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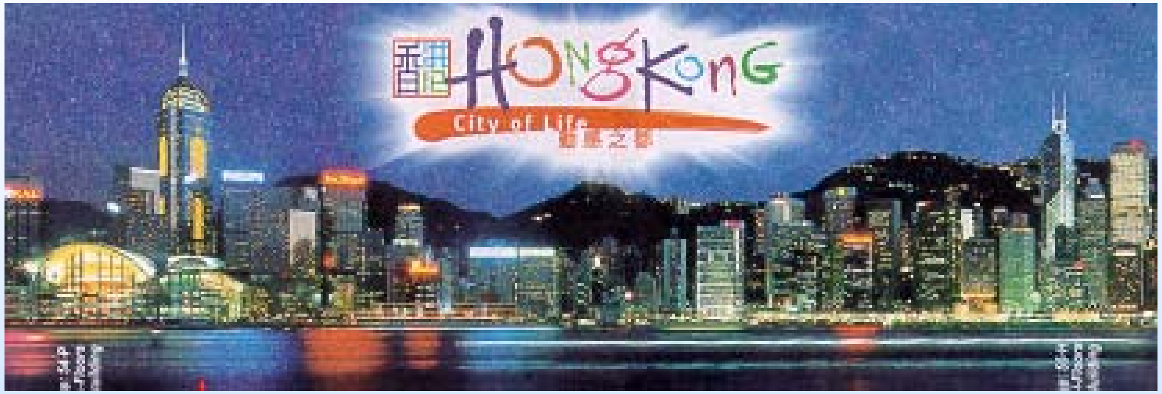
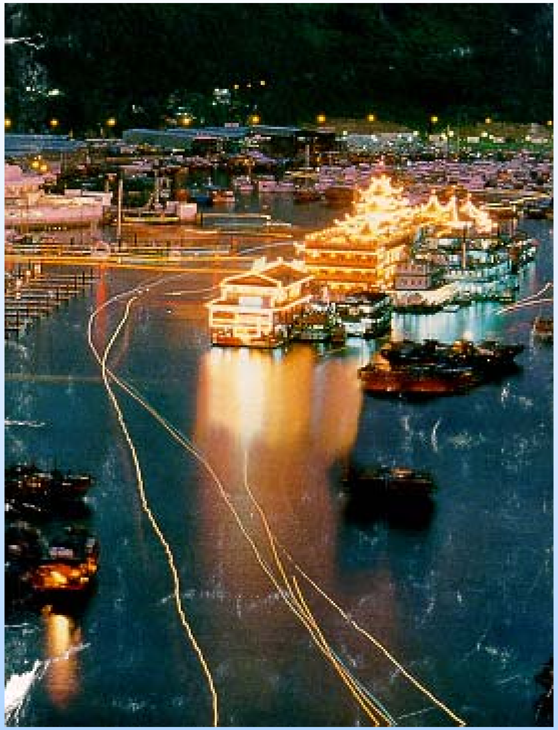
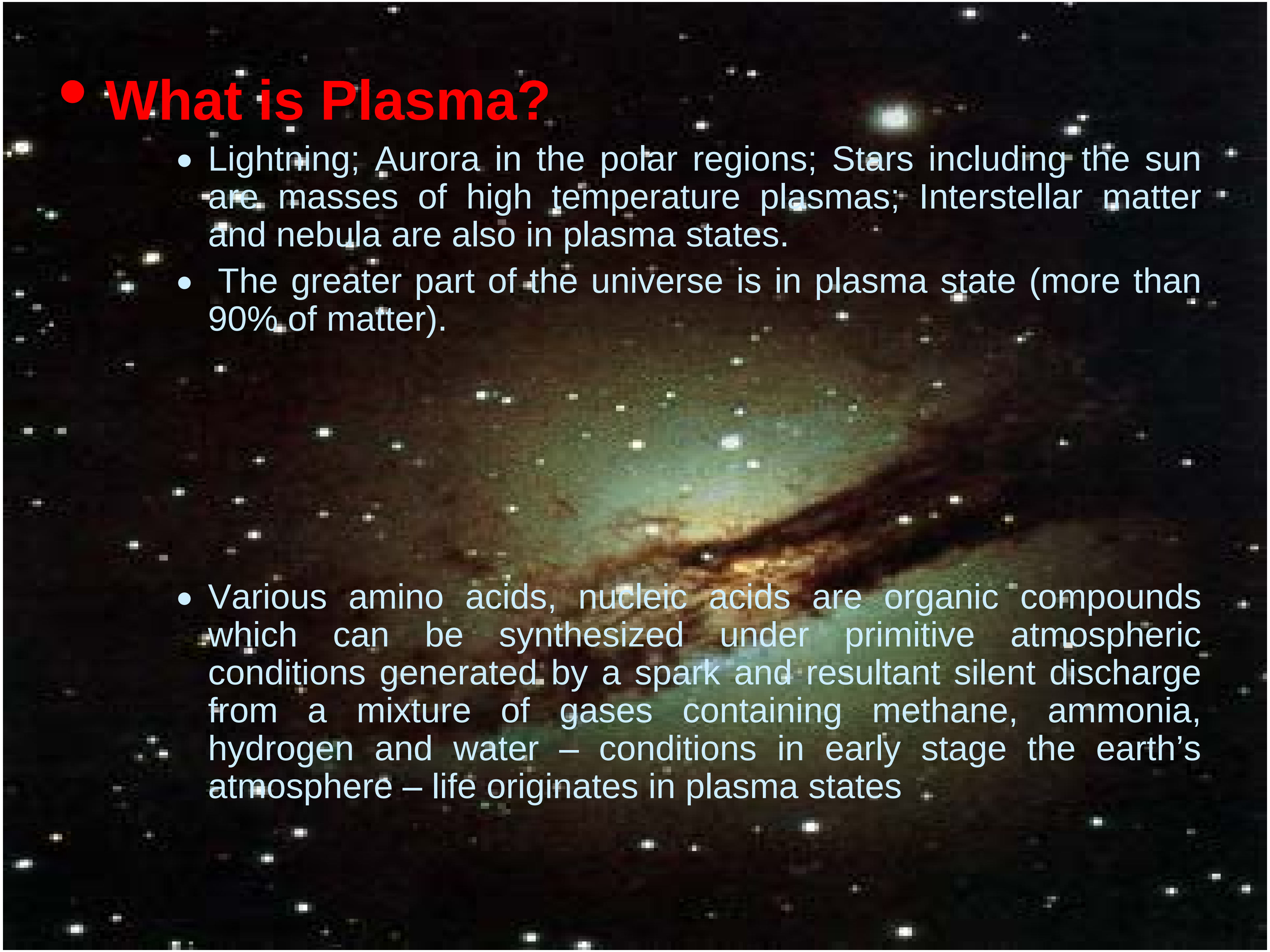
• What is Plasma?





- Conducting gas in a fluorescent tube
- Neon signs



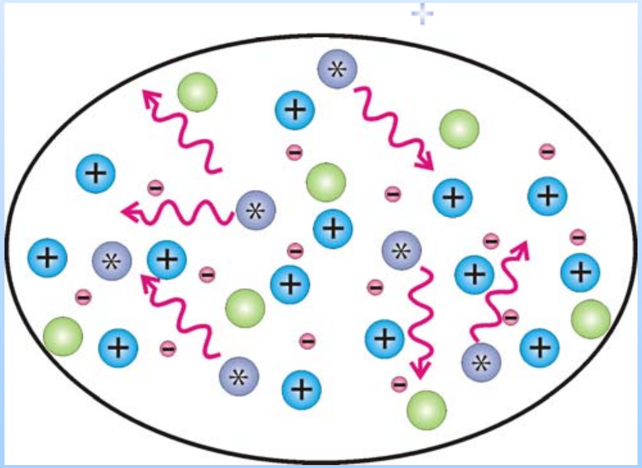
What is Plasma?

- Lightning; Aurora in the polar regions; Stars including the sun are masses of high temperature plasmas; Interstellar matter and nebula are also in plasma states.
- The greater part of the universe is in plasma state (more than 90% of matter).
- Various amino acids, nucleic acids are organic compounds which can be synthesized under primitive atmospheric conditions generated by a spark and resultant silent discharge from a mixture of gases containing methane, ammonia, hydrogen and water – conditions in early stage the earth’s atmosphere – life originates in plasma states

Plasma Definition

- More complicated system than the gas phase
- Obeys the gas laws and in many respects behaves like gases
- May be initiated in gases and vapors at various conditions: high temperatures or low temperatures using electric discharges.
- Physical system: neutrals, molecules, atoms, excited particles, ions, electrons and electromagnetic radiation.

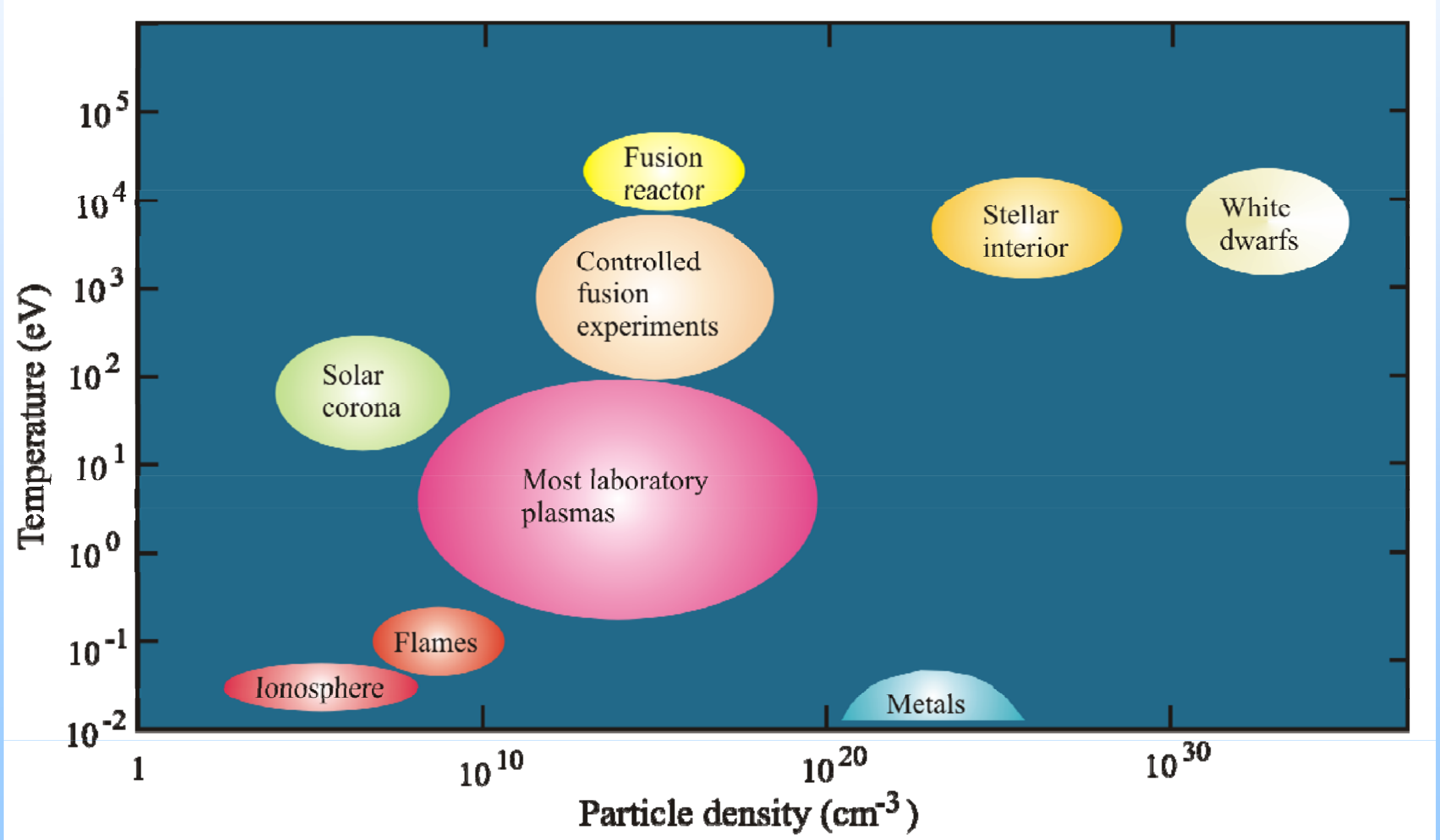
$$\Sigma Q_i^{+} + \Sigma Q_j^{-} = 0$$



- Sum of the positive and negative charges in any sufficiently large volume is equal to zero.

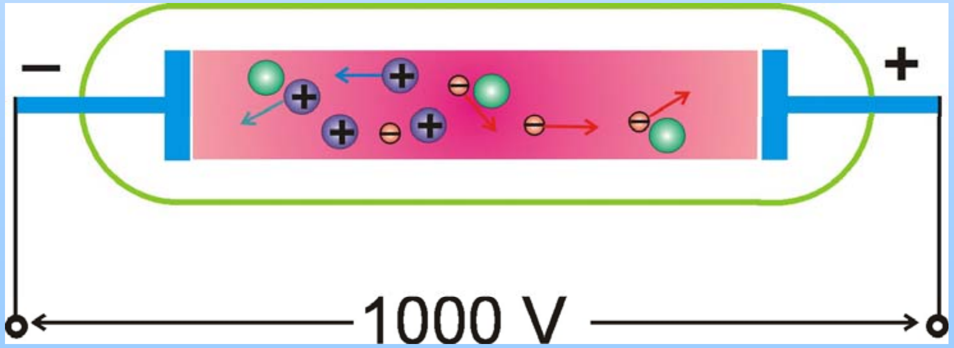
Plasma in Different Environments

- Plasma is characterized by its electron energy and density
- Plasma in nature and laboratory
- In laboratory: Glow discharges: 10-10^{-3} Torr; Arc discharges: low pressure and near atm

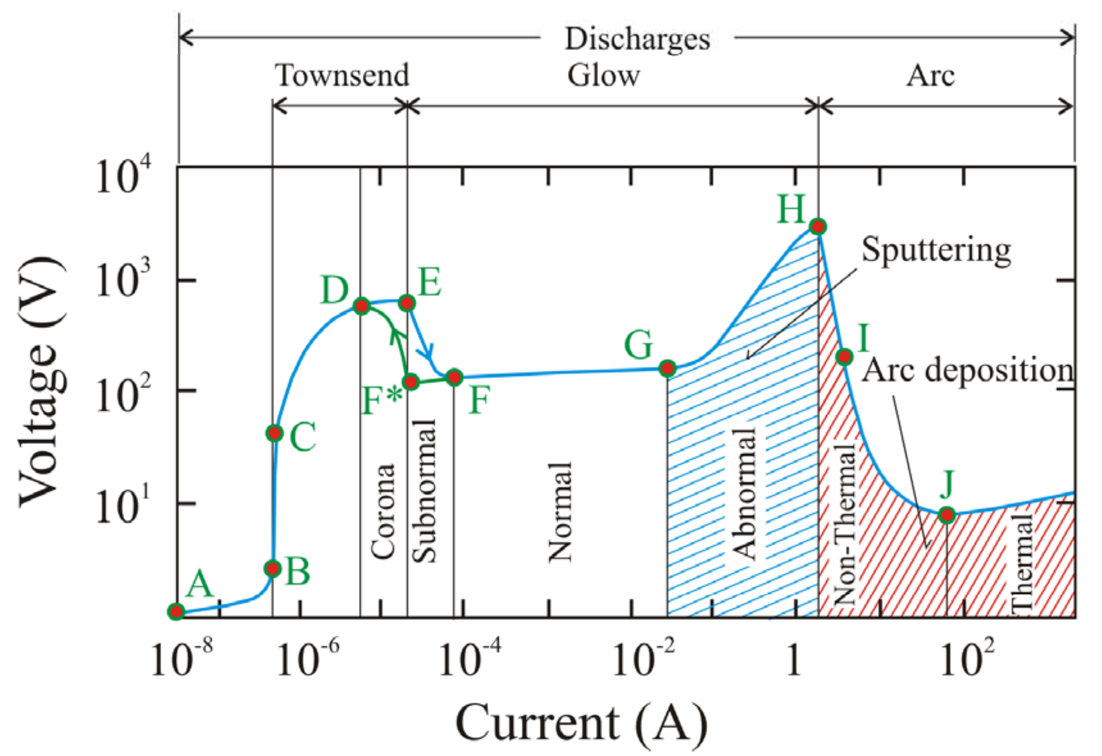


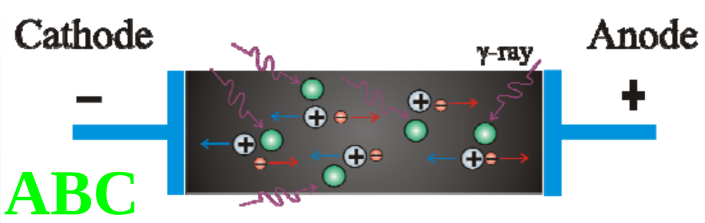
Inducing Plasma

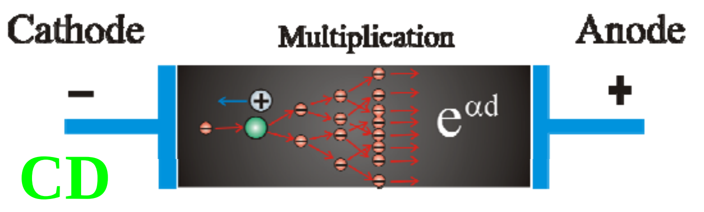
- Electrical discharges
- Glass discharge tube - two electrodes
- Pressure range between 1 - 10^{-3} Torr
- Application of high voltage
- Electrical current through the tube abruptly increases
- Visible light in violet-red color (in air)
- Gas became electrically conductive due to its ionization
- Positively charged ions and negative electrons drift with statistically distributed random velocities to the respective electrodes

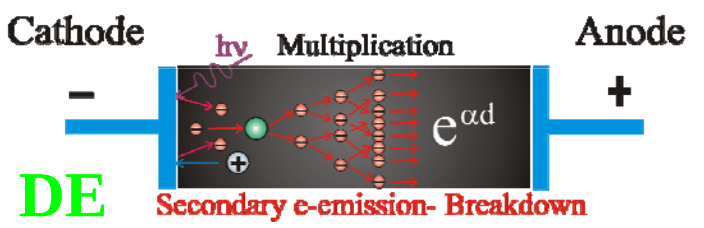


Voltage – Current Characteristic of Electrical Discharges

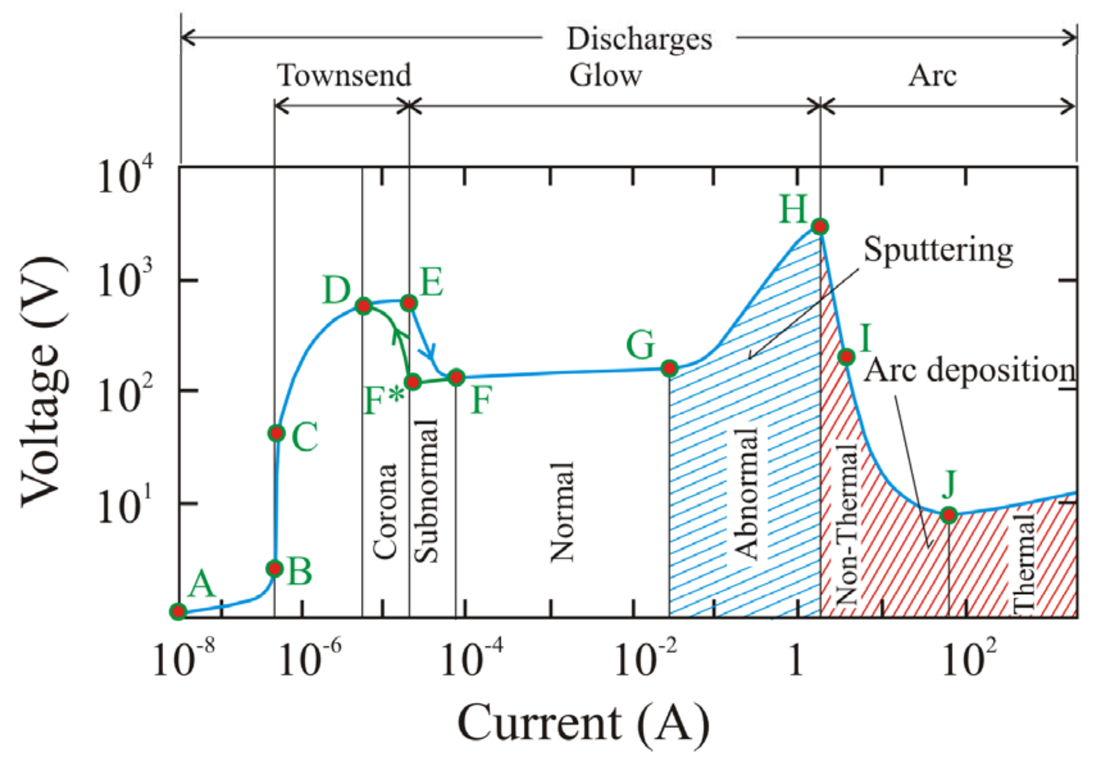


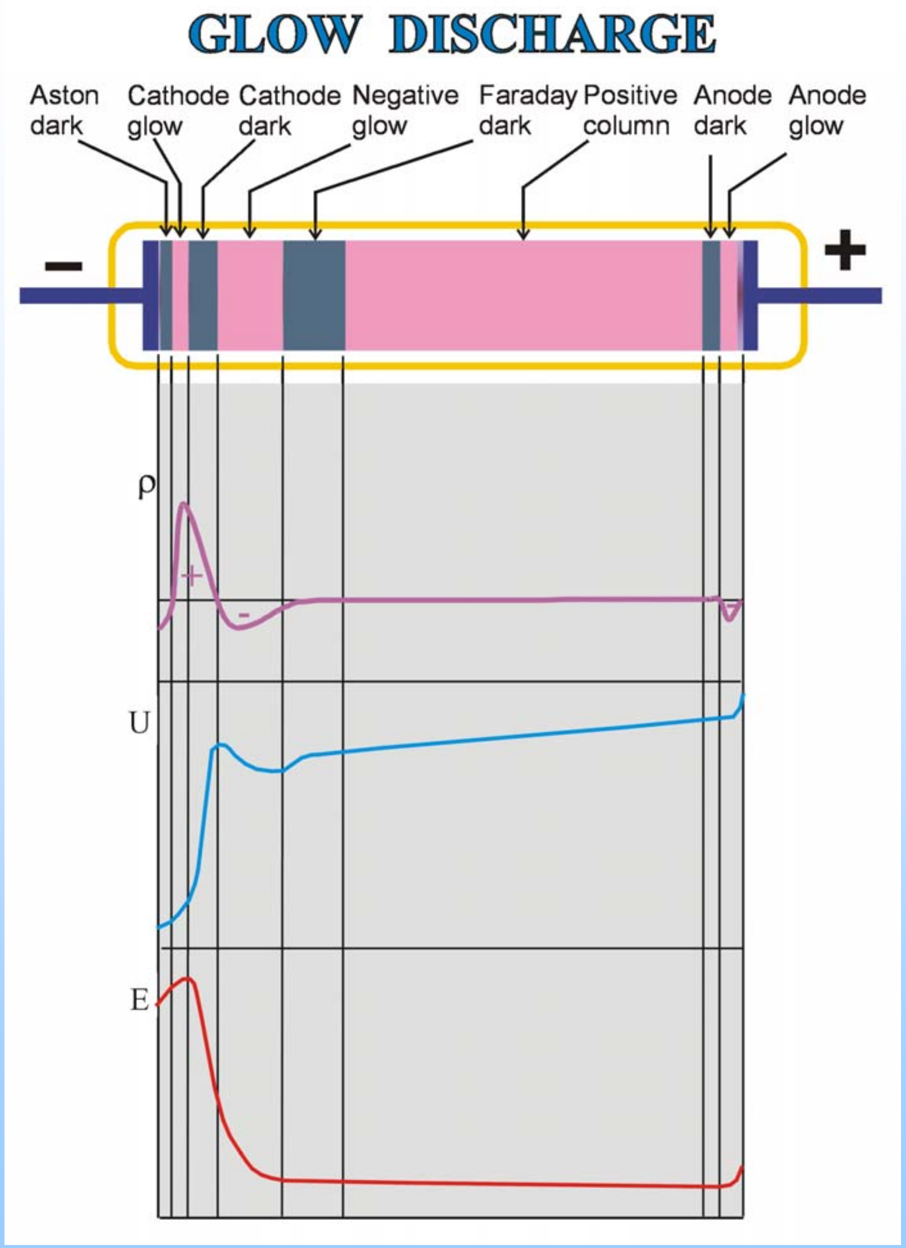




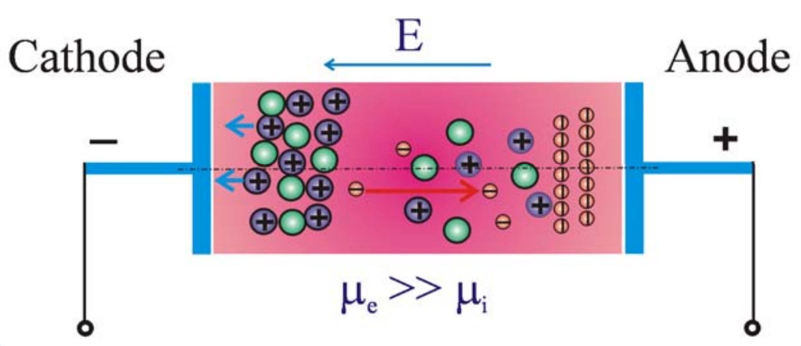


Voltage – Current Characteristic of Electrical Discharges



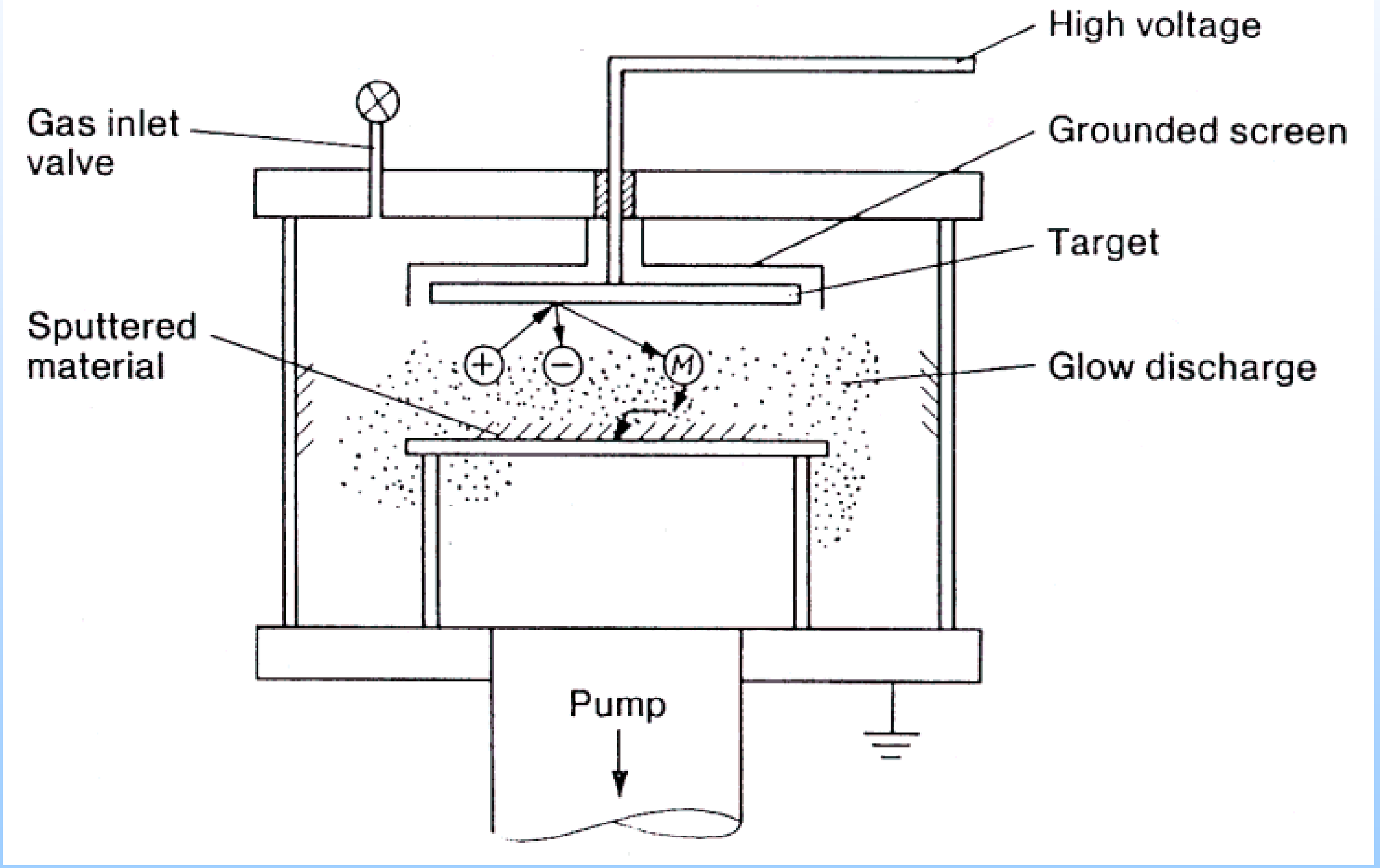


Effect of Space Charge



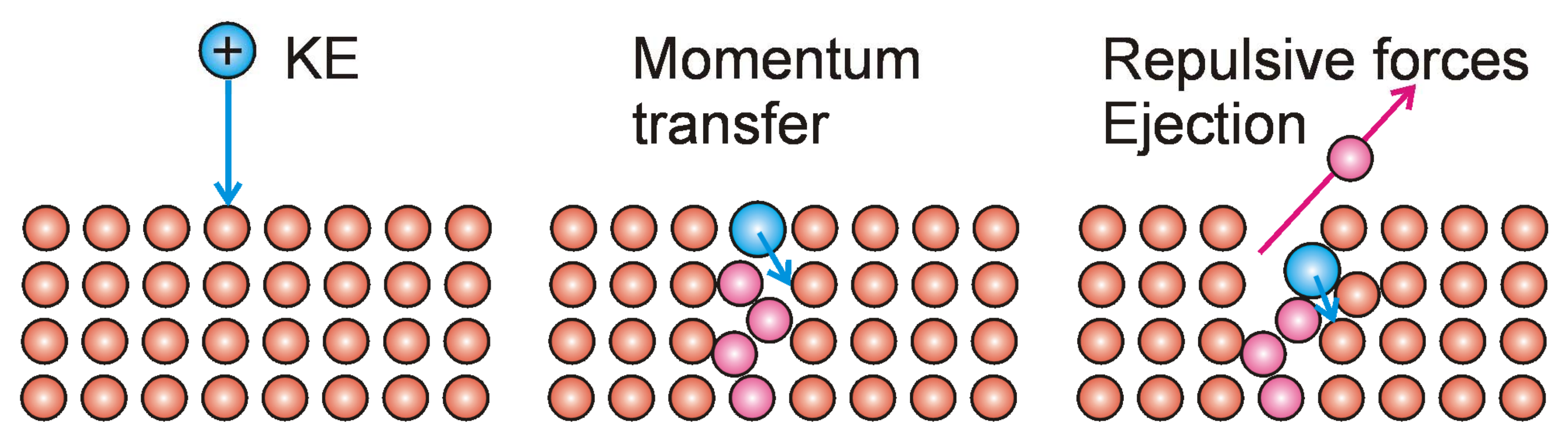
- So far, assumed uniform electric field.
- If current **i** is high, the uniformity of **E** is disturbed.
- In steady state, positive ions must reach the cathode in the same number as corresponding electrons anode. Mobility of ions is lower than that of electrons.
- Difference in ion and electron mobility implies the accumulation of space charge in different regions.

Simple diode type sputtering system

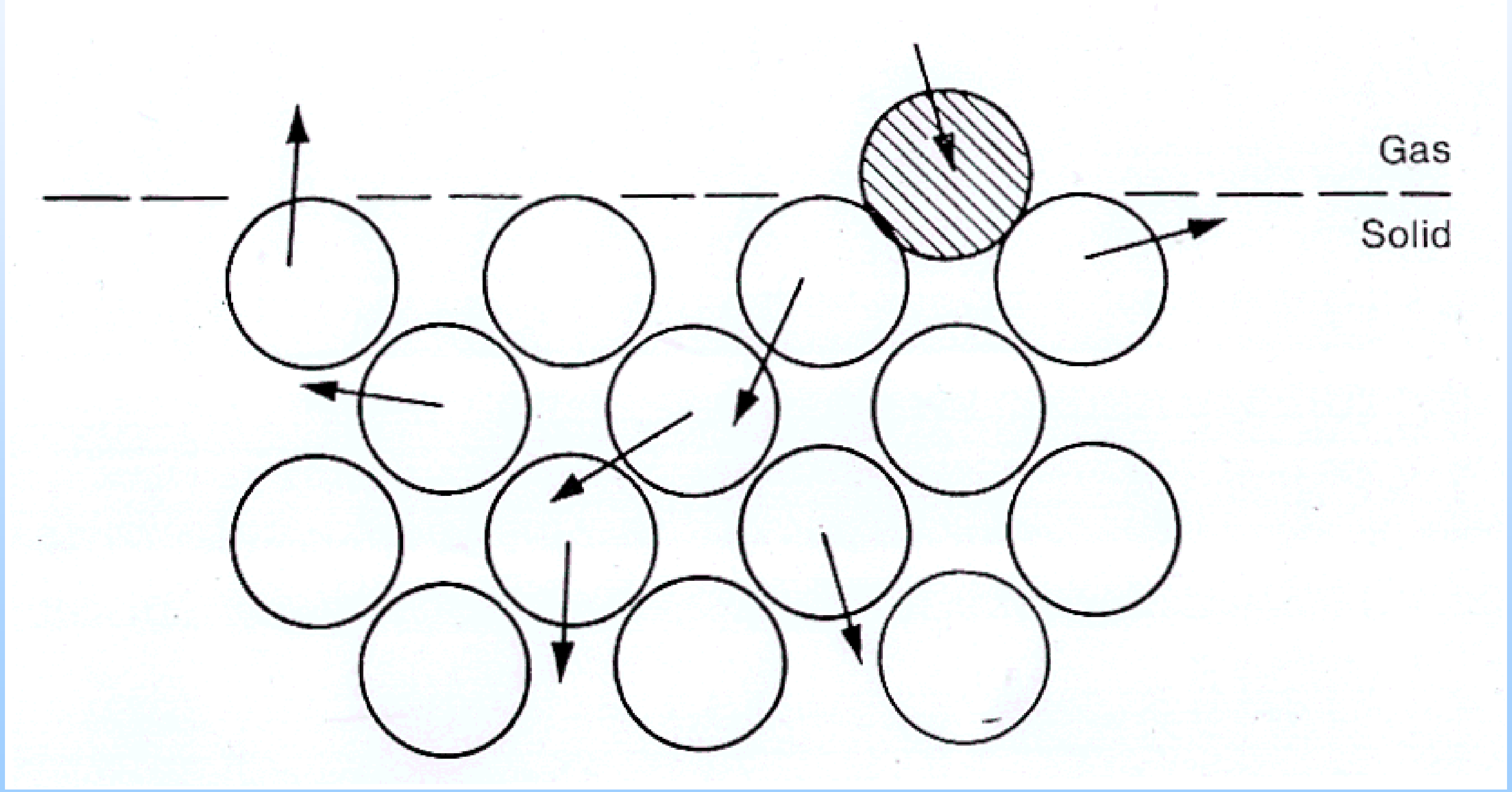


Sputtering

Ion bombardment - momentum transfer



Collision cascade in a condensed material during the ion bombardment with knocking out of two atoms



States of sputtered atoms and molecules

In general, the state of sputtered particles depends on the acceleration voltage (kinetic energy of incident ions) – the higher the KE is, the more the clusters

For example, Cu target sputtered with Ar ions

E_{Ar} = 100 eV, 5% Cu + Cu_2
E_{Ar} = 12 keV, Cu + Cu_2 + Cu^+_n ($n = 1$-11)

For Al target sputtered with Ar and Xe ions, Al_n ($n = 1$-7 and 1-18, respectively) will be sputtered.

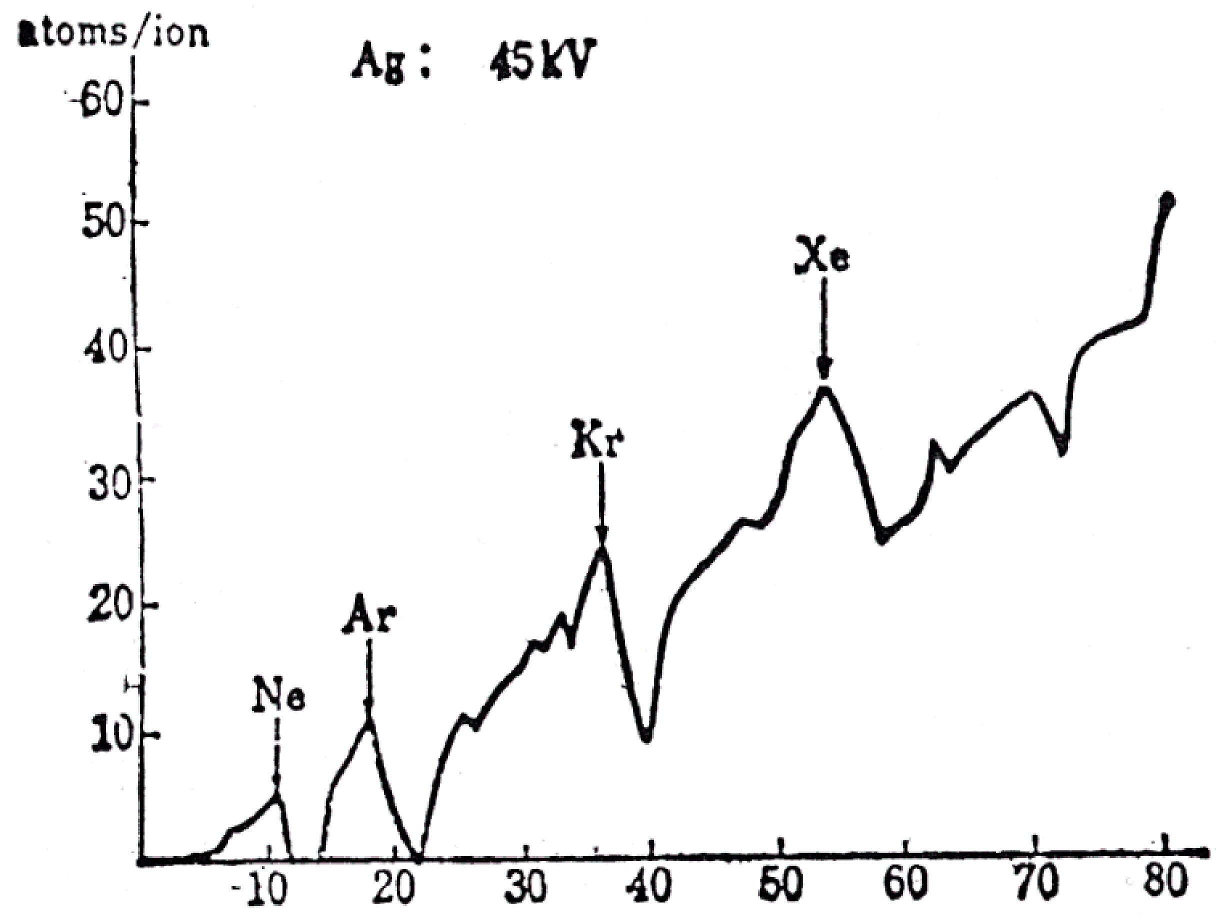
Compounds:
GaAs sputtered with Ar ions, 99% are the Ga and As neutral atoms and 1% GaAs molecules.

Sputtering Yield (1)

- Definition: Number of sputtered atoms per incident ion
- Sputtering Yield is affected
    - Surface structure
    - Ion mass
    - Incident energy
    - Rather <u>insensitive</u> to temperature (in certain cases, decreasing sputtering yield with increasing target temperature
- Sputtering yield maximum for inert ions
- Minimum for C, Mg, Al, Ca and Sc ions - sticking coefficient
- Periodicity of element can be recognized as atomic number of bombarding ions is changed
- Sputtering by neutrals – lesser significance
- No sputtering is initiated by electrons

Sputtering Yield (2)

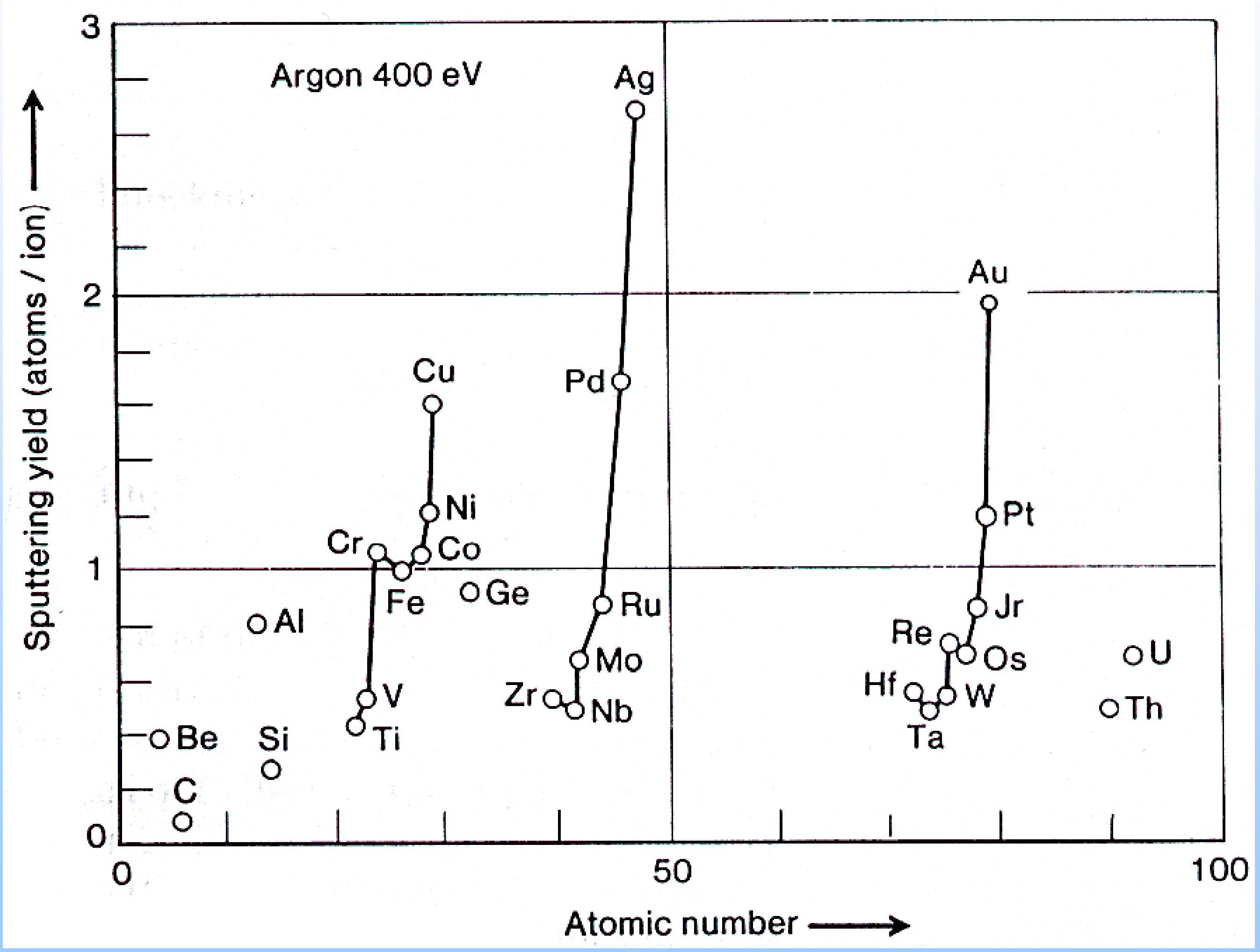
is dependent on the atomic number of incident ions



Atomic number

Sputtering Yield (3)

is dependent on the atomic number of target materials



Sputtering Yield (4)

is dependent on the crystallographical orientation

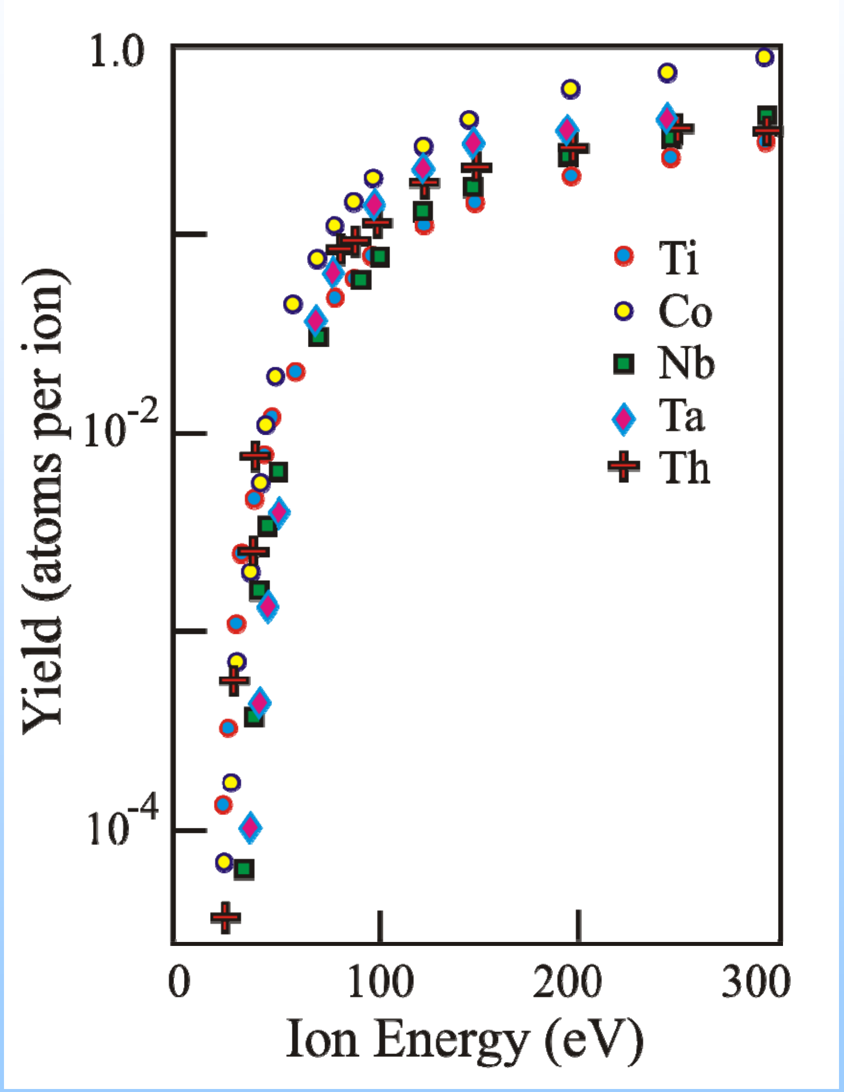
In general, crystal surface with high atomic density has higher sputtering yield. The reason is the higher impact probability

PPolycrystalline targets are used!!!

Sputtering Yield (5)

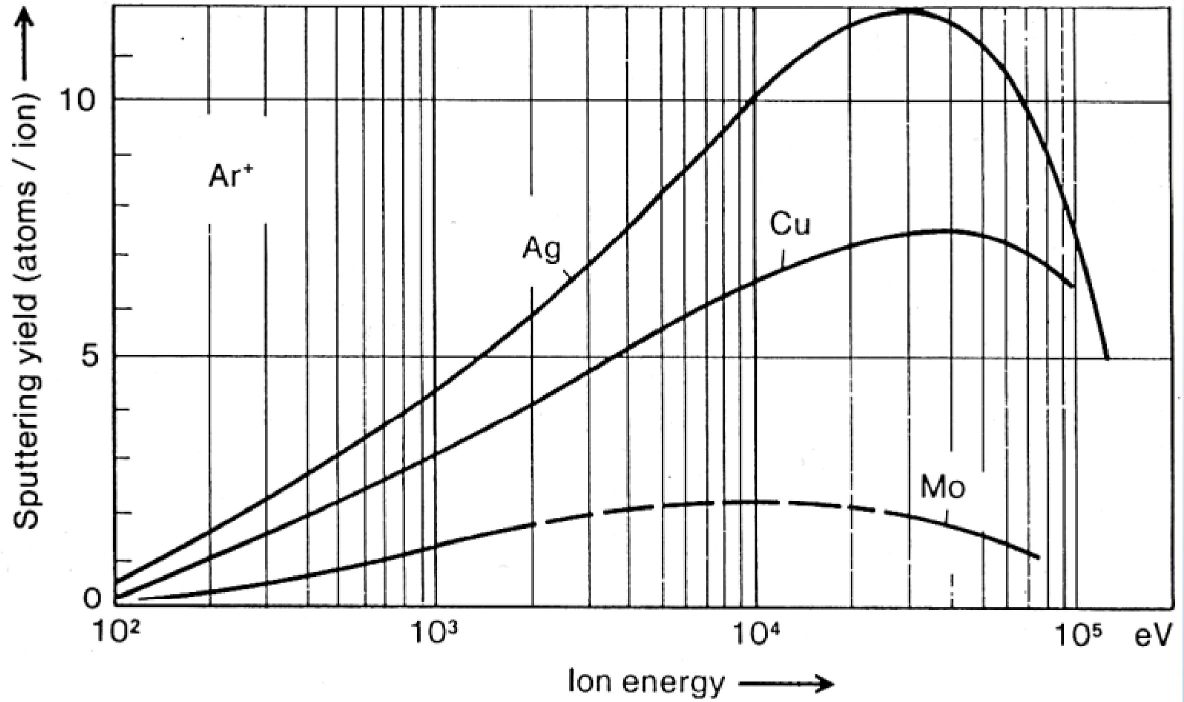
is dependent on the ion energy

- Rises rapidly from a threshold energy
- Threshold 10 - 30 eV for metals
- Above 100 eV, increases ~ linearly



Sputtering Yield (6)

is dependent on the ion energy



- Thereafter, a broad maximum and then decreases slowly
- Decrease with increasing ion energy – penetration depth too large to eject atoms from the deeper regions
- Light ions (H, He) maximum at a few thousand eV – large penetration depth. Heavy ions (Xe, Mg) - maximum at around 50 keV.

Sputtering Yield

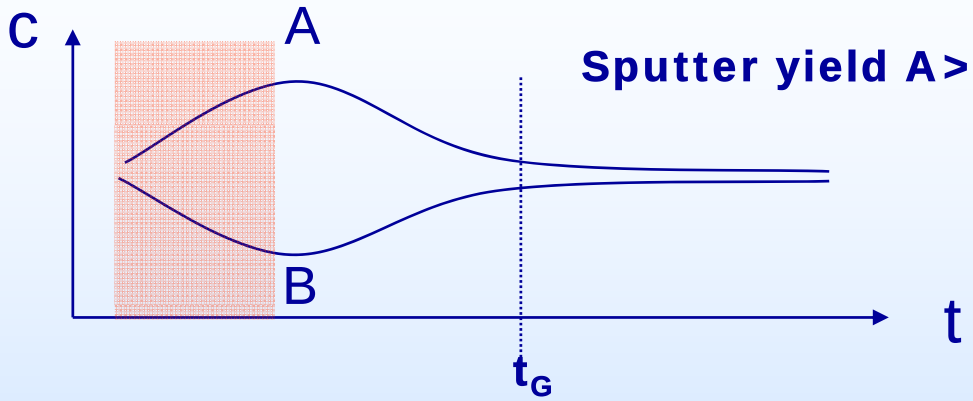
for argon ion bombardment at 600 eV

Target	Yield	Target	Yield	Target	Yield	Target	Yield
Be	0.56	Mo	0.54	Al_2O_3	0.18	CdS	1.2
Al	0.83	Ru	0.67	SiO_2	1.34	GaAs	0.9
Ti	0.54	Rh	0.77	TiO_2	0.96	GaP	0.95
V	0.55	Pd	1.32	V_2O_3	0.45	GaSb	0.9
Cr	1.05	Ag	1.98	Cr_2O_3	0.18	InSb	0.55
Fe	0.97	Hf	0.39	Fe_2O_3	0.71	SiC	1.8
Co	0.99	Ta	0.30	ZrO_2	0.32		
Ni	1.34	W	0.32	Nb_2O_3	0.24		
Cu	2.00	Os	0.41	In_2O_3	0.57		
Ge	0.82	Ir	0.46	SnO_2	0.96		
Zr	0.42	Pt	0.7	Sb_2O_3	1.37		
Nb	0.42	Au	1.18	Ta_2O_5	0.15		

Sputtering of alloy films

For AB

Sputter yield A>B



a) The cathode temperature is not too high, so that the component of low concentration can not always volume-diffused from inner to the surface.

b) The cathode elements do not separate (*entmisch*) themselves.

c) The cathode surface does not change chemically, e.g. by oxidation.

d) The direction dependency of the sputter yield is the same for both components.

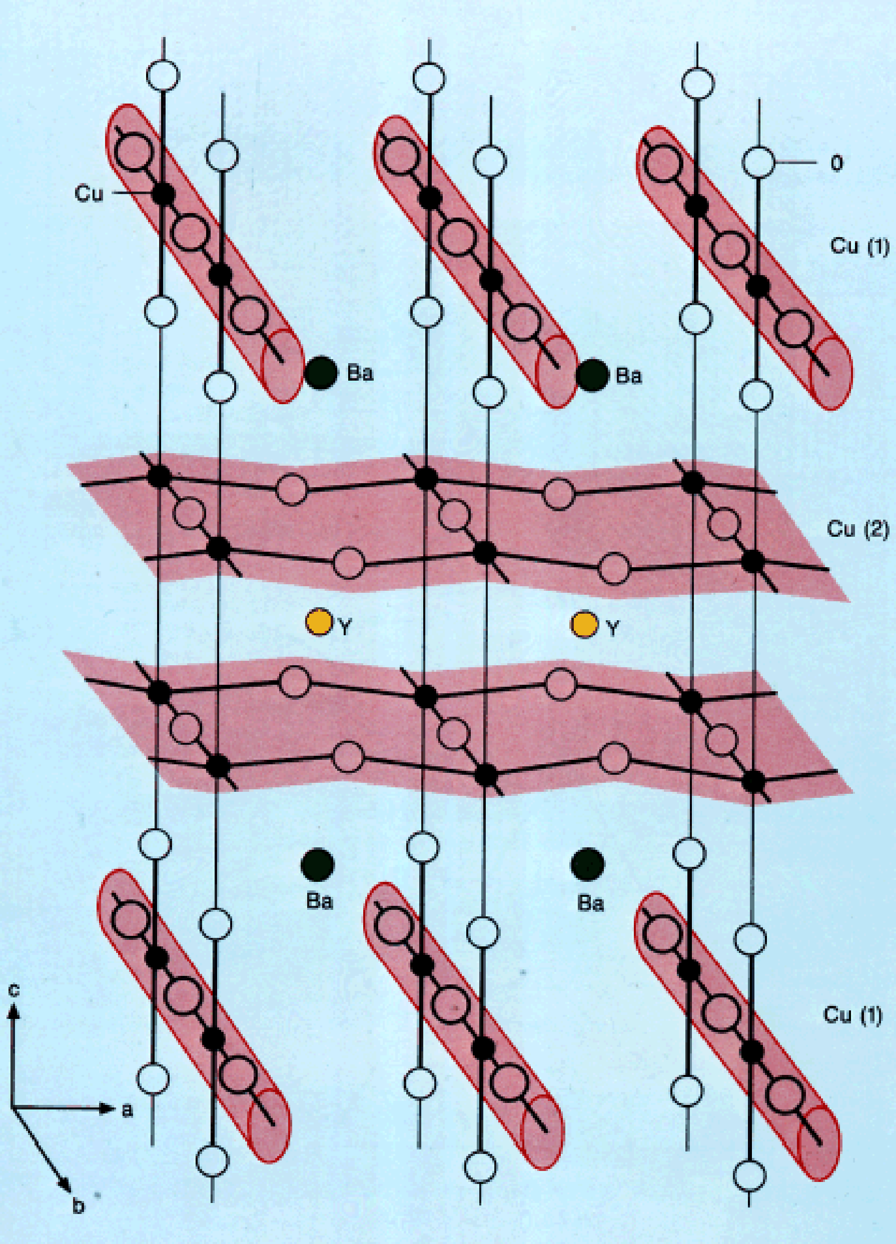
e) The sticking coefficients of the components on substrate are same. This condition is often not fulfilled, if a component is a gaseous element, like nitride and oxide. Then this deficit of gaseous component must be compensated, in order to prepare stoichiometric films (reactive sputtering).

Reactive Sputter Deposition of Compounds

- Target compounds - multiple elements with extremely different volatilities (e.g. metal oxides or nitrides).
- Deposited film often differs from the composition of the target.
- Compounds decompose during the process of sputtering.
- Concentration of the volatile component such as oxygen or nitrogen, is reduced in the deposited film.
- The target composition also changes.
- To compensate - reactive gas of higher vapor pressure component is added into the plasma.
- Sputter deposition technique employing plasma with a reactive gas and elemental metal target.
- Various compound films have been prepared by reactive sputter deposition and the reactive gases.
- Composition of the compound can be controlled by changing the partial pressure of the reactive gas added into an inert gas (Ar).
- Partial pressure of reactive gases (N_2 or O_2) affects the deposition rate and film properties.

Table: Compound films formed by reactive sputtering

Compounds	Reactive gases	Compounds	Reactive gases	Compounds	Reactive gases
Oxides	O_2, H_2O	**Nitrides**	N_2, NH_3	**Silicides**	SiH_4
TiO_2		TiN		Ti-Si	
ZrO_2		ZrN		Ta-Si	
Ta_2O_5		HfN		Cr-Si	
Mo-O		NbN		$MoSi_2$	
Cr_2O_3		TaN		W-Si	
MnO_2		W_2N		Fe-Si	
Cu-O		AlN			
Al_2O_3		GaN		**Sulfides**	H_2S
In_2O_3		InN		MoS_2	
SnO_2		Si_3N_4		CdS	
In_2O_3-SnO_2		BN (cBN/hBN)		Cu-S	
WO_3					
RuO_3		**Carbides**	CH_4, C_2H_2	**Others**	
ZnO		TiC		InP	PH_3
La-Sr-Cu-O		NbC		GaAs	AsH_3
Y-Ba-Cu-O		TaC		$LiNbO_3$	O_2
Gd-Ba-Cu-O		WC			



$YBa_2Cu_3O_x$

$x < 6$

Phase instable

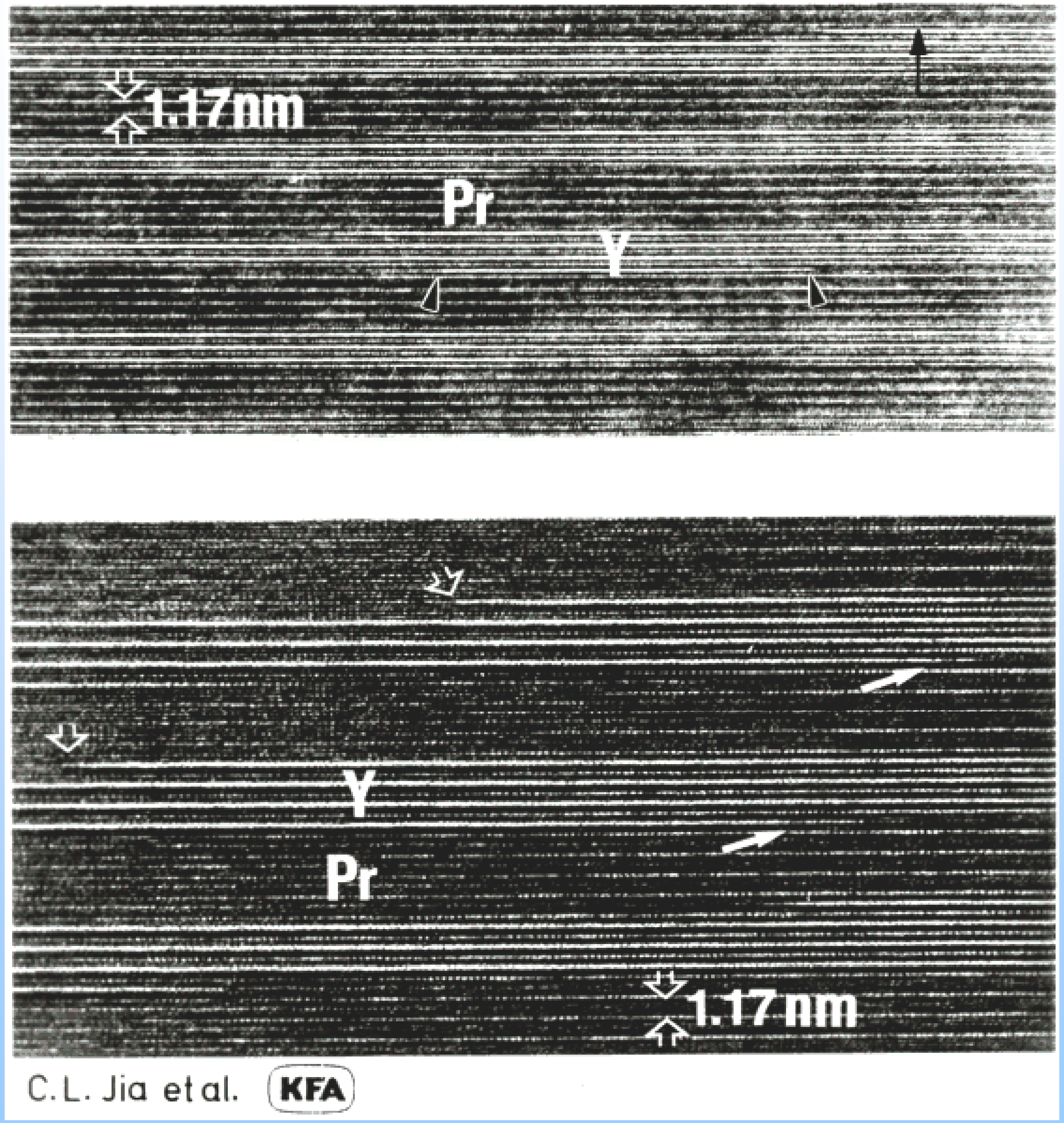
$x = 6,4$

Semiconductor

$x = 7$

Superconductor

$T_c = 92$ K



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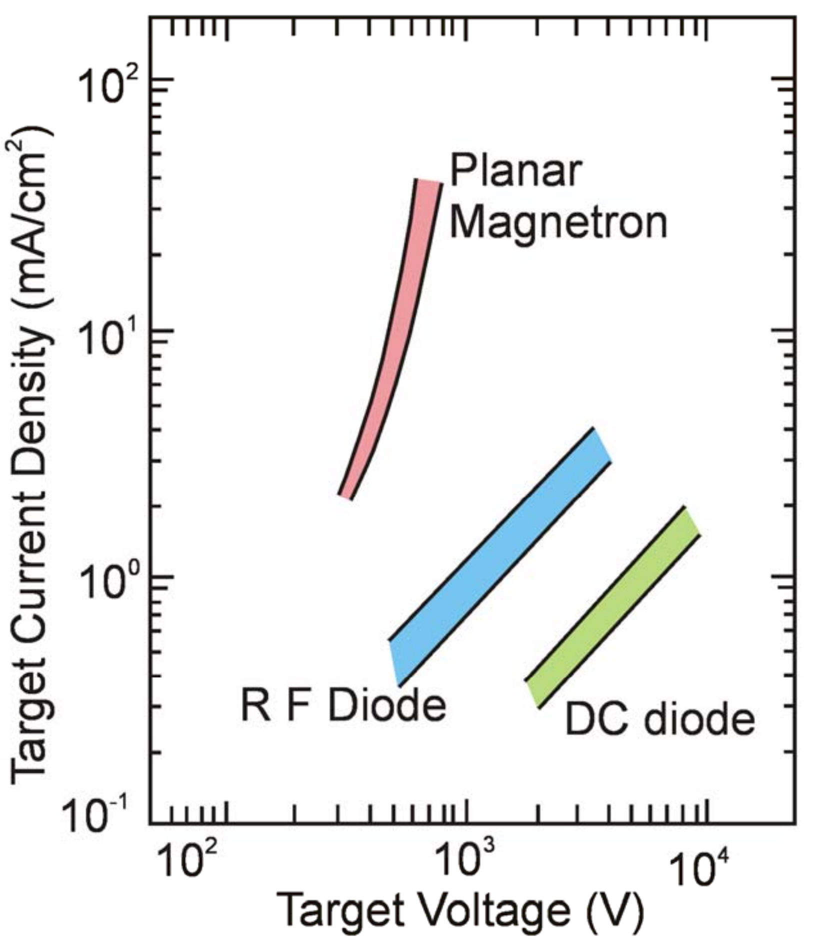
Reactor Configuration

Sputter deposition system

Configurations

- Diode
- Triode – 3rd electrodes with substrate.
- Magnetron
  arranged magnet
  E perpendicular to B



I-V characteristics of three different methods used for sputtering

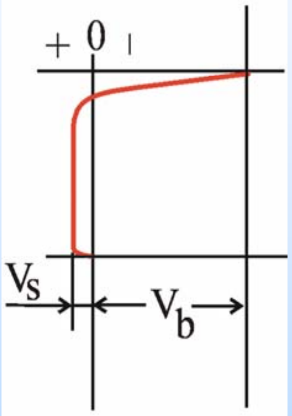
Sputter Deposition System – Excitation

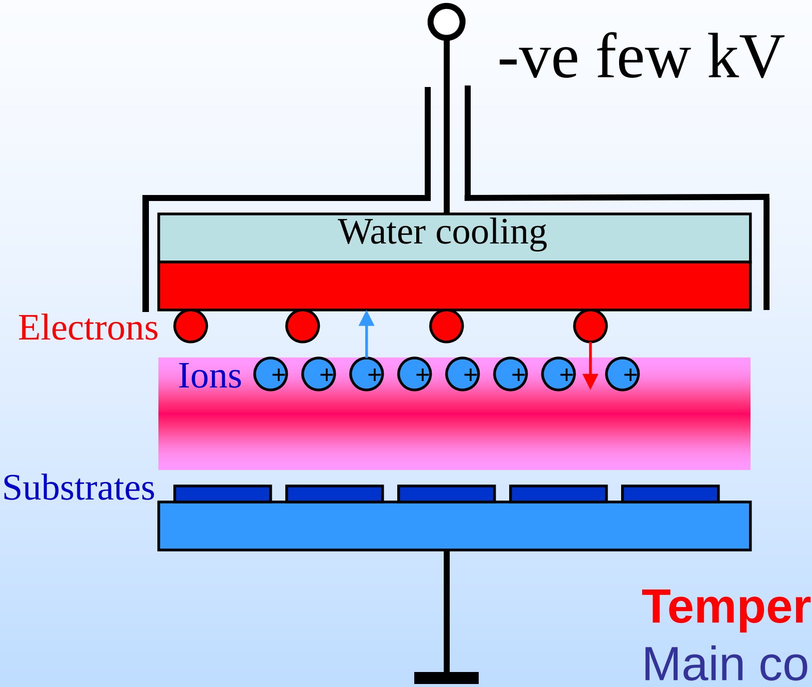
DC or RF

DC diode system

- Substrate on the grounded holder.
- Several kV applied to a target opposite the substrate holder.
- Discharge is in the abnormal glow region.
- Ar^+ are accelerated by the cathode fall potential.
- Ions bombard and sputter a target material.
- Secondary electrons keep discharge going.
- Target is cooled.
- Electric power - voltage applied between the electrodes and current which flowing through discharge.
- Power density - 0.5 and 15 W/cm^2.

DC Diode System



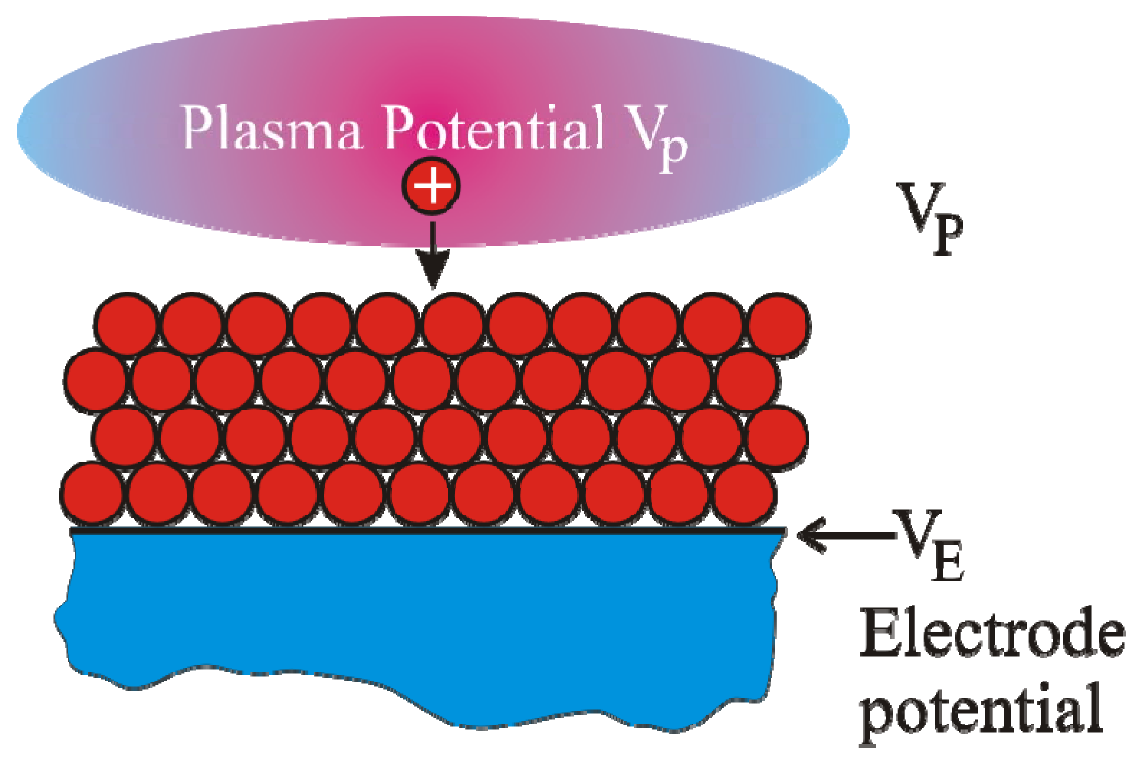


Temperature increase

Main contribution from the secondary electrons.

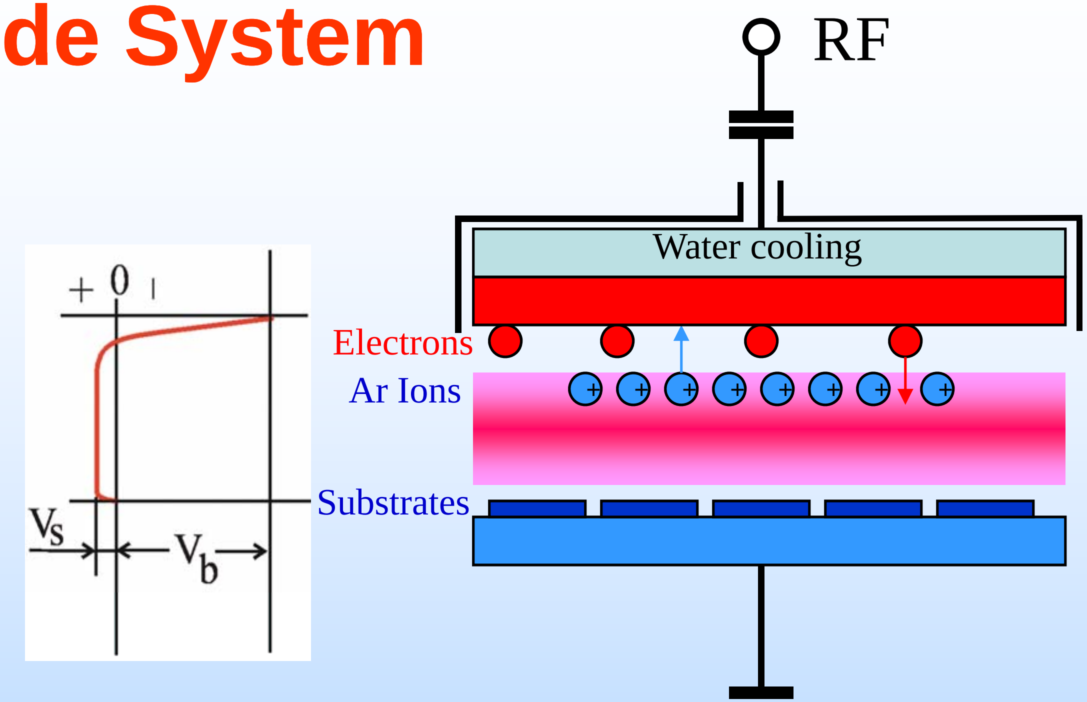
- Widely used because of simplicity
- DC glow discharge well understood
- Sputtering limited to metals and semiconductors
- DC sputter deposition requires ion current > 1mA/cm^2 to achieve reasonable deposition rates

Plasma Potential –Electrode Potential: Determine the Energy of Impact Ions



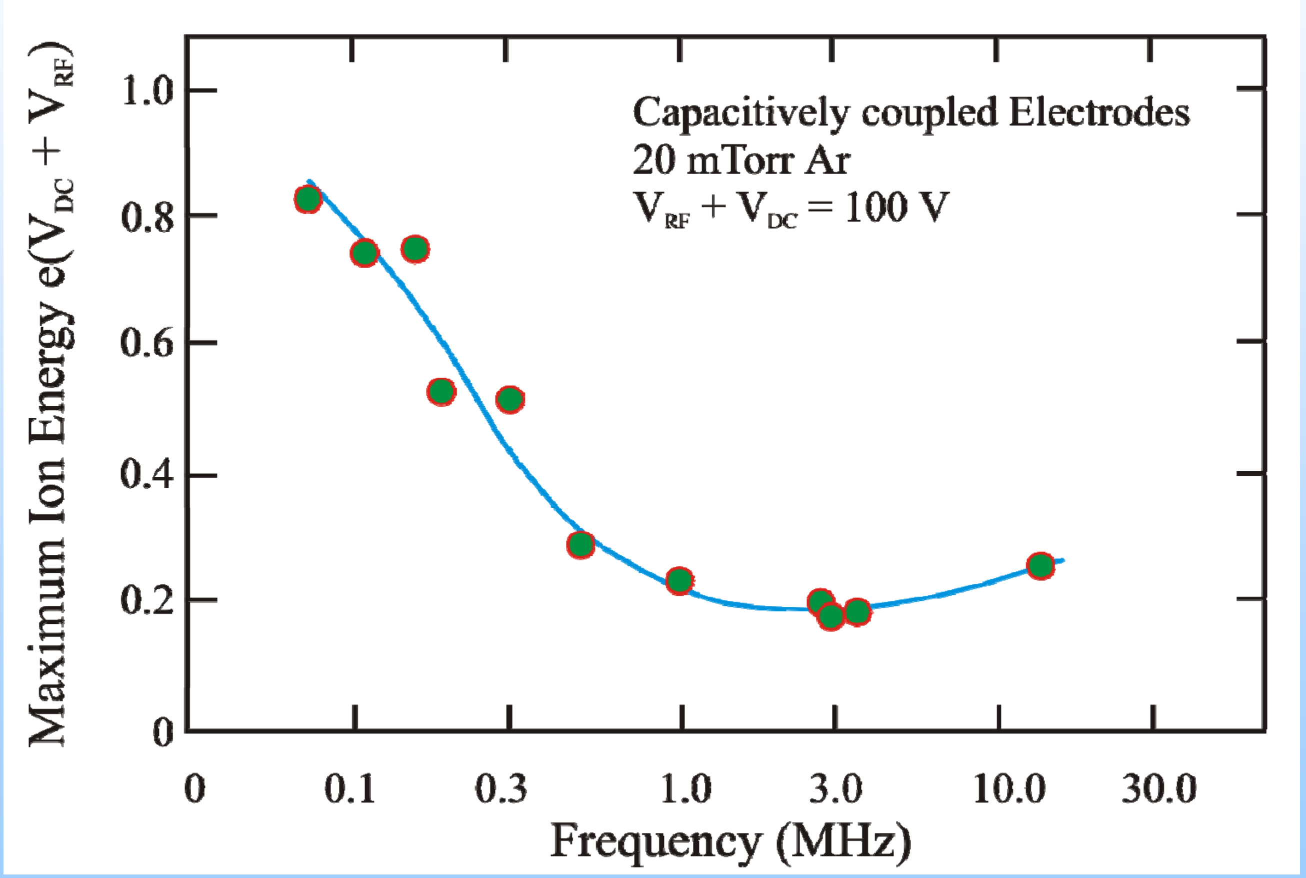
Ion energy: e (V_P - V_E) should be understood

RF Diode System

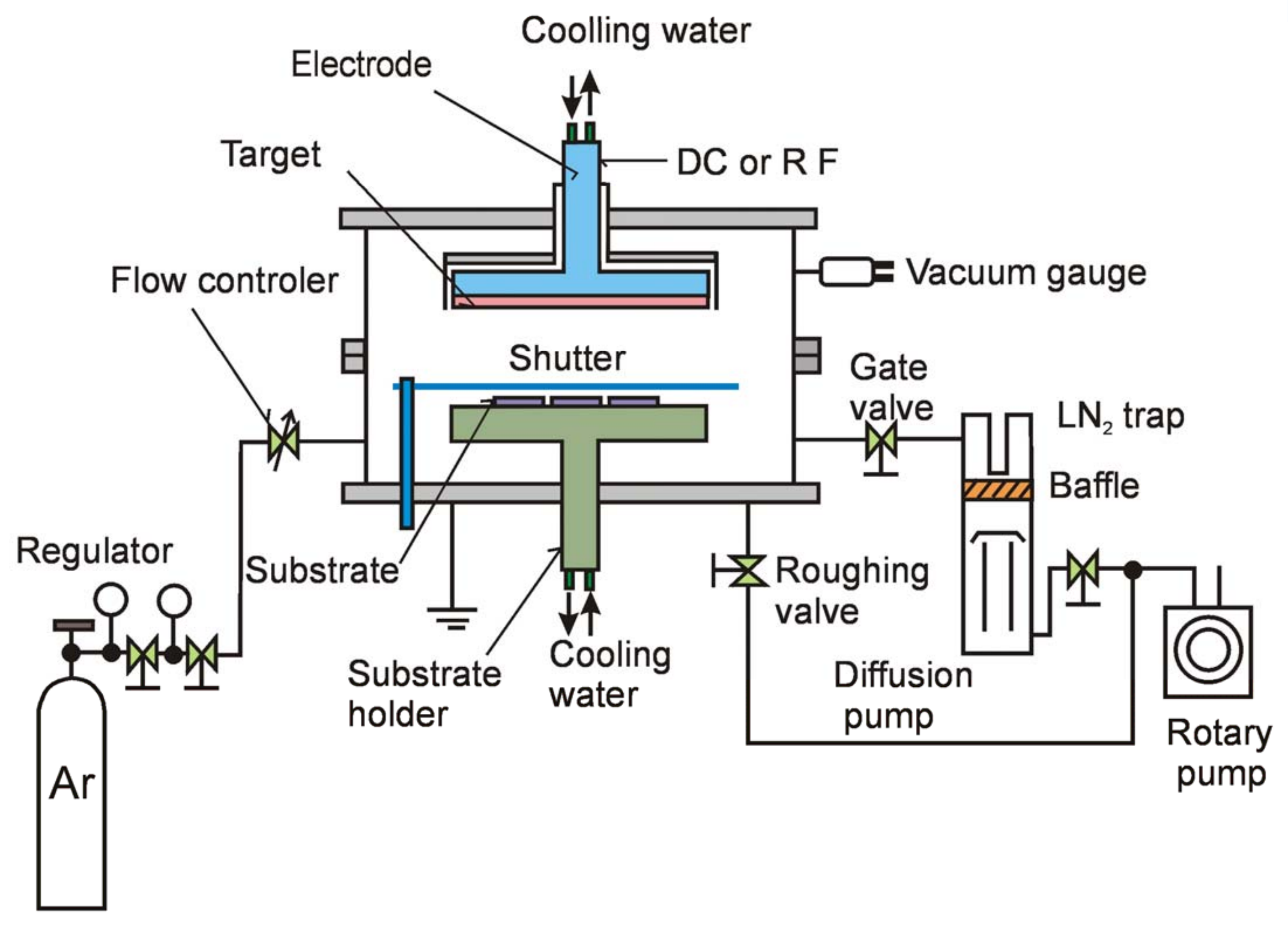


- The frequency most commonly used is 13.56 MHz (27.12 MHz)
- Blocking capacitor – floating electrode: self-bias potential
- Conductive electrode: self-bias is not generated without C
- High frequency voltage - applied to an insulating target: self-bias
- Deposition of insulating materials is possible and very effective
- Average current density ~ 1 mA/cm^2 at ~ 1 kV electrode voltage

Ion Energy Depends on Frequency



Schematic Diagram of Sputtering Deposition System

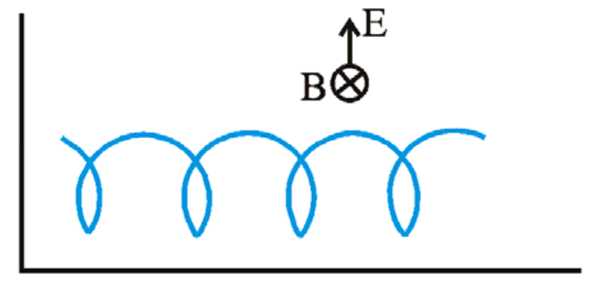


Magnetron Sputtering

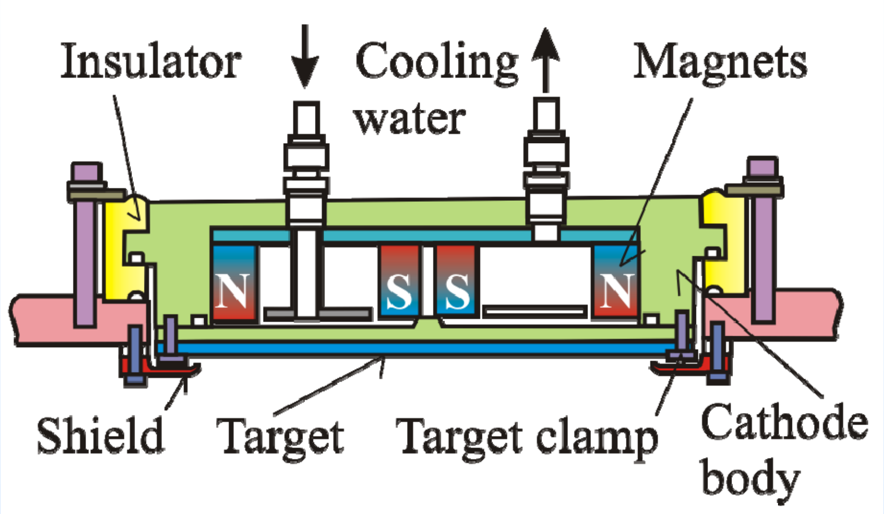
- Magnetron – device with a magnetic field perpendicular to an electric field – crossed electric and magnetic fields.

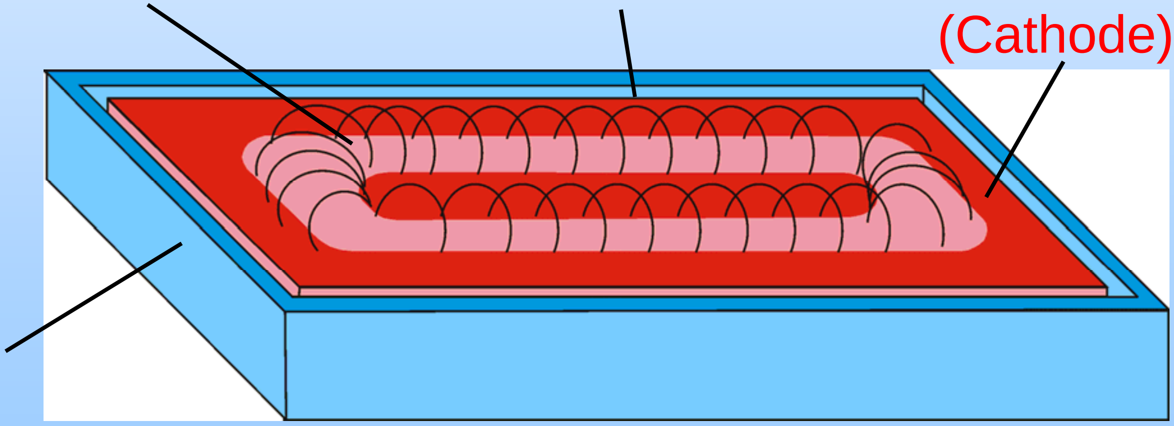
Several types of magnetrons

- Cylindrical; Planar: circular, rectangular
- Operated using either DC or RF.
- Plasma density increases in magnetically confined region - decrease in discharge impedance.
- Higher ion current density, 10 – 100 times than that in RF diode type.
- Increase in the deposition rate.
- Deposition rate per unit power density at the target also increases.



Circular Planar Magnetron





Sputter Erosion Truck

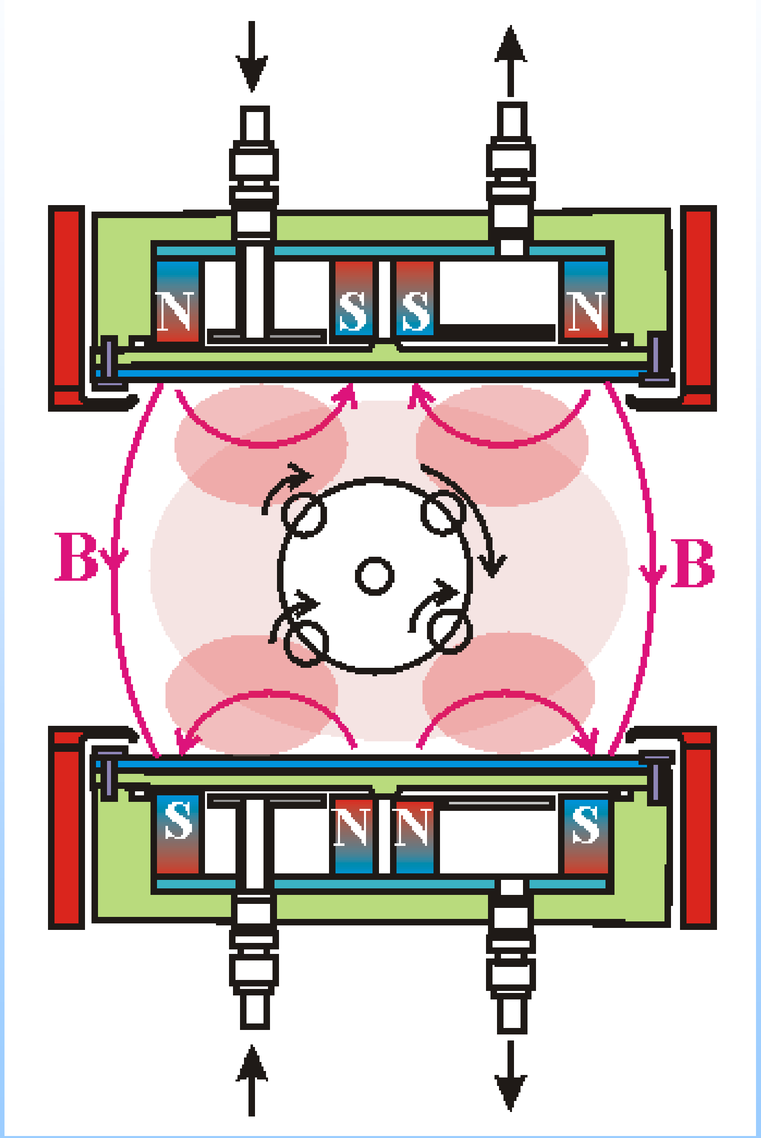
Magnetic Field

Sputter Target (Cathode)

Magnet Assembly Case

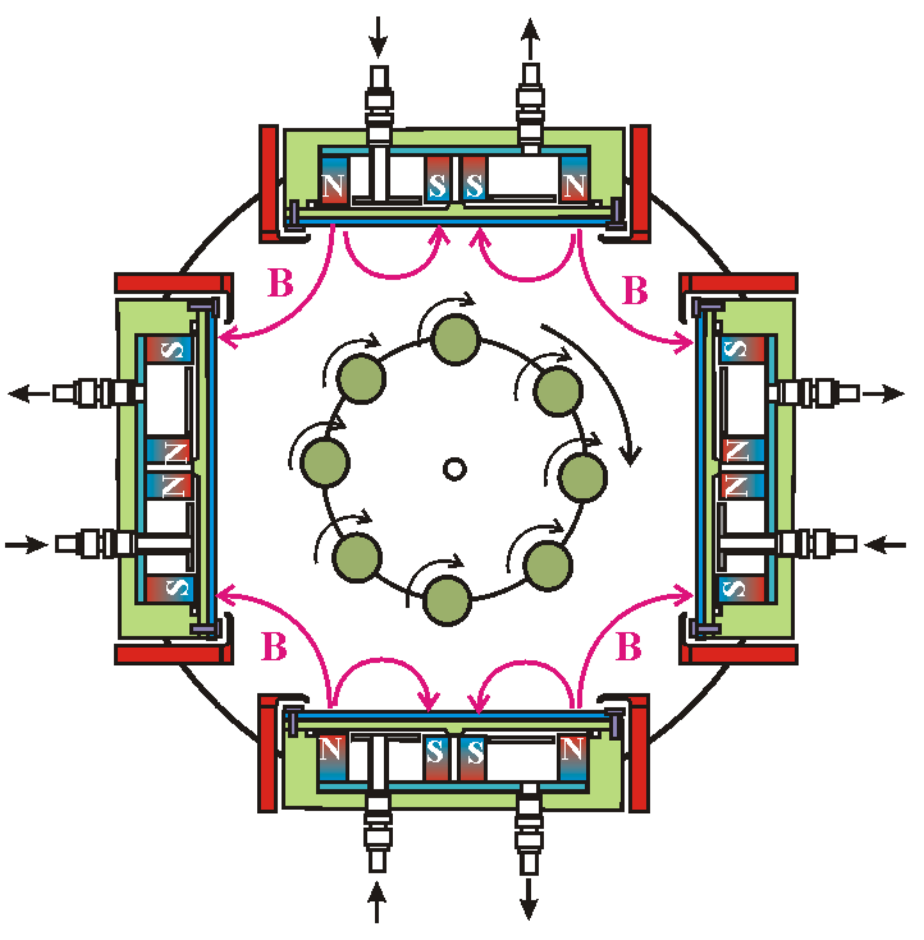
Rectangular Planar Magnetron

Deposition Systems with Two Magnetrons



- Two unbalanced
- Closed mg field
- Planetary motion

Sputtering System with Four Planar Magnetrons



- Production configuration
- Four unbalanced magnetrons
- Plasma density is enhanced by the closed magnetic field.
- Planetary motion for coating is provided