Ch. 10 Thin Film Process

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Outline

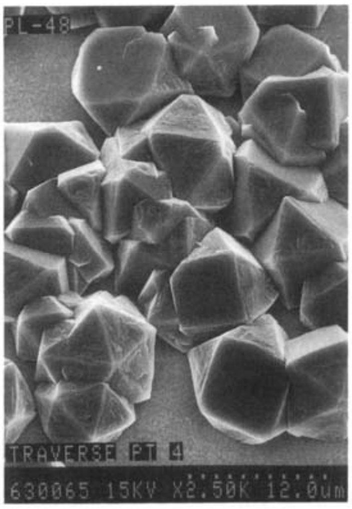
- Thin film applications
- Overview of deposition
- Physical vapor deposition
- Chemical vapor deposition
- Epitaxial growth
- Thin film materials sciences

Part I:Thin film applications

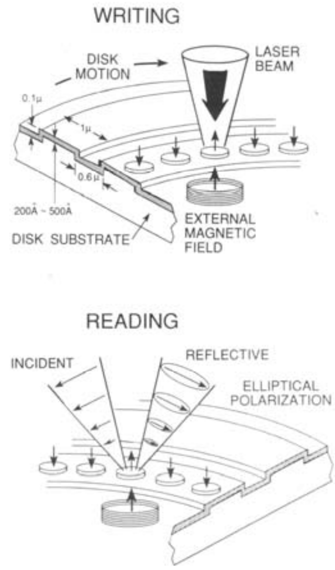
Why Thin Films?

- Thin films are required for many steps in semiconductor fabrication
  - Masks
  - Isolated elements
  - Metal interconnections
  - MOS gate
  - Barriers

Examples



CVD Diamond



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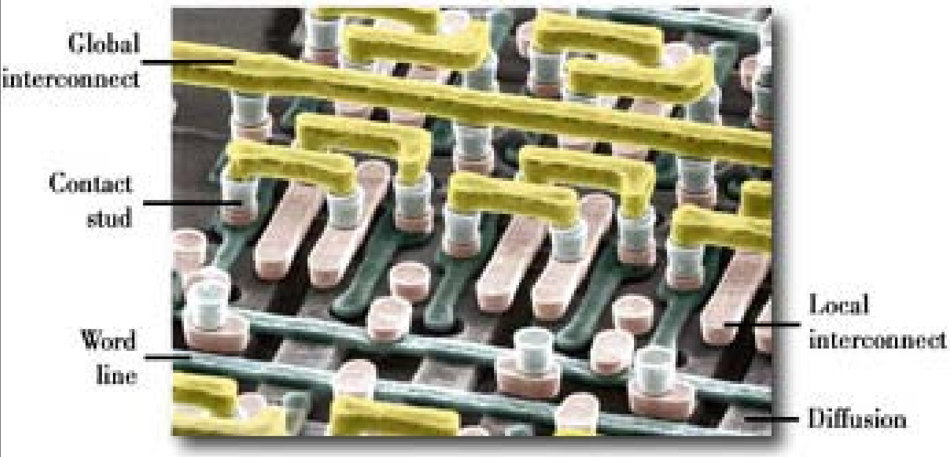
Applications: Interconnection



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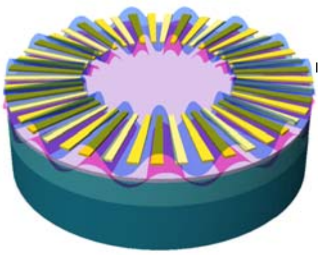
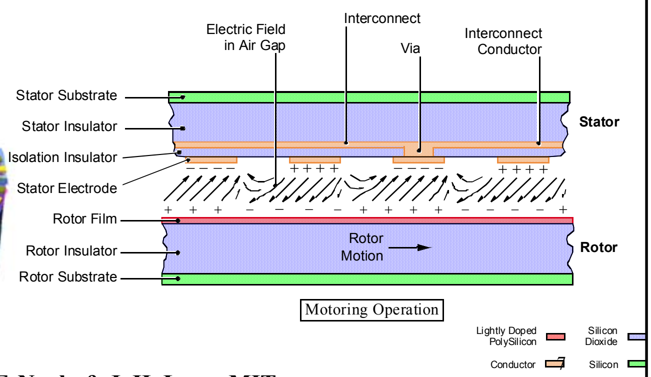
Electric Induction Micro-Motor

Torque applied across air gap by inducing and dragging charges in the rotor film:

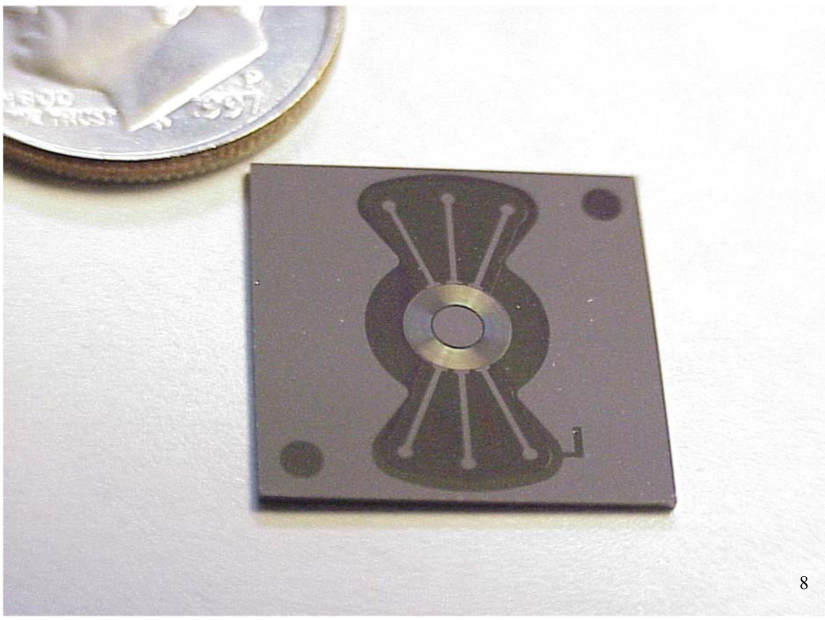
- **Polar array of 786 electrodes connected in 6 phase**
- **Sinusoidal stator excitation of ±300V at 3 MHz**
- **Rotor coated with a film of controlled conductivity**
- **3 μm air gap**



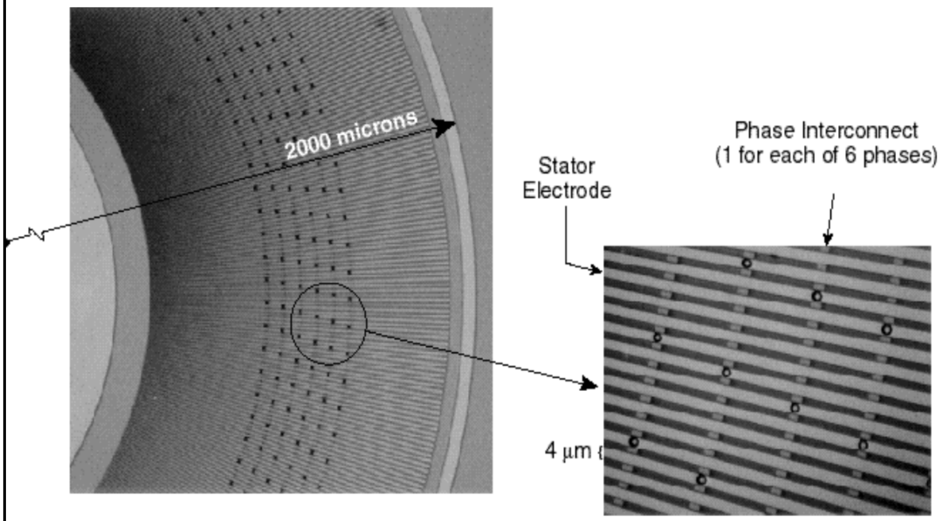


In Collaboration with S. F. Nagle & J. H. Lang, MIT

Two-Level Polysilicon Stator Device



Two-Level Polysilicon Stator Device



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Part II: Overview of Deposition

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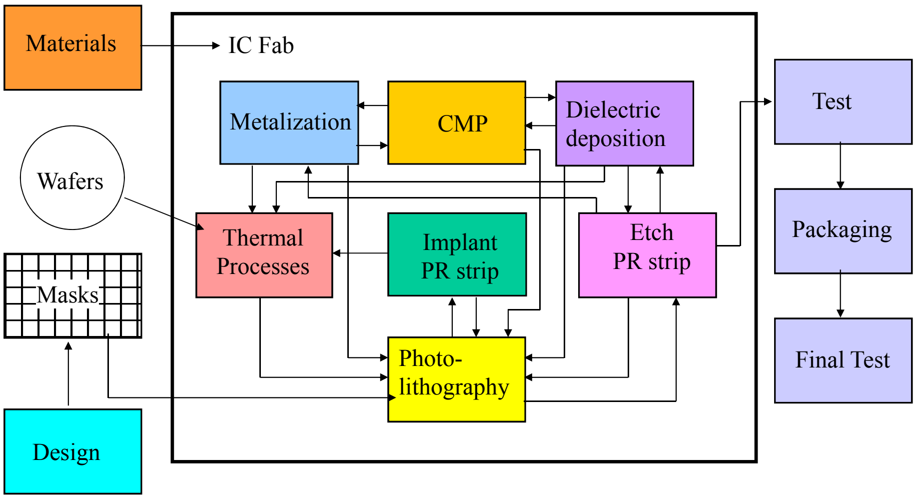
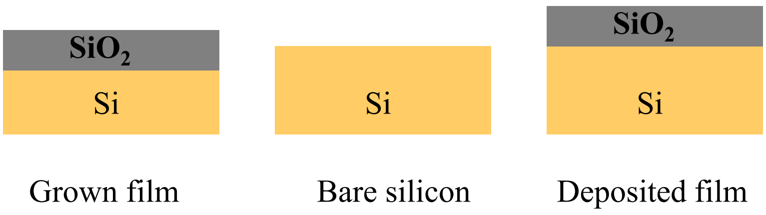
Wafer Process Flow



Applications of Deposited Films

- Gate materials
  - polysilicon
- Conductive layers
  - Metal lines
- Dielectric layers
  - Inter-metallic dielectric (IMD)

Example: CVD Oxide vs. Grown Oxide



Example: CVD Oxide vs. Grown Oxide

Grow

- Oxygen is from gas phase
- Silicon from substrate
- Oxide grow into silicon
- Higher quality

CVD

- Both oxygen and silicon are from gas phase
- Deposit on substrate surface
- Lower temperature
- Higher growth rate

Dielectric Thin Film Applications

- Multi-level metal interconnection
- CVD and SOG plus CVD dielectrics
- Shallow trench isolation (STI)
- Sidewall spacer for salicide, LDD, and the source/drain diffusion buffer
- The passivation dielectric (PD)
- Dielectric ARC for feature size < 0.25 μm

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Dielectric Thin Film Applications

- Inter layer dielectric, or ILD, include PMD and IMD
- Pre-metal dielectric: PMD
  - normally PSG or BPSG
  - Temperature limited by thermal budget
- Inter-metal dielectric: IMD
  - USG or FSG
  - Normally deposited around 400 °C

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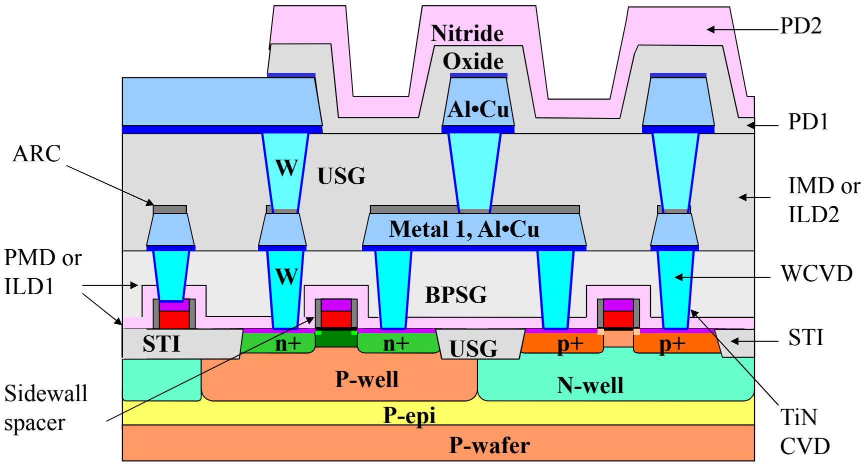
Figure 10.2



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Key Performance Index of Thin Film Processes

- Deposition rate
- Dimension control
- Residual stress
- Comformality
  - Step coverage
  - Flatness
  - Surface roughness
- Adhesion of film to substrate

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Key Considerations of Evaporation

- Deposition rate
- Temperature
  - some metals requires excessive high temperature
- Contamination
- Step Coverage
  - an important issue in evaluating performance of deposition, usually poor in evaporation
- Residual stresses
  - usually due to mismatch of CTE and micro structures transformation

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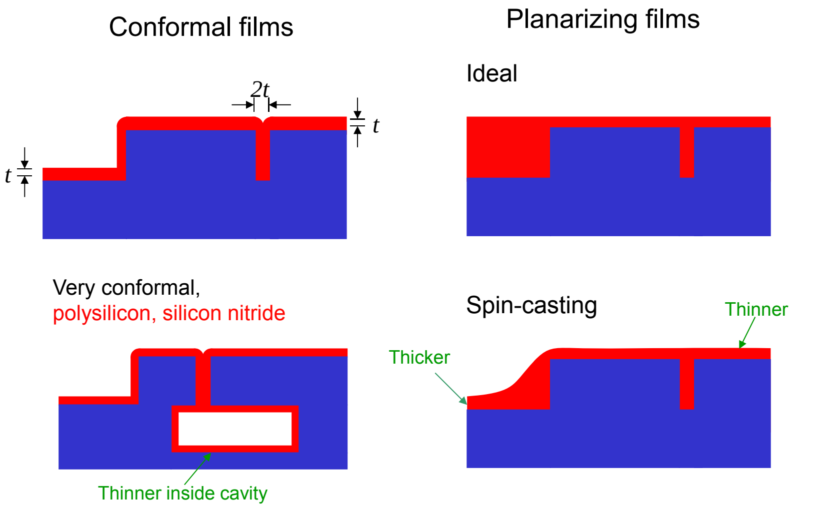
Conformality
(Step Coverage)



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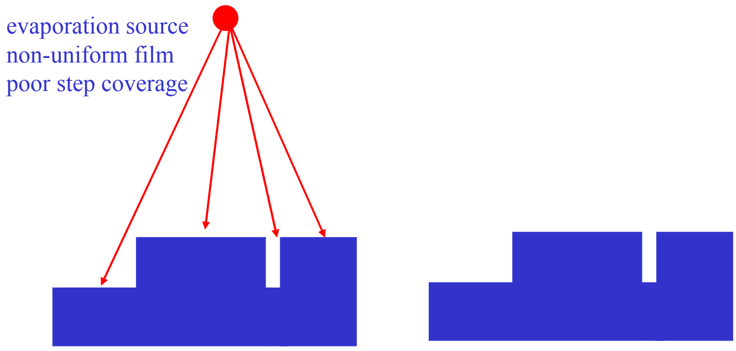
Conformality
(Step Coverage)

Non-conformal films

Line of sight



Part III: Physical Vapor Deposition

PVD

- Deposit film by physical methods
  - Thermal evaporation
    - Material source is heated to sublimation temperature in a vacuum
    - Material is vapor transported to target in vacuum
    - Deposition is by ”line-of-sight” (mean free path = 50m)
  - Sputtering
    - Material is removed from target by momentum transfer
    - Gas molecules are ionized in a glow discharge, ions strike target and remove mainly neutral atoms
    - Atoms condense on the substrate
    - Vacuum level ~ 10 mtorr --> mean free path ~ 5 mm
    - Easy to deposit alloys

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蒸鍍原理

1. 控制蒸氣壓以調節原子到達的數量
   $\log P\ (\text{torr}) = A - (\Delta H_v/2.3RT)$
2. 原子到達的能量
   Thermal Energy ＝ 3kT/2
   e.g. 0.1 eV at 500°C
   0.2 eV at 1265°C

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真空的要求

- 真空中殘留氣體分子有機會在薄膜成長過程中摻入，基板溫度愈高則機會愈小。
- 真空中原子碰撞的平均自由路徑(Mean free path) ，e.g. L＝5 cm when P＝10^{-3} torr；L＝5000 cm when P＝10^{-6} torr

$$L(cm) = \frac{5\times10^{-3}}{P(torr)}$$

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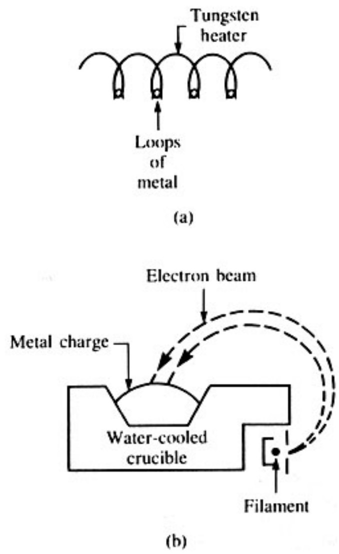
Type of Evaporation

- Filament evaporation
  - major problems
    - high contamination level
    - hard to form composite films
- Electron-beam evaporation
  - using high density electron beam to evaporate metals
  - dual E-beams with dual target can be used to coevaporate composite materials
  - major problem: radiation damage



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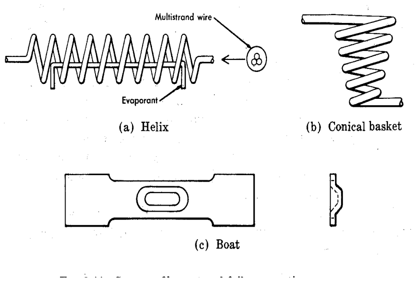
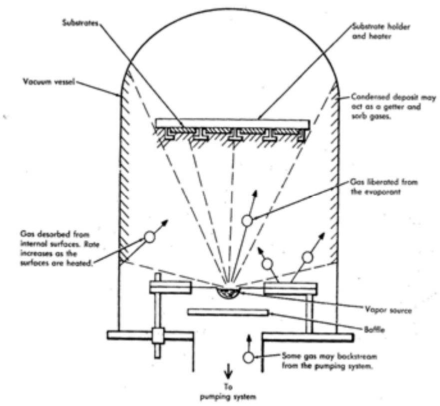
熱蒸鍍
(Thermal Evaporation)





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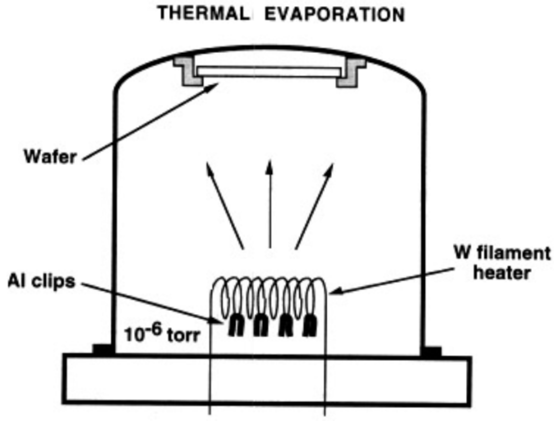
Evaporation



- Need high temperature
- Need high vacuum environment

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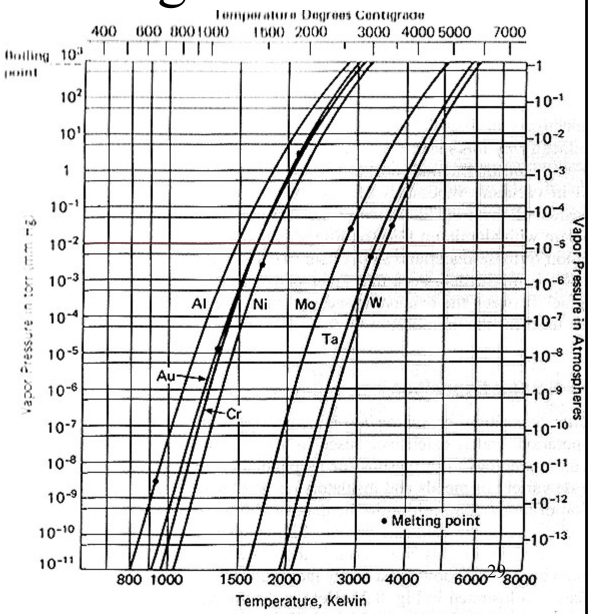
Phase Diagram

- Usually at least 10 mTorr is required to obtain reasonable deposition rate
- Refractory metals required very high temperature
  - W, Ta, Mo,



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Applications

- Usually widely used in GaAs technology
  - in silicon, it was replaced by sputtering in most fields
- A necessary step for many other applications
  - SEM
    - to form a thin conduction layer on specimen surface
  - LIGA or LIGA-like MEMS processes
    - need to form a conduction layer on PMMA for the subsequent electroplating process
- Since high temperature is required, usually this technology is restricted on metal only

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Key Considerations of Evaporation

- Deposition rate
- Temperature
  - some metals requires excessive high temperature
- Contamination
- Step Coverage
  - an important issue in evaluating performance of deposition, usually poor in evaporation
- Residual stresses
  - usually due to mismatch of CTE and micro structures transformation

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Step Coverage

- A primary limitation of evaporation
  - material beams are nondivergent
- Need wafer rotation to improve step coverage
- Performance index
  - AR (step height/step diameter)
  - OK for AR < 0.5
  - marginal 0.5 < AR < 1
  - poor if AR >1

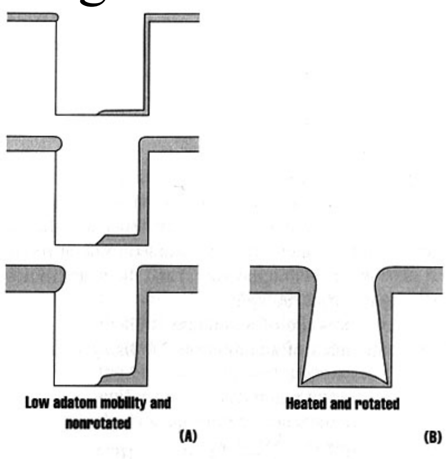

Figure 12-5 (a) Time evolution of the evaporative coating of a feature with aspect ratio of 1.0, with little surface atom mobility (i.e., low substrate temperature) and no rotation. (b) Final profile of deposition on rotated and heated substrates.

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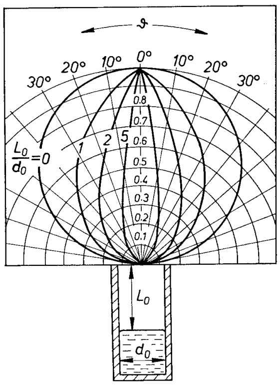
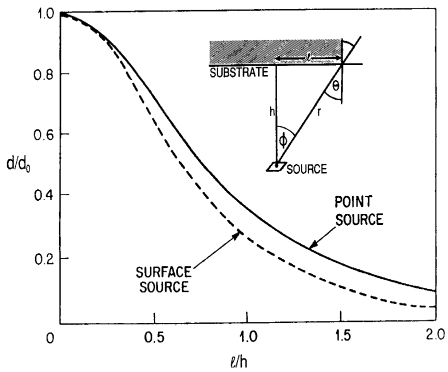
Film Thickness Uniformity





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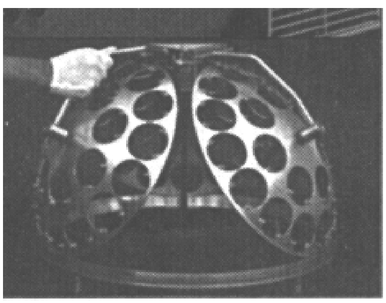
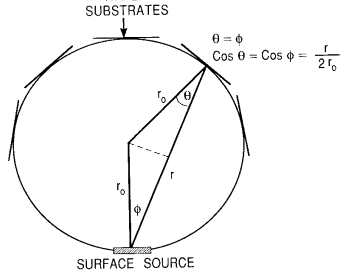
Evaporation Scheme to achieve Uniform Deposition





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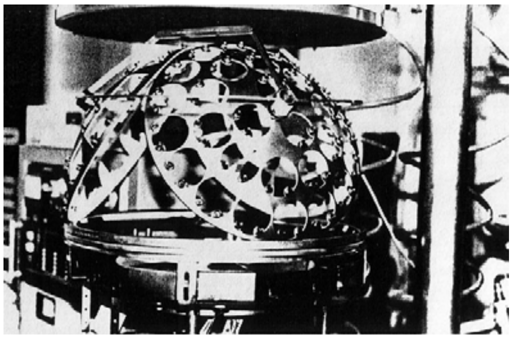
Evaporator



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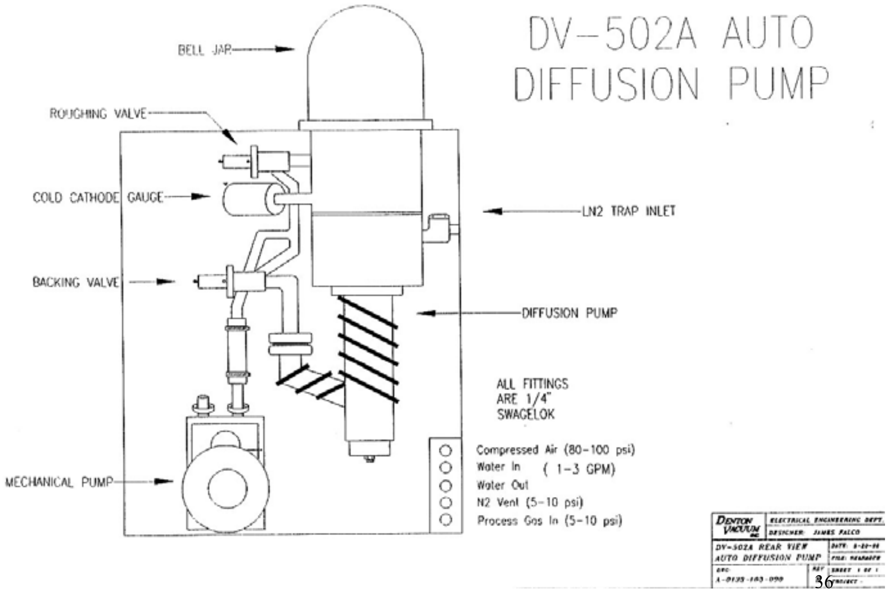
Evaporator



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電子束蒸鍍
(E-Beam Evaporation)

- ❑可聚焦的電子束，能局部加溫元素源，因不加熱其他部分而避免污染。
- ❑高能量電子束能使高熔點元素達到足夠高溫以產生適量的蒸氣壓。

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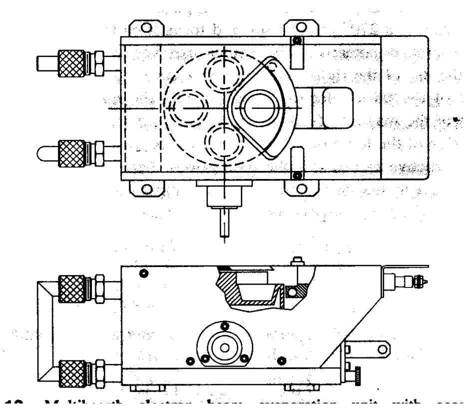
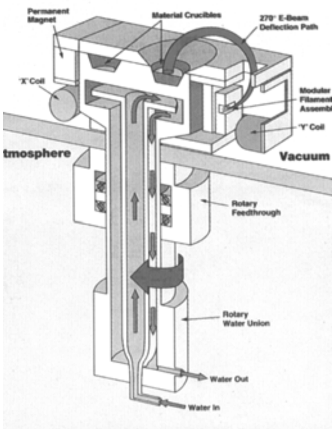
E-Gun Source





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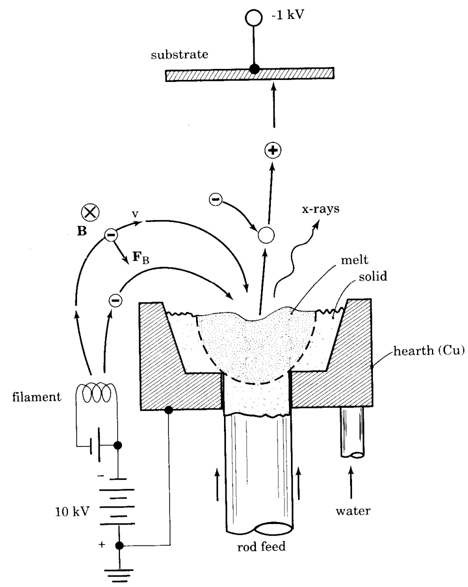
電子束與蒸發源之作用



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Beam-Material Interactions and Operations

- A raster scan of e-beam improves the film uniformity.
- For an accurate deposition-rate control, vapor flux monitoring with feedback control to the filament power should be used.
- The macroparticle-spitting problem may be minimized by using a vacuum-melted charge.
- The energies of vapor atoms are about 0.2 eV.
- X-rays are emitted and may cause charge-trapping defects in the dielectric materials.
- The fraction of vapor ionized varies with beam density and vapor composition and is of the order of 0.01 to 0.1. A negative bias may be applied to the substrate to affect the film structures – so-called Ion Plating.

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量產型電子束蒸鍍系統

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E-Beam NCKU

最小均勻薄膜厚度100A, 提供靶材金、鋁、鎳、鉑、鈦、鉻、銀

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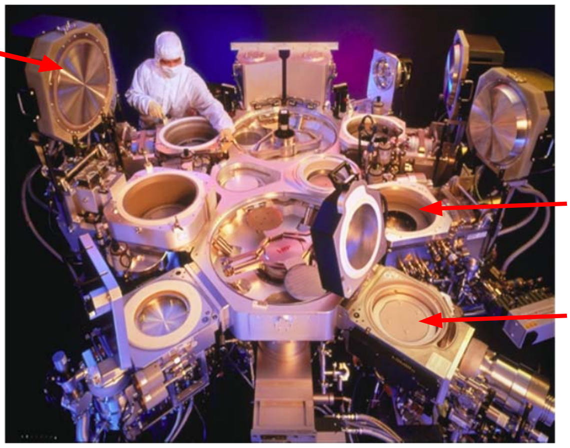
E-Beam NCKU

最小均勻薄膜厚度100A，提供靶材金、鋁、鎳、鉑、鈦、鉻、銀 43

Endura® PVD System



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Sputtering

- The major PVD method in silicon technology
- Using ion bombardment to introduce mass transfer
- Basically, it is a low temperature process
  - can deposit virtually any materials, including metals, ceramics, and organic materials
  - can deposit composite film with controllable composition
- Substrate damage is the major disadvantage

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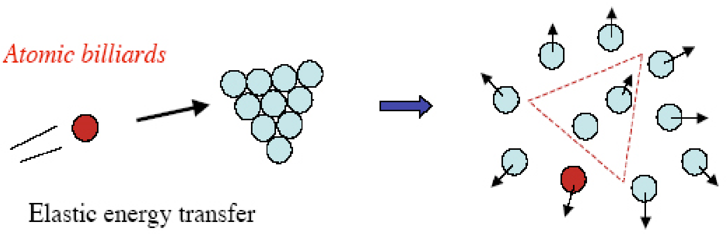
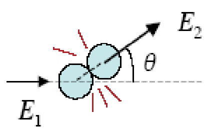
Sputtering process

Ar^+ impact, momentum transfer at cathode $\Rightarrow$ e^- avalanche and released target atoms, ions.



Elastic energy transfer



$$\frac{E_2}{E_1} \propto \frac{4M_1M_2}{(M_1+M_2)^2}\cos^2\theta$$

E_2 greatest for $M_1 \cong M_2$

For e^- hitting anode, substrate, $M_1 << M_2$ $\qquad \frac{E_2}{E_1} \approx \frac{4M_1}{M_2}$ (small)

But e^- can give up all its E_K in ***in***elastic collision:

$$\frac{1}{2}m_e v_e^2 \Rightarrow \Delta U$$

Excitation of atom or ion

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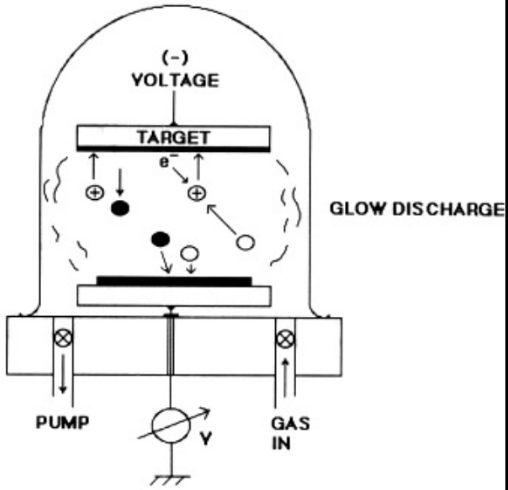
Sputtering

- Argon (Ar) atoms is usually used as the ion source



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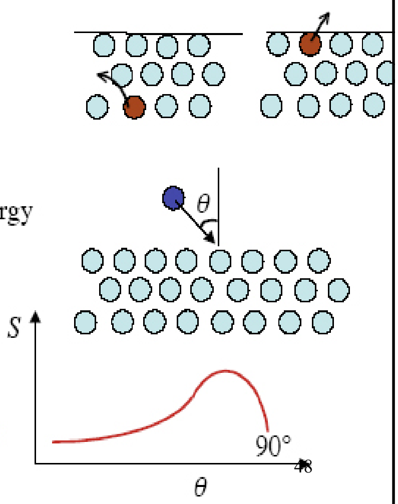
Sputtering yield

$$S = \text{Sputtering yield} = \frac{\#\ \text{atoms, molecules from target}}{\#\ \text{incident ions}}$$

$$S = \sigma_0 n_A \frac{\overline{E}_2}{4E_{\text{thresh}}} \times \left[\ldots\sqrt{\ln\left(\frac{E_v}{E_b}\right)}\right]$$

πd^2 | # / area | # excited in each layer | Random walk to surface; E_b = binding energy

Oring, Fig. 3.18,
Table 3-4



Sputter rate depends on angle of incidence, relative masses, kinetic energy.

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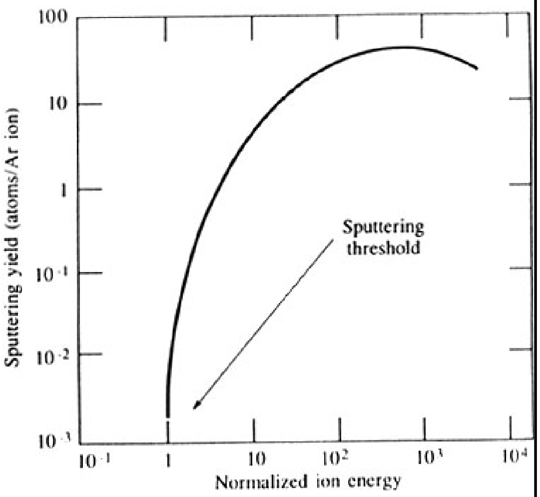
Sputtering Yield

- See Campbell 12.8 for detail
- Each material has its sputtering threshold
  - ~ 10 - 30 eV
- Ion energy ↑, sputtering yield ↑
- However, if energy is too high, it becomes "ion implantation"



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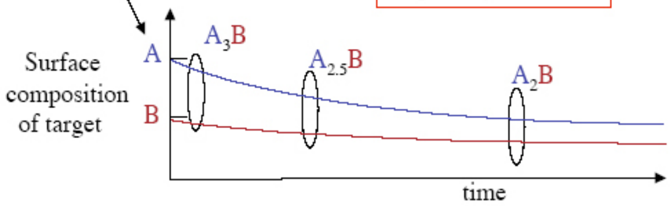
Target composition vs. film composition

Sputtering removes outer layer of target => more uniform composition

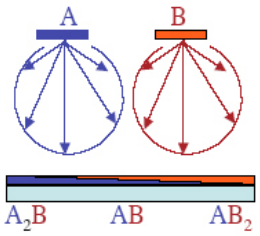
(problem with multicomponent system only initially)

Initial target composition A_2B (e.g. Si_2W)

If sputter yield A > B



Co-sputtering => composition control, sample library



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Sputtering vs. Evaporation

- Temperature
  - evaporation requires high temperature
- Materials
  - evaporation: metal only
  - sputtering: virtually any materials
- Sputtering has better step coverage
- contamination problem
- Sputtering results more severe damage in substrate than evaporation

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Sputter

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Magnetron Sputter NCKU

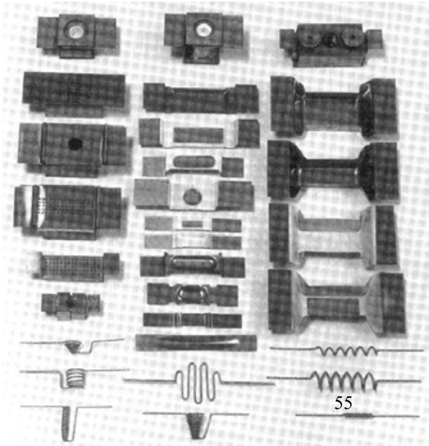
利用磁力控制增加電漿密度，以離子轟擊靶材濺鍍銅、鋅、鉻、鋁、鈦金屬薄膜(DC gun)與金屬氧化物氧化鋅、二氧化矽薄膜(RF gun)於基板上，最小均勻厚度200A。

濺鍍(Sputtering) vs. 蒸鍍 (Evaporation)

- Temperature
  - evaporation requires high temperature
- Materials
  - evaporation: metal only
  - sputtering: virtually any materials
- Sputtering has better step coverage
- contamination problem
- Sputtering results more severe damage in substrate than evaporation

物理氣相沉積系統硬體

- Thermal Evaporator
  - Vacuum pump
  - Resistance heated evaporation sources
  - Sublimation furnaces, crucible sources
- E-beam evaporator
  - Vacuum pumps
  - Electron generators
  - Electrical bias system



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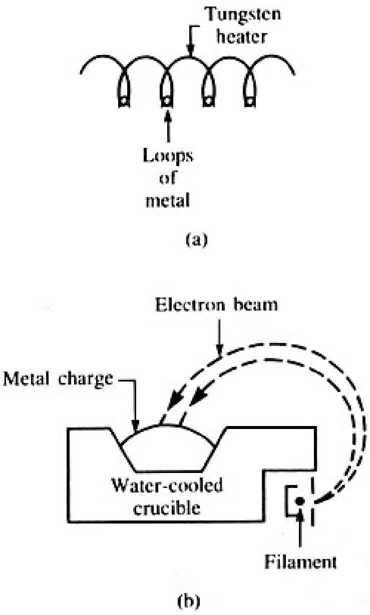
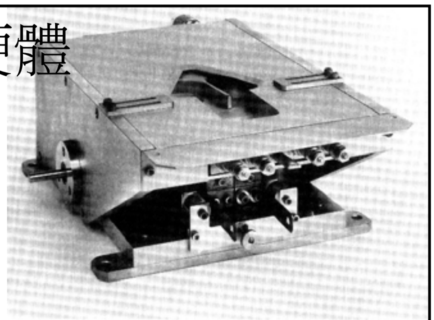
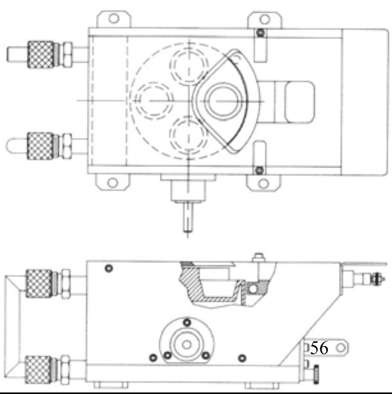
物理氣相沉積系統硬體







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E-beam evaporator

物理氣相沉積系統硬體

- Sputter
  - Vacuum pump
  - Power supply for DC or RF glow discharge
  - Sputtering gas source

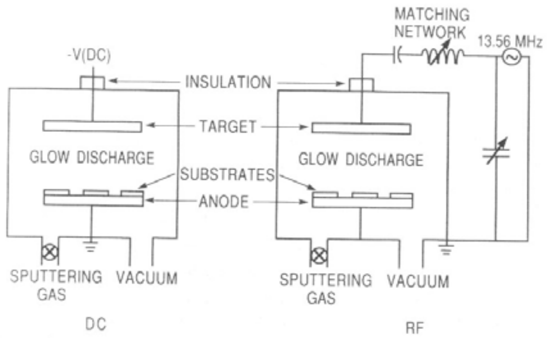

Figure 3-13. Schematics of simplified sputtering systems: (a) dc, (b) RF.

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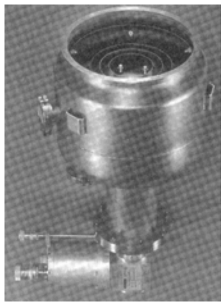
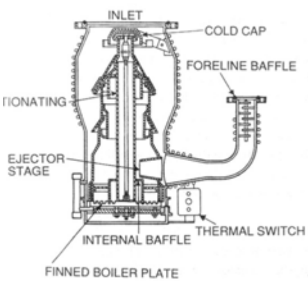
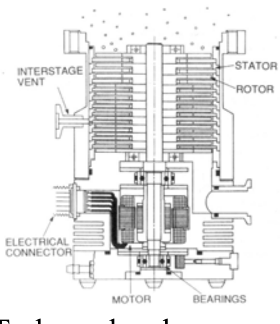
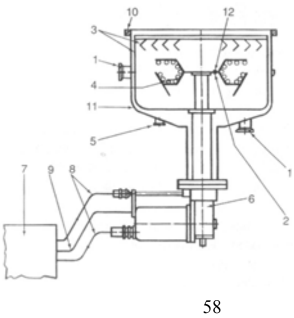
Vacuum Pumps









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Diffusion pump　Turbomolecular pump　Cryopump

Vacuum Pumps

- Vacuum pumps

Turbo pump

Momentum transfer
Mass-dependent compression ratio

Diffusion pump

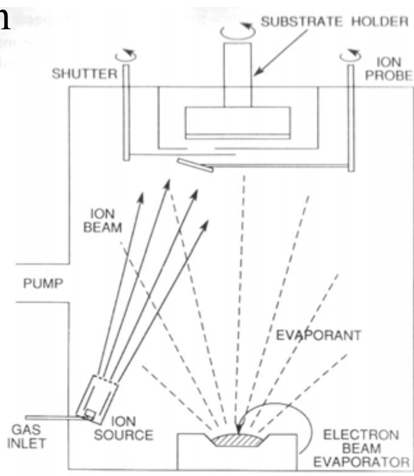
Momentum transfer
Cracking & contamination

Cryopump

Trap molecules
Liquid Helium

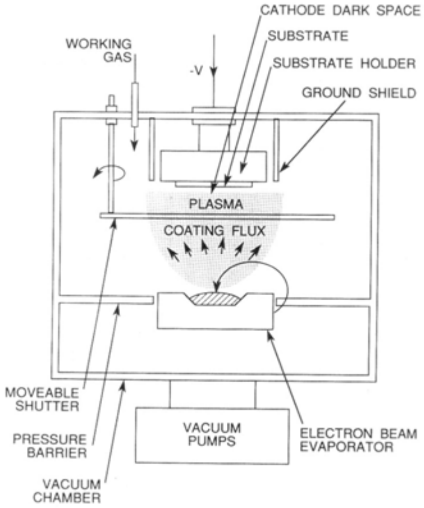
Hybrid and Modified PVD Processes

- Ion beam assisted deposition
  - Use ion bombardment to adjust PVD films
- Ion plating
  - Thermal evaporation + ion supttering
  - Provide excellent adhesion
- Reactive evaporation
  - Metal vapor reacts with a gas to form compound deposits

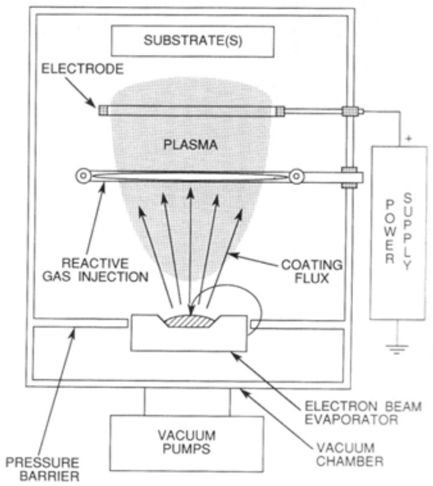


Ion-beam-assisted deposition

Hybrid and Modified PVD Processes



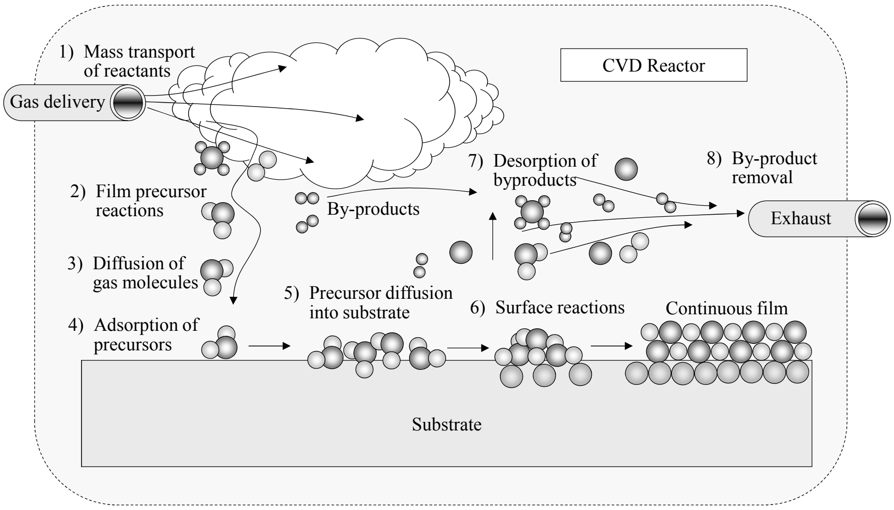
Ion plating



Activated reactive evaporation

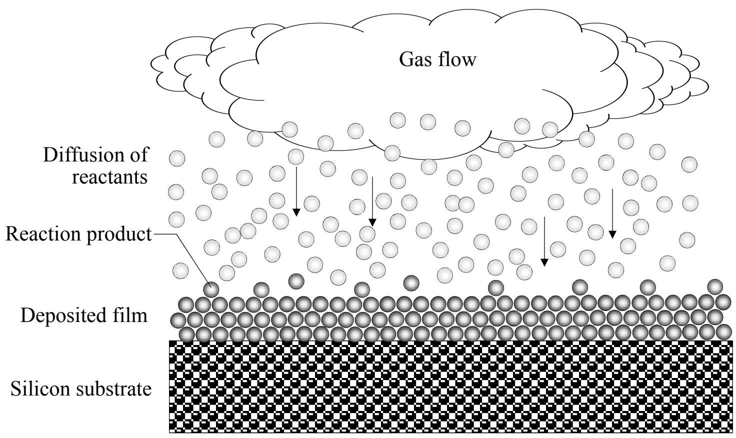
Part IV: Chemical Vapor Deposition

Schematic of CVD Transport and Reaction Steps



Semiconductor Manufacturing Technology Figure 11.8 *© 2001 by Prentice Hall*
by Michael Quirk and Julian Serda

Gas Flow in CVD



Semiconductor Manufacturing Technology Figure 11.9 *© 2001 by Prentice Hall*
by Michael Quirk and Julian Serda

CVD Applications

	FILMS	*PRECURSORS*
Semiconductor	Si (poly) Si (epi)	SiH_4 (silane) $SiCl_2H_2$ (DCS) $SiCl_3H$ (TCS) $SiCl_4$ (Siltet)
Dielectrics	SiO_2 (glass)	LPCVD SiH_4, O_2 PECVD SiH_4, N_2O PECVD $Si(OC_2H_5)_4$ (TEOS), O_2
		LPCVD TEOS APCVD&SACVD[TM] TEOS, O_3 (ozone)
	Oxynitride	SiH_4, N_2O, N_2, NH_3
	Si_3N_4	PECVD SiH_4, N_2, NH_3 LPCVD SiH_4, N_2, NH_3 LPCVD $C_8H_{22}N_2Si$ (BTBAS)
Conductors	W (Tungsten) WSi_2 TiN Ti Cu	WF_6 (Tungsten hexafluoride), SiH_4, H_2 WF_6 (Tungsten hexafluoride), SiH_4, H_2 $Ti[N(CH_3)_2]_4$ (TDMAT) $TiCl_4$

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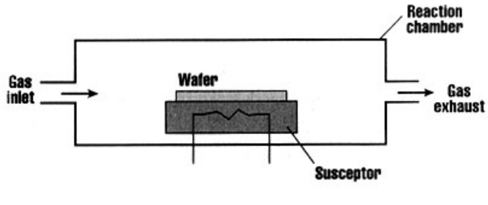
Introduction to CVD

- Form thin films on the surface of a substrate by thermal decomposition and/or reaction of gaseous compounds
- Usually performed at high temperature
  - Can be performed at various pressure and with assistance of plasma
  - Usually at viscous flow regime



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Type of CVD

- APCVD
  - high deposition rate, poor uniformity, high contamination level, 250-450 °C
  - for dielectrics
- LPCVD
  - low deposition rate, high uniformity, 575-650 °C
  - for polysilicon
- PECVD
  - for extremely low deposition temperature
  - e.g, oxide and nitride
  - quality is poor

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Plasma **Enhanced** CVD

- PECVD with SiH_4 and NO_2 (laughing gas)

$$e^- + SiH_4 \rightarrow SiH_2 + 2H + e^-$$

$$e^- + N_2O \rightarrow N_2 + O + e^-$$

$$SiH_2 + 3O \rightarrow SiO_2 + H_2O$$

- Plasma enhanced chemical reaction
- PECVD can achieve high deposition rate at relatively lower temperature

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Film Formation during Plasma-Based CVD

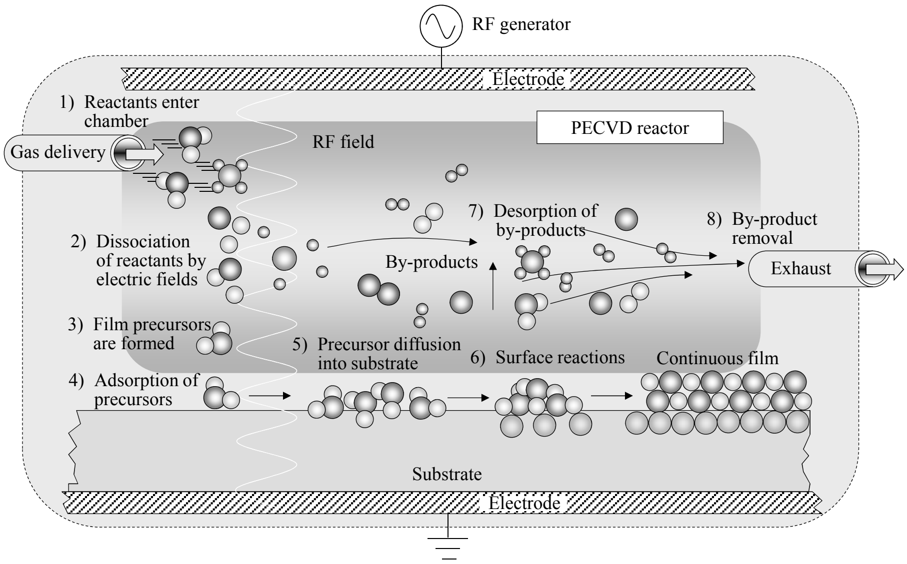

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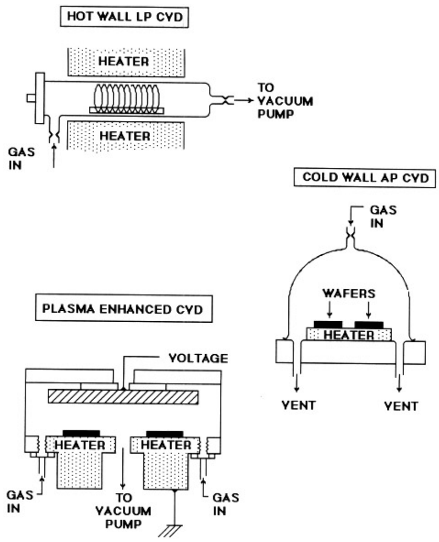
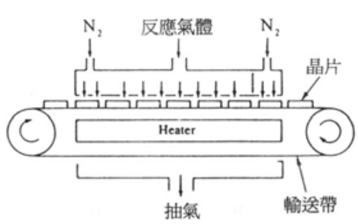
Figure 11.19

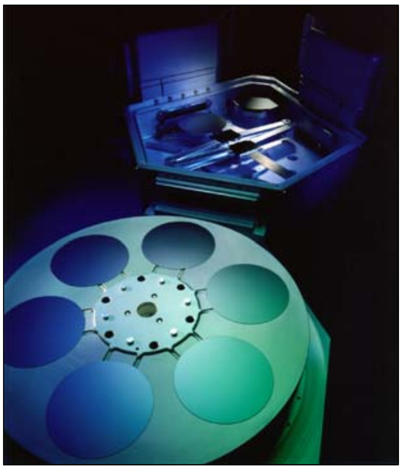
CVD Reaction Chambers





APCVD

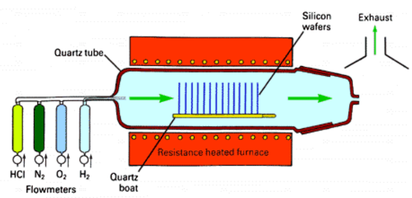
Chemical Vapor Deposition Tool

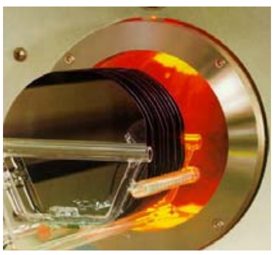


Photograph courtesy of Novellus, Sequel CVD

Furnace Tubes

Thermal Oxidation and LPCVD





LPCVD NCKU

(1)多晶矽，主要氣體 SiH4、N2；溫度約 620℃、壓力約300 mtorr，

(2)低應力氮化矽，主要氣體 NH3、DSC、N2；溫度約810℃、壓力約200 mtorr

(3)低溫氧化矽，主要氣體 SiH4、O2、N2；溫度約450℃、壓力約 200 mtorr

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STATE UNIVERSITY OF NEW YORK at STONY BROOK

Poly-Silicon LPCVD

Process:

SiH_4, H_2 : $SiH_{4\,(g)} \rightarrow SiH_{2(g)} + H_{2\,(g)}$, $SiH_{2\,(a)} \rightarrow Si_{\,(s)} + H_{2\,(g)}$

pressure :~500 mtorr.

temp.: 540 °C(amorphous) ~ 650 ° C (polysilicon, 0.03~0.3μm)

dep. rate: 100~200 Å/min.

Conducting poly-Si: PH_3, AsH_3 reduce deposition rate, while B_2H_6 increases deposition rate.

Conformality: spectacular, excellent uniformity

Compatibility: thermal issue (no Al)

SiH_4 is extremely toxic gas and extremely *flammable* at atmospheric pressure ! (Osaka University)

amorphous Si (solar cells & TFT), poly-Si (LCD projector)

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LTO LPCVD

Process:

SiH_4, O_2 (PH_3, AsH_3, B_2H_6) Note SiH_4 and O_2 at 350 mtorr. will not explode!

pressure :~350 mtorr. temp.: 300 °C ~ 400 ° C

dep. rate: 175 Å/min. for 4" wafer

Planarization → flow → add dopants to reduce melting point

PSG (Phosphosilicate): phosphine doped LTO

(6~8% wt., 1000 ° C), "gettering" of small positive ions

BPSG (Borophosphosilicate):

(4~5% wt. each, 900°C), contact dielectrics

flow process may be replaced by CMP planarization

Conformality: not so good (P glass reflow)

Compatibility: good for Aluminum

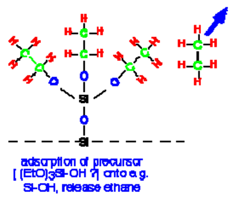
PH_3, AsH_3, B_2H_6 are all extreme toxic gases, usually shipped with SiH_4 for safety (explosive alert !).

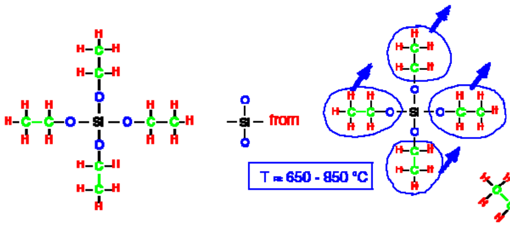
TEOS LPCVD

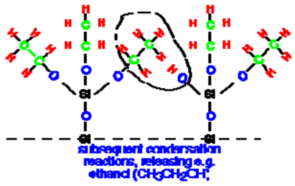
Process:

TEOS → $SiO_2 + 2C_2H_4 + 2CH_3CH_2OH$

pressure : 1 atm, N_2 temp.: 650~ 850° C







Conformality: excellent

Compatibility: Thermal

Nitride LPCVD

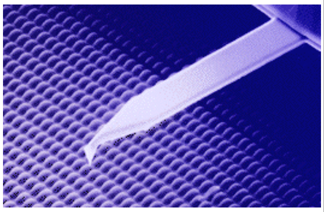
Process:

SiH_4, $SiCl_2H_2$, NH_3
pressure :~250 mtorr. temp.: ~ 800 ˚C
dep. rate: 35 Å/min. for 4" wafer
1100MPa tensile stress

$3SiH_4 + 4NH_3 \rightarrow Si_3N_4 + 12H_2$ (700~900 ˚C)

$3SiCl_2H_2 + 4NH_3 \rightarrow Si_3N_4 + 6HCl + 6H_2$

(700~800 ˚C)



Conformality: good to excellent

Compatibility: Thermal

Olympus, Tetra Tip

Oxide

- Silane based

$$SiH_4 + O_2 \rightarrow (300-500^oC)\; SiO_2 + 2H_2$$

- PSG

$$4PH_3 + 5O_2 \rightarrow 2P_2O_5 + 6H_2$$

- TEOS (LPCVD 650-700 °C) (PECVD 350 °C)

$$Si(OC_2H_5)_4 \rightarrow SiO_2 + by\ product$$

- Silane based PECVD

$$SiH_{4(g)} + 2N_2O_{(g)} \xrightarrow[\Delta]{RF} SiO_{2(s)} + 2N_{2(g)} + 2H_{2(g)}$$

Oxide

Table 6.1 Properties of Various Deposited Oxides. (After ref. [2].)

Source	Deposition Temperature (°C)	Composition	Conformal Step Coverage	Dielectric Strength (MV/cm)	Etch Rate (Å/min) [100:1 H_2O:HF]
Silane	450	$SiO_2(H)$	No	8	60
Dichlorosilane	900	$SiO_2(Cl)$	Yes	10	30
TEOS	700	SiO_2	Yes	10	30
Plasma	200	$SiO_{1.9}(H)$	No	5	400

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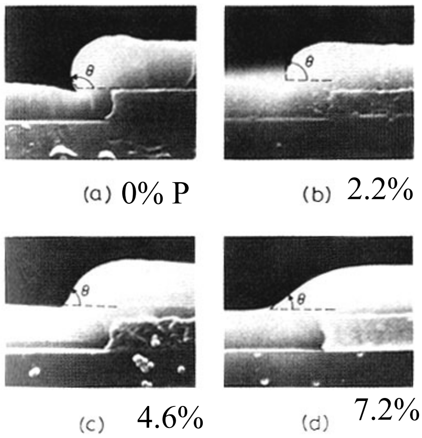
PSG and BPSG

- Phosphosilicate glass (PSG)
  - reducing stress
  - improve step coverage
  - flow at high temperature (1000-1100 °C) to create smooth surface
- Borophosphosilicate glass (BPSG)
  - flow temperature is reduced to 700 °C
  - for isolation and surface planarization



(a) 0% P (b) 2.2% (c) 4.6% (d) 7.2%

1100 °C for 20 min.

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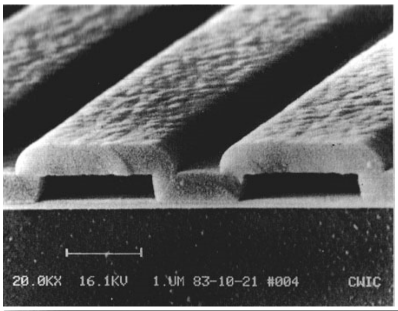
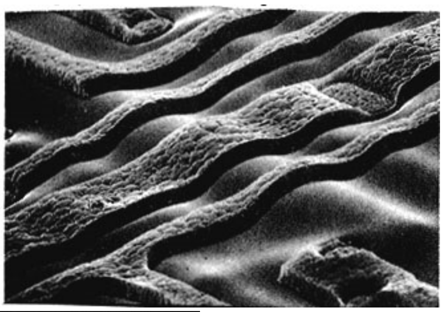
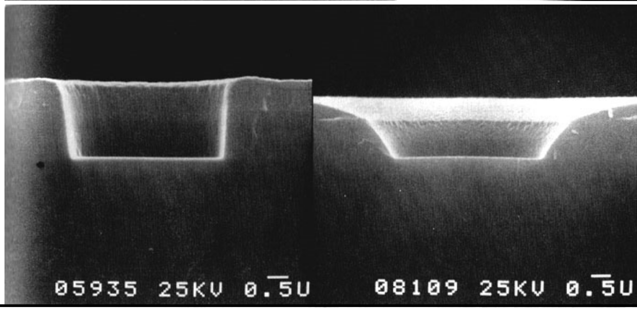
Reflow of BPSG







BPSG
(4%P, 4% B)
930 ^{o}C
30 min.

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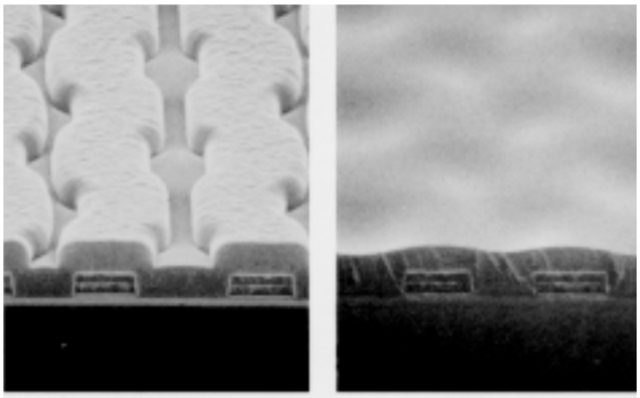
4×4 BPSG Reflow at 850 °C, 30 Minutes in N_2 Ambient



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Silicon Nitride

- Application:
  - masks to prevent oxidation for LOCOS process
  - final passivation barrier for moisture and sodium contamination
- APCVD

$$3SiH_4 + 4NH_3 \rightarrow Si_3N_4 + 12H_2$$

- LPCVD

$$3SiCl_2H_2 + 4NH_3 \rightarrow Si_3N_4 + 6HCl + 6H_2$$

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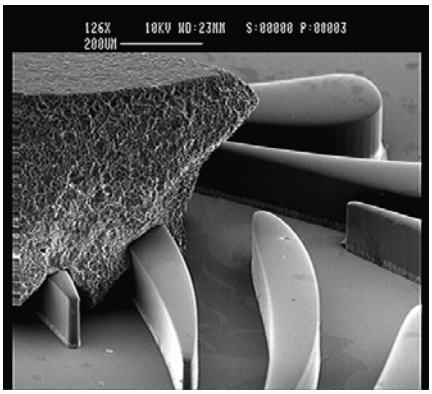
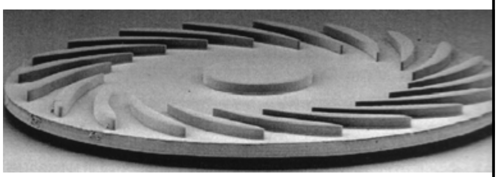
CVD SILICON CARBIDE PROCESSING





Procedure:
1. DRIE silicon substrate
2. Wafer bonding
3. CVD silicon carbide
4. Etch silicon

Lohner, MIT 1999

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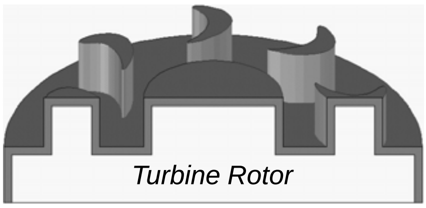
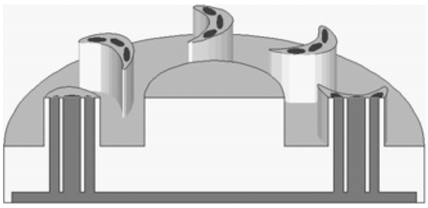
BASIC PROCESSING CONCEPTS

Key: = SiC = Si

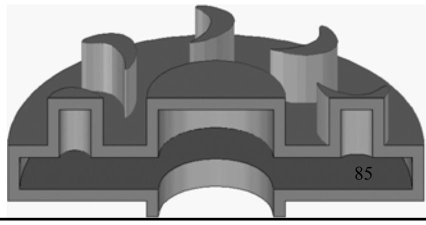
Positive Mold | **Negative Mold**



Hybrid Structure



Dissolve Silicon



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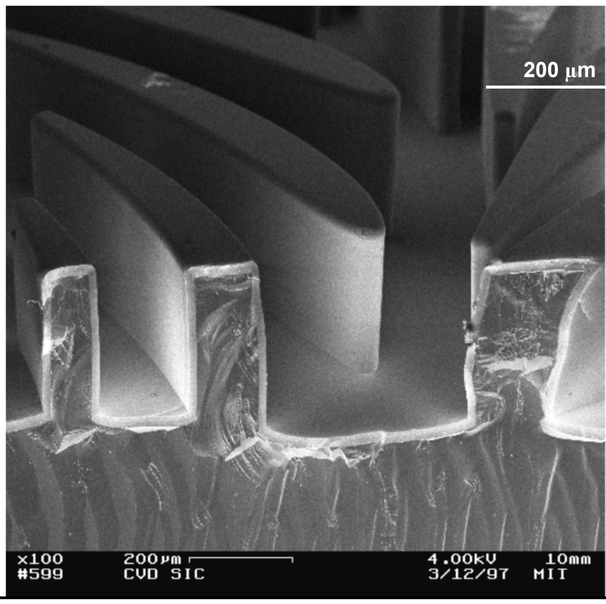
POSITIVE MOLD RESULTS

16μm THICK SiC COATING



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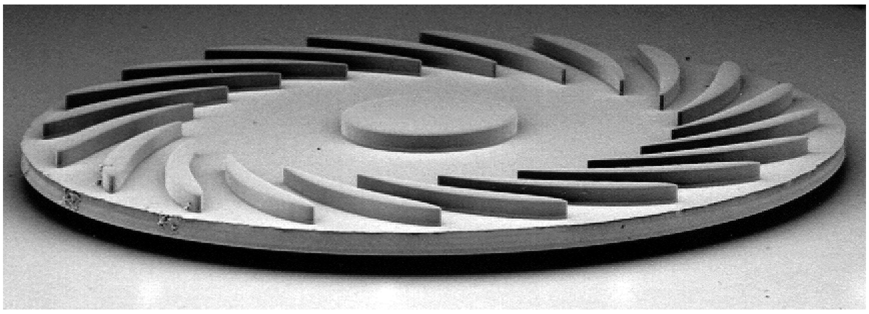
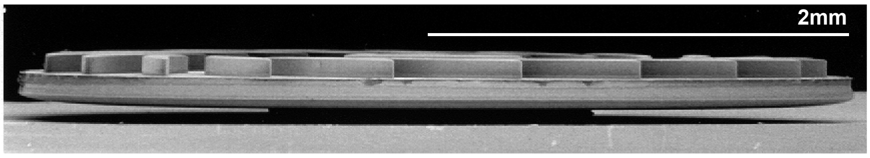
NEGATIVE MOLD RESULTS

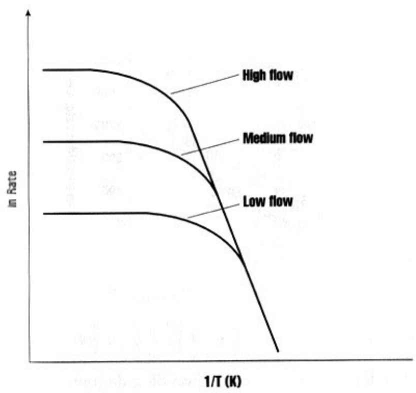
50 µm THICK SHELL SILICON CARBIDE ROTOR



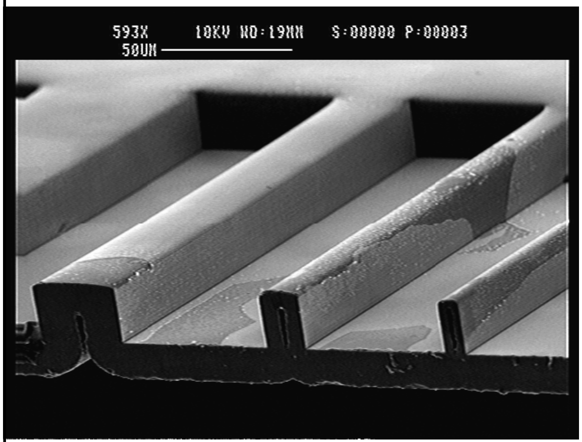


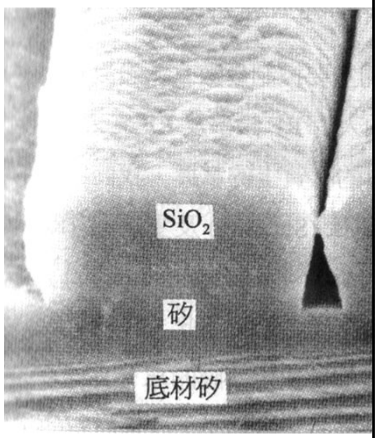
CVD Rate Control

- Typical CVD deposition rate is shown
  - at lower temperature, surface reaction is the control mechanism
    - increase temperature
  - at higher temperature, bulk transportation is the control mechanism
    - increase flow rate



Step Coverage





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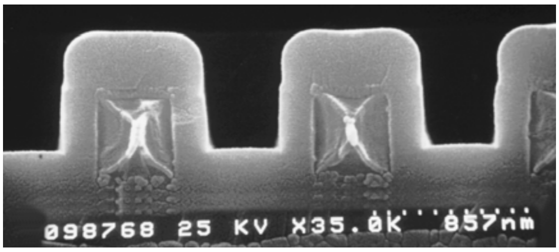
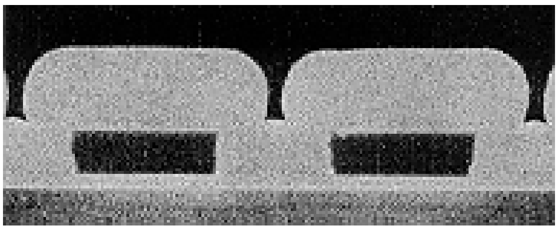
Step Coverage of TEOS and Silane Oxide



TEOS



Silane

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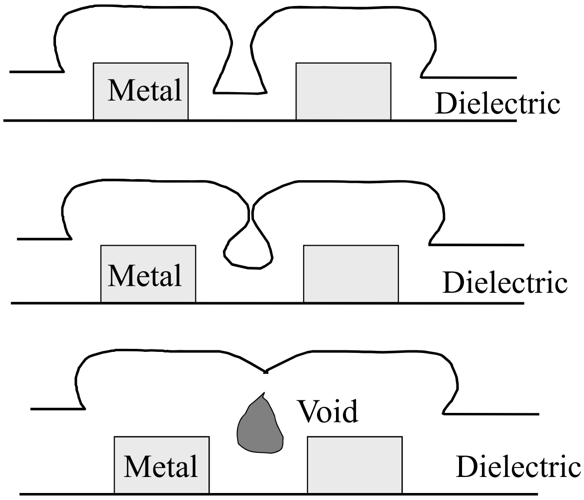
Void Formation Process



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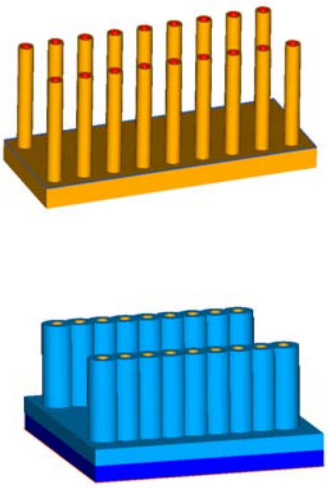
CVD Example: Micro Heat Exchanger



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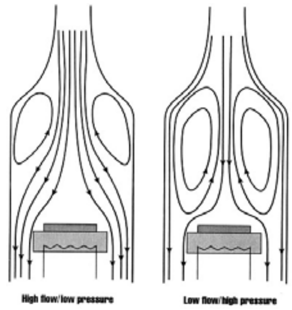
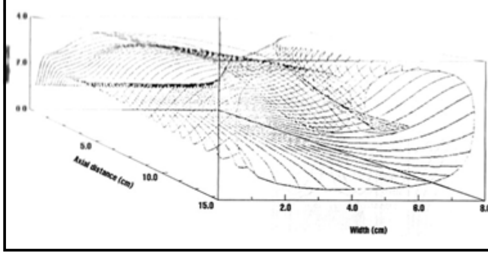
CVD Reactors





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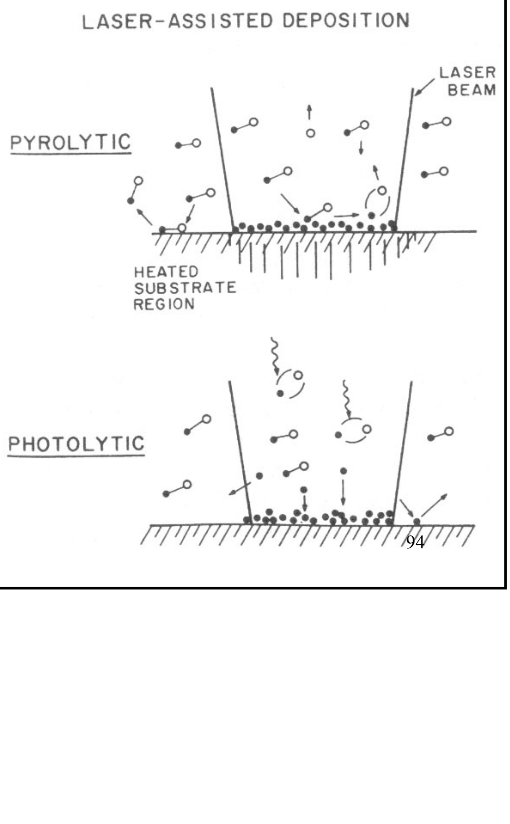
Laser Assisted Deposition

- Pyrolytic
  - By heating substrate to enhance reactivity
- Photolytic
  - Direct dissociation of molecules by energetic photons



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LCVD

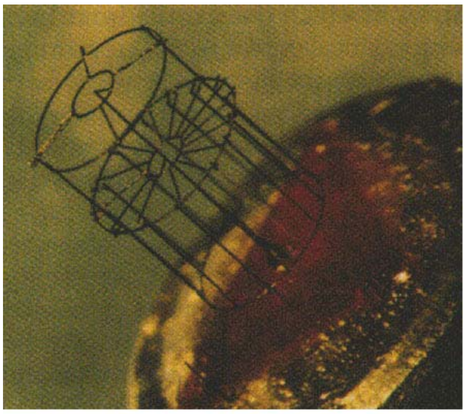

Figure 6. A 3-dimensional structure of alumina grown with the LCVD process.

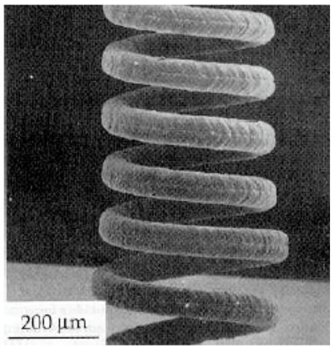

Figure 7. Tungsten coil made by LCVD.

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Part V: Epitaxial Growth

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Epitaxy

- Deposition of single crystal films on single crystal substrate
  - Single silicon acts as a seed
  - This is called vapor phase epitaxy (VPE)
  - Other technologies include liquid phase epitaxy (LPE) and molecular beam epitaxy (MBE), they are widely used in GaAs process
- To grow single crystal n-type layers on p-type substrates for bipolar processing
- Prevent CMOS latchup

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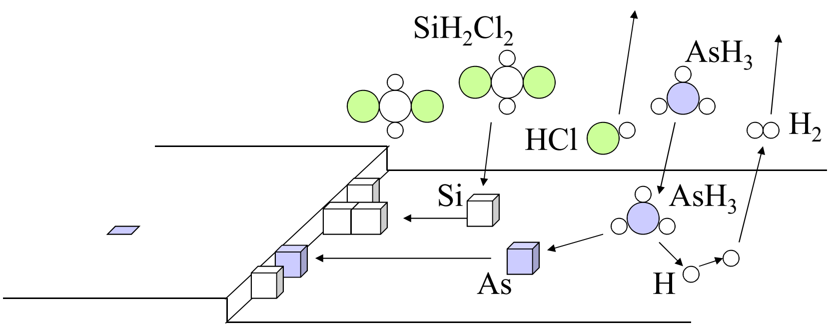
Schematic of DCS Epi Grow and Arsenic Doping Process



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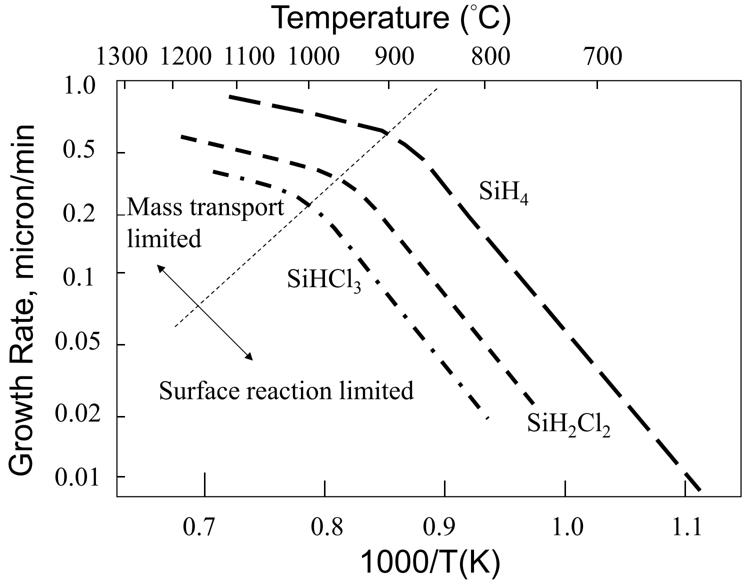
Epitaxial Silicon Growth Rate Trends



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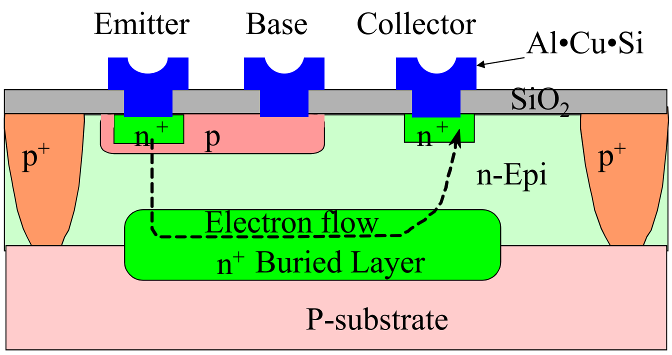
Epitaxy Application, Bipolar Transistor



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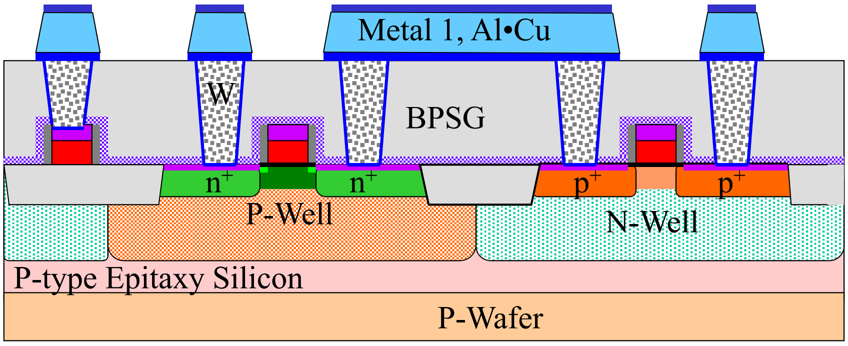
Epitaxy Application: CMOS



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VPE (Vapor Phase Epitaxy)

- Single silicon from single silicon
- Use the same raw materials as polysilicon CVD
- Careful control is required to prevent polysilicon formation
- Resistivity can be adjusted by doping
- Buried layer
  - Heavily doped layer first, then epitaxy layer
  - Auto doping
  - Out-diffusion

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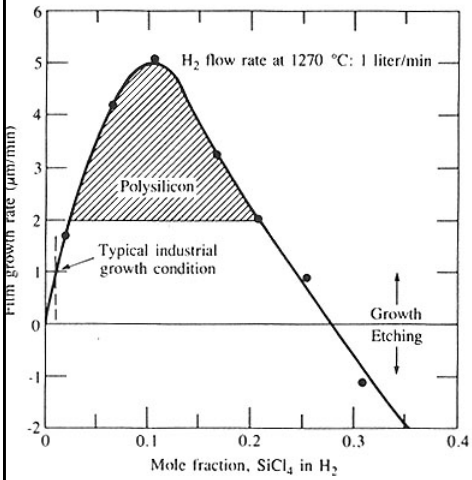
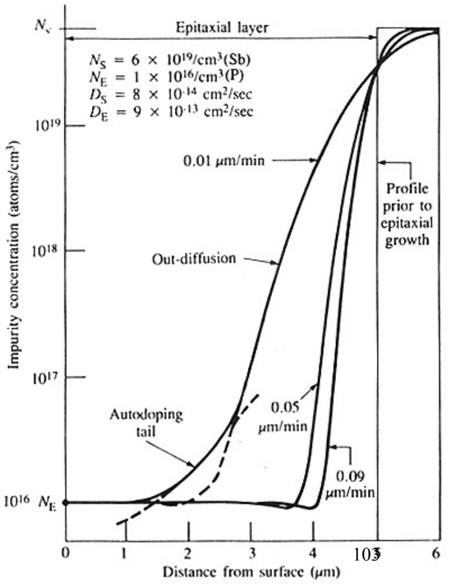
VPE



$SiH_4 + 2Cl_2 \rightarrow Si + 4HCl$



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LPE and MBE

- LPE:
  - Substrate is brought into contact with a solution containing the material to be deposited in liquid form
  - Material crystallizes directly from the solute
  - 0.1 – 1 μm/min.
- MBE:
  - Crystalline layer is formed by deposition from a thermal beam of atoms or molecules
  - Deposition is performed in ultrahigh-vacuum condition (10^{-8} Pa)
  - 0.001-0.3 μm/min

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CVD Vs. Epitaxy

- Crystalline
  - CVD: Polysilicon or amorphous
  - Epitaxy: single crystal
- Fluid dynamics
  - CVD: viscous flow regime
  - Epitaxy: molecular flow regime
- Technology
  - CVD: quite popular in Si technology
  - Epitaxy: mostly used in GaAs and BJT technology

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Part VI: Thin Film Materials Sciences

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Step Coverage

- A primary limitation of evaporation
  - material beams are nondivergent
- Need wafer rotation to improve step coverage
- Performance index
  - AR (step height/step diame
  - OK for AR < 0.5
  - marginal 0.5 < AR < 1
  - poor if AR >1

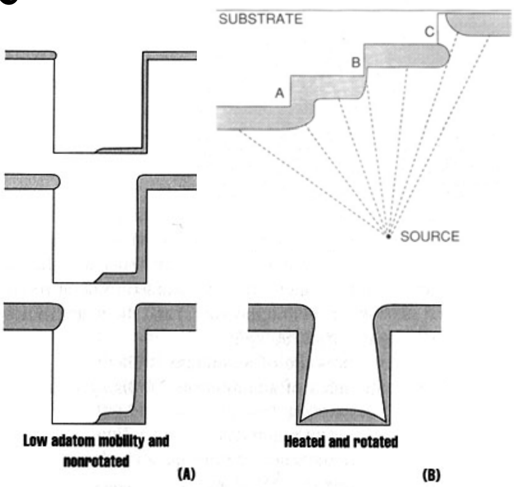

Figure 12-5 (a) Time evolution of the evaporative coating of a feature with aspect ratio of 1.0, with little surface atom mobility (i.e., low substrate temperature) and no rotation. (b) Final profile of deposition on rotated and heated substrates.

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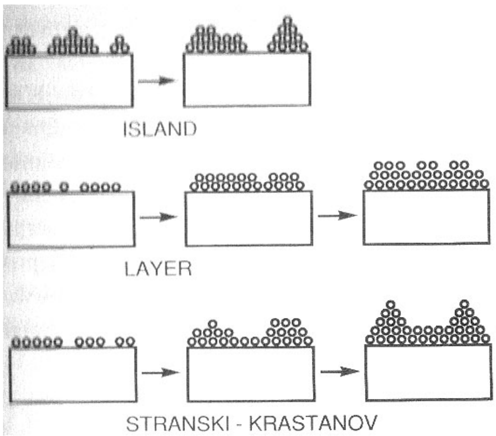
Thin Film Growth Modes

- Island (Volmer-Weber)
  - Film materials have stronger bonds
  - E.g., metals on insulators
- Layer (Frank-Van der Merwe)
  - Film / substrate has stronger bonds
    - E.g., epi of semiconductor
- Stranski-Krastanov



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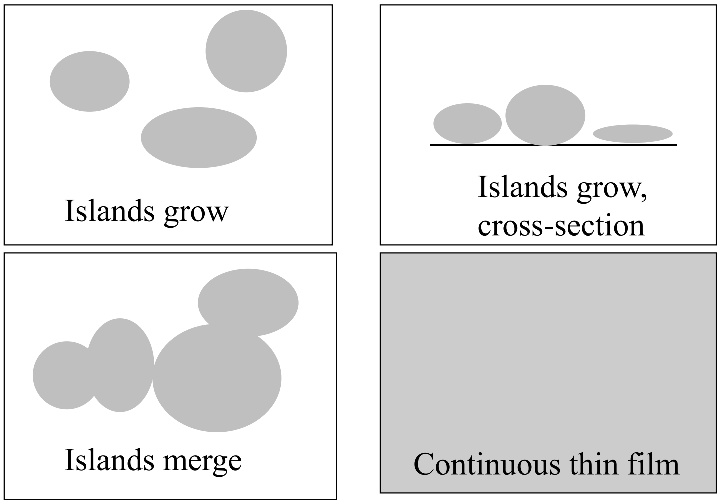
Deposition Process



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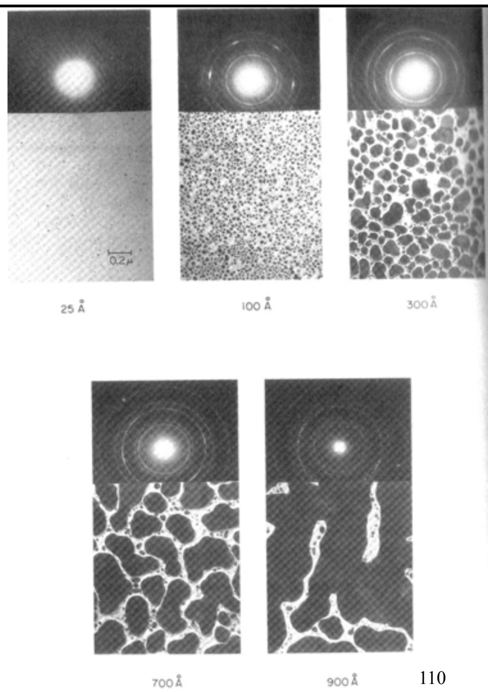
MicroStructures of PVD Films

- Microstructures are thickness and deposition period dependent
- E.g., Ag film on NaCl substrate



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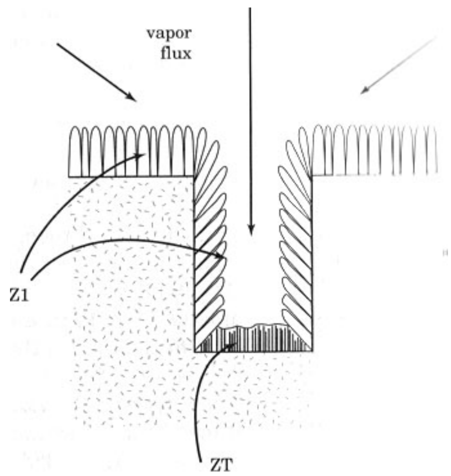
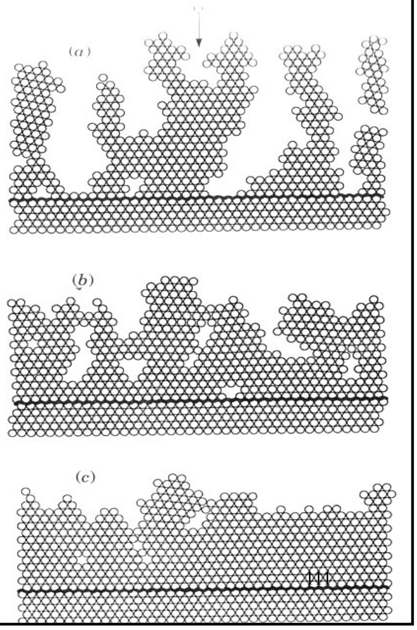
Micro Structures





- Column-liked structure
- Porous structure

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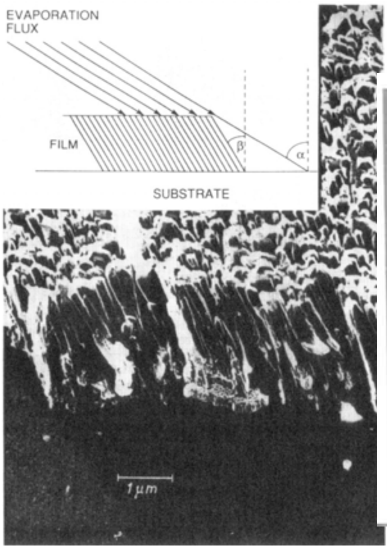
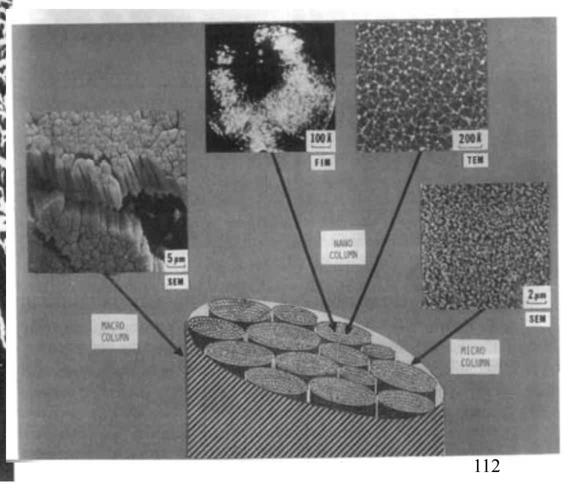
Micro and Nanostructure of Films





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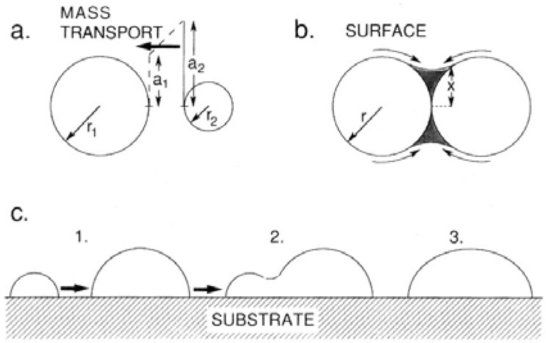
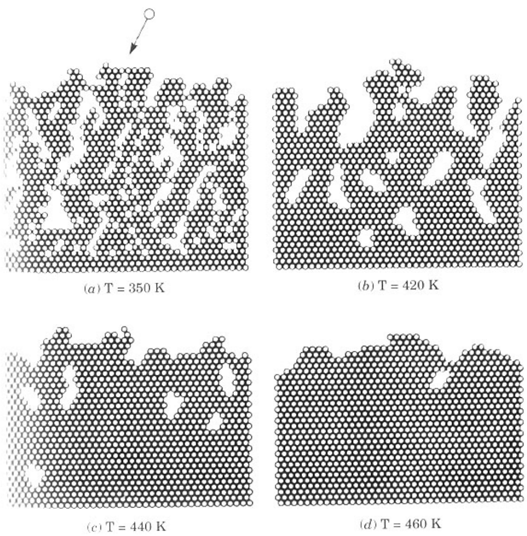
Coalescence of Clusters and Stress Generation



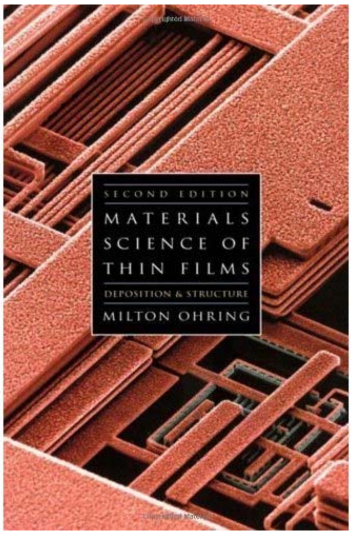
- Cluster migration causes the elimination of grain boundary and induces tensile strains

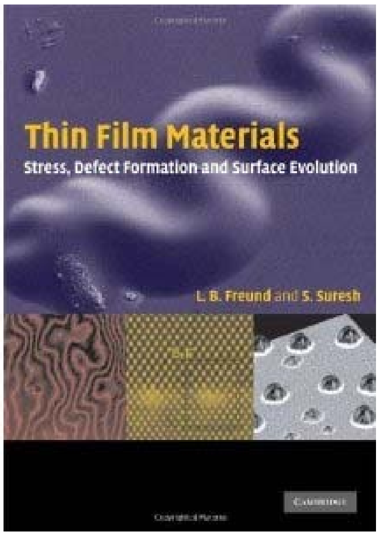
Molecular Dynamics Simulation



Low substrate temperature will result in porous structure

Two Good Textbooks





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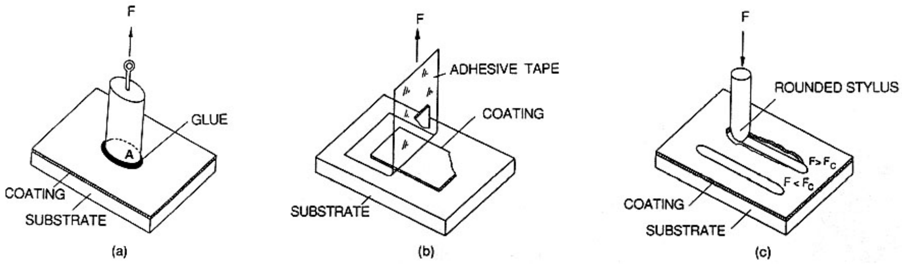
Adhesion



(a)pull test, (b)shear test, (c)scratch test

- Metal film must have enough adhesion force to substrate

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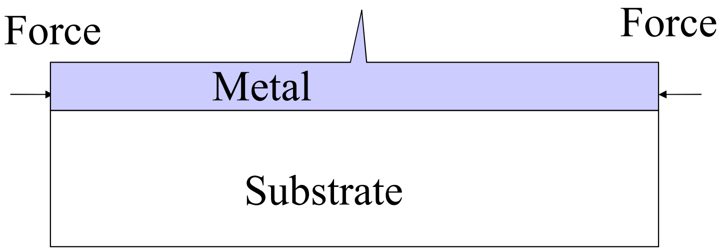
Compressive Stress Causes Hillock



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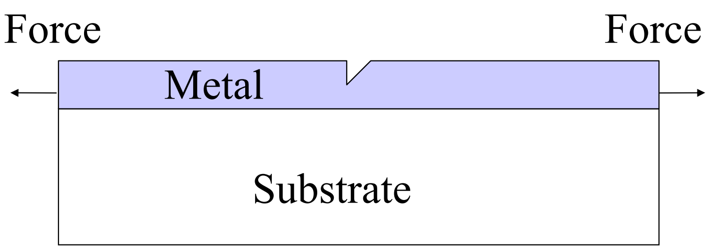
Tensile Stress Causes Crack



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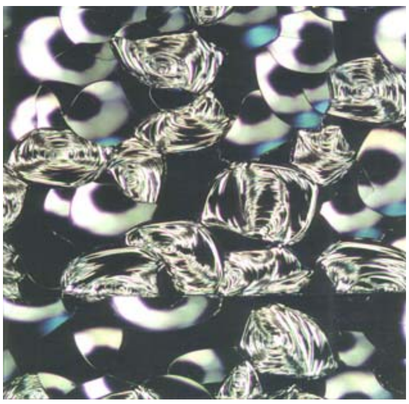
Failure of Thin Films

- Compressive failure
  - Bulking
  - Hillocks formation
- tensile failure
  - Cracking

Failure of Oxide Films



Microstructures

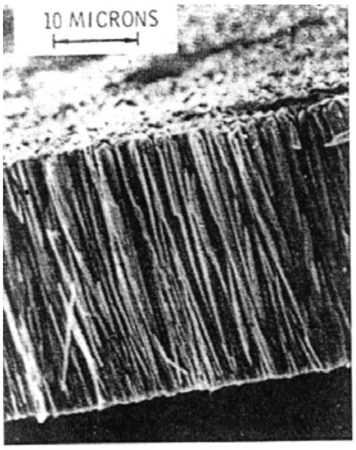
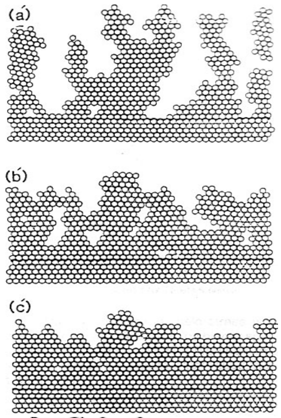
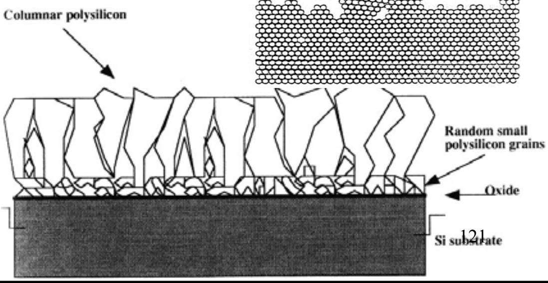


FIGURE 20. Scanning electron micrograph showing the porous, zone 1-type microstructure of Cr film deposited by magnetron sputtering at about 80°K. (From Thornton, J. A., *J. Vac. Sci. Technol.*, 11, 666, 1974. With permission.)





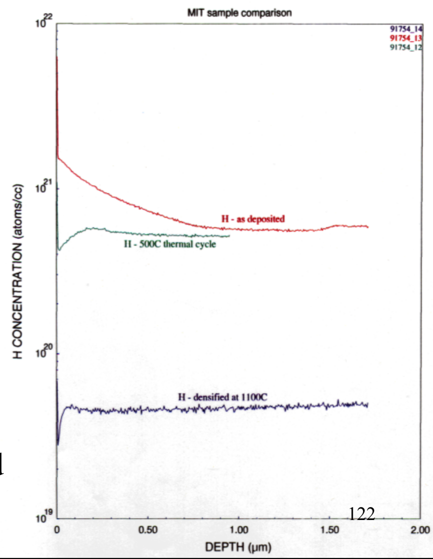
Hydrogen in PECVD Films

Table I. Hydrogen concentration of PECVD TEOS oxide

T (°C)	350	700	800	900	1000	1100
H_2 (%)	4.00	0.67	0.13	0.20	0.17	0.17

SIMS and RBS analysis to find hydrogen concentration in oxide

PECVD Silane oxide



PECVD Silane oxide
H ~ 10% as deposited

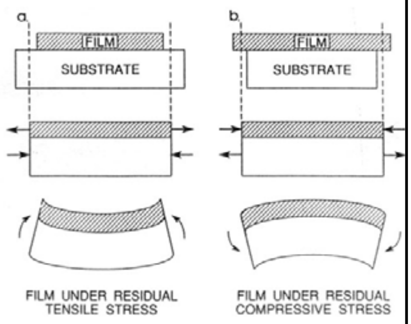
Stoney Formula

- Simple 1-D thermal stress

$$\sigma = (\alpha_f - \alpha_s)(T_1 - T_2)E_f/(1 - \nu_f)$$

- Stoney formula for thin film material
  - by curvature measurement to find residual stress

$$\sigma_f = \frac{E_s h_s^3}{6(1-\nu_s)Rh_f^2(1+h_s/h_f)}$$



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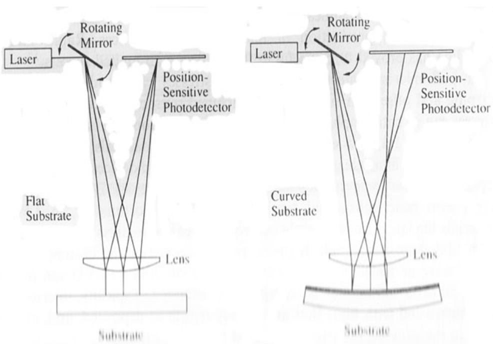
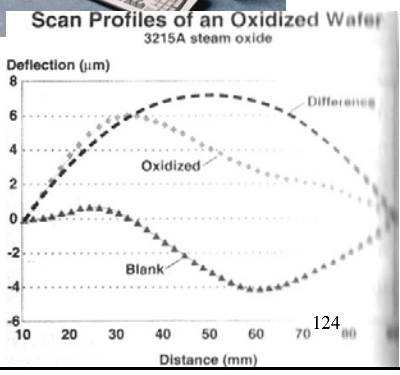
Residual Stress Measurement





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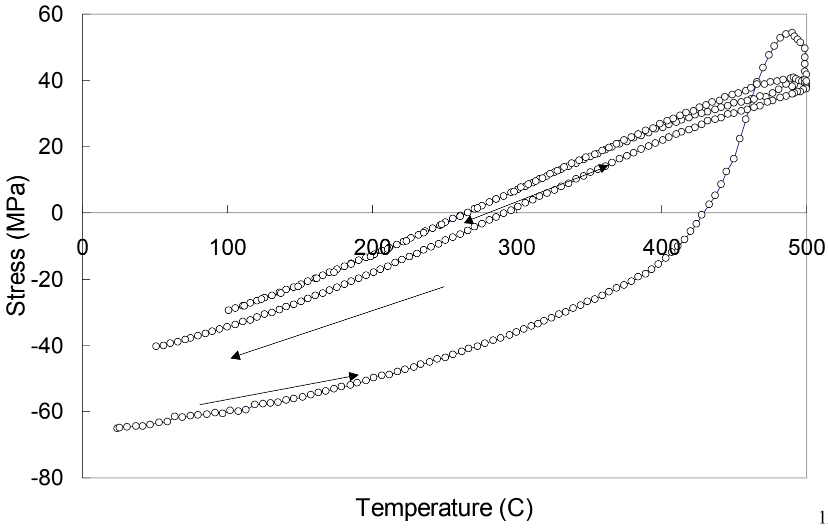
Thermal Cycling



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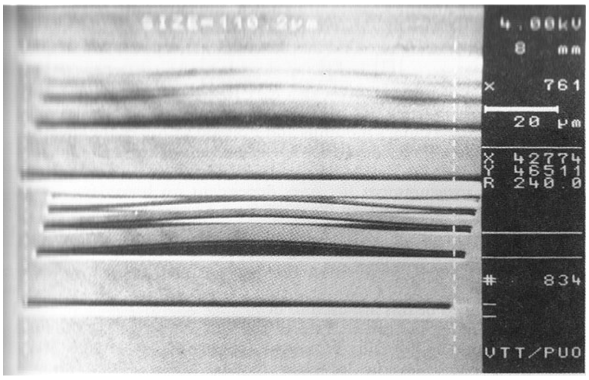
Buckling



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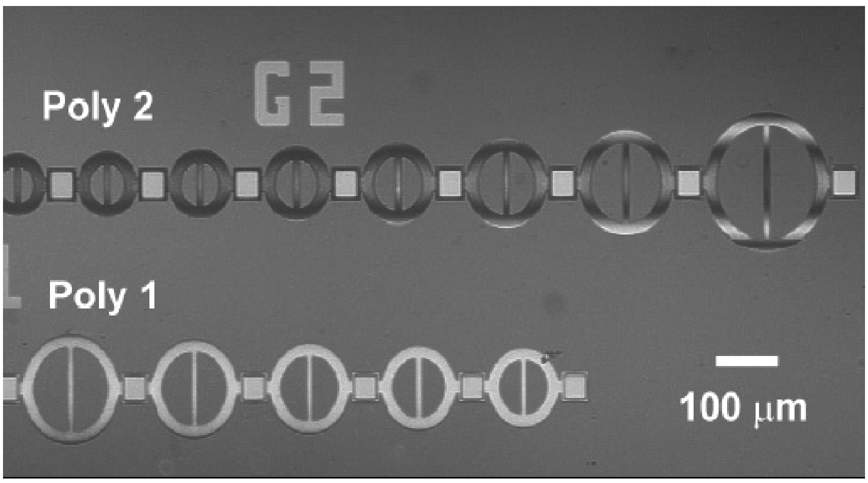
薄膜製程殘留應力量測



Guckel’s Rings: for tensile residual stress evaluation

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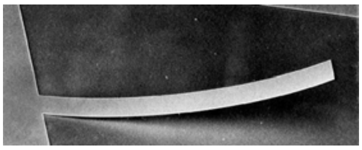
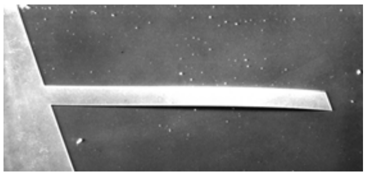
Residual Stress Gradient

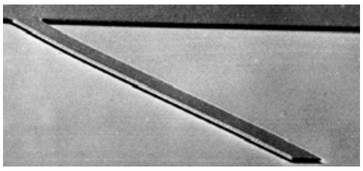
Tensile thin film on top



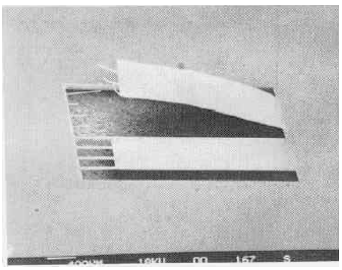
Compressive thin film on top

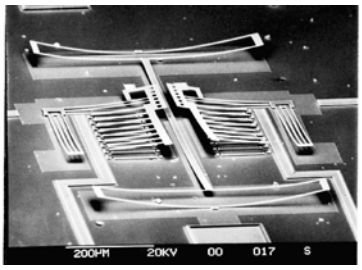


Perfect! Annealing poly-Silicon within oxide layers with similar phosphorous content at 1000°C for 60 seconds or so is enough!

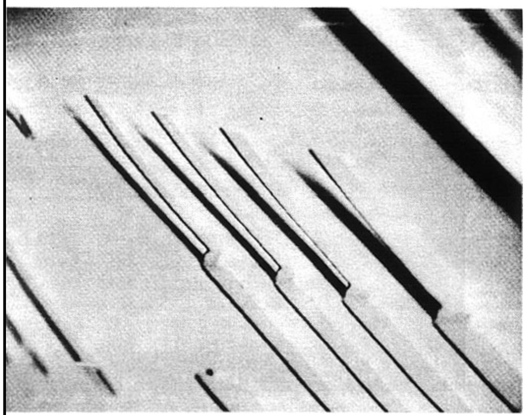


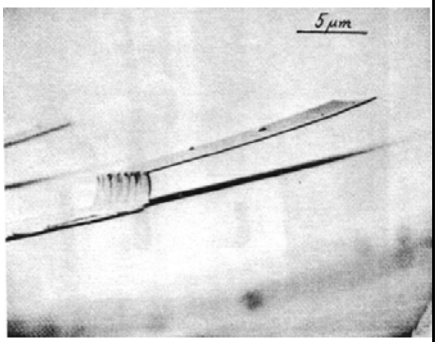
Failure due to Residual Stress Gradient





Stress Gradient





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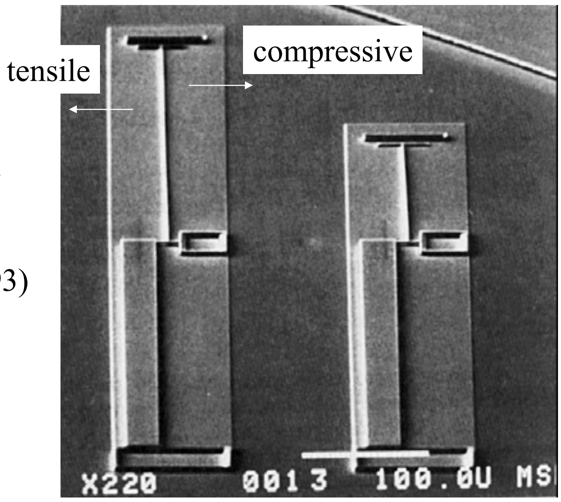
薄膜製程殘留應力量測

- In situ measurement for residual stress during thin film processing
- (L. Lin, UC Berkeley, 1993)



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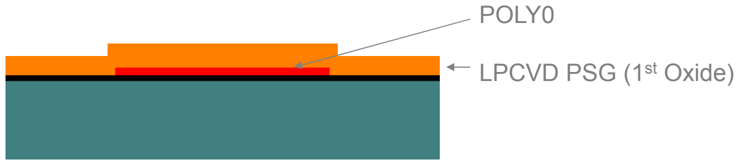
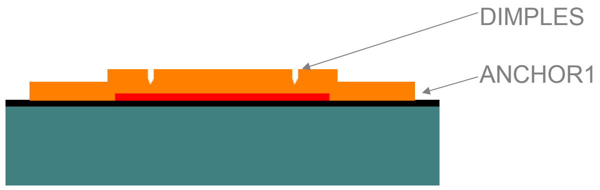
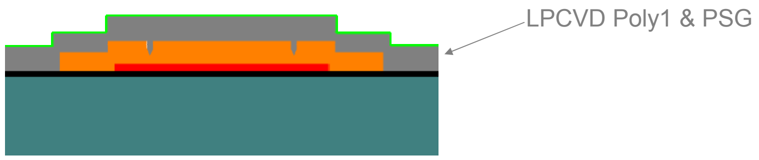
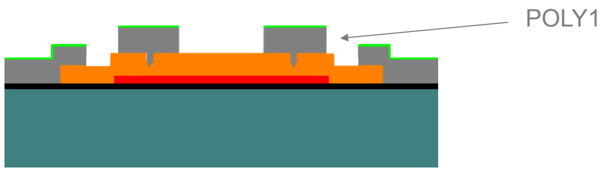
Process Overview





Process Overview





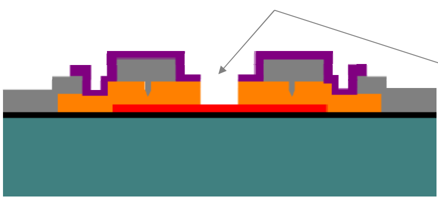
Process Overview

Remove PSG

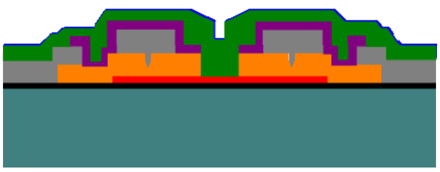
LPCVD PSG (2nd Oxide)

Poly1_Poly2_VIA

Process Overview



ANCHOR2



LPCVD Poly2 & PSG

Process Overview