Outline

1 Introduction

2 Basic IC fabrication processes

3 Fabrication techniques for MEMS

4 Applications

5 Mechanics issues on MEMS

2. Basic IC fabrication processes

2.1 Deposition and growth

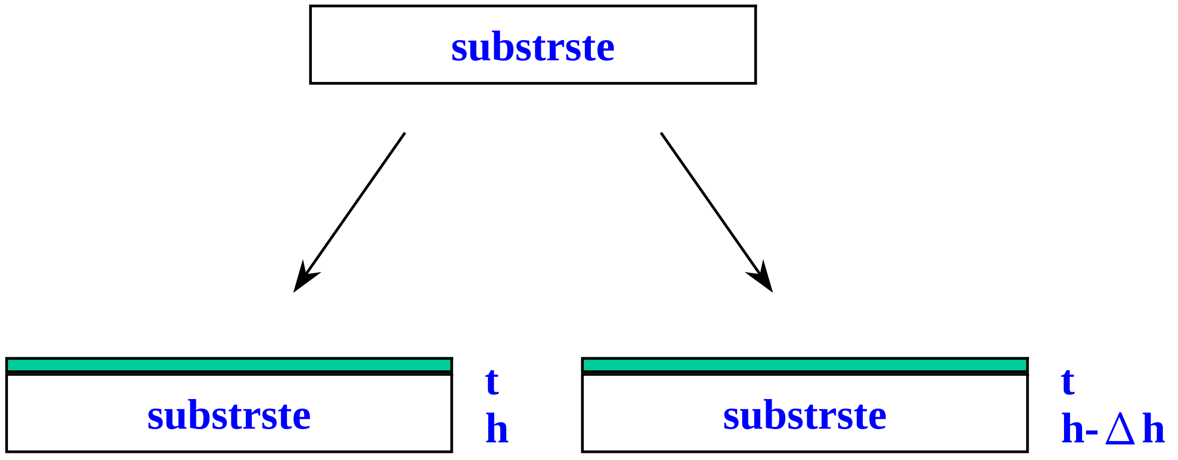
2.2 Photolithography

2.3 Etching

2.4 Bonding

2.1 Deposition and growth

- **Deposition and growth are the processes to produce a thin film on the surface of substrate**
- **Deposition vs Growth**



substrste

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t
h

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t
h-Δh

- **Two approaches for deposition**

  + **Physical vapor deposition (PVD)**

    Evaporation
    Sputtering

  + **Chemical vapor deposition (CVD)**

    LPCVD
    PECVD

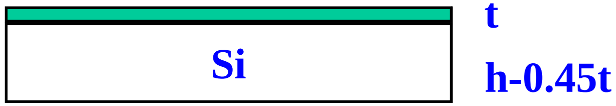
2.1.1 Growth

Reading: Runyan Chap. 3, or 莊達人 Chap. 10

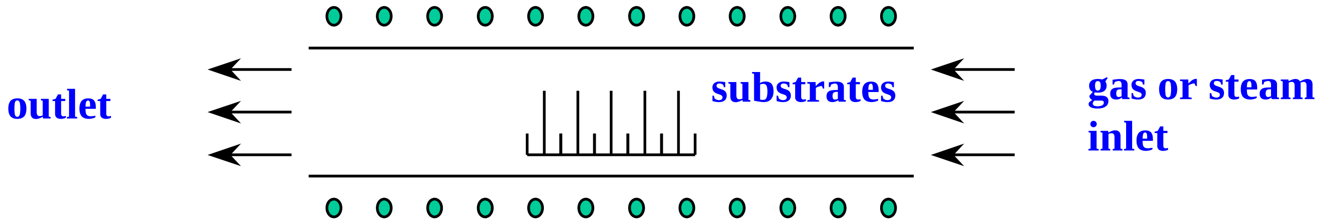
- **Thermal oxidation is the most common growth process**

  + Dry oxidation: $Si + O_2 \rightarrow SiO_2$

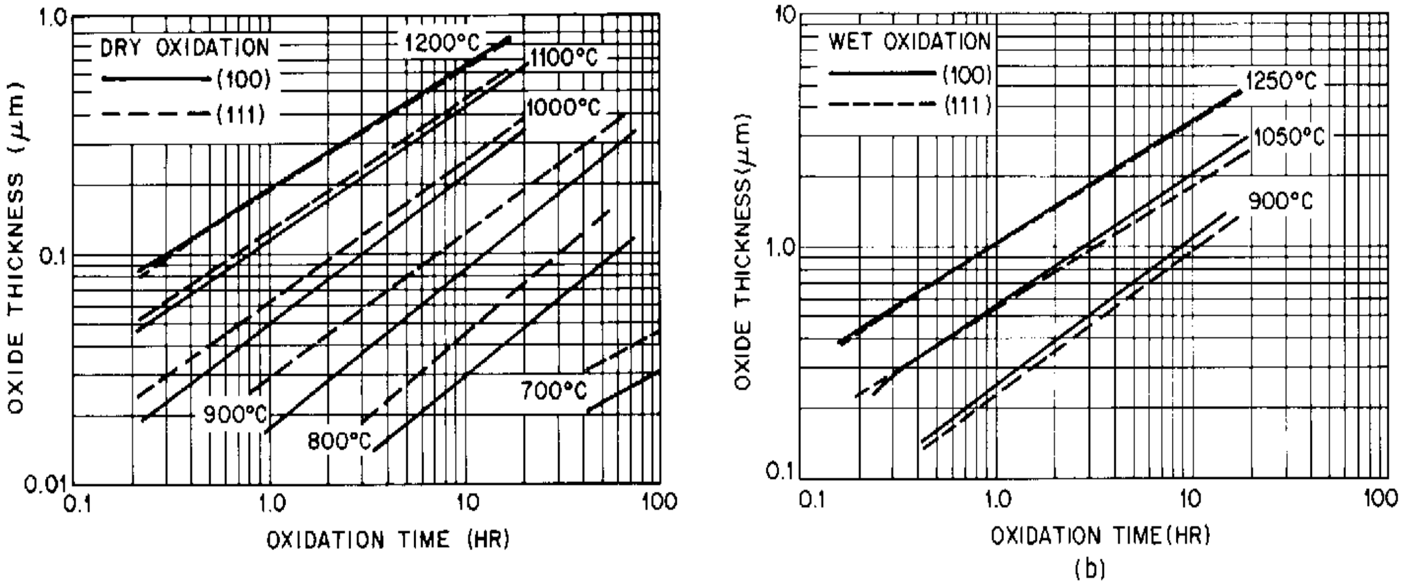
  + Wet oxidation: $Si + H_2O \rightarrow SiO_2 + 2H_2$



- **Furnace**



- Oxide growing rate depends on both chemical reaction and diffusion rate (of oxygen or steam)
  - + Initially the process constrained by the reaction rate
  - + When oxide reach a certain thickness, the process constrainted by the diffusion rate
- Wet oxidation has higher growing rate



S.M. Sze, Physics of Semiconductor Devices, 1981

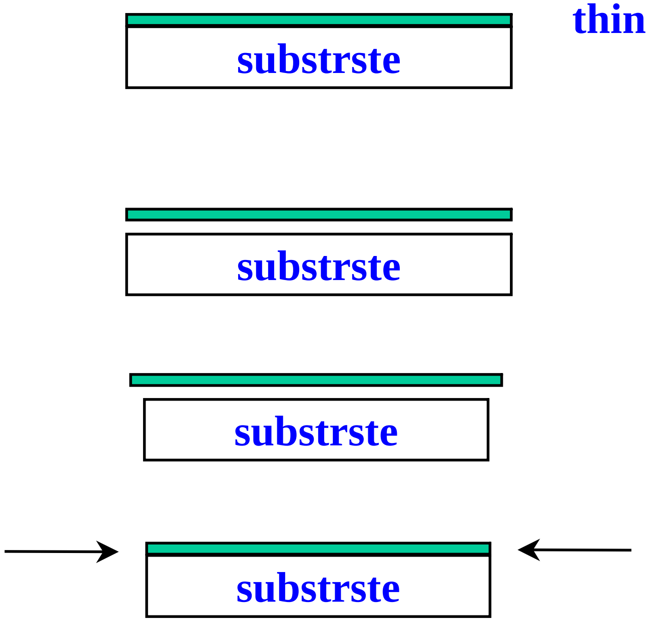
- **Thermal residual stress induced by the difference of thermal expansion coefficients between substrate and thin films**

Residual strain

Thermal expansion coefficient

$$\varepsilon = \Delta\alpha\Delta T$$

Temperature



high temperature (inside the furnace)

low temperature (outside the furnace)

- **Effect of growing process on oxide Young's modulus**

57 GPa (wet)
67 GPa (dry)
K.E. Petersen and C.R. Guarnieri, J. Applied Physics, 1979.

60 GPa (20% dry and 80% wet)

W. Fang and J.A. Wickert, DSSC Annual report, Carnegie Mellon University, 1992.

- **Effect of oxidation temperature on oxide density**

Temperature(C)	Density
600	2.286
700	2.265
800	2.253
900	2.236
1000	2.224
1150	2.208

E.A. Irene et al., J. Electrochemical Society, 1982.

- **Advantage : easy to operate and inexpensive**
  good quality

- **Disadvantage : high operating temperature**
  thermal residual stress
  time consuming

- **Silicon nitride can be grown through the same mechanism, however the growing temperature is too high**

$$3Si + 2N_2 \rightarrow Si_3N_4$$

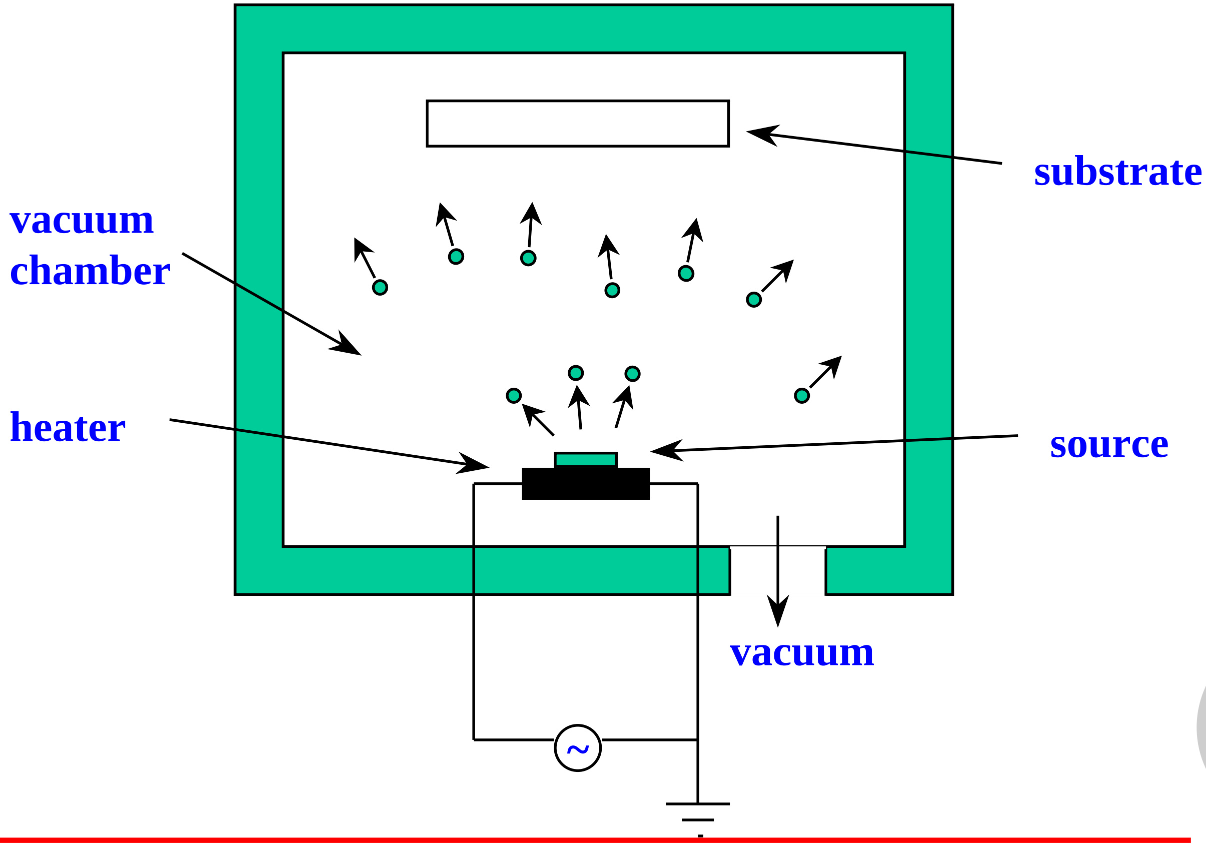
Physical Vapor Deposition (PVD)

Reading : Ohring Chap.3, or 莊達人 Chap.5, or Vossen and Kern Chap.2

- The films generated by growth process are limited to silicon compound only (e.g. SiO_2 , Si_3N_4 , etc.)
- PVD can be applied to deposit a film other than silicon compound (e.g. metal film)
- PVD processes have the following three steps
  + The material to be deposited is physically converted to a vapor phase
  + The vapor is transported from the source to the substrate through a reduced pressure region
  + The vapor condenses on the substrate to form a thin film

2.1.2 Evaporation

- Evaporation is the process to deposit the thin film by applying heat (or electron beam) to evaporate the source of film material
  - \+ Electron beam (E-gun)
  - \+ Inductive heating



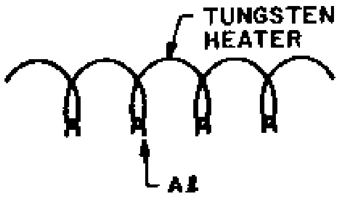
vacuum chamber

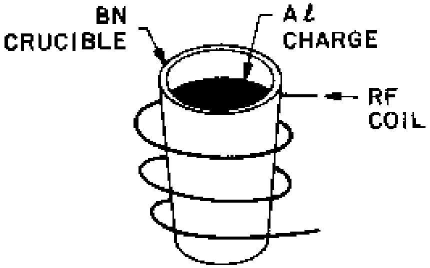
heater

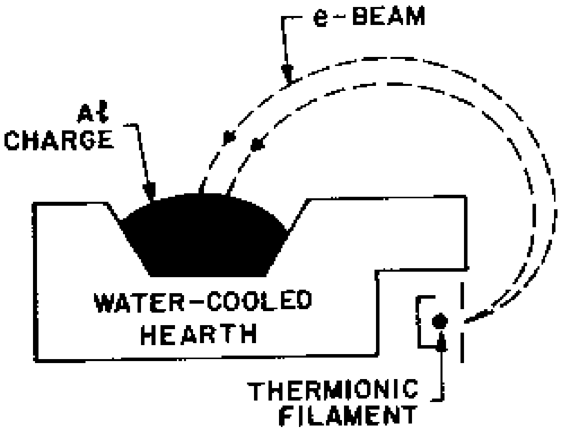
substrate

source

vacuum





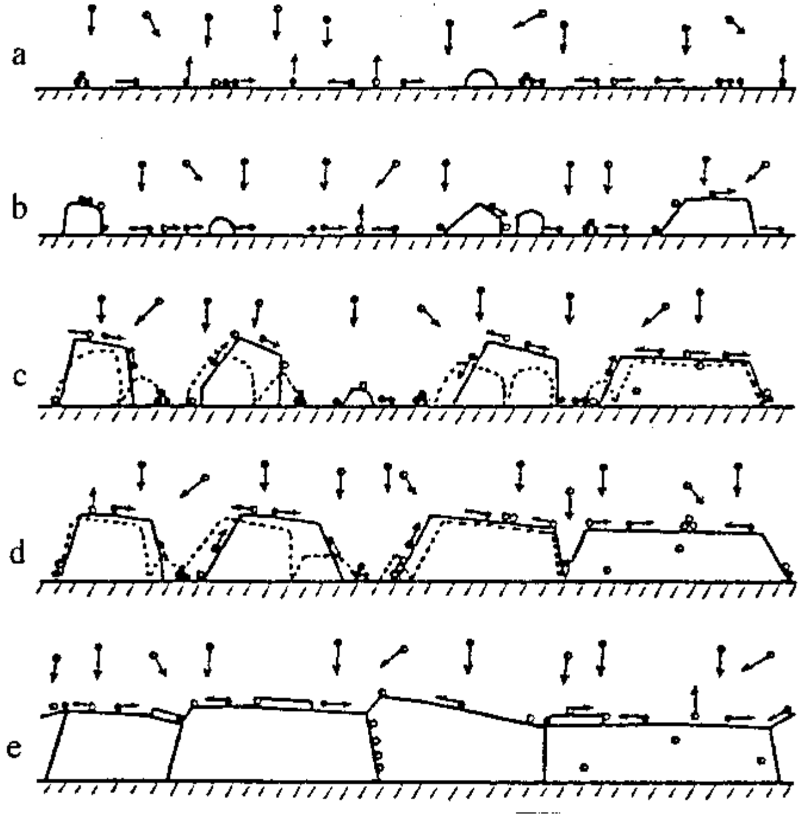


S.M. Sze, Semiconductor devices, 1985

Deposition Mechanism

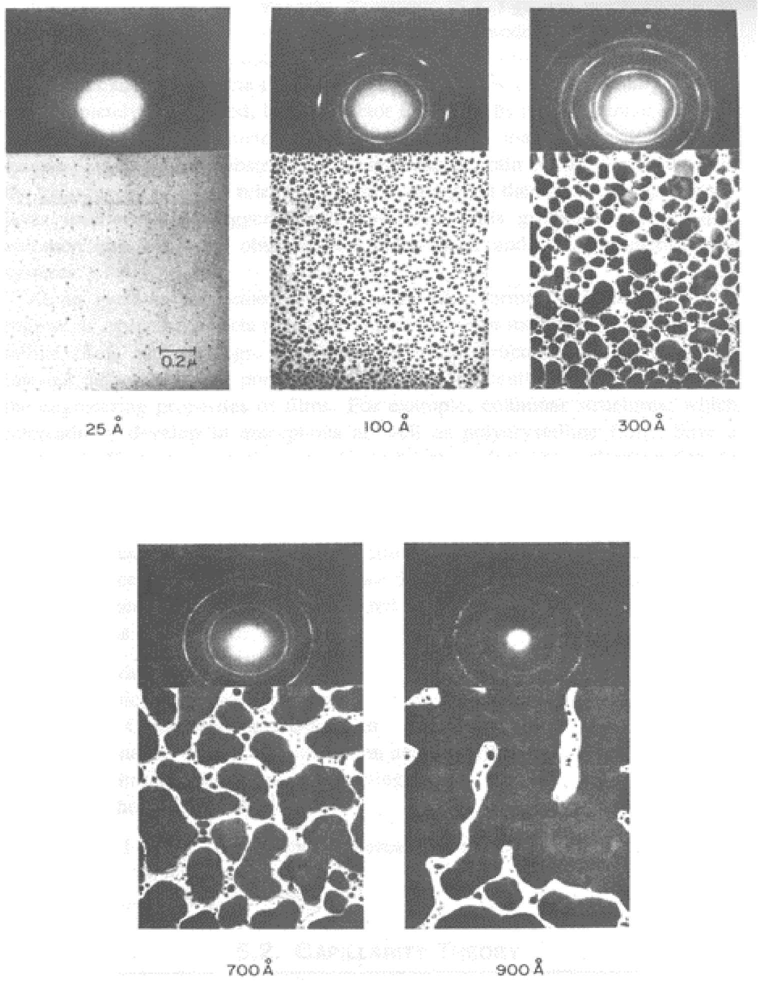
- The vapor deposits on the substrate through five steps

  (a) Nucleation
  (b) Nuclei growth
  (c) Coalescence
  (d) Filling of channels
  (e) Film growth



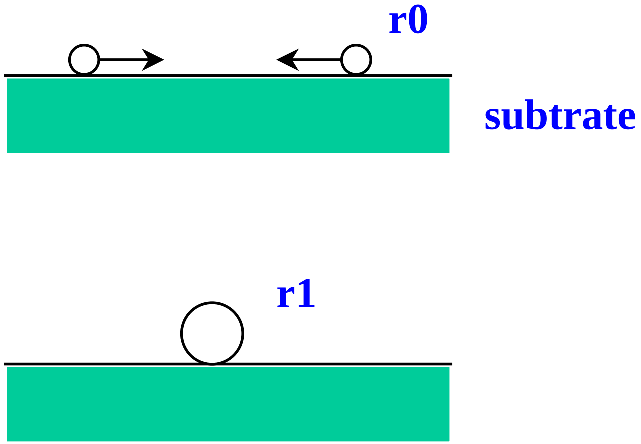
L. Eckertova and T. Ruzicka, Diagnostics and Applications of Thin Films, 1993.

- **Nucleation, growth, and coalescene of Ag films**



R.W. Vook, International Metals Review, 1982.

- **Nucleation**

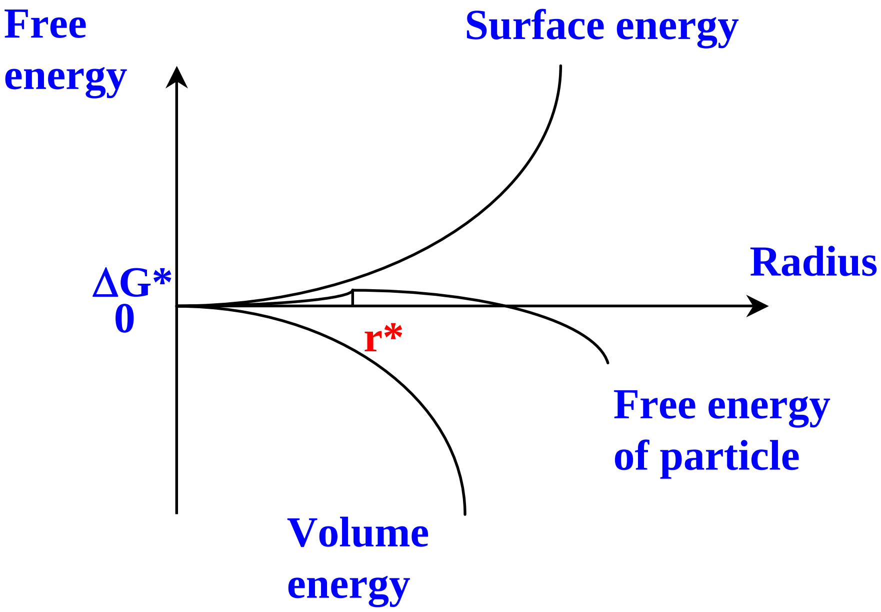


- **Free energy of particles**

+ **Surface energy:** $4\pi r^2 \cdot A$

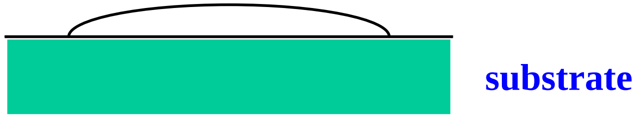
+ **Volume energy:** $\frac{4}{3}\pi r^3 \cdot B$

+ **Free energy of particle: surface energy + volume energy**



r* is critical radius

- **In the real case**



Advantages

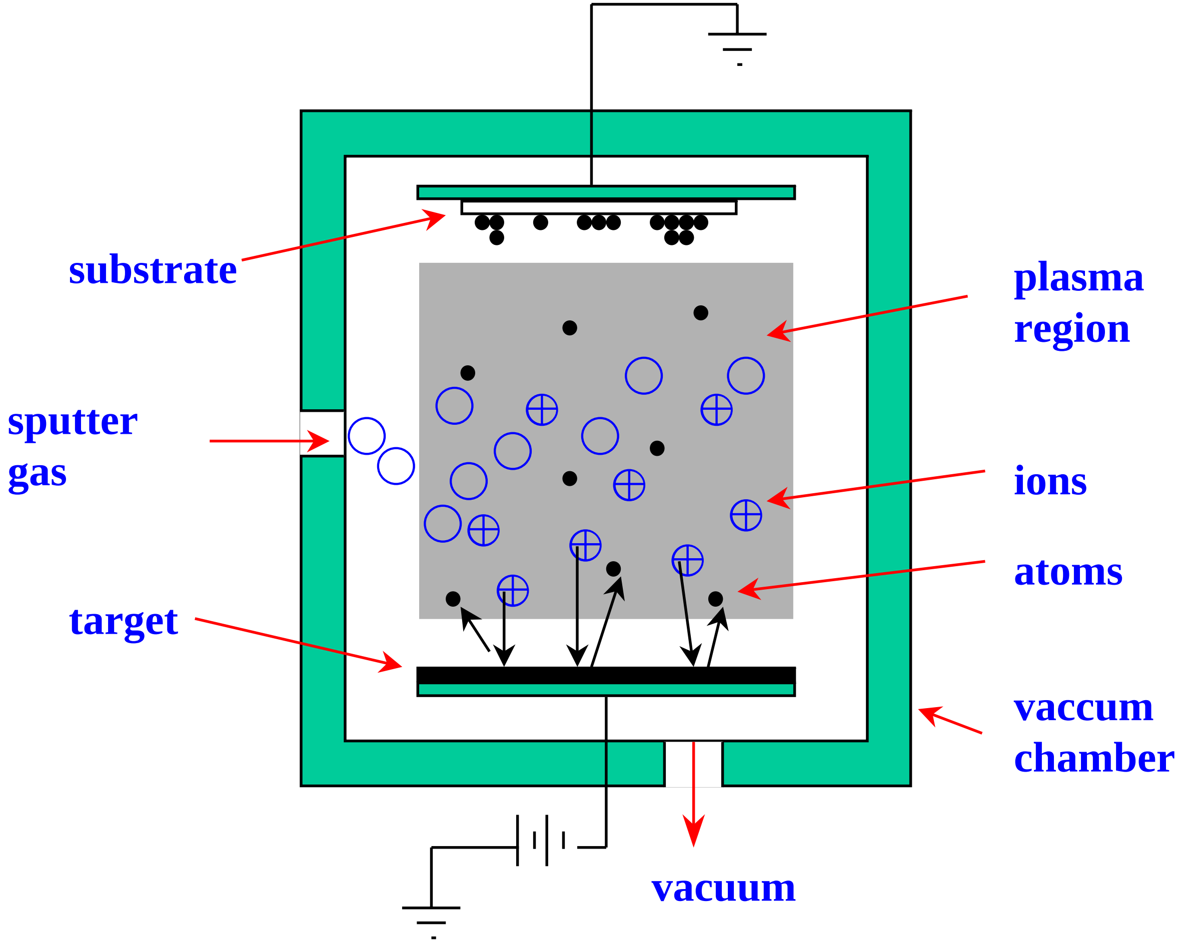
- **High deposition rate (e.g. 0.5 μm/min for *Al*)**
- **The low energy of the impinging metal atoms onto the substrate leaves the substrate surface undamaged**
- **Due to high vacuum environment, less residual gas will be incorporated in the deposited film**

Disadvantages

- It is difficult to deposit multicomponent (e.g. AlCu) by evaporation, since their vapor pressure are different
- It is necessary to operate vaporation process in higher vacuum environment to prevent collision between evaporant and gas molecules
- It is difficult to melt high melting point material (need electron beam to complete the processes)
- Poor step coverage

2.1.3 Sputtering

- Sputter deposition is the process to form a film on the substrate from the atoms which are generated by the bombarding of high energy particles (ie ions in plasma) on a target



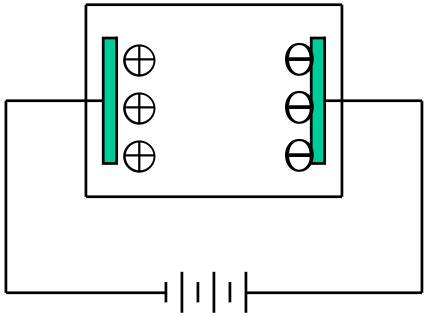
Four Major Steps of Sputtering Processes

- Ions are generated through plasma
- Ions are directed and accelerated to impact the target
- Target atoms are ejected by the ions, and then transported to the substrate
- Atoms condense and form a thin film

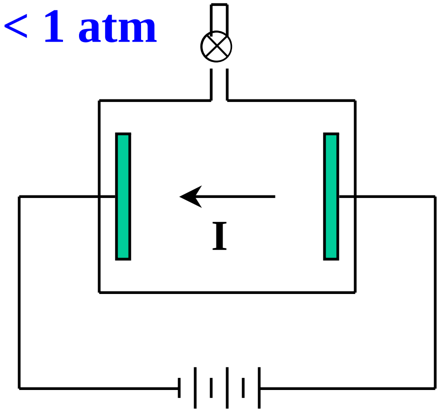
Plasma

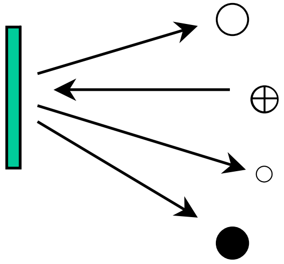
- Plasma is a partially ionized gas which contains ions, electrons, molecules, and radicals

p = 1 atm



p << 1 atm





○ Neutralizeed gas molecule

⊕ Bombarding ionize

○ e - Secondary electron

● Atom of the electrode

- Ionized reactions induced by secondary electron

$$e^- + H_2 \rightarrow H_2^+ + 2e^-$$ (ionization reaction)

Plasma process

1. Clean the chamber by pumping it to high vacuum (< 10^{-6} Torr)
2. Add Ar gas and the chamber becomes low vacuum (usually arround 1 ~ 10m Torr)
3. Applied a high voltage to the electrode
4. A free electron existing in the electric field will be accelerated (this free electron is most likely created from Ar by a passing cosmic ray)
5. The accelerated electron will hit an Ar atom after traveling a distance (its mean free path)
6. If the electron has enough energy (> 15.7 eV for Ar), this Ar atom will be ionized by releasing its electron
7. If the electron do not have enough energy, the orbital electron of this Ar atom will be excited to a higher energy state

8. **When the number of free electron increased, the area between two electrode will reach a condition called gas break down and then current flows in the external circuit**

9. **The current will decay to zero unless there is a mechanism available for generating additional free electrons**

10. **In the mean time, the ions generated in step 6 will also hit the electrode (cathode) after accelerated in the electric field. Thus the cathode emits free electrons (secondary electron) when struck by ions**

11. **Finally, the current in step 8 is sustained by the free electron generated in step 10**

More details can be found in :

(1) B. Chapman, Glow Discharge Processes, 1980.
(2) J.L. Vossen and W. Kern (editors), Thin Film Processes, 1978.

- **The most common gas for plasma is Argon (Ar)**
  - **+ Noble gas**
  - **+ Cost**
  - **+ Mass**

- **Excitation reactions induced by secondary electron**

$e^- + Ar \rightarrow Ar^* + e^-$ **(excitation reaction)**

$Ar^* \rightarrow Ar + h\upsilon$ **(Ar* is excitated state)**

- **DC sputtering**

  + Apply an DC voltage to the electrode

  + For conductor only

- **RF sputtering**

  + Apply an AC voltage to the electrode

  + For both conductor and insulator

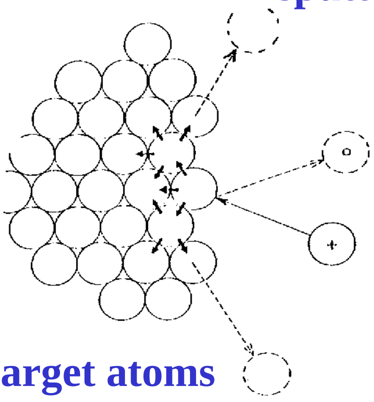
- **Magnetron sputtering**

  + Add magnetic field near the target - change the motion of secondary electron from linear to cycloid

  + Increase the percentage of electrons that cause ionizing collisions

Mechanics of Sputtering

- Particles collision model



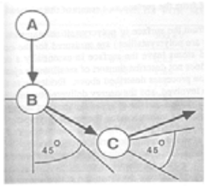
sputtered atom

neutralized gas molecule, rebounded from the target surface

Bombarding ionized gas molecule

Target atoms

sputtered atom



G.K. wehner and G.S. Anderson, The Nature of Physical Sputtering, 1970.

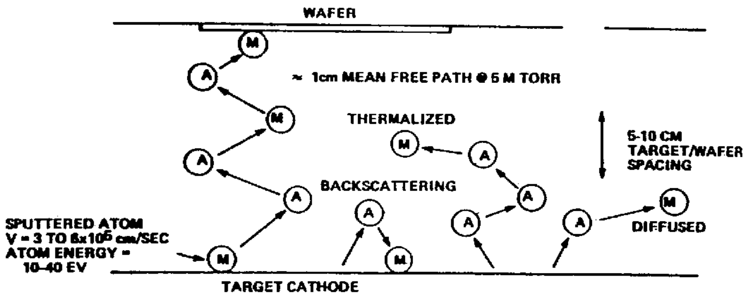
- Sputtering yield - the number of atoms ejected per incident ions
- Sputtering yield depends on four factors

  (1) Direction of incidence of the ions
  (2) Mass of bombarding ions
  (3) Energy of the bombarding ions
  (4) Target material

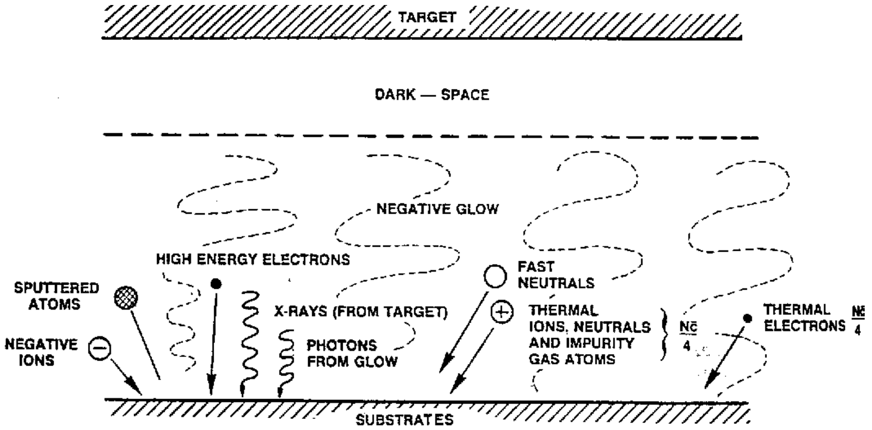
- **Response and the kinetic energy of the ions**
  - + **High energy (> 10 KeV) : the bombarding ions are most likely to be embedded in the target**
  - + **Low energy (< 10 KeV) : reflection or absorption of the bombarding ions**
  - + **Energy between the above two extremes : the energy of the bombarding ions is (1) transferred to the solid in the form of heat and crystal damage, and (2) ejected the atoms from the surface**

- **Sputtering is a low efficient process, after ion bombardment:**
  - + **70% of the ion energy becomes heat**
  - + **25% of the ion energy generating secondary electrons**
  - + **only 2% of the ion energy used for sputtering process**

- **Path during the condensation of the sputtered atoms**



- **Species arriving at the substrate in a sputtering system**



S. Wolf and N. Tauber, Silicon Processing for the VLSI Era, 1986

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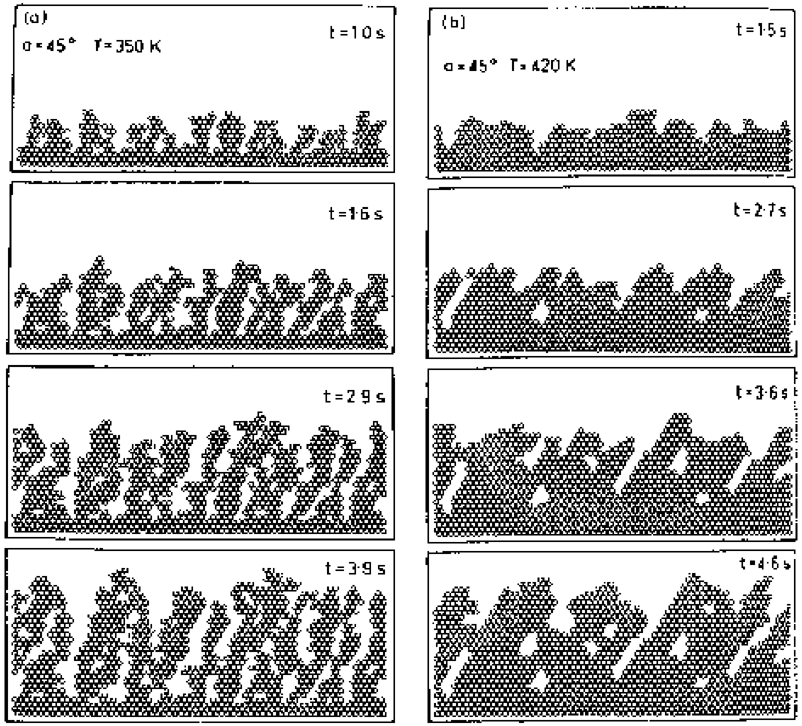
Intrinsic residual stress

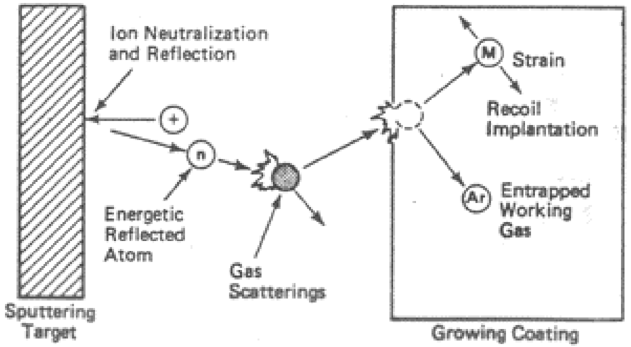
- Computer simulation of a film deposited by evaporation at different temperature
- Tensile residual stress due to the voids of the film



M. Ohring, The Material Science of Thin Films, 1992.

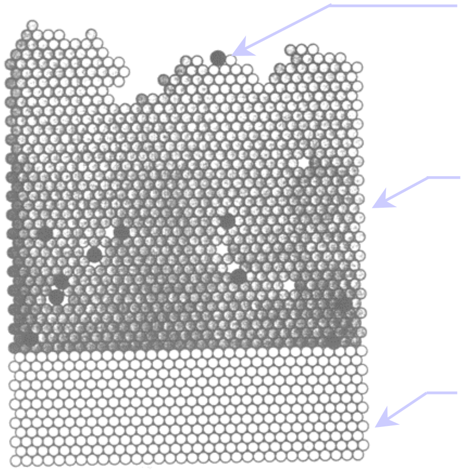
- Compressive residual stress due to atomic peening and ion bombardment

+ Atomic peening



J.A. Thorntorn and D.W. Hoffman, J. Vacuum Science and Technology, 1985.

+ Computer simulation of a film structure after ion bombardment



Tungsten (W) film

Substrate

C.C. Fang et.al., J. Vacuum Science and Technology, 1993.

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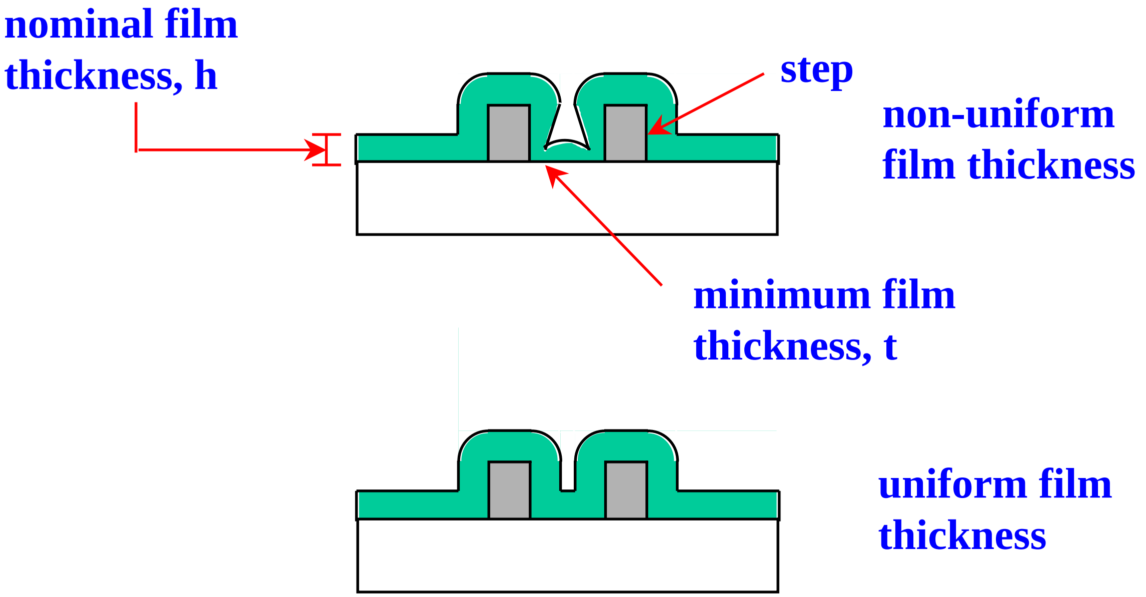
Step coverage

- If the surface of the substrate has a **step structure**, the thickness of the deposited film may not be uniform
- **Step coverage** is defined as the **ratio** of the minimum thickness of the film as it cross a step to the nominal thickness of the film on the flat region

Step coverage (%) : $t/h \times 100\%$



- **Step coverage is determined by**

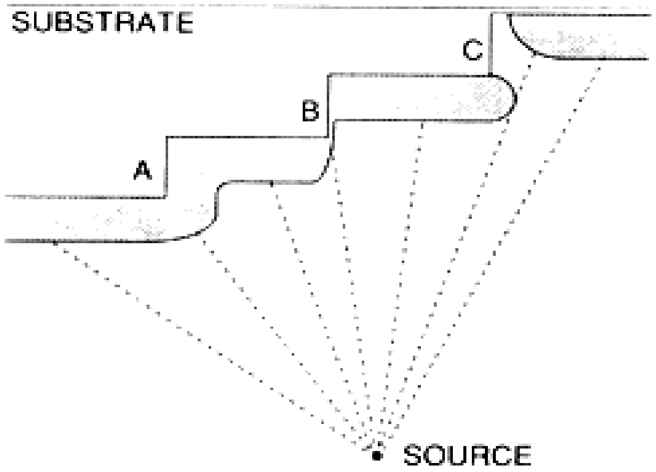
  + **height of the step**

  + **aspect ratio**

  + **the slope of the step**

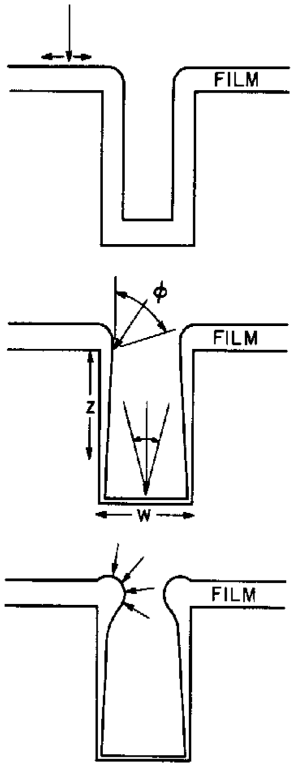
  + **shape of the step**

  + **deposition method**



M. Ohring, The materials science of thin films, 1992

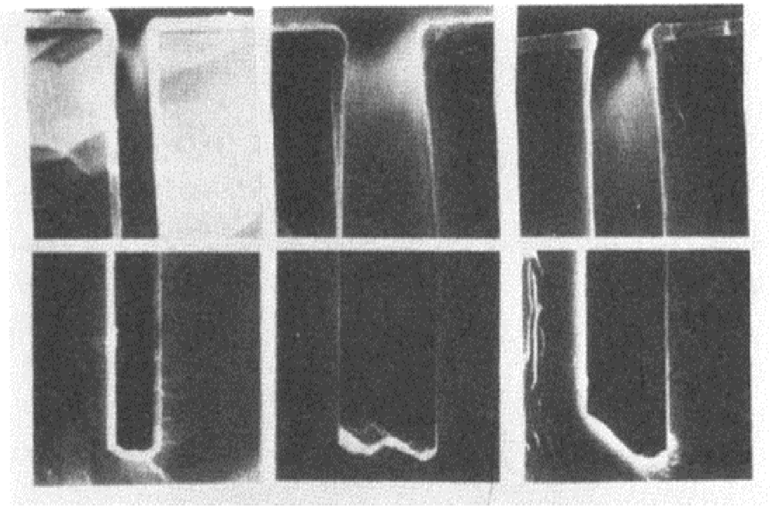
- **Step coverage for deposited films**



(a) **surface migration**

(b) **long mean free path**

(c) **short mean free path**



S.M. Sze, VLSI Technology, 1988

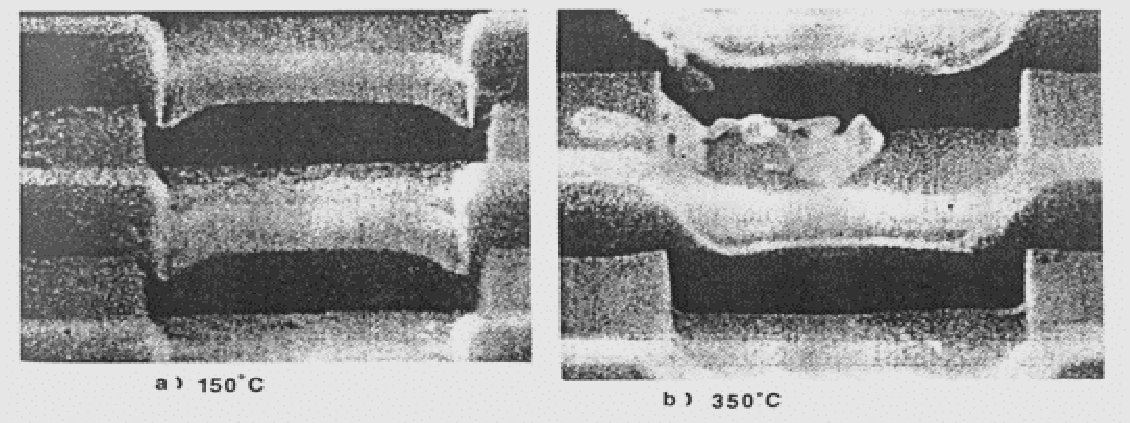
- Step coverage can be improved by the following approaches

  + heating the substrate can improve the step coverage

  + sputter etching the underlying substrate before deposition

  + optimize the target design

  + bias sputtering



S. Wolf and N. Tauber, Silicon Processing for the VLSI Era, 1986

Advantages (vs evaporation)

- **Uniform thickness over large substrates**
- **Control film thickness easily**
- **Control alloy composition**
- **Control step coverage, grain structure, stress by varying the deposition conditions**
- **Better adhesion**

Disadvantages (vs evaporation)

- **Expensive equipment**
- **Ion bombardment is critical to some materials (organic)**
- **More impurities due to lower vacuum**

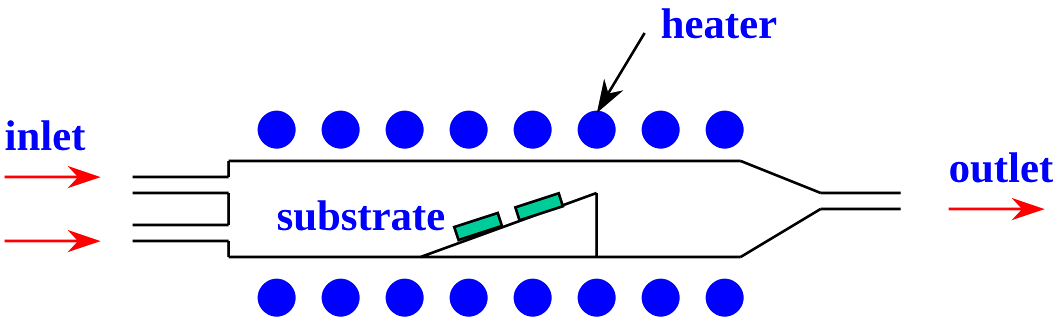
2.1.4 Chemical Vapor Deposition (CVD)

- **CVD** - CVD is the process to produce a solid film on the substrate by **chemically reacting a gas** (or a set of gases) which is the compound of the material to be deposited

+ Examples :

$$SiH_4 \rightarrow Si + 2H_2$$

$$SiH_4 + O_2 \rightarrow SiO_2 + 2H_2$$



Five Basic Steps of CVD Processes

- The reactants are transported onto the substrate surface
- The reactants are adsorbed on the substrate surface
- A chemical reaction takes place on the surface leading to the formation of the film and reaction products
- The reaction products are desorbed from the substrate surface
- The reaction products are transported away from the substrate surface

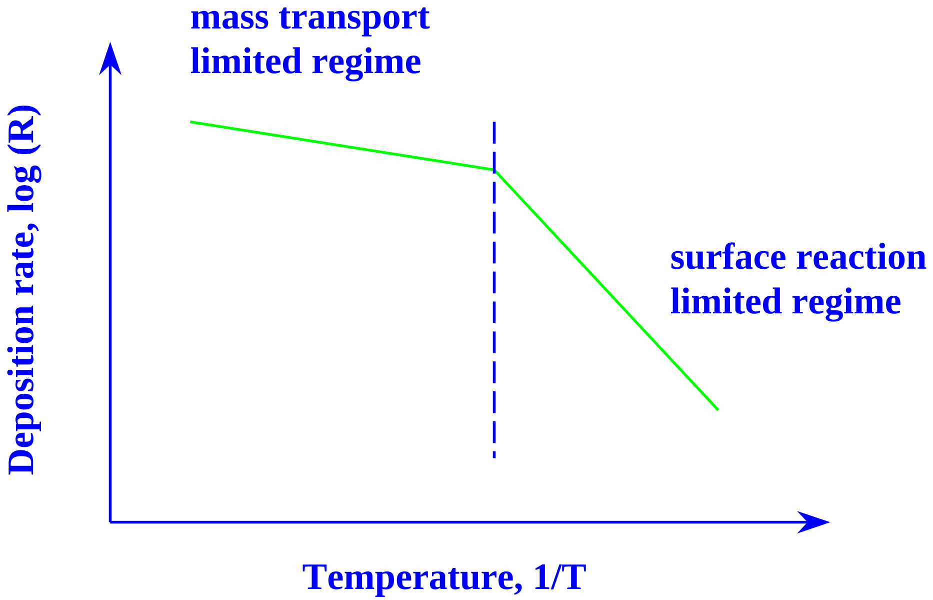
Deposition Rate

- Since the five steps of CVD process are sequential, the one with slowest rate will determine the deposition rate

- The deposition rate is determined by (1) surface reaction rate, or (2) mass transportation rate

  + surface reaction rate, $R = K_0C_1e^{-E_1/kT}$

  + mass transportation rate, $R = DC_2e^{-E_2/kT}$



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- **Mass transport limited regime**

  + high temperature (compare with surface reaction regime)

  + Need to control the flux of reactant to insure films with uniform thickness

  + poor thickness uniformity

- **Surface reaction rate limited regime**

  + low temperature (compare with mass transport regime)

  + Need to control temperature well

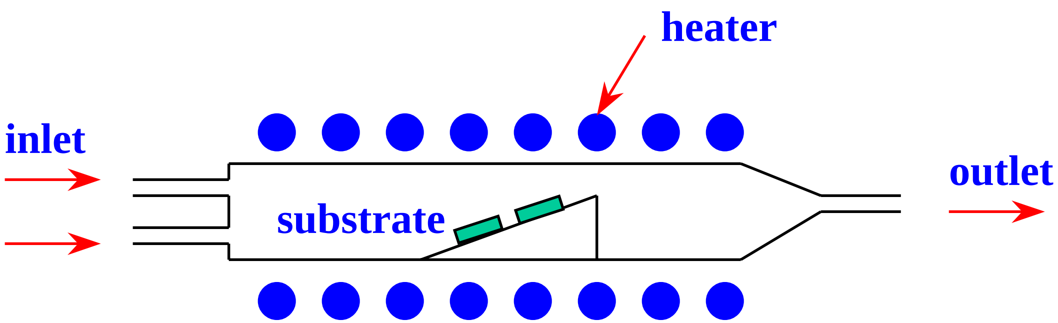
  + better thickness uniformity

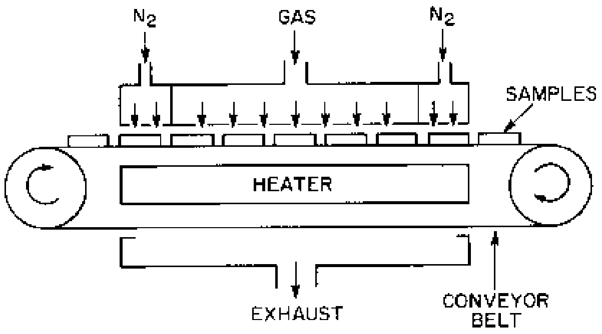
Three most common CVD process

- **Atmospheric pressure CVD (APCVD)**

  + APCVD is CVD process operating at atmospheric pressure

  + Conducted in mass transporation limited regime - the reactant flux to all parts of every substrate in the reactor must be controlled





(b)

VLSI Technology edited by S.M. Sze, 1988.

- **Low pressure CVD (LPCVD)**

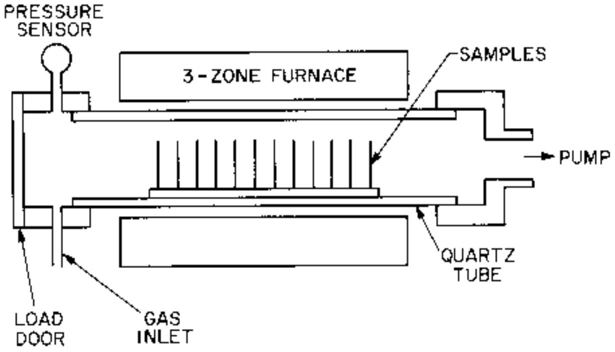
+ LPCVD is CVD process operating at medium vacuum (0.25 ~ 2.0 torr) and higher temperature (550 ~ 600 C)

+ Conducted in surface reaction rate limited regime

+ Better thickness uniformity - temperature control is relatively easy to achieve (compare with flux control)

+ Higher wafer capacity - less restriction on the location of the substrate

+ Less particulate contamination - gas phase reaction is reduced by low pressure



VLSI Technology edited by S.M. Sze, 1988.

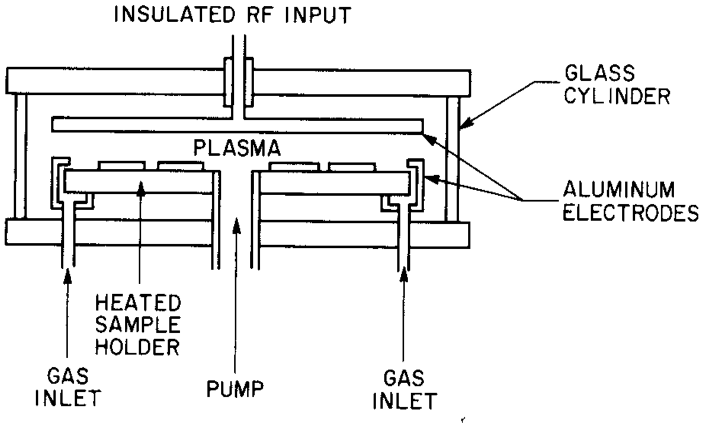
- **Plasma enhanced CVD (PECVD)**

  + **PECVD uses both the thermal energy and RF-induced plasma to transfer energy into the reactant gases**

  + **Conducted in surface reaction rate limited regime**

  + **Residual stresses can be adjusted by ion bombardment**

  + **Deposited film is contaminated by by-products**



VLSI Technology edited by S.M. Sze, 1988.

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- **Summary of three major CVD processes**

Process	Advantages	Disadvantages	Applications
APCVD	Simple reactor Fast deposition Low temperature	Poor step coverage Particulate contamination	Oxide
LPCVD	Excellent purity, uniformity, and step coverage Large wafer capacity	High temperature Low deposition	Oxide Polysilicon Silicon Nitride
PECVD	Low temperature Fast deposition Good step coverage	Chemical and particulate contamination	Metals Silicon Nitride

S. Wolf and R.N. Tauber, Silicon Processing for the VLSI Era Vol.1, 1986

Conclusions

- The approach of thin film deposition (or growth) is depended on several conditions

  + The purpose of the deposited (grown) film

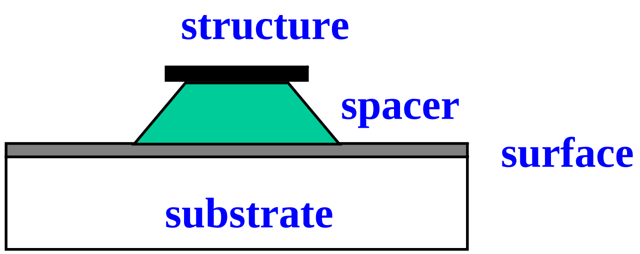
  + The material to be deposited

  + The allowable operating condition (eg. temperature)

  + Available equipment and budget

- **The MEMS materials used in different places**

Place	Structure material	Spacer material	Surface material
UC-Berkeley	polysilicon	oxide	silicon nitride
MIT	polysilicon	aluminum	oxide
Stanford	aluminum	polymide	oxide
Carnegie Mellon	oxide and aluminum	bulk silicon	bulk silicon
Nissan	silicon nitride	polysilicon	silicon nitride



Appendix

- Properties of silicon dioxide depend on the deposition processes

Material	Deposition temperature (C)	Step coverage	Stress (10^9 dynes/cm^2)	Etch rate (A/min)
Thermal	800 - 1200	conformal	3C	
PECVD	200	good	3C-3T	400
APCVD	450	poor	3T	60
LPCVD	700	conformal	1C	30

Source: Prof. G. Kovacs at Stanford University

Purpose

- **The selection of thin film materials is determined by its application**

  + Static

  + Dynamic

  + Wear and friction

  + Insulator or conductor

  + Brittle or ductile

Materials for Thin Film Structures

- Typical materials semiconductor
  - + silicon (Si)
  - + silicon dioxide (SiO_2)
  - + silicon nitride (Si_3N_4)
  - + polycrystalline silicon (polysilicon, or poly)
  - + aluminum alloy (AlCu, etc.)

- Metals
  - + titanium (Ti)
  - + tungsten (W)
  - + gold (Au)
  - + nickel (Ni)
  - + others

- Active films
  - + lead-zirconate-titanate (PZT)
  - + zinc oxide (ZnO)
  - + aluminum nitride (AlN)
  - + shape memory alloy (TiNi)

- **Carbon films**
    - \+ silicon carbide (SiC)
    - \+ diamond-like carbon (DLC)
    - \+ fluorocarbon (FC)

- **Polymer films**
    - \+ polyimide
    - \+ poly-methl-metha-acrylate (PMMA)
    - \+ poly-vinyl-di-fluoride (PVDF)

- **Available substrate materials**
    - \+ single crystal silicon (nature semiconductor)
    - \+ GaAs (compound semiconductor)
    - \+ glass
    - \+ quartz
    - \+ metals, plastics, ceramics etc..

Material Properties for Thin Films

- **Mechanical properties**
  - + Young's modulus
  - + Density
  - + Hardness
  - + Yield stress
  - + Thermal expansion coeff.
  - + Thermal conductivity
- **Electrical properties (for your reference)**
  - + Energy gap at 300 ^{o}K
  - + Resistivity
  - + Dielectric constant
  - + Electron mobility
  - + Hole mobility
  - + atoms/volume

- **Mechanical properties of some basic thin film materials**
- **These mechanical properties may depend on the deposition processes**

Material	Thermal expansion coefficient (10^{-6}/K)	Young's modulus (10^{11} N/m^2)	Thermal conductivity (W/mK)	Density (10^3 kg/m^3)
Si	2.6	1.62	149	2.42
SiO_2	0.4	0.67 (dry) 0.57 (wet) 0.7 (bulk)	1.4	2.66
Si_3N_4	2.8	1.46 (CVD) 1.3 (sputtered)	18.5	3.0
Polysilicon	2.33			
Polyimide	20-70	0.03	0.167	
Al	23.0	0.69	237	2.692
Au	14.3	0.8	318	19.4
Ni	12.8	2.1	90.9	9.04

Source: Prof. G. Kovacs at Stanford University

- **Comparison of the mechanical properties of some basic semiconductor materials and mechanical materials**

Material	Steel	Stainless steel	Al	Si	SiO$_2$	Si$_3$N$_4$
Young's modulus (10^{11} N/m^2)	2.1	2.0	0.7	1.9	0.73	3.85
Yield strength (10^{9} N/m^2)	4.2	2.1	0.17	7	8.4	14
Density (10^{3} kg/m^3)	7.9	7.9	2.7	2.3	2.5	3.1
Thermal conductivity (W/mK)	0.97	0.33	2.36	1.57	0.014	0.19
Thermal expansion coefficient (10^{-6}/K)	12	17.3	25	2.33	0.55	0.8
Knoop hardness (Kg/mm^2)	1500	660	130	850	820	3500

Source: K.E. Petersen, Proceeding of the IEEE, 1982.

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