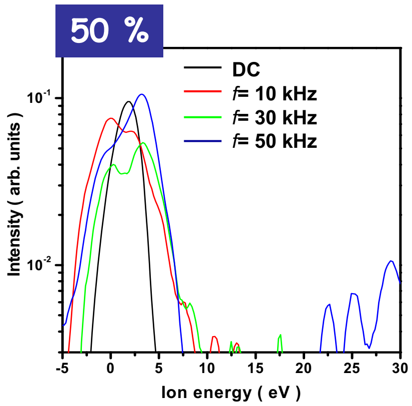
50 kHz



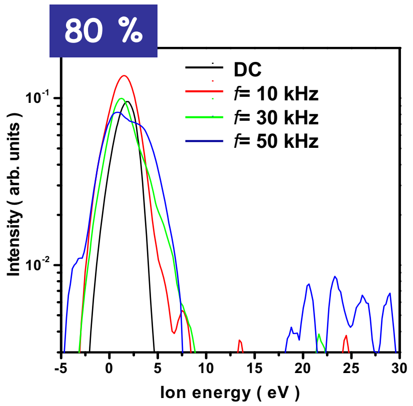
20 %



50 %



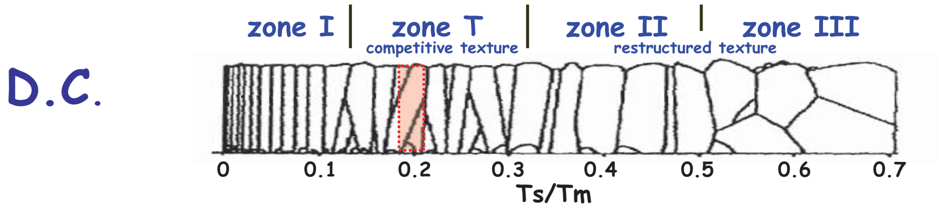
80 %

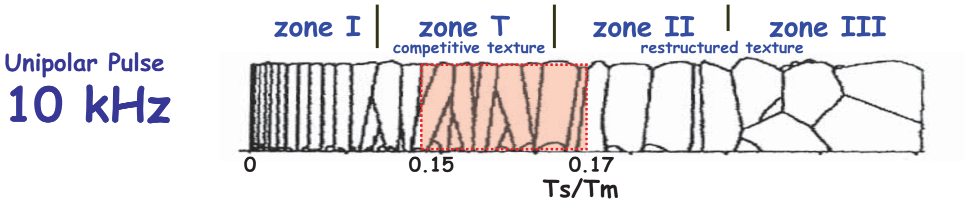


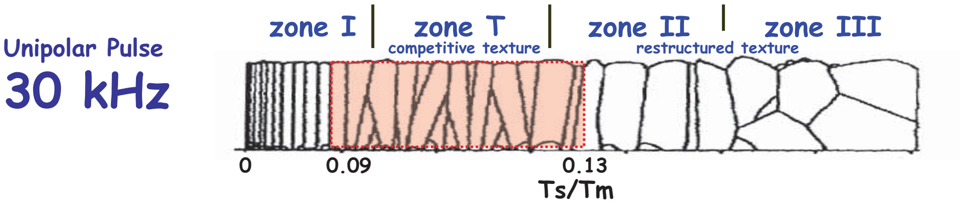
Modified Thin Film Model

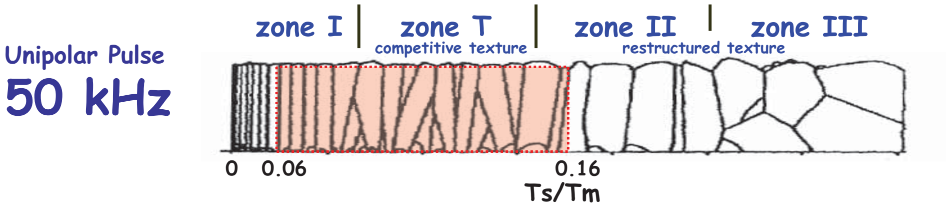
Ts : Film Surface Temperature

Tm : Film Melting Temperature









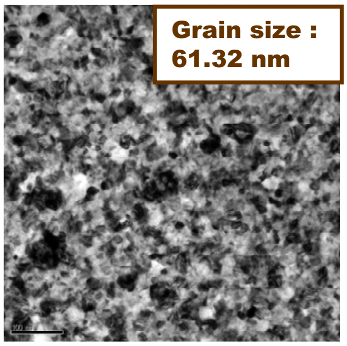
J. G. Han, *et.al.*,
Thin Solid Films, 400 (2006)

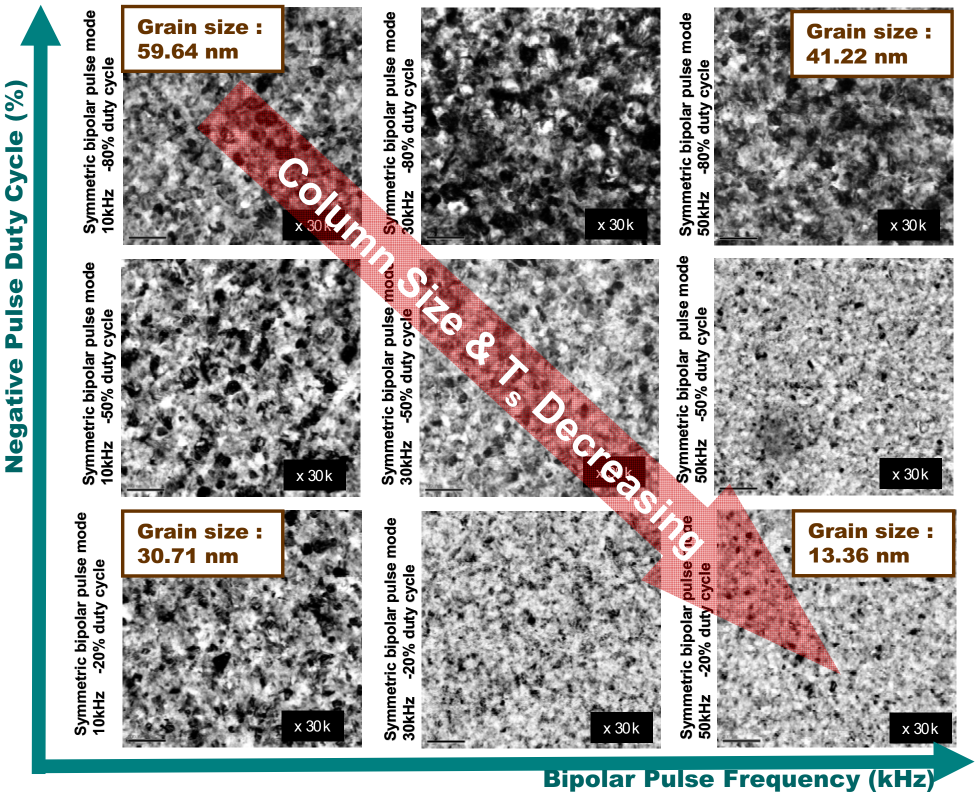
Microstructure Variations
with Pulse Parameters

Sym-Bipolar Pulse

Film Thickness :
150 nm

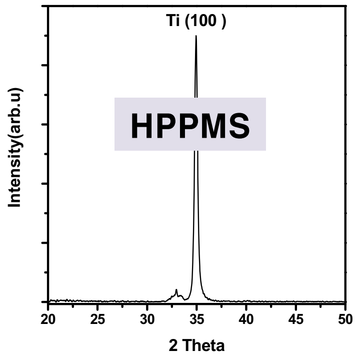
DC mode



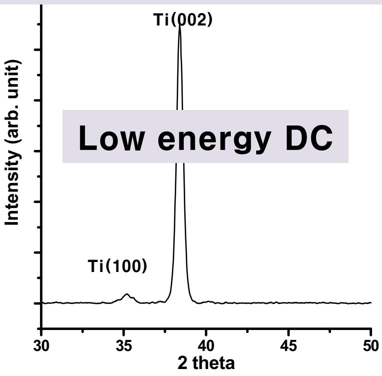


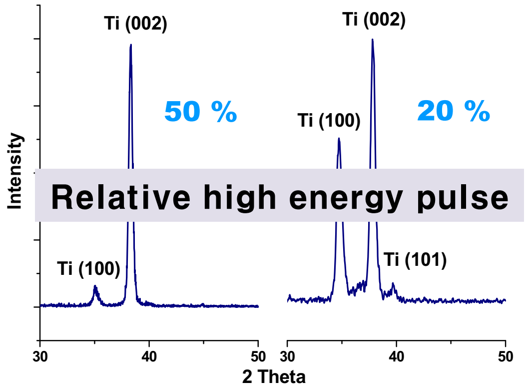
Microstructure change by energy and heat flux

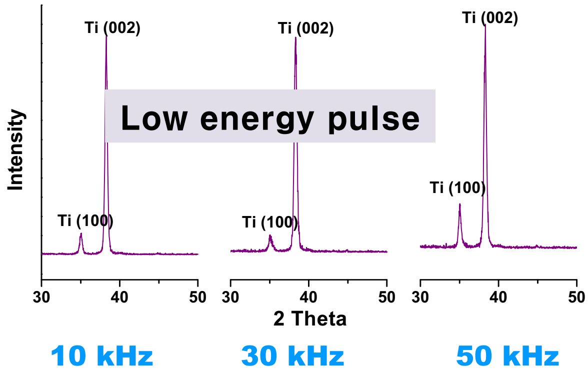
- High ionization of metal atoms
- High ion energy



- Low ion flux & energy
- relative high temperature in DC MS

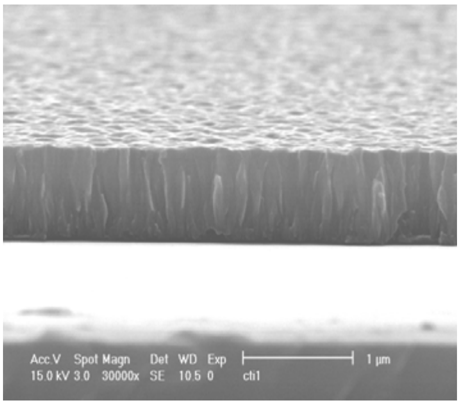




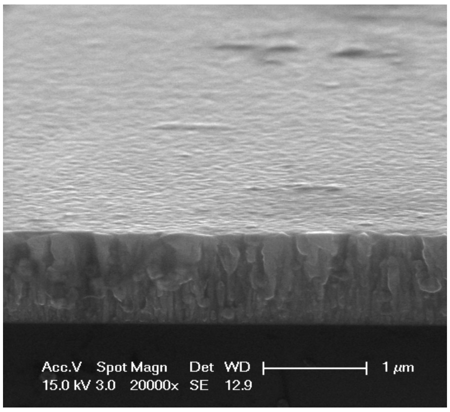


Typical control of film structure by process design

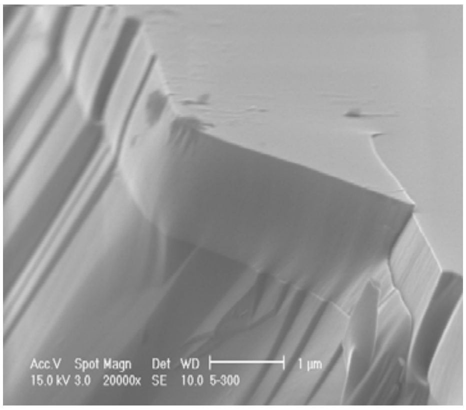
Low ion energy
Low ion density



Middle ion energy
High ionization



Ion energy &
density control



Avg. Surface Roughness (Rms)	**6 nm**	**2.4 nm**	**0.6 nm**

Recent progress and perspective of magnetron sputtering technology

---

State of Art in Magnetron Sputtering Processes

- ❑ **High rate deposition of metals & compound films**
  - UBM, CFUBM & Double magnetron devices
  - Reduction of target poisoning
  - Deposition rate : Max. 3 ㎛/min (Cu) & 0.5 ㎛/min (Al_2O_3)
- ❑ **Low pressure & self sputtering**
  - Unbalanced magnetron with additional magnetic confinement
  - Magnetron discharge was sustained at 1×10^{-5} torr
- ❑ **Large area coatings**
  - Dual magnetron devices
  - Maximum target length > 4,200mm
- ❑ **High efficiency of target utilization**
  - Variable magnetic field / Moving magnet magnetron device
  - Target efficiency : > 80%
- ❑ **Energy and flux controlled magnetron sources**

High rate deposition

● Objectives of high rate deposition

❑ Cost effective coating by reducing film processing time

❑ Formation of high density films combined with high ionization

● Methods of high rate deposition

❑ High Current / Laser Arc Ion Plating

-. Deposition rate : 5-10㎛/min (Cu)

-. Characteristics : micro-droplet, expensive equipment

❑ E-Beam evaporation

-. Deposition rate : due to source power & melting point of materials

-. Characteristics : high power consumption(100KW), low film density

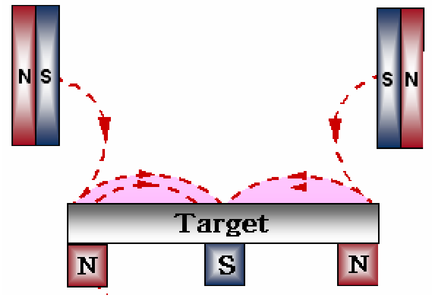
❑ Magnetron Sputtering

-. Deposition rate : 3 ㎛/min (Cu) by high power sputtering

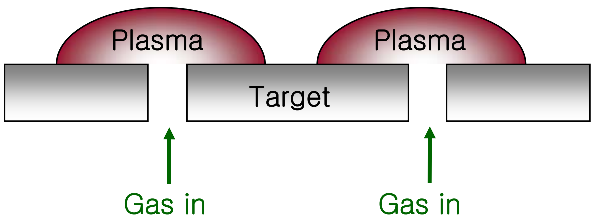
-. Characteristics : high density film, less damage in film

Low pressure sputtering

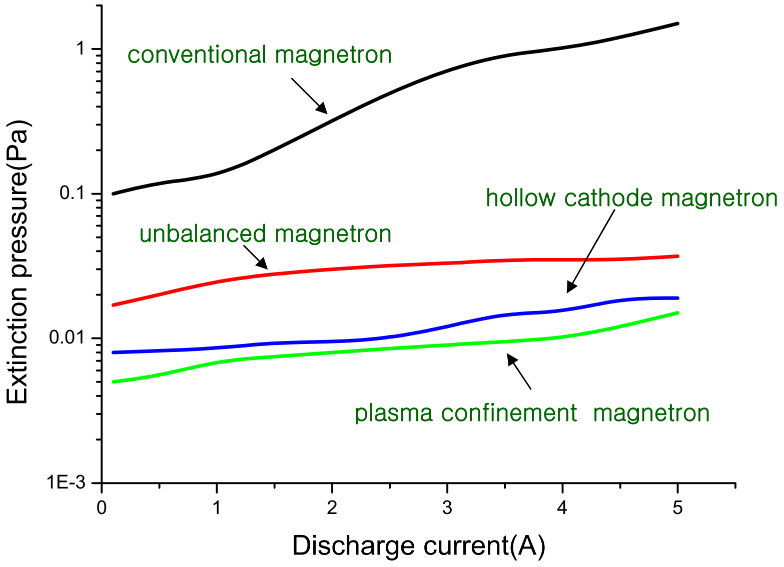
● Plasma confinement



● Hollow cathode magnetron



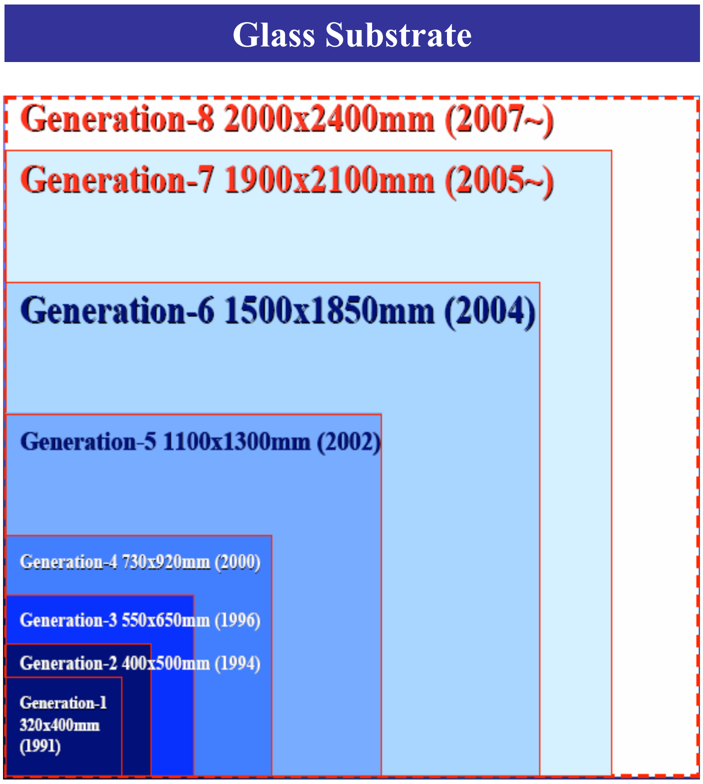
● Discharge characteristics



Courtesy by Prof. J. Musil
Univ. of West Bohemia, Czech Republic

Large area deposition

Trend of substrate size for FPD(LCD) process



Trends toward large substrate

- **Enlargement of display size (demand of wide display)**
- **To increase number of panels taken from a mother sheet (cost reduction)**

Process requirements

- **Large area and uniform**
  - **-. Area size > 2 meters**
  - **-. Uniformity ± 5-10 %**
- **High throughput**

Large area deposition

Major specifications required for the plasma sources to be employed in advanced large-area processing

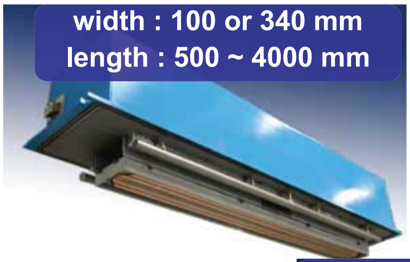
- Uniformity over large-area
  - ✓ *standing-wave free*
  - ✓ *controllability of power deposition profile*
- Low plasma potential (low electron temperature)
  - ✓ *high quality processing (suppressed plasma damage)*
- High-density plasma production
  - ✓ *high throughput (production efficiency)*
- Low-pressure processing
  - ✓ *enhanced utilization efficiency of materials gas*
  - ✓ *controllability of plasma and radical production*
  - ✓ *suppression of dust-particle formation*

Large area magnetron sources

- **Large area In-line sputtering system**

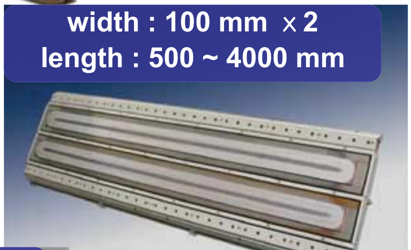

Substrate : 2060 x 1240

www.vonardenne.biz


width : 100 or 340 mm
length : 500 ~ 4000 mm

Single Magnetron sputtering source

Dual Magnetron sputtering source

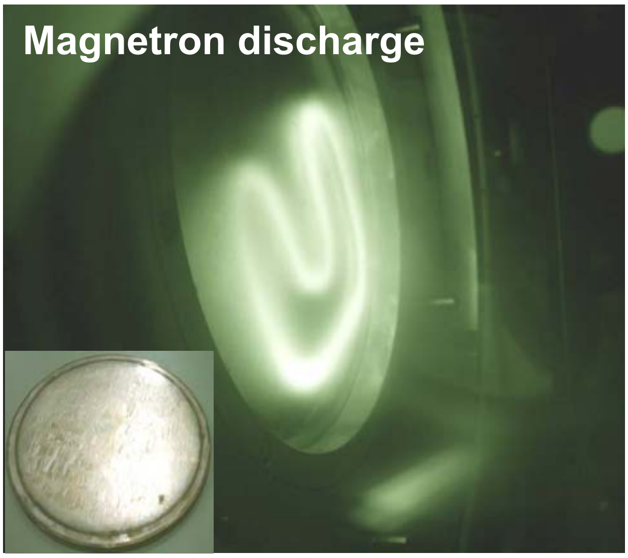

width : 100 mm x 2
length : 500 ~ 4000 mm

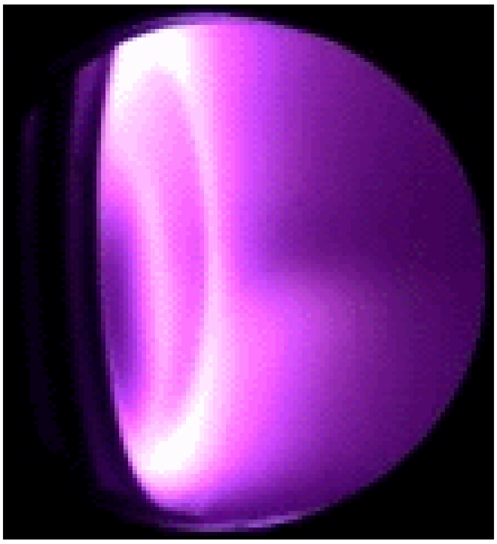

diameter : 143 ~ 160 mm
length : 100 ~ 3850 mm

Single/Dual Cylindrical Magnetron sputtering source

High target efficiency

- **Circular moving magnetron (FLATRON –CAPST/SKKU)**



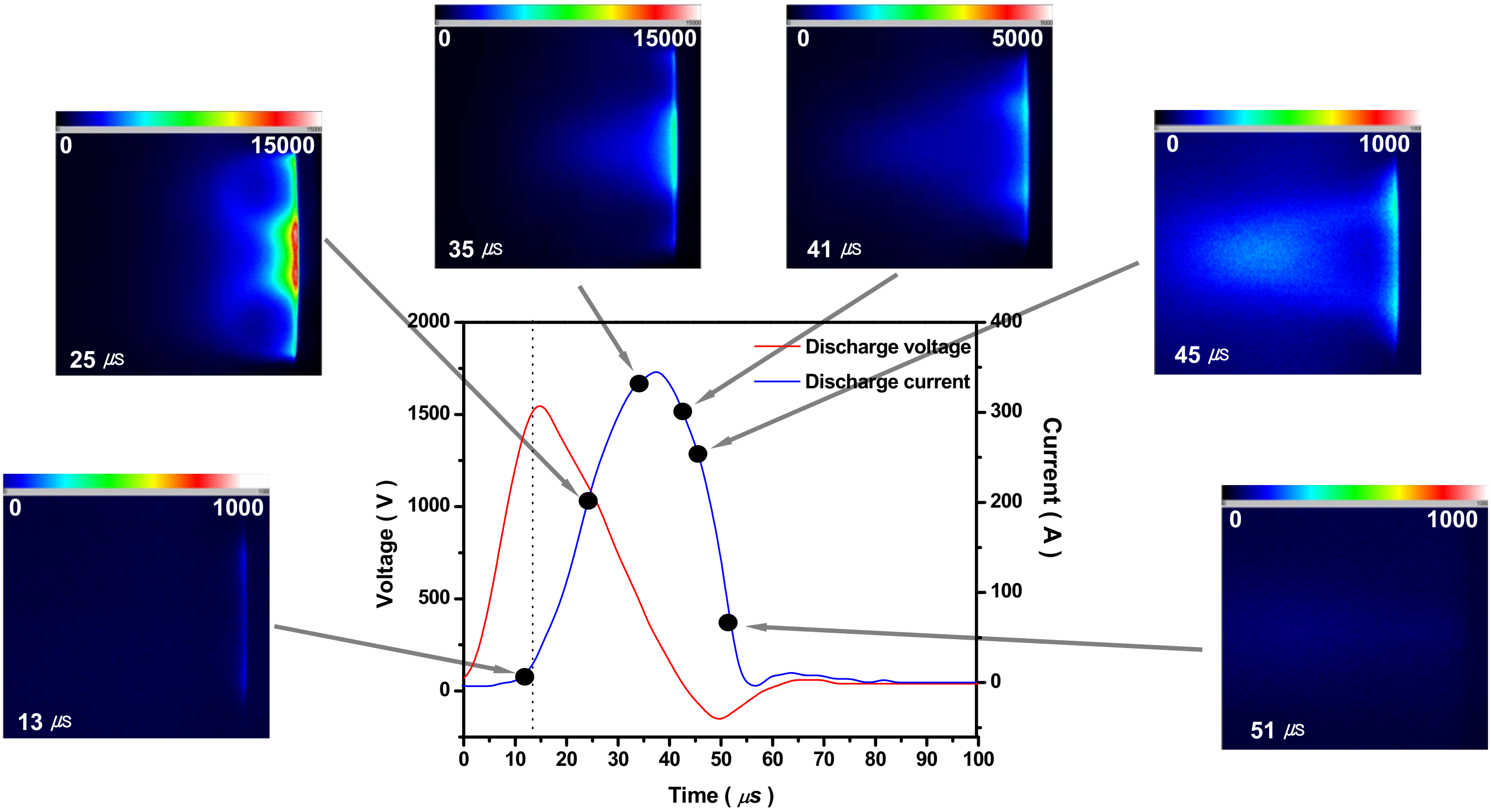


- ❑ Rotation of magnet on the circumference
- ❑ Cyclical movement of plasma on the target by control of electromagnetic fields
- ❑ Target efficiency : up to 80%

High Power Pulsed Magnetron Sputtering

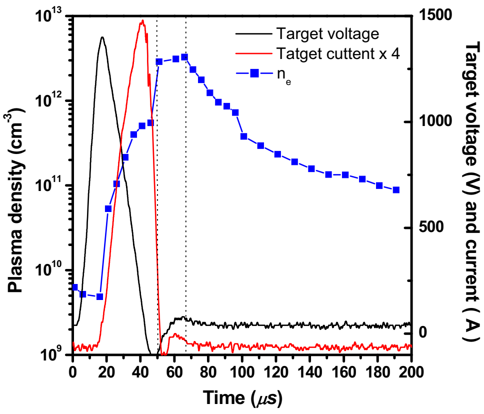
- **Improving the purity of thin films deposited at a large flux of sputtered vapors** (reduced contamination by rest gases)
- The possibility of **conducting high purity processes** during **sustained self-sputtering**
- Potential for new geometrical deposition(e.g. **metallization into deep holes and trenches in VLSI applications**)
- **Versatile variation of the texture** of thin films sputtered at high rates
- Possibility for new reactive sputtering processes (higher sputtering efficiency as a result of destroying reactive films of low sputtering coefficient)

Voltage-current waveforms for pulsed sputtering

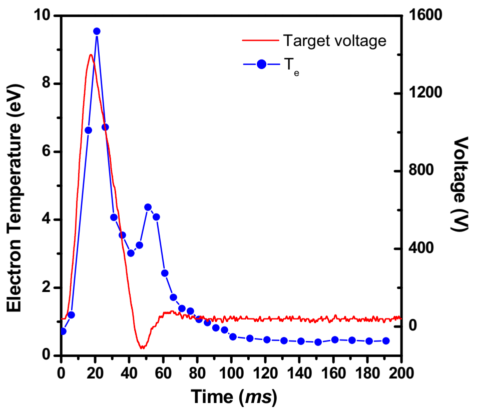


Time dependence of plasma parameters

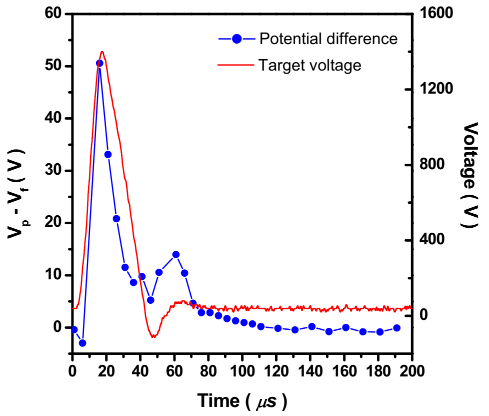
❑ **Electron density**



❑ **Electron temp.**



❑ **Potential difference (V_p-V_f)**



- **Max. n_e → 5 x 10^{12} cm^{-3}**
  (9 cm below the target)
- **DC mode → ~10^9 - 10^{10} cm^{-3}**

- **Peak T_e → 9.7 eV**
  (9 cm below the target)
- **DC mode → 2~4 eV**

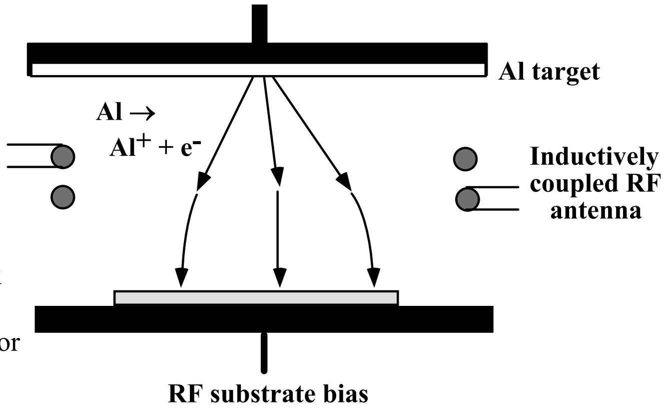
- **Peak (V_p-V_f)_ → 50 V**

  (9 cm below the target)

❑ **Floating substrate**

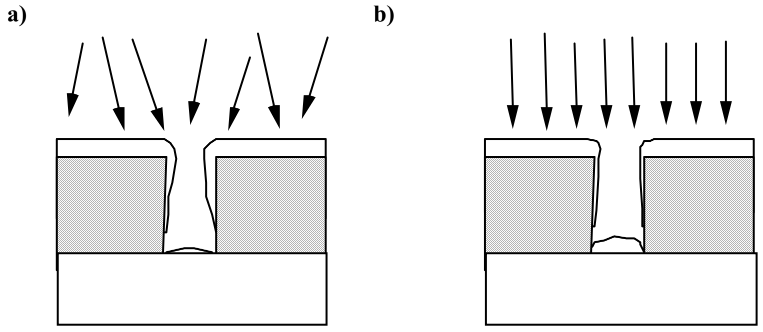
Ionized Sputter Deposition

Magnetron sputter



Highly
directional flux
Better solution
than a collimator
(holes)

- the depositing atoms themselves can be highly ionized with sppecified source or system design. An RF coil around the plasma typically induces collisions in the plasma creating high density ions (50-85% ionized).



- This provides a narrow distribution of arrival angles which may be useful when filling or coating the bottom of deep contact hole.

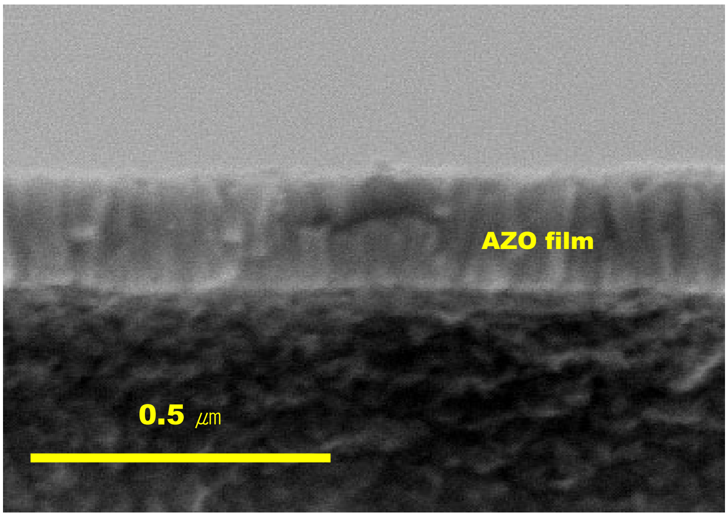
SILICON VLSI TECHNOLOGY
Fundamentals, Practice and Modeling
By Plummer, Deal & Griffin

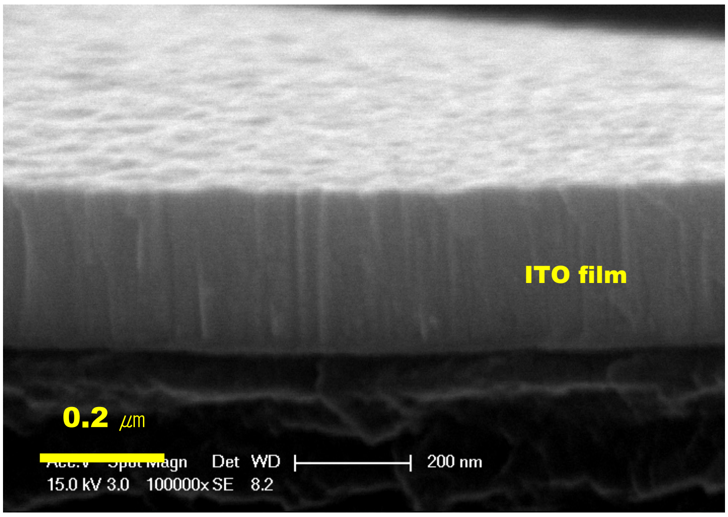
Low temperature processing

metallization on polymer below 50 C

- Transparent Conductive Oxide Films on Polymer

Al doped ZnO	Indium tin Oxide

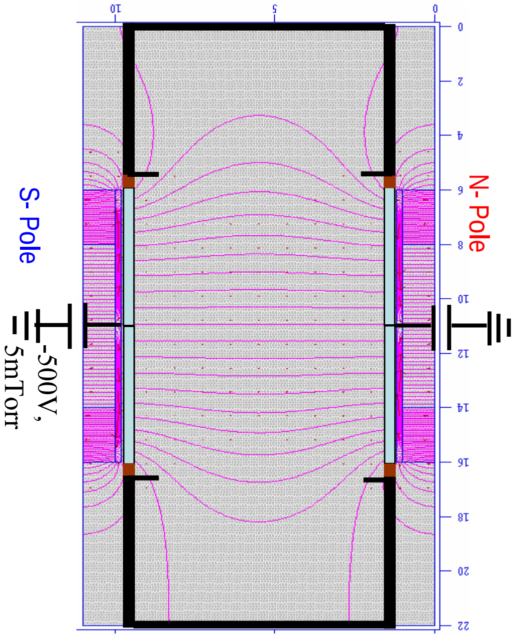




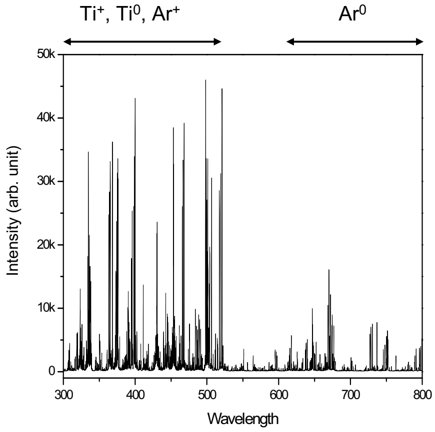
Low temperature processing

- Facing target sputtering

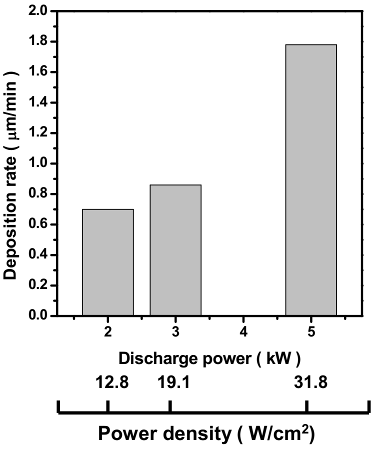
- Magnetic flux of facing configuration



- high ionization potential



- High rate deposition



- Reduction of substrate damage by ion bombardment
- Low temperature process
- Low discharge impedance
- Low pressure process (< 1 mTorr)

Acknowledgement for

Financial Support from MOST & KOSEF

Research contribution from all CAPST members