

Appunti & trasparenze - Parte 7

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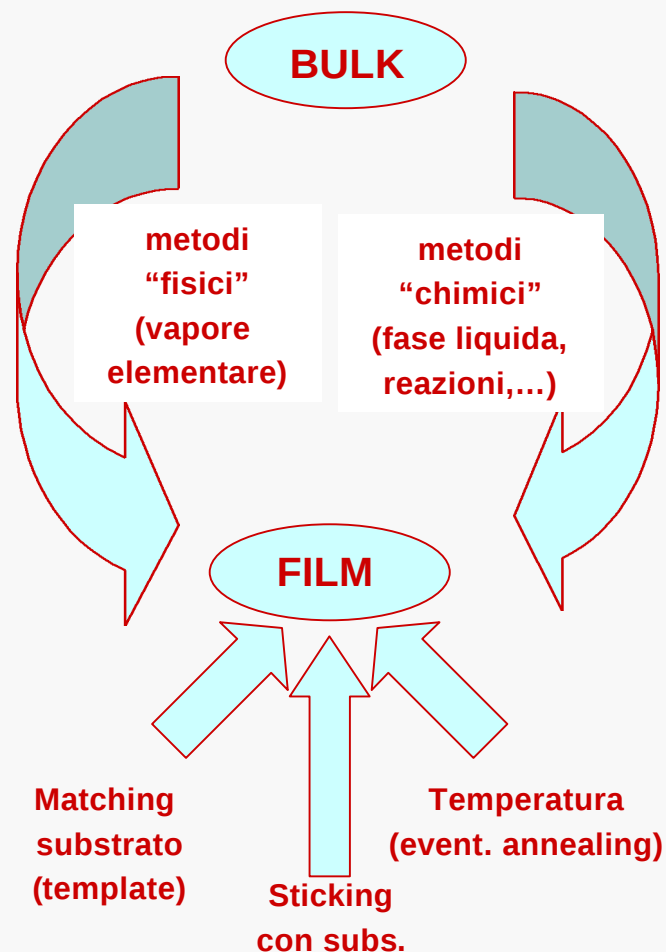
Fabbricazione di film sottili: nucleazione, coalescenza e crescita;
alcuni metodi fisici e chimici di deposizione: MBE, MOMBE,
Sputtering, PLAD, CVD, MOCVD, LPE, ...

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Introduzione

Film sottile: strato di materiale con spessore $\ll$ dimensioni superficiali (typ., 1-100 nm)

Crescita di film sottili è fortemente richiesta per applicazioni di ogni tipo (funzionali, es. elettronica, ottica, tribologia e strutturali, es. hard-coatings, adesione, etc.)



	Physical Vapor Deposition			Chemical Vapor Deposition
	Evaporation / MBE	Sputtering	PLD	CVD / MOCVD
Mechanism of production of depositing species	Thermal energy	Momentum transfer	Thermal energy	Chemical reaction
Deposition rate	High, up to 750,000 Å/min	Low, except for pure metals	Moderate	Moderate Up to 2,500 Å/min
Deposition species	Atoms and ions	Atoms and ions	Atoms, ions and clusters	precursor molecules dissociate into atoms
Energy of deposited species	Low 0.1 to 0.5 eV	Can be high 1-100 eV	Low to high	Low; Can be high with plasma-aid
Throwing power				
a) Complex shaped object	Poor, line of sight	Nonuniform thickness	Poor	Good
b) Into blind hole	Poor	Poor	Poor	Limited
Scalable to wafer size	up to large	up to large	limited	up to large

Crescita da vapore elementare (metodi fisici) o da soluzione (metodi chimici)

Problemi nella crescita

Generalmente l'obiettivo è un film sottile
cristallino (es. semiconduttori, alcuni metalli,...)
 o **policristallino** (es. alcuni ossidi, ceramiche,...)

Crescita (etero)**epitassiale**: ordine piani reticolari
 lungo l'asse c (per cristalli, ordine anche nel
 piano ab , cioè tessitura biassiale)

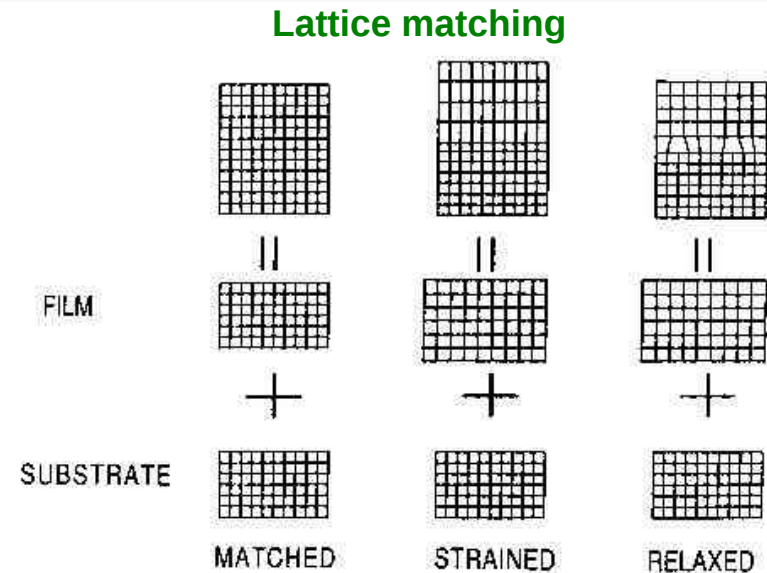


Figure 7-1. Schematic illustration of lattice-matched, strained, and relaxed heteroepitaxial structures. Homoepitaxy is structurally very similar to lattice-matched heteroepitaxy.

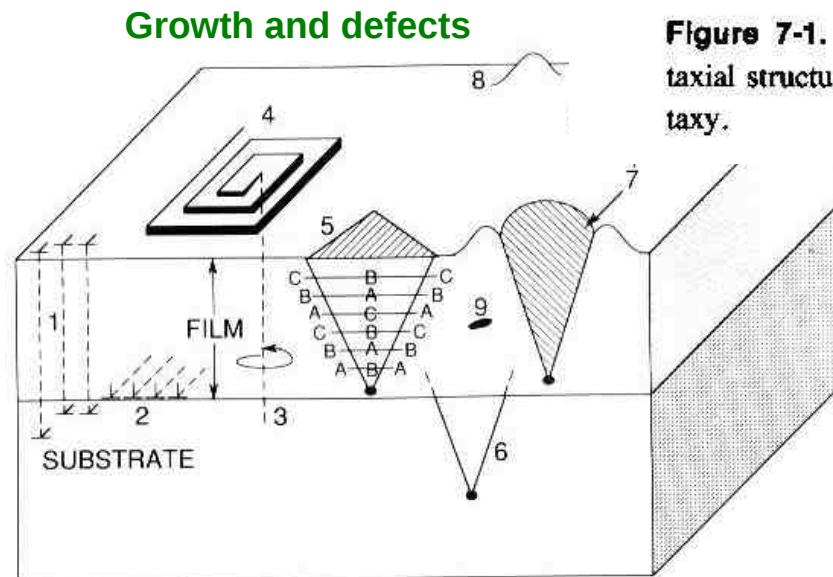


Figure 7-10. Schematic composition of crystal defects in epitaxial films: (1) threading edge dislocations; (2) interfacial misfit dislocations; (3) threading screw dislocation; (4) growth spiral; (5) stacking fault in film; (6) stacking fault in substrate; (7) oval defect; (8) hillock; (9) precipitate or void.

Numerosi fenomeni contribuiscono
 a determinare la "qualità" della
 crescita

Crescita epitassiale

2.3 Film Growth Modes

Nucleation and growth of a film proceeds from energetically favourable places on a substrate surface and even the cleanest polished surface shows some structure. Figure 5 shows schematically the structure of a well-polished single-crystal surface. The characteristic features are the terraces of length, l_s , the steps and the kinks within the step line, which otherwise runs along well-defined crystallographic directions. If the surface diffusion is fast enough a randomly deposited adatom will diffuse to the energetically most favourable places like steps and especially kinks. If at lower temperatures the diffusion is slower, several mobile adatoms may encounter each other within a terrace and may form additional immobile adatom clusters within the terraces. Similarly, advacancies and their clusters might be formed at the end of the coverage of a terrace. By reducing the step distance and hence the diffusion length by vicinal surfaces, Figure 6, the step controlled growth may be extended to lower temperatures.

The details of the growth modes for the simplest case of **homoeepitaxy**, the growth of a film on a single-crystalline surface of the same material, is indicated in Figure 7. As discussed above, step propagation dominates at higher temperatures and/or small deposition rates and two-dimensional island growth will predominate if immobile clusters are formed by the encounters of mobile adatoms. This simple picture is, however, quite frequently modified: if the jump across the step is kinetically hindered multilayer growth will be observed. This enlarged activation energy for the jump across the step is called the **Ehrlich-Schwoebel effect** and can be understood in a simple model as the adatom is nearly dissociated from the surface in the saddle point of this jump.

Superficie vicinale

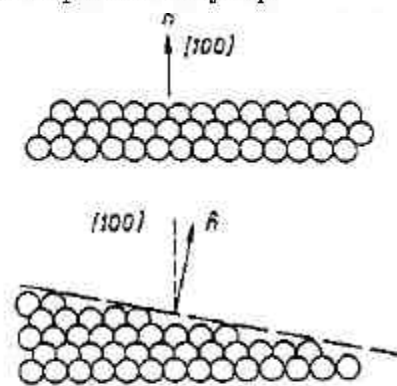


Figure 6: Change of the step distance, l_s , by cutting a surface at a small angle to a major crystallographic direction, i.e., forming a vicinal surface.

Da R. Waser Ed., Nanoelectronics and information technology (Wiley-VCH, 2003)

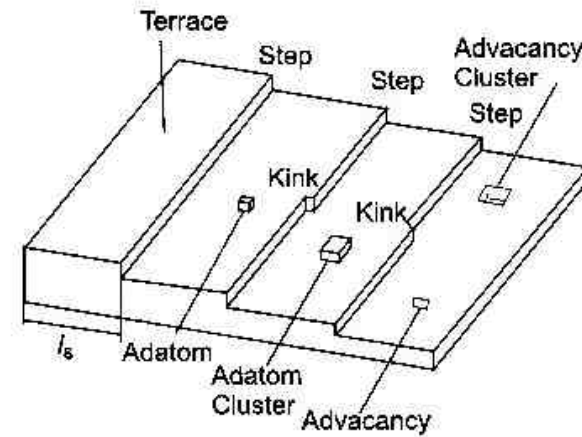


Figure 5: Schematic view of the elements of the surface morphology [3].

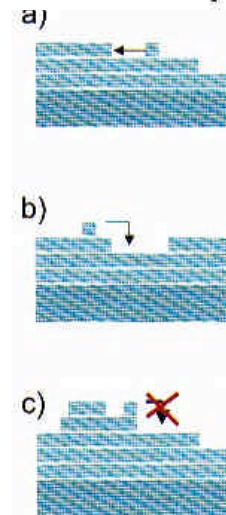
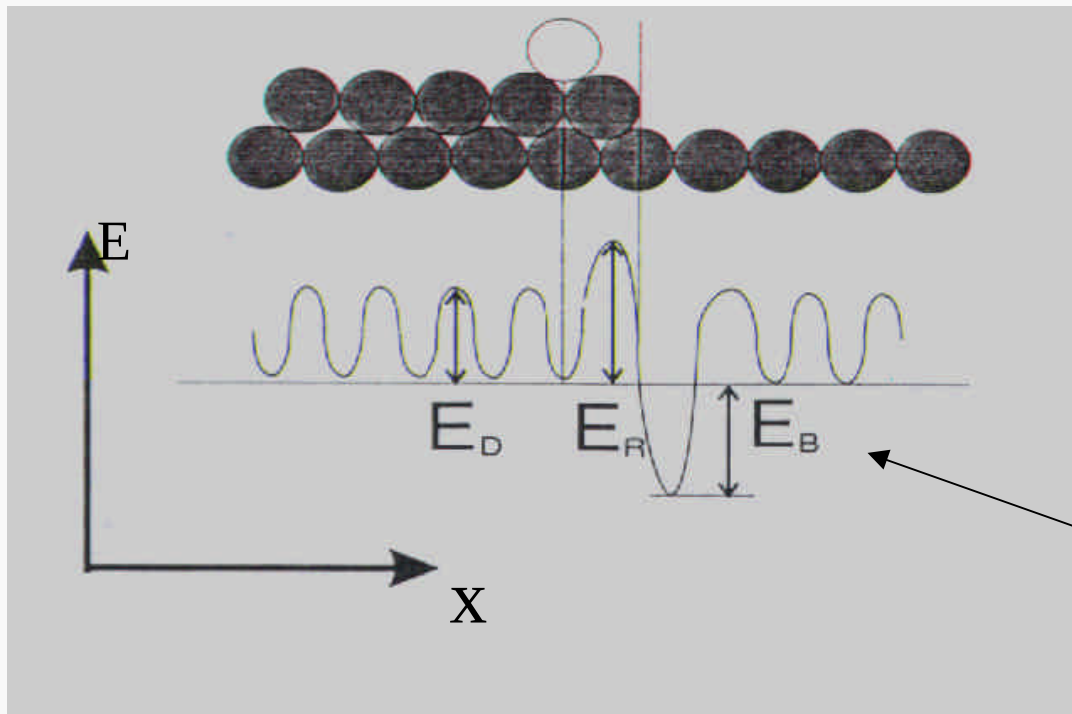


Figure 7: Growth modes of homoeepitaxy: (a) step-propagation, (b) 2d-island growth, and (c) multi-layer growth.

Diffusione e
barriera di Schwoebel

Barriera di Schwoebel

La diffusione delle particelle che arrivano sul substrato (elemento essenziale per avere copertura omogenea e formazione del film) è controllata da temperatura e da barriere di energia per muoversi su una “piattaforma”, salire o scendere tra “piattaforme” diverse



Coefficiente di diffusione:

$$D = D_0 \exp(-E/kT)$$

Barriera di Schwoebel:
energie diverse localmente

Crescita eteroepitassiale

If we want to grow an epitaxial film on a different substrate (so-called **heteroepitaxy**), two material parameters have to be considered in addition: the surface energy, γ , and the lattice parameter or lattice match of the two materials. For the case of good lattice match the difference in surface energy leads to two different growth modes as indicated in Figure 8a and b. As long as:

$$\gamma_{\text{layer}} + \gamma_{\text{substrate/layer}} \leq \gamma_{\text{substrate}} \quad (4)$$

we observe perfect wetting and pure layer by layer or **Frank-van-der-Merve growth**. For the opposite case, we observe island or **Volmer-Weber growth**. For this consideration the surface energies of the crystallographic orientations of actual interest must be applied, which are often not available in data reference tables. If there is a lattice mismatch between substrate and film, an additional growth mode may be observed as indicated in Figure 8c, **Stranski-Krastanov growth**. A first layer may grow matched to the substrate, which yields additional strain energy. With growing thickness this strain energy increases in proportion to the strained volume and an island formation may become more favourable in spite of the larger surface area.

The contributions of strain and surface energy can quite generally be described in a simple model and the resulting difference in energy between island growth and layer growth is given by Eq. (5) and illustrated in Figure 9.

$$\Delta W = W_{\text{surf}} + W_{\text{relax}} = \text{const}_1 \gamma d^2 - \text{const}_2 k \xi^2 d^3 \quad (5)$$

k = bulk modulus, ξ = strain

Considering films of the same volume content, the increased surface energy for the island growth Figure 8b, is proportional to the island area, d^2 , whereas the energy released by relaxation of the lattice is proportional to the island volume, d^3 . A relaxation mode which is characteristic of isolated islands is shown in Figure 10 for a case where the film material has a larger bulk lattice parameter than the substrate. The model predicts a critical value, d_{crit} , where the island growth is finally more favourable and a fast decrease of the energy for larger sizes. However, the limits of the model are reached in this region as the simple relaxation mode is obviously no longer valid for large sizes.

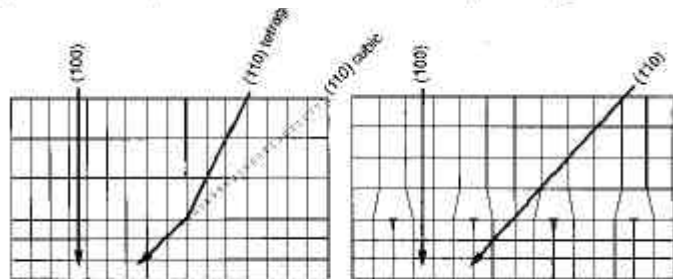
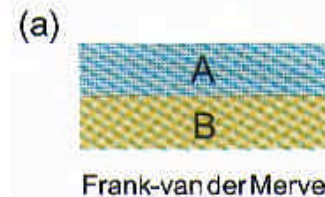
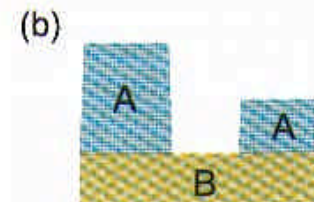


Figure 11: Strain relaxation by misfit dislocations for the example of two initially cubic crystals. As the film has a larger lattice constant than the substrate the forced matching at the interface yields a

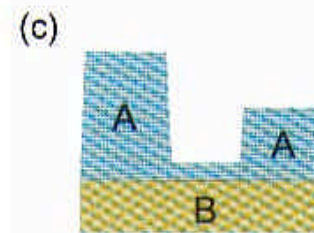
tetragonal distortion of the film. By misfit dislocations this strain can be relaxed and the film can re-approach its cubic structure.



Frank-van der Merve



Volmer-Weber



Stranski-Krastanov

Figure 8: Growth modes of the hetero-epitaxy.

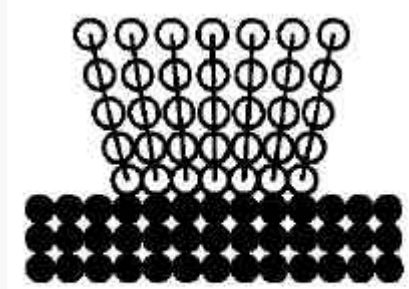


Figure 10: Strain relaxation in pseudo-morphic (dislocation-free) islands.

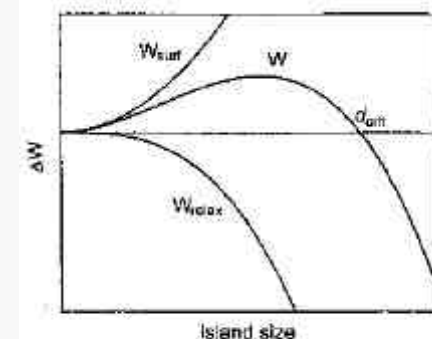


Figure 9: Energy contributions as a function of the island size [5].

Eteroepitassia regolata da rapporto tra energie superficiali
Possibili difettosità (misfits) dipendenti dallo spessore

Crescita delle isole I: nucleazione

Nucleation

This phase of growth is based on spontaneous formation of aggregate of atoms which is large enough to be energetically stable.

This condition is reached when the gain in volume energy for an additional monomer exceeds the energy loss due to surface formation

Kinetic concept (Venable's model)

Critical cluster of size i^ : adding a further monomer to a critical cluster leads to a stable cluster which does not decompose anymore.*

Assumptions

- 1. All stable clusters can be considered a group in the form $N_x = \sum_{j=1^*+1}^{\infty} N(j)$*
- 2. The number of subcritical clusters reaches a steady-state*

Rate equations

$$\frac{dn}{dt} = F - \frac{n}{\tau} - \frac{d}{dt} j_x N_x$$

$$\frac{dN(j)}{dt} = 0 \quad \text{For } 1 < j < i^*$$

$$\frac{dN_x}{dt} = n \sigma_m(i^*) N(i^*) - 2 N_x \frac{d\mathcal{G}}{dt}$$
$$\mathcal{G} = A j_x N_x$$

Modelli a rate-equations per la crescita di isole

Materiale tratto dal seminario di Barbara Fazio
IPCF/CNR Messina, Aprile 2003

Crescita delle isole II: coalescenza

Coalescence

During a film growth process, when the experimental conditions past the nucleation regime and favor merging of clusters, the system continues to evolve towards a coalescence morphology.

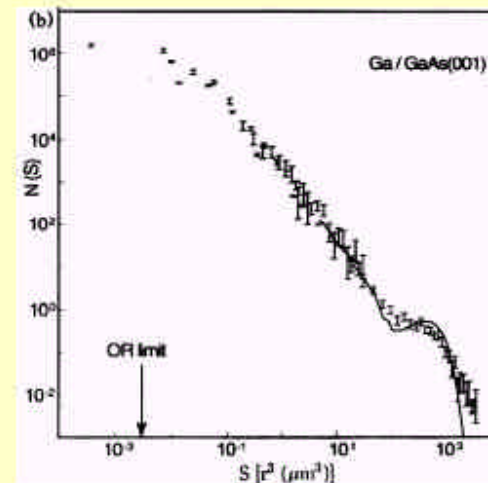
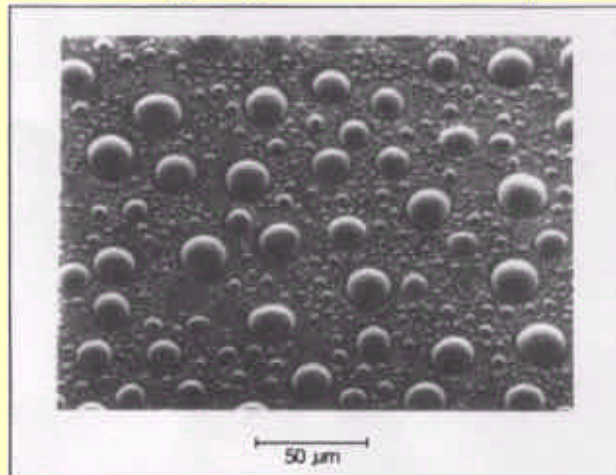
In this regime has been characterized the following three cluster growths (Beysens et al.):

- *Nucleation and individual cluster growth without cluster density reduction or **pre-coalescence** and **transient coalescence** stage (diffusive mass transport limited growth)*
- *Cluster merging or **late stage of coalescence** (static and dynamic)*
- *Secondary nucleation and cluster growth on exposed fraction of surface.*

Esempio di studio di coalescenza (fasi iniziali della crescita)

Experimental study of coalescence regime in the system Ga on GaAs(001)
(M.Zinke-Altmann et al.)

- *Base pressure $< 5 \cdot 10^{-9}$ Pa*
- *Deposition equivalent to a coverage of about 13 monolayers at room temperature.*
- *Annealing temperature = 660°C for 5 min.*



Good agreement between experimental results and theoretical model of coalescence regime (even if microscopic details in Monte Carlo simulations differ from the experiment quite substantially)

Coalescenza/nucleazione:
processi concorrenti

Dipendenza da caratteristiche
del substrato (diffusione)

Deposizione da fase di vapore

2.1 Gas Kinetics

The residual gas pressure in the system is one of the basic parameters to be controlled during film deposition as the residual gas atoms may collide with the depositing species or may hit the growing surfaces and may thus be incorporated in the film, Figure 1. For the simplest assumption that the gas atoms may be considered as not interacting masses with a Maxwell velocity distribution we obtain the mean free path length, λ , of the atoms or molecules

$$\lambda = \frac{1}{\sqrt{2} \pi N d^2} \quad (1)$$

d = molecular diameter, N = concentration of the gas. With the law of the ideal gas: $N = p/k_B T$, k_B = Boltzmann constant, we obtain:

$$\lambda = \frac{k_B T}{\sqrt{2} \pi p d^2} \quad (2)$$

For the example of air molecules we obtain a free path length which is of the order of a typical distance from source to substrate of about 20 cm at a pressure of $0.5 \cdot 10^{-3}$ mbar. This rather moderate vacuum level shows that the beam interaction is not a critical condition for the base vacuum. More critical is the number of residual gas atoms which hit the growing surface and limit the purity of the film if they are incorporated. This number can be expressed as

$$N_i = p_i \sqrt{\frac{1}{2 \pi k_B m_i T}} \quad (3)$$

m_i = atomic or molecular mass. Typical results are summarized in Tab. 2. Assuming a sticking coefficient of unity, the incorporation of residual gas atoms may be expressed in terms of monolayers and this growth rate may be rather high as compared to a typical growth rate of an epitaxial film i.e., one monolayer / s. Hence, for clean films **ultra-high vacuum** (UHV, better than 10^{-9} mbar) may be necessary.

p , mbar	Mean free path, cm (between collisions)	Collisions / s (between molecules)	Molecules/(cm ² s) (sticking surface)	Monolayer / s*
10^0	$6.8 \cdot 10^{-3}$	$6.7 \cdot 10^6$	$2.8 \cdot 10^{20}$	$3.3 \cdot 10^5$
10^{-3}	$6.8 \cdot 10^0$	$6.7 \cdot 10^3$	$2.8 \cdot 10^{17}$	$3.3 \cdot 10^2$
10^{-6}	$6.8 \cdot 10^3$	$6.7 \cdot 10^0$	$2.8 \cdot 10^{14}$	$3.3 \cdot 10^{-1}$
10^{-9}	$6.8 \cdot 10^6$	$6.7 \cdot 10^{-3}$	$2.8 \cdot 10^{11}$	$3.3 \cdot 10^{-4}$

* Assuming the condensation coefficient is unity

Table 2: Some facts about residual air at 25 °C in a typical vacuum used for film deposition (after Chopra [2]).

2.2 Thermodynamics

Phase-diagrams are the starting point for considering the deposition of a new material in order to see the stability range of the envisaged phase and the existence of concurrent phases. Standard phase diagrams are given at ambient pressure, however, changes with pressure must be considered for vacuum deposition methods. Figure 3 shows as a simple example the phase diagram of the completely intermixing binary system Si-Ge and the change from ambient pressure down to the UHV region [3]. At 1 mbar there is not much change compared to atmospheric pressure and we observe a wide range of stability of the mixed homogeneous crystalline phase, c, of Si-Ge (the decomposition of this homogeneous phase at very low temperature is somewhat speculative). At higher temperatures the liquid, l, to solid (crystalline) phase transition is indicated and above 2000 K the liquid to vapour, v, transition is shown. With decreasing pressure there is a strong decrease in temperature of the l-v borderlines and even an overlap with the c-l lines. Finally, in the UHV region, 10^{-9} mbar, the liquid has disappeared and only direct sublimation, c, v is left at temperatures around 1100 K. Hence, re-evaporation of the material under UHV conditions and high temperatures must be considered. In addition, a comparison with the deposition rates and gas pressures discussed along with Table 2 shows that the deposition of the films usually proceeds under high supersaturation, i. e. conditions far from thermodynamic equilibrium.

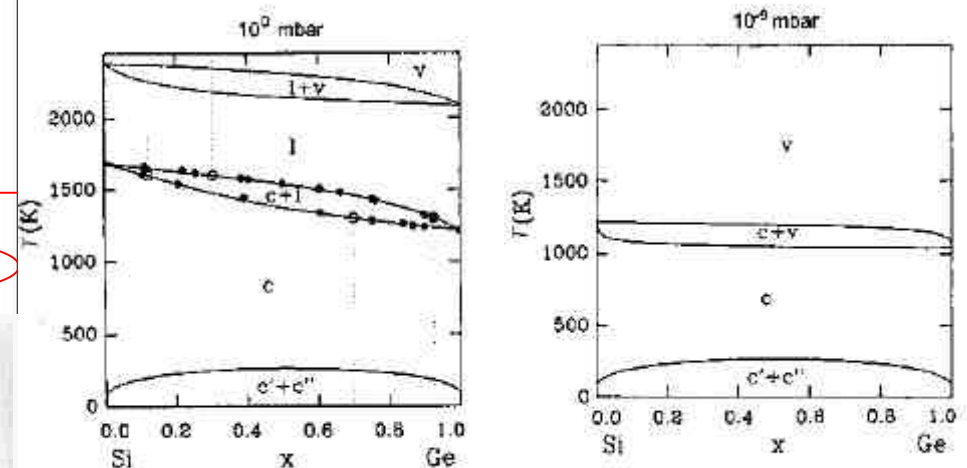
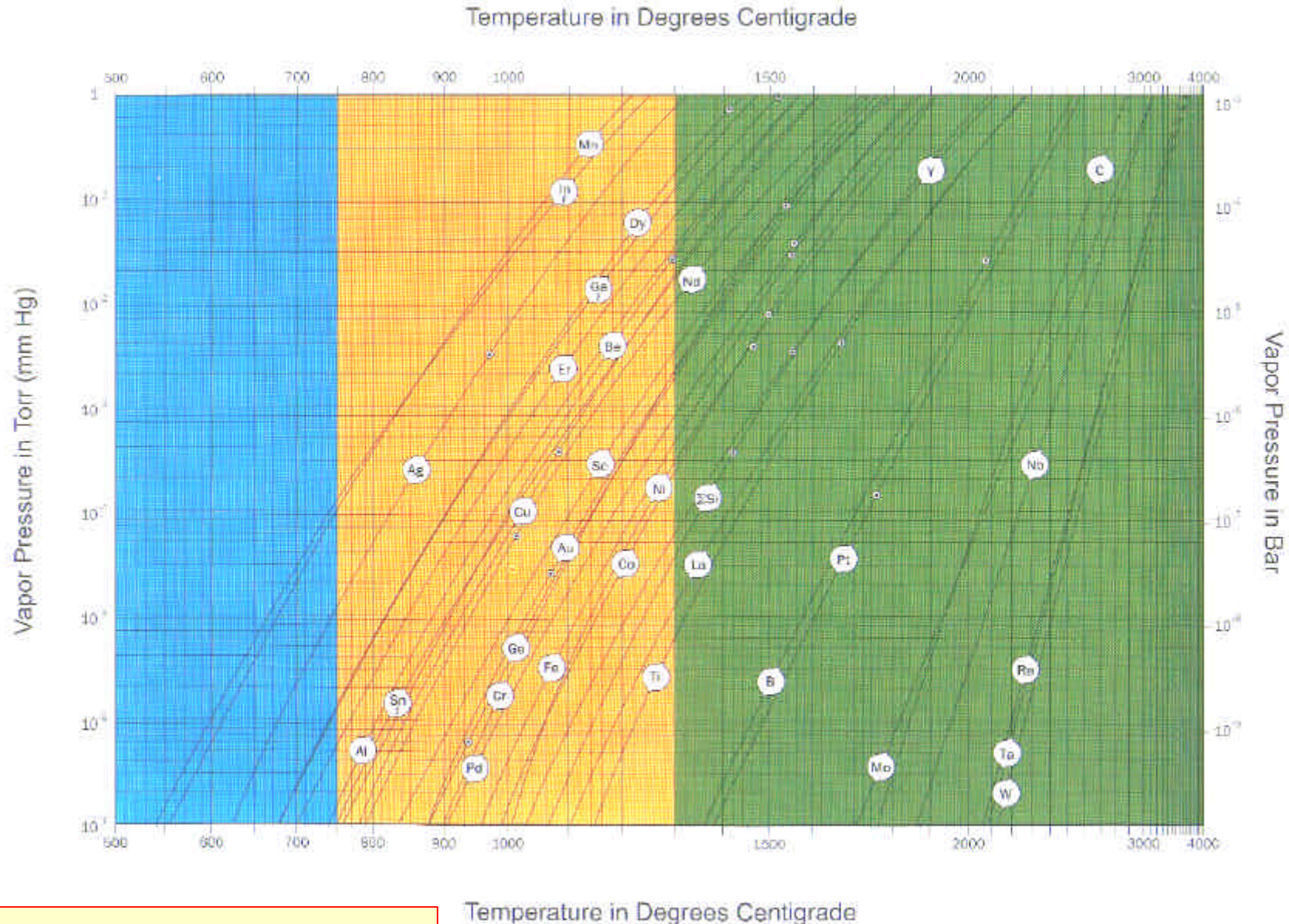


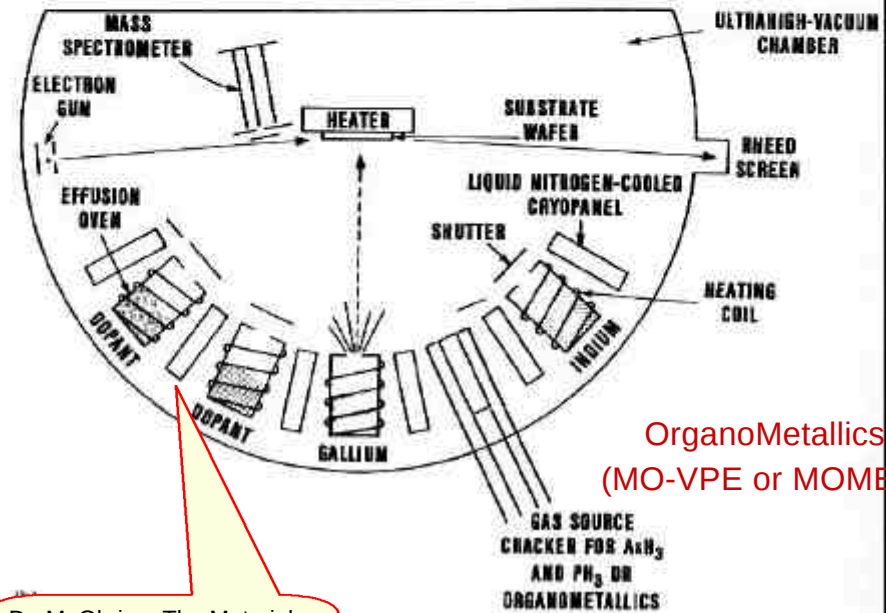
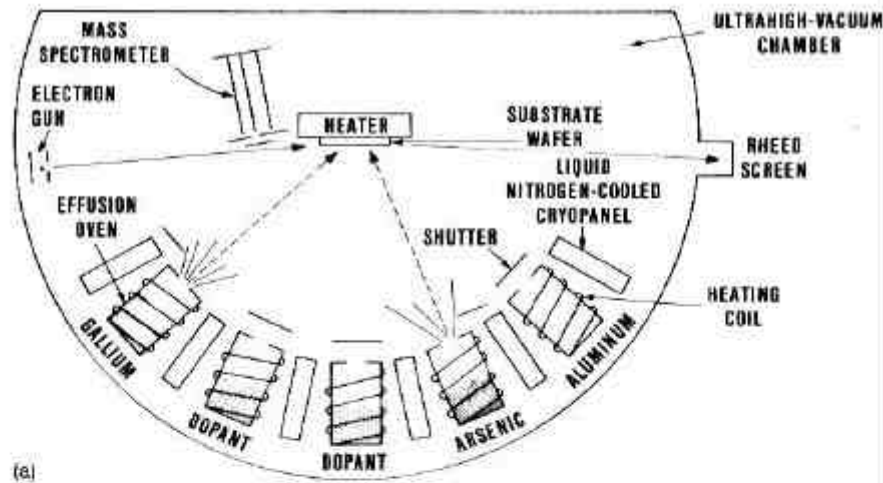
Figure 3: x-T phase diagram of the $Si_{(1-x)}Ge_x$ systems at 10^0 and 10^{-9} mbar [3].

Vaporizzazione (effusiva)



Riscaldamento efficace
per produrre vapori atomici

Molecular Beam Epitaxy: MBE, MOMBE



OrganoMetallics
(MO-VPE or MOMBE)

Da M. Ohring, The Materials Science of Thin Films, Academic (1992)

Elementi chiave MBE:

- alta pulizia (UHV, $p \sim 10^{-10}$ mbar)
- basso growth rate in continua ($\sim 1 \mu\text{m/h}$)
- operazione con *tutti* i semiconduttori



elevato controllo spessori a livello atomico
alta purezza
fabbricazione eterostrutture



Forno effusivo (EPI):
alte temperature
--> reattività materiali?
--> pulizia?

Sorgenti per MBE

3.1.1 Sources

The schematic of the classical MBE source, the Knudsen cell, is illustrated in Figure 13. The evaporation rate, N_e , is described by the Hertz-Knudsen (or Langmuir) equation:

$$N_e = \frac{p_e A_e}{\sqrt{2\pi m k_B T}} \quad (6)$$

p_e is the equilibrium vapour pressure and A_e the area of the aperture [7]. Therefore, the source can be precisely controlled by a single parameter, the temperature. However, the technical details are very complex and involve more parameters than shown in Eq. (6).

Figure 14 shows the principle of an electron beam evaporator. The electron beam is magnetically deflected by 270° and is centred on the source material. In this way a melt of the source material is produced on a block of the same material which can be held in a water-cooled cold crucible in order to avoid contamination of the melt.

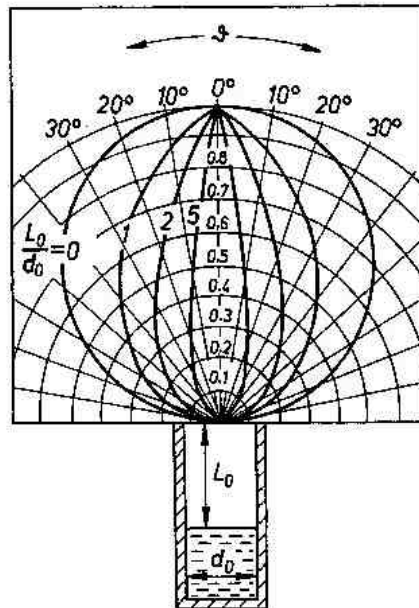


Figure 13: Schematics of a Knudsen cell and the distribution of the vapour beam intensity [7]. The distribution depends on the ratio L_0/d_0 and consequently on the filling level of the cell.

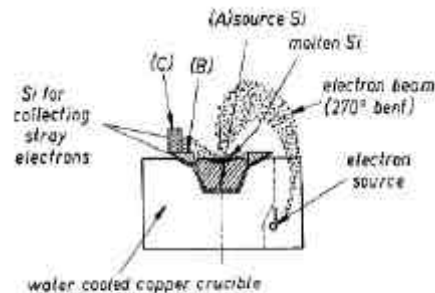


Figure 14: Schematics of an electron beam evaporator for Si evaporation [7]; B: Si guard ring, C: catcher for backscattered electrons.

Consider now a substrate positioned a distance l from a source aperture of area A , with $\phi = 0$. An expression for the number of evaporant species striking the substrate is

$$\dot{R} = \frac{3.51 \times 10^{22} PA}{\pi l^2 (MT)^{1/2}} \text{ molecules/cm}^2\text{-sec.} \quad (7-13)$$

As an example, consider a Ga source in a system where $A = 5 \text{ cm}^2$ and $l = 12 \text{ cm}$. At $T = 900^\circ \text{C}$ the vapor pressure $P_{\text{Ga}} \approx 1 \times 10^{-4} \text{ torr}$, and substituting $M_{\text{Ga}} = 70$, the arrival rate of Ga at the substrate is calculated to be $1.35 \times 10^{14} \text{ atoms/cm}^2\text{-sec}$. The As arrival rate is usually much higher, and, therefore, film deposition is controlled by the Ga flux. An average monolayer of GaAs is $2.83 \text{ \AA}$ thick and contains $\sim 6.3 \times 10^{14} \text{ Ga atoms/cm}^2$. Hence, the growth rate is calculated to be $(1.35 \times 10^{14}) / (6.3 \times 10^{14}) \times 2.83 \times 60 = 36 \text{ \AA/min}$, a rather low rate when compared with VPE.

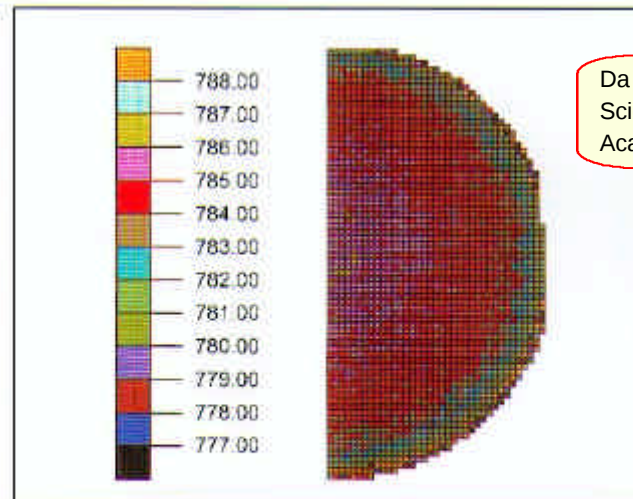


Figure 4-3: Thickness uniformity across a 3" wafer represented as a mapping of quantum well photoluminescence. The MQW structure was grown using a SUMO Ga cell in a MOD GEN II system. Uniformity better than $\pm 1\%$ was achieved. Data courtesy R. Sacks, Ohio State University and K. Stair, Northwestern University.

Da M. Ohring, The Materials Science of Thin Films, Academic (1992)

Crescita di monostrati via MBE

Crescita di monostrati
controllabile con diagnostiche in-situ
(es. RHEED)

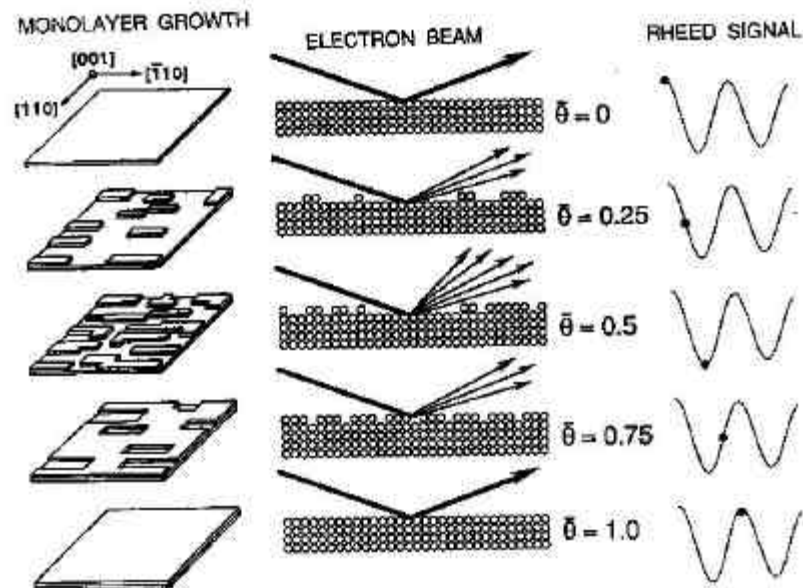


Figure 7-22. Real space representation of the formation of a single complete monolayer; $\bar{\theta}$ is the fractional layer coverage; corresponding RHEED oscillation signal is shown.

Controllo accurato dello spessore del film fino a
livelli molto bassi (monostrati)

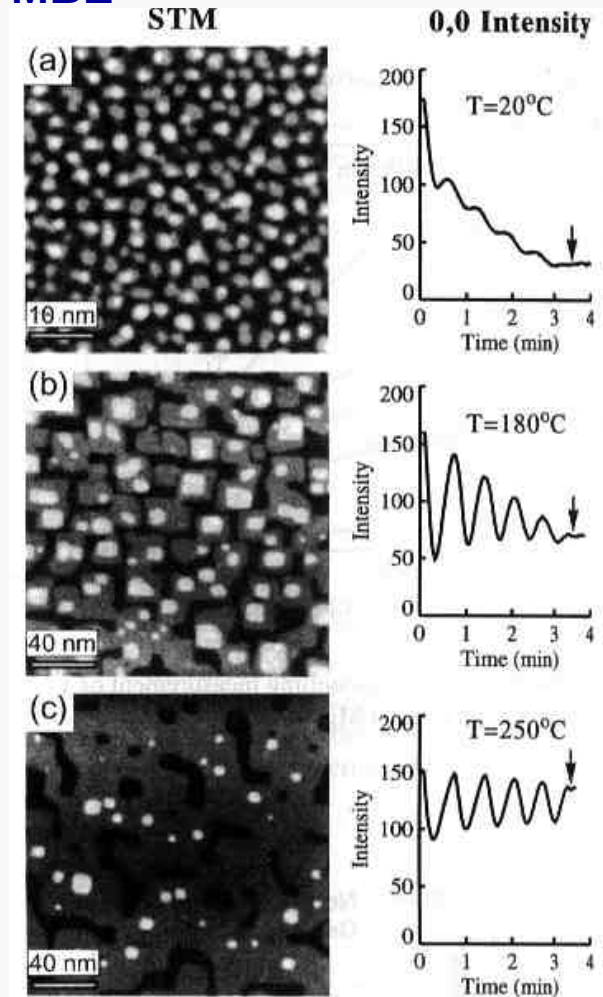
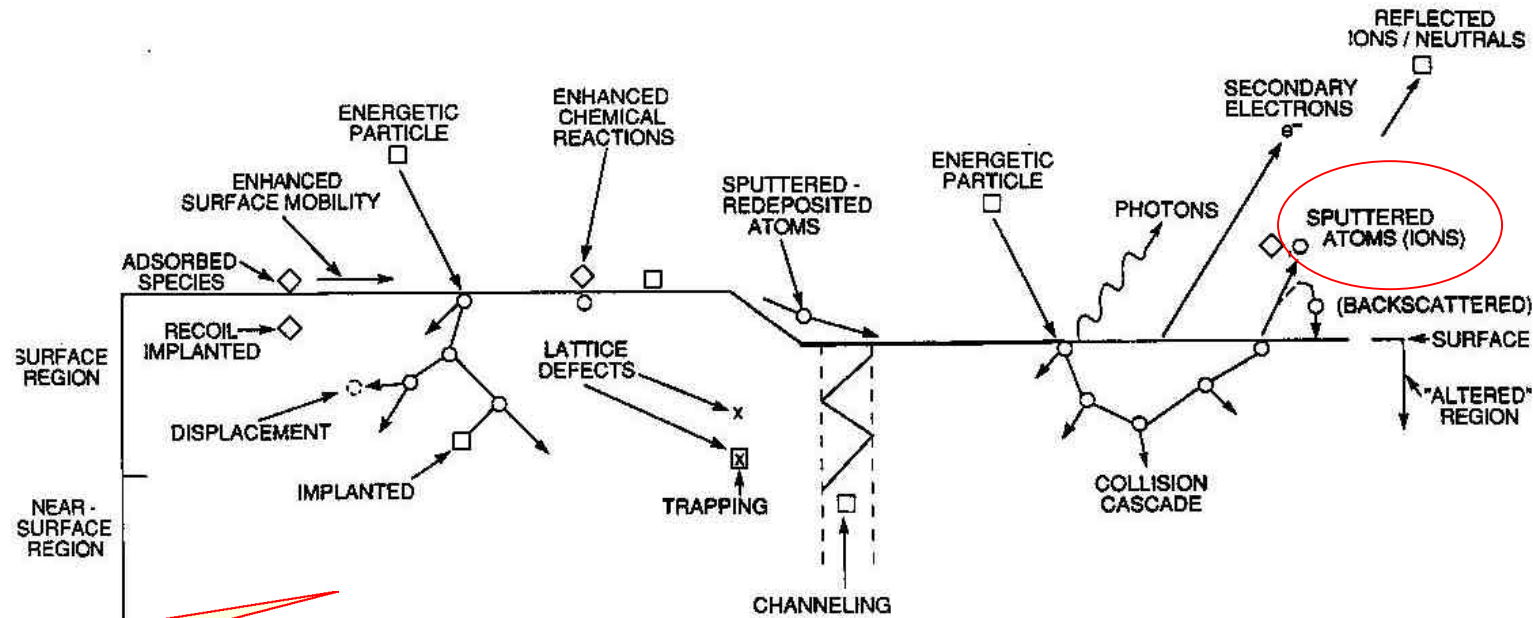


Figure 19: STM and RHEED results for the homo-epitaxial growth of Fe films on Fe(100) substrates. The growth was interrupted after 5 oscillations, as indicated by the arrow. The scale of the STM was changed between part a and b! The roughness of the films decreases strongly with temperature: rms (root mean square) amplitude 0.116 nm, 0.095 nm and finally at 250°C 0.06 nm [9].

Sputtering (e bombardamento con cariche)

Particelle cariche (ioni od elettroni) accelerati verso la superficie di un target solido
--> desorbimento (via numerosi processi) --> vaporizzazione (*non solo elementare*)



Da M. Ohring, The Materials Science of Thin Films, Academic (1992)

-16. Depiction of energetic particle bombardment effects on surfaces and growing films. (From Ref. 18).

Punti di forza principali:

- efficienza anche con materiali “refrattari”, es. ceramiche ed alcuni metalli con alta T_{vap}
- alti growth rate (fino a diversi $\mu\text{m/h}$)

DC, RF, Magnetron sputtering

Sputtering: cariche (accelerate) prodotte da **plasma**, tipicamente di gas inerte, prodotto in *continua* (DC) o con *radiofrequenza* (RF)

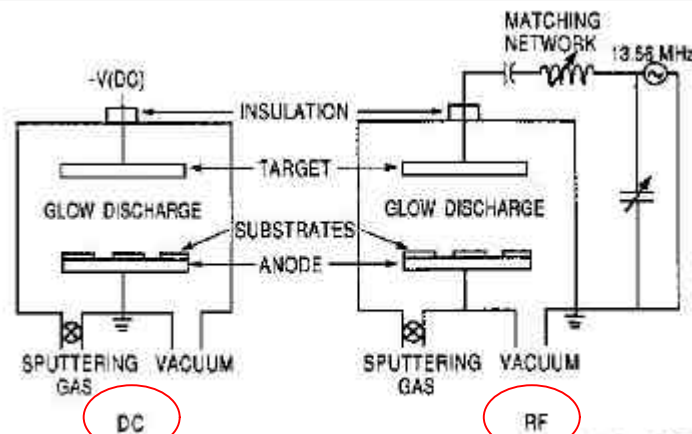


Figure 3-13. Schematics of simplified sputtering systems: (a) dc, (b) RF.

Table 3-4. Sputtering Yield Data for Metals (atoms/ion)

Sputtering Gas Energy (keV)	He 0.5	Ne 0.5	Ar 0.5	Kr 0.5	Xe 0.5	Ar 1.0	Ar Threshold Voltage (eV)
Ag	0.20	1.77	3.12	3.27	3.32	3.8	15
Al	0.16	0.73	1.05	0.96	0.82	1.0	13
Au	0.07	1.08	2.40	3.06	3.01	3.6	20
Be	0.24	0.42	0.51	0.48	0.35		15
C	0.07	—	0.12	0.13	0.17		
Co	0.13	0.90	1.22	1.08	1.08		25
Cu	0.24	1.80	2.35	2.35	2.05	2.85	17
Fe	0.15	0.88	1.10	1.07	1.00	1.3	20
Ge	0.08	0.68	1.1	1.12	1.04		25
Mo	0.03	0.48	0.80	0.87	0.87	1.13	24
Ni	0.16	1.10	1.45	1.30	1.22	2.2	21
Pt	0.03	0.63	1.40	1.82	1.93		25
Si	0.13	0.48	0.50	0.50	0.42	0.6	
Ta	0.01	0.28	0.57	0.87	0.88		26
Ti	0.07	0.43	0.51	0.48	0.43		20
W	0.01	0.28	0.57	0.91	1.01		33

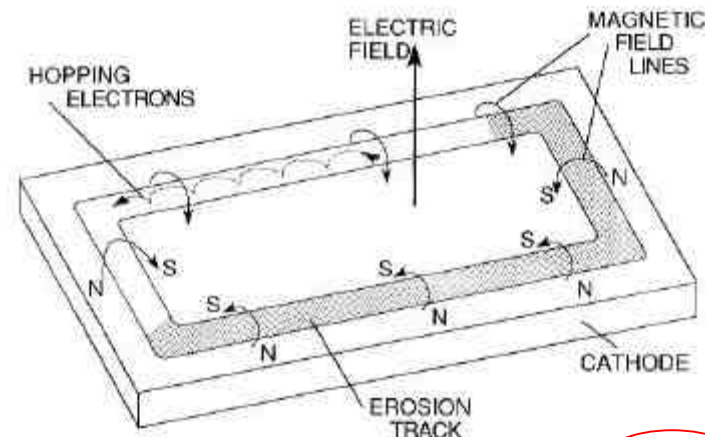


Figure 3-21. Applied fields and electron motion in the planar magnetron.

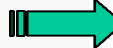
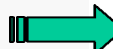
Campi magnetici aumentano ionizz. collisionale

Principali **svantaggi** sputtering:

- presenza di gas ambiente (per il plasma)
--> scarsa purezza
- possibilità backscattering
--> danneggiamento film
- scarsa efficacia atomizzazione
--> scarso controllo crescita

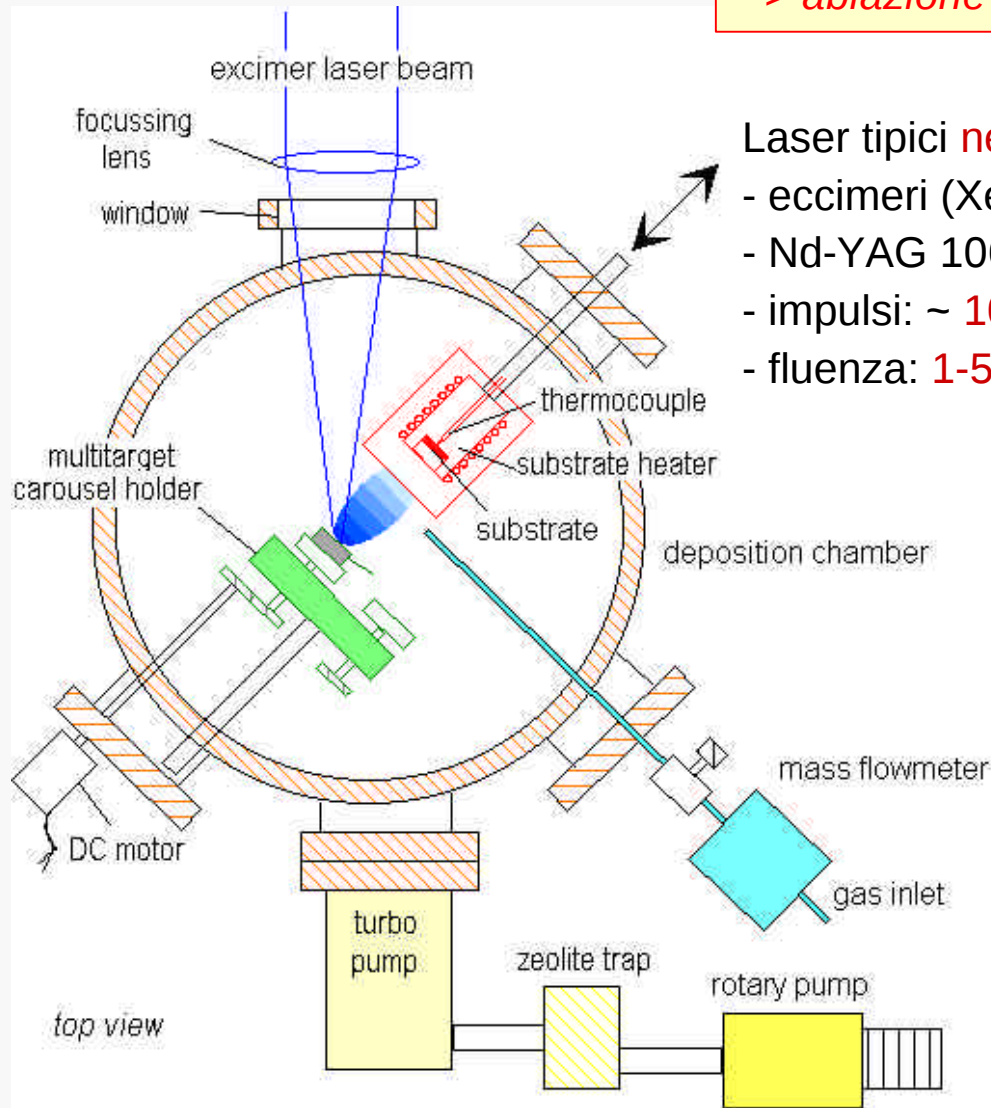
Confronto vaporizzazione/sputtering

Da M. Ohring, The Materials Science of Thin Films, Academic (1992)

Evaporation	Sputtering
A. Production of Vapor Species	
1. Thermal evaporation mechanism	1. Ion bombardment and collisional momentum transfer
2. Low kinetic energy of evaporant atoms (at 1200 K, $E = 0.1$ eV)	2. High kinetic energy of sputtered atoms ($E = 2-30$ eV) 
3. Evaporation rate (Eq. 3-2) (for $M = 50$, $T = 1500$ K, and $P_e = 10^{-3}$) $\approx 1.3 \times 10^{17}$ atoms/cm ² -sec.	3. Sputter rate (at 1 mA/cm ² and $S = 2$) $\approx 3 \times 10^{16}$ atoms/cm ² -sec
4. Directional evaporation according to cosine law	4. Directional sputtering according to cosine law at high sputter rates 
5. Fractionation of multicomponent alloys, decomposition, and dissociation of compounds	5. Generally good maintenance of target stoichiometry, but some dissociation of compounds. 
6. Availability of high evaporation source purities 	6. Sputter targets of all materials are available; purity varies with material 
B. The Gas Phase	
1. Evaporant atoms travel in high or ultrahigh vacuum ($\sim 10^{-6}$ - 10^{-10} torr) ambient	1. Sputtered atoms encounter high-pressure discharge region (~ 100 mtorr)
2. Thermal velocity of evaporant 10^5 cm/sec	2. Neutral atom velocity $\sim 5 \times 10^4$ cm/sec 
3. Mean-free path is larger than evaporant-substrate spacing. Evaporant atoms undergo no collisions in vacuum 	3. Mean-free path is less than target-substrate spacing. Sputtered atoms undergo many collisions in the discharge
C. The Condensed Film	
1. Condensing atoms have relatively low energy	1. Condensing atoms have high energy 
2. Low gas incorporation	2. Some gas incorporation 
3. Grain size generally larger than for sputtered film	3. Good adhesion to substrate
4. Few grain orientations (textured films) 	4. Many grain orientations

Ablazione e deposizione laser impulsata (PLAD)

Interazione fascio laser impulsato/bulk solido
--> *ablazione* (vaporizzazione) localizzata materiale

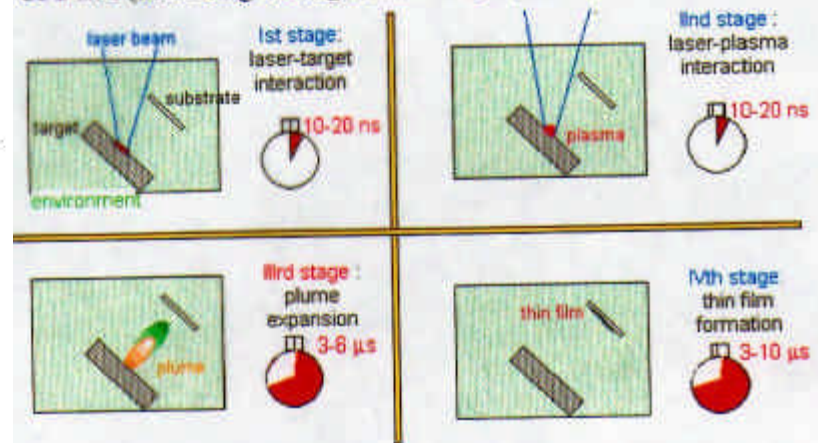


Laser tipici nell'UV:

- eccimeri (XeCl 308nm, KrF 248nm, ArF 193nm,...)
- Nd-YAG 1064 nm (III o IV armonica nell'UV)
- impulsi: ~ 10 ns (ma anche sub-ns)
- fluensa: 1-5 J/cm² (cioè centinaia di MW/cm²)

Processo impulsato e tempi caratt.

of PLA (according to Singh and Narayan, 1990)



Accoppiamento laser UV/target

Processi di assorbimento di origine elettronica (anche con rottura di legami)

--> *ablazione fredda*

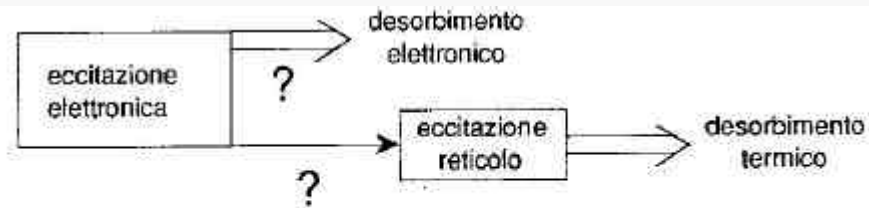


Fig. 2.3. Schema dell'approccio microscopico al problema dell'interazione laser-materia.



Fig. 2.4. Schema dei processi di interazione laser-materia che conducono alla liberazione di materiale dalla superficie di un target dielettrico (adattata da [37]).

Materiale	YBCO	Si	Ni
Conduttività termica ($\text{W cm}^{-1} \text{K}^{-1}$)	0.025	$1600 \times T^{-1.23}$, $T < 1370 \text{ K}$ 0.2 , $T > 1370 \text{ K}$	$11 \times T^{-0.4}$, $T < 630 \text{ K}$ $0.08 \times T^{0.3}$, $630 < T < 1726 \text{ K}$
Coefficiente di assorbimento (cm^{-1})	1.75×10^5	$> 1.5 \times 10^6$	1.0×10^6
Riflettività (per $\lambda_L \sim 308 \text{ nm}$)	0.11	0.59 0.73 (fase liquida)	0.40 0.70 (fase liquida)
Temperatura di evaporazione (K)	1900	3400	3187
Calore latente (J/cm^3)	14940	4206	2660
Calore specifico ($\text{J/cm}^3 \text{K}$)	2.46	$2 \times T^{-3.68}$	$0.72 \times T^{0.3}$, $T < 630 \text{ K}$ $0.5 \times T^{0.3}$, $T > 630 \text{ K}$

Tab. 2.1. Valori dei parametri termofisici ed ottici per diversi materiali (da [52, 53]).

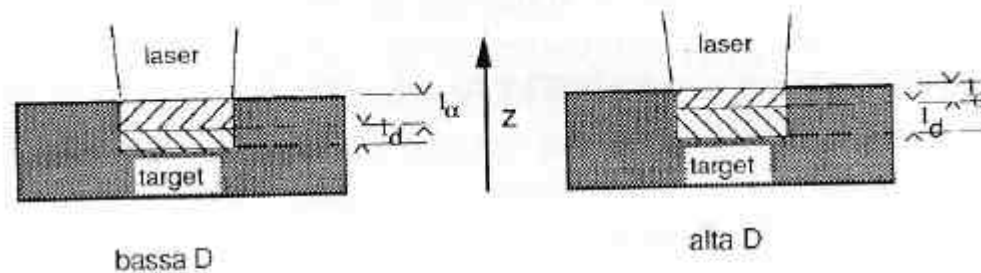


Fig. 2.7. Range di assorbimento di radiazione l_α e di diffusione del calore l_d in materiali con bassa ed alta diffusività termica D (a sinistra e destra nella figura, rispettivamente); indicato è anche l'asse z considerato nel testo.

Alcuni vantaggi della PLAD:

- grande efficacia con ogni mat.
- riscaldamento *molto* localizzato
- congruenza

Peculiarità PLAD

2.3.2 Stima semiempirica della profondità di ablazione.

Una stima della profondità di ablazione può essere data in modo semiempirico considerando il bilancio tra l'energia assorbita dal target e quella necessaria a produrne la vaporizzazione. Tenendo conto delle perdite per irraggiamento e conduzione (E_{cond}) e delle perdite dovute all'assorbimento da parte del plasma che si forma sopra la superficie (E_{pl}), secondo i processi che saranno discussi nei prossimi paragrafi, l'equazione di bilancio si scrive [29]:

$$(1 - R) \left(I_L - \frac{E_{\text{cond}} + E_{\text{pl}}}{S} \right) = \Delta z (\rho C_p \Delta T + L) \quad (2.7)$$

con:

R : riflettività del target;

Δz : spessore di materiale ablato;

ΔT : aumento di temperatura che conduce all'ablazione;

S : superficie irradiata dal laser

L : calore latente di vaporizzazione.

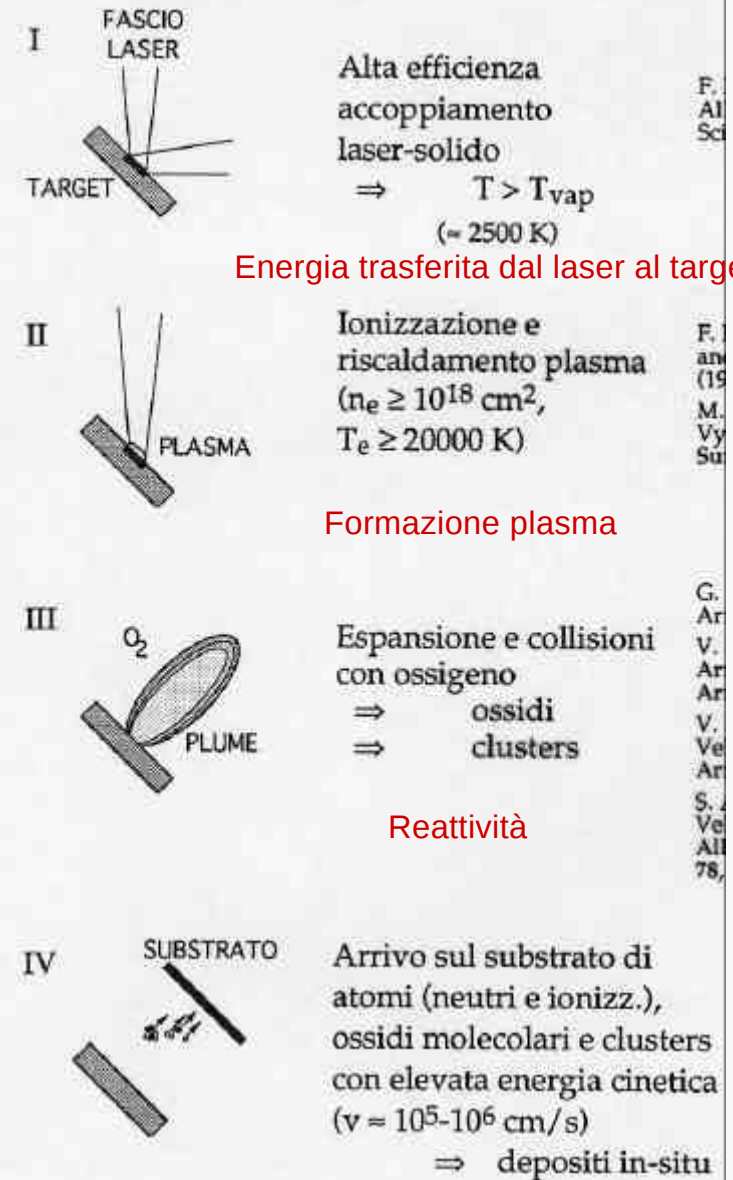
L'approssimazione semiempirica consiste nell'introdurre la densità d'energia di soglia dell'ablazione $I_{L_{\text{thr}}}$ ponendola pari alle perdite di energia per unità di superficie, ottenendo:

$$\Delta z = (1 - R) \frac{I_L - I_{L_{\text{thr}}}}{\rho C_p \Delta T + L} \quad (2.8)$$

Lo spessore di materiale ablato per $I_L = 2.0 \text{ J/cm}^2$ ottenuto dalla (2.8) utilizzando i parametri riportati in Tab. 2.1 per l'YBCO e ponendo $I_{L_{\text{thr}}} = 0.3 \text{ J/cm}^2$ (misurato nel corso dei nostri esperimenti) è $\Delta z \approx 700 \text{ \AA}$, simile a quello da noi determinato dalla misura della quantità di materiale ablato per l'YBCO [14], corrispondente alla rimozione di $\approx 0.5 \text{ \mu g}$ di materiale per colpo laser.

Ulteriori vantaggi PLAD:

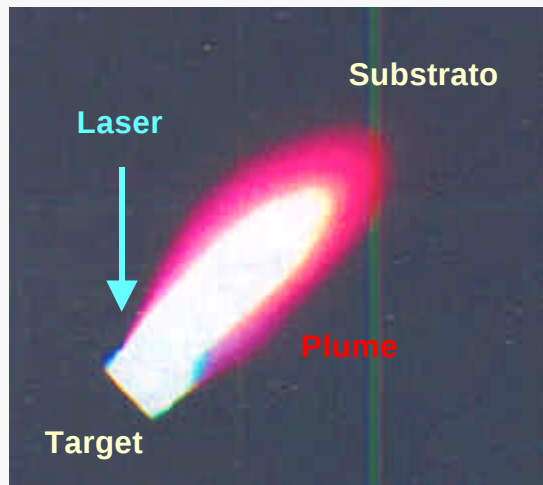
- elevato tasso di ablazione per laser shot
- elevata energia cinetica particelle ablate
- elevata direzionalità
- possibilità reazioni collisionali (gas ambiente)



Limiti PLAD

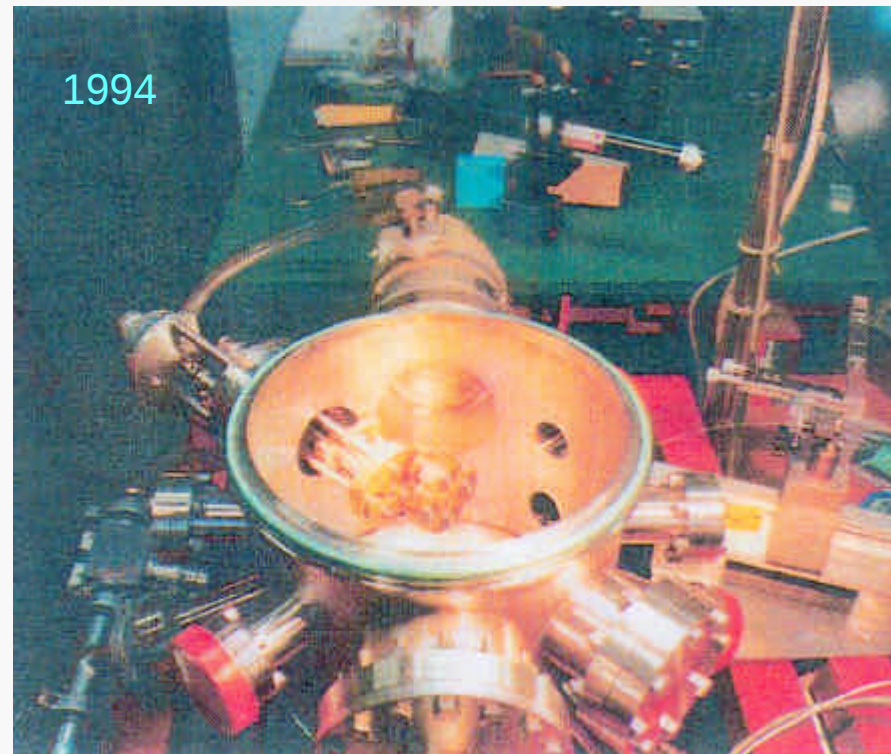
PLAD diffusa in ambito di laboratorio per film di materiali “difficili” (es. ceramiche superconduttrici, ferroelettrici, ferromagnetiche, ossidi,...)

Può essere usata anche per formare nanoparticelle (CNT, Si-nanocrystals,...)



Alcuni **svantaggi** PLAD:

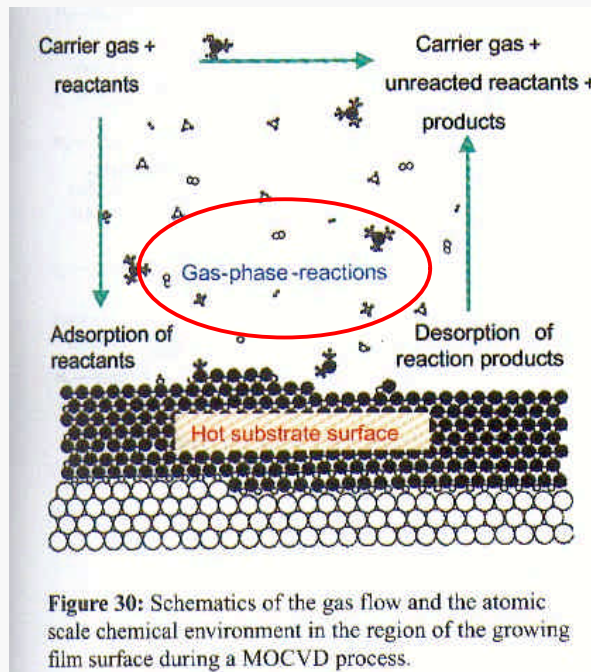
- copertura piccole superfici ($\sim \text{cm}^2$)
- scarsa omogeneità superficiale e formazione *droplets*
- difficile diffusione industriale (laser)
- scarsa resa complessiva



Tecnica chimica: Chemical Vapor Deposition (CVD)

4 Chemical Deposition Methods

Chemical deposition generally includes **chemical solution deposition (CSD)** as well as **chemical vapour deposition (CVD)**. In both cases, chemical precursors are employed which undergo chemical reactions for the formation of the film. We will place special emphasis on CVD as this method finally allows the deposition of ultrathin films and the conformal deposition on complex-shaped structures which are essential for ULSI. CSD includes sol-gel techniques and metal-organic decomposition MOD and typically uses spin-on techniques for the distribution of a solute film which is subsequently processed and crystallized. Finally, we give a short introduction to a very different method for deposition from solutions, the **Langmuir-Blodgett (LB)** technique. LB techniques allow the deposition of monomolecular organic films on different substrates making use of the hydrophilic/hydrophobic orientation of the molecules.

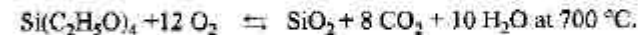


4.1 Chemical Vapour Deposition

The general principles of CVD are well established and a number of reviews and textbooks are available [20], [21], [22], which cover many generic issues common to all type of material. In CVD, film growth occurs through the chemical reaction of the component chemicals (i.e. precursors) which are transported to the vicinity of the substrate via the vapour phase. The film-forming chemical reactions typically utilize thermal energy from a heated substrate as depicted schematically in Figure 30. Other more special methods, which cannot be discussed here, couple non-thermal energy sources such as RF or microwave power or light into the reaction process in order to reduce the thermal reaction temperature required. In order to complete the system, a delivery system for the precursors and, finally, an exhaust system must be added. The most straightforward type of CVD involves chemical precursor compounds that are sufficiently stable gases and such processes are standard processes in CMOS technology for the deposition of insulators and interlayer dielectrics like poly-Si, SiO₂, SiN₄ and BPSG glasses. Figure 31 shows the schematics of a reactor for handling large batches of wafers simultaneously. Examples of the reactions involved are the thermal decomposition of silane, SiH₄, for the deposition of:

- Poly Si : $\text{SiH}_4 \rightleftharpoons \text{Si(s)} + 2 \text{H}_2$ at 580-650 °C, and a pressure of ≈ 1 mbar;
- Si-Nitride: $3 \text{SiH}_4 + 4 \text{NH}_3 \rightleftharpoons \text{Si}_3\text{N}_4 + 12 \text{H}_2$ at 700-900 °C, and atmospheric pressure;
- Si-Dioxide: $\text{SiH}_4 + \text{O}_2 \rightleftharpoons \text{SiO}_2 + 2 \text{H}_2$ at 450 °C;

These SiO₂ films are usually under high stress and are not conformal. Therefore alternative routes using organic precursors have been developed e.g., the TEOS (tetra-ethyl-ortho-silane) process:



Similarly, for the processing of many metals and especially the group-II metals, special precursors in the form of organometallic compounds had to be developed and a special subgroup of CVD techniques, **metal-organic-CVD (MOCVD)**, has therefore evolved. Efficient, reproducible MOCVD processes hinge critically upon precursors with high and stable vapour pressures and the chemistry is therefore the decisive step in the development of MOCVD.

Precursori per CVD e MO-CVD

4.1.1 Precursor Chemistry and Delivery

Only a sufficiently high vapour pressure enables vapour-phase mixing of precursor components and transport of the reactants to the growing film and a vapour pressure of > 0.1 mbar at 100°C is considered to be a lower limit. Adequate molecular stability of the precursor vapour is required to prevent premature reaction or decomposition of the precursor during vapour phase transport; these requirements characterize a process window between vaporization and decomposition of the precursor. Additional requirements are long-term stability of the precursors (e.g. low moisture sensitivity), complete decomposition (no contamination of the film e.g. by fluorine) and last but not least low toxicity and environmental regulatory requirements.

For complex oxides the precursor molecules typically contain the metal atoms, M, and organic groups, R. In most cases, such as in alkoxides, ketonates, and carboxylates, the metal atom is bound to the organic group through an oxygen atom, i.e. M-O-R. This is different from precursors used for the MOCVD of compound semiconductors where the precursors are conventional metal organic compounds, i. e. M-R systems. For heavy cations (especially group-II elements), a reasonable volatility is often reached only by organometallic precursors, e.g. by β -diketonates with several alkyl groups, such as in tetramethylheptadionate (thd) (and this type of organometallic precursor is the origin of an alternative acronym occasionally used: OMCVD). The two keto groups chelate the cation while the outer alkyl groups effectively shield any polar region of the molecule. Typically two (thd) ligands are reacted with one cation yielding $\text{Ba}(\text{thd})_2$. Since the outer shell of this molecule consists entirely of alkyl groups there is only a weak van-der-Waals interaction between neighbouring molecules and, hence, a relatively low boiling temperature. For cations with a higher electronegativity (i.e. a lower tendency to form ionic bonds), alkyl compounds, such as $\text{Pb}(\text{C}_2\text{H}_5)_4$, and alkoxide compounds, such as $\text{Ti}(\text{OC}_3\text{H}_7)_4$, may give rise to a sufficient volatility [23].

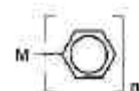
The different types of precursors used for oxide deposition are summarized in Figure 32. The main applications for the present topics of IT are included in the figure: e.g., the diketonates for Ba and Sr, thd = tetramethylheptadionate, alkoxides for Ti (TIP = titaniumisopropoxide = $\text{Ti}(\text{O}-i\text{-Pr})_4$) and Zr. Mixed precursors like $\text{Ti}(\text{O}-i\text{-Pr})_2(\text{thd})_2$ are also used to increase compatibility with other precursors. In addition, adducts or stabilizers are used in order to avoid reactions and oligomerization e.g., tetraglyme or pmdeta. Most of these precursors are liquid or solid at room temperature and reach a sufficient vapour pressure only at elevated temperature. Therefore, special delivery systems are necessary, i.e. bubblers or liquid source delivery systems.

β -Diketonates

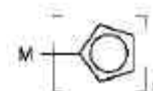


$\text{R}_1=\text{R}_2=\text{CH}_3$ (acetylacetonate)
 $\text{R}_1=\text{R}_2=\text{C}(\text{CH}_3)_2$ (tetramethylheptadionate) — $\text{Ba}(\text{thd})_2$, $\text{Sr}(\text{thd})_2$
 $\text{R}_1=\text{C}(\text{CH}_3)_2$, $\text{R}_2=\text{CF}_3$ (trifluorodimethylhexanedionate)
 $\text{R}_1=\text{C}(\text{CH}_3)_2$, $\text{R}_2=\text{C}_2\text{F}_5$ (heptafluorodimethyloctanedionate)
 $\text{R}_1=\text{R}_2=\text{CF}_3$ (hexafluoroacetylacetonate)

Organometallics



phenyl



cyclopentadienyl

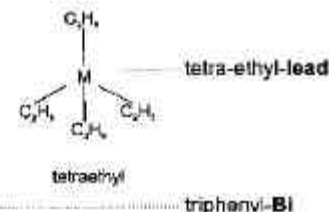
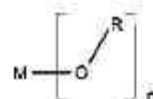


Figure 32: Selection of precursor molecules for oxide deposition [25].

Alkoxides



$\text{R}=\text{CH}_3$ (methoxide)
 $\text{R}=\text{C}_2\text{H}_5$ (ethoxide)
 $\text{R}=\text{CH}(\text{CH}_3)_2$ (isopropoxide) — Ti: TIP, Zr: ZIP
 $\text{R}=\text{C}(\text{CH}_3)_3$ (t-butoxide) — Zr -tert -butoxide

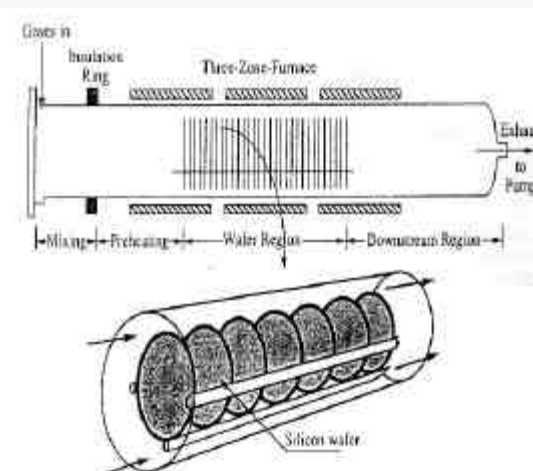


Figure 31: Schematic representation of a hot-wall multiple-wafer in-tube CVD reactor [26].

Altri esempi di reazioni per CVD I

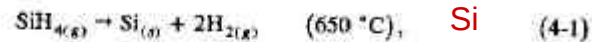
Reazioni in fase di vapore a partire da *precursori* di varia natura (solida, gassosa, liquida) usate per produrre i componenti elementari del film

Da M. Ohring, The Materials Science of Thin Films, Academic (1992)

Alcune reazioni per metalli e semiconduttori:

4.2.1. Pyrolysis

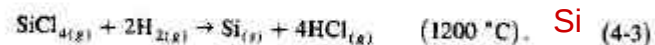
Pyrolysis involves the thermal decomposition of such gaseous species as hydrides, carbonyls, and organometallic compounds on hot substrates. Commercially important examples include the high-temperature pyrolysis of silane to produce polycrystalline or amorphous silicon films, and the low-temperature decomposition of nickel carbonyl to deposit nickel films.



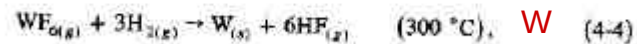
Interestingly, the latter reaction is the basis of the Mond process, which has been employed for over a century in the metallurgical refining of Ni.

4.2.2. Reduction

These reactions commonly employ hydrogen gas as the reducing agent to effect the reduction of such gaseous species as halides, carbonyl halides, oxyhalides, or other oxygen-containing compounds. An important example is the reduction of SiCl_4 on single-crystal Si wafers to produce epitaxial Si films according to the reaction



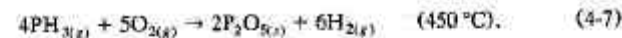
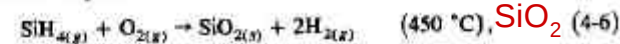
Refractory metal films such as W and Mo have been deposited by reducing the corresponding hexafluorides, e.g.,



Tungsten films deposited at low temperatures have been actively investigated as a potential replacement for aluminum contacts and interconnections in integrated circuits. Interestingly, WF_6 gas reacts directly with exposed silicon surfaces, depositing thin W films while releasing the volatile SiF_4 by-product. In this way silicon contact holes can be selectively filled with tungsten while leaving neighboring insulator surfaces uncoated.

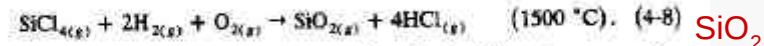
4.2.3. Oxidation

Two examples of important oxidation reactions are



The deposition of SiO_2 by Eq. 4-6 is often carried out at a stage in the processing of integrated circuits where higher substrate temperatures cannot be tolerated. Frequently, about 7% phosphorous is simultaneously incorporated in the SiO_2 film by the reaction of Eq. 4-7 in order to produce a glass film that flows readily to produce a planar insulating surface, i.e., "planarization."

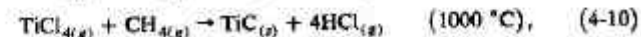
In another process of technological significance, SiO_2 is also produced by the oxidation reaction



The eventual application here is the production of optical fiber for communications purposes. Rather than a thin film, the SiO_2 forms a cotton-candy-like deposit consisting of soot particles less than $1000 \text{ \AA}$ in size. These are then consolidated by elevated temperature sintering to produce a fully dense silica rod for subsequent drawing into fiber. Whether silica film deposition or soot formation occurs is governed by process variables favorable to heterogeneous or homogeneous nucleation, respectively. Homogeneous soot formation is essentially the result of a high SiCl_4 concentration in the gas phase.

4.2.4. Compound Formation

A variety of carbide, nitride, boride, etc., films and coatings can be readily produced by CVD techniques. What is required is that the compound elements exist in a volatile form and be sufficiently reactive in the gas phase. Examples of commercially important reactions include

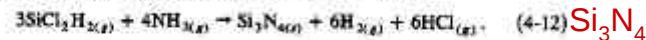


for the deposition of hard, wear-resistant surface coatings. Films and coatings of compounds can generally be produced through a variety of precursor gases and reactions. For example, in the much studied SiC system, layers were first

Altri esempi di reazioni per CVD II

produced in 1909 through reaction of $\text{SiCl}_4 + \text{C}_2\text{H}_6$ (Ref. 8). Subsequent reactant combinations over the years have included $\text{SiCl}_4 + \text{C}_2\text{H}_6$, $\text{SiBr}_4 + \text{C}_2\text{H}_6$, $\text{SiCl}_4 + \text{C}_2\text{H}_4$, $\text{SiHCl}_3 + \text{CCl}_4$, and $\text{SiCl}_4 + \text{C}_6\text{H}_5\text{CH}_3$, to name a few, as well as volatile organic compounds containing both silicon and carbon in the same molecule (e.g., CH_3SiCl_3 , CH_3SiH_3 , $(\text{CH}_3)_2\text{SiCl}_2$, etc.). Although the deposit is nominally SiC in all cases, resultant properties generally differ because of structural, compositional, and processing differences.

Impermeable insulating and passivating films of Si_3N_4 that are used in integrated circuits can be deposited at 750 °C by the reaction



The necessity to deposit silicon nitride films at lower temperatures has led to alternative processing involving the use of plasmas. Films can be deposited below 300 °C with SiH_4 and NH_3 reactants, but considerable amounts of hydrogen are incorporated into the deposits.

4.2.5. Disproportionation

Disproportionation reactions are possible when a nonvolatile metal can form volatile compounds having different degrees of stability, depending on the temperature. This manifests itself in compounds, typically halides, where the metal exists in two valence states (e.g., GeI_4 and GeI_2) such that the lower-valent state is more stable at higher temperatures. As a result, the metal can be transported into the vapor phase by reacting it with its volatile, higher-valent halide to produce the more stable lower-valent halide. The latter disproportionates at lower temperatures to produce a deposit of metal while regenerating the higher-valent halide. This complex sequence can be simply described by the reversible reaction



and realized in systems where provision is made for mass transport between hot and cold ends. Elements that have lent themselves to this type of transport reaction include aluminum, boron, gallium, indium, silicon, titanium, zirconium, beryllium, and chromium. Single-crystal films of Si and Ge were grown by disproportionation reactions in the early days of CVD experimentation on semiconductors employing reactors such as that shown in Fig. 4-2. The enormous progress made in this area is revealed here.

4.2.6. Reversible Transfer

Chemical transfer or transport processes are characterized by a reversal in the reaction equilibrium at source and deposition regions maintained at different temperatures within a single reactor. An important example is the deposition of single-crystal (epitaxial) GaAs films by the chloride process according to the reaction



Here AsCl_3 gas from a bubbler transports Ga toward the substrates in the form of GaCl vapor. Subsequent reaction with As_4 causes deposition of GaAs.

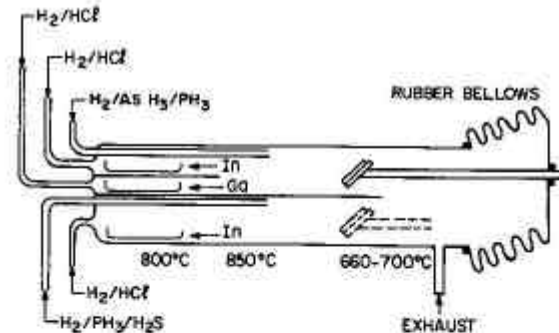
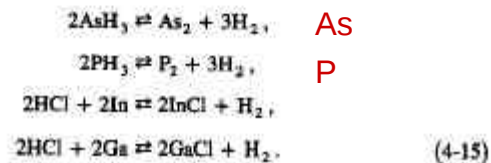
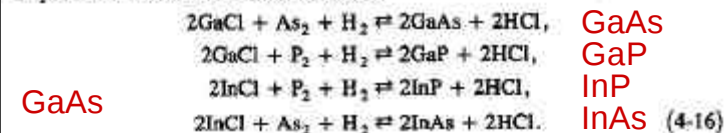


Figure 4-3. Schematic of atmospheric CVD reactor used to grow GaAs and other compound semiconductor films by the hydride process. (Reprinted with permission from Ref. 10).

Alternatively, in the hydride process, As is introduced in the form of AsH_3 (arsine), and HCl serves to transport Ga. Both processes essentially involve the same gas-phase reactions and are carried out in similar reactors, shown schematically in Fig. 4-3. What is significant is that single-crystal, *binary* (primarily GaAs and InP but also GaP and InAs) as well as *ternary* (e.g., $(\text{Ga}, \text{In})\text{As}$ and $\text{Ga}(\text{As}, \text{P})$) compound films have been grown by these vapor phase epitaxy (VPE) processes. Similarly, in addition to binary and ternary semiconductor films, *quaternary* epitaxial films containing controlled amounts of Ga, In, As, and P have been deposited by the hydride VPE process. Combinations of gas mixtures and more complex reactors are required in this case to achieve the desired stoichiometries. The resulting films are the object of intense current research and development activity in a variety of optoelectronic devices (e.g., lasers and detectors). For quaternary alloy deposition by the hydride process, single-crystal InP substrates are employed. Gas-phase source reactions include



Deposition reactions at substrates include



Da M. Ohring, The Materials Science of Thin Films, Academic (1992)

Anche Plasma-Enhanced CVD!!
(vedi fabbricazione nanotubi)

Deposizioni da soluzione (CSD, MOD)

4.2 Chemical Solution Deposition

The chemical solution deposition (CSD) method comprises a range of deposition techniques and of chemical routes which have been reviewed recently [23], [33]. A generalized flow chart of the CSD of oxide thin films is shown in Figure 42. The process starts with the preparation of a suitable coating solution from precursors according to the designated film composition and the chemical route to be used. Besides mixing, preparation may include the addition of stabilizers, partial hydrolysis, refluxing, or else. The coating solution is then deposited onto substrates by:

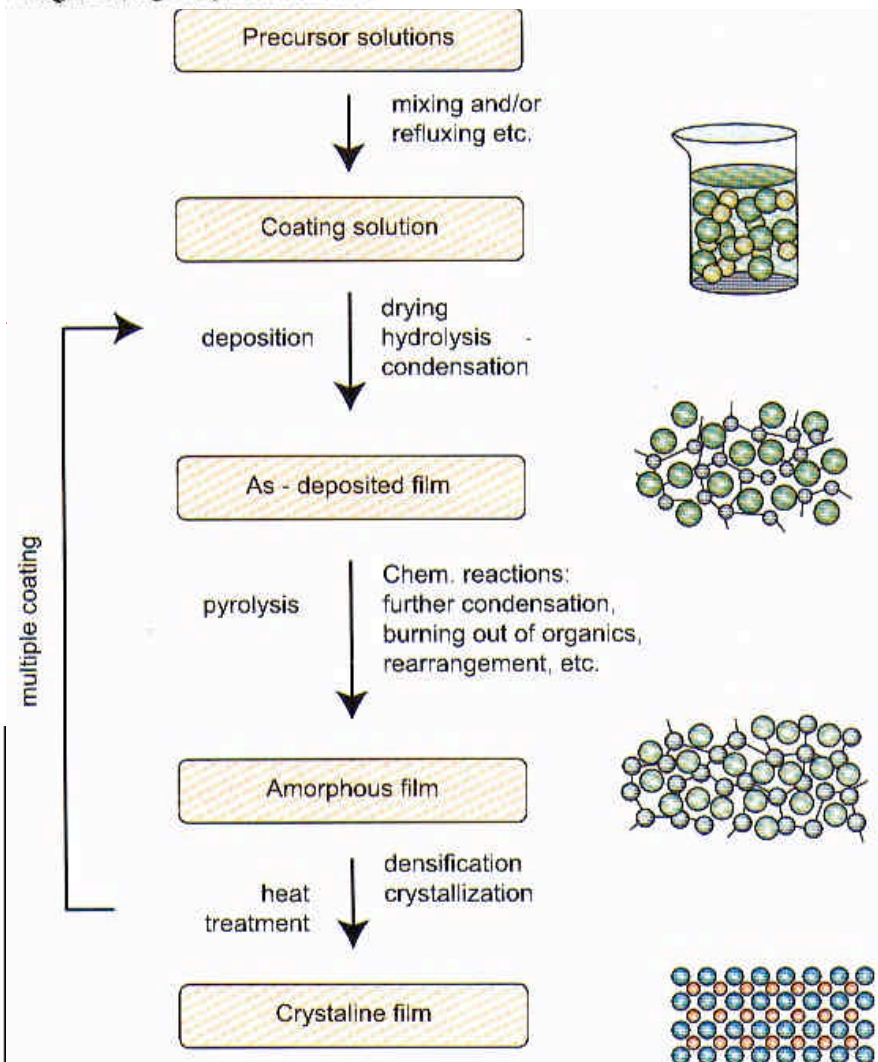
- *spin-coating*, where typically a photoresist spinner is employed and which is suitable for semiconductor wafers,
- *dip coating*, which is often used in the optics industry for large or non-planar substrates, and
- *spray coating*, which is based on a misting of the coating solution and deposition of the mist exploiting gravitation or an electrostatic force.

The wet film may undergo drying, hydrolysis and condensation reactions depending on the chemical route. The as-deposited film possibly represents a chemical or physical network. Upon subsequent heat treatment, a further hydrolysis and condensation and/or a pyrolysis of organic ligands may take place, again depending on the chemical route. The resulting film consists of amorphous or nanocrystalline oxides and/or carbonates. Upon further heat treatment, any carbonate will decompose and the film will crystallize through a homogeneous or a heterogeneous nucleation. Typically, the desired final film thickness is built up by multiple coating and annealing.

Depending on the type and reactivity of the precursors, the chemistry shows a wide spectrum of reaction types. On the one hand, there are the pure sol-gel reactions i.e. alkoxide precursor systems, which undergo hydrolysis and condensation reactions. The formation of SiO_2 coatings starting from Si alkoxides is the classical example of this type of reaction. The condensation leads to a chemical gelation in which – under appropriate reaction conditions – no pyrolysis reaction of any organic ligand occurs. At the other extreme, there is **metal organic decomposition (MOD)**, which typically starts from carboxylates of the cations or, in special cases, from the nitrates. The carboxylates do not chemically react with water. Consequently, during heat treatment, first the solvents are evaporated, a process which is sometimes referred to as physical gelation. Upon further heating, the carboxylates pyrolytically decompose into amorphous or nanocrystalline oxides or carbonates. There is a wide spectrum of possible reaction routes between the pure sol-gel route and the MOD route. Depending on the type of alkoxides and a possible stabilization of the precursors, there may be a partial hydrolysis and condensation while some organic ligands remain in the gelated film and undergo pyrolysis upon further heat treatment. In the synthesis of multicomponent oxide films, often hybrid routes are followed, i.e. there may be some precursors employed which tend to follow the sol-gel or partial sol-gel route while others undergo typical MOD reactions.

The microstructure formed during the CSD process strongly depends on the thermodynamics and kinetics of the solidstate reaction from the intermediate amorphous or nanocrystalline state after pyrolysis to the final equilibrium crystalline phase. This is controlled by the chemical composition of the film system (for details see e.g. ref. [23]).

Due to their low capital investment and simple processing, CSD techniques are widely used and are also applicable for micro- and nanoelectronics on a low level of integration, e.g. for present state FeRAMs.



Liquid Phase Epitaxy (LPE) e Sol-Gel

LPE: deposizione da soluzione sopra-satura

techniques. LPE involves the precipitation of a crystalline film from a super-saturated melt onto the parent substrate, which serves as both the template for epitaxy and the physical support for the heterostructure. The process can be understood by referring to the GaAs binary-phase diagram on p. 31. Consider a Ga-rich melt containing 10 at% As. When heated above 950°C, all of the As dissolves. If the melt is cooled below the liquidus temperature into the two-phase field, it becomes supersaturated with respect to As. Only a melt of lower than the original As content can now be in equilibrium with GaAs. The excess As is, therefore, rejected from solution in the form of GaAs that grows epitaxially on a suitably placed substrate. Many readers will appreciate that the

Sol-Gel: deposizione da precursori
sciolti in solventi gelificanti
(adatta anche per ceramiche)

Alcuni vantaggi dei metodi chimici:

- economia
- scalabilità
- resa

Principali **svantaggi** dei metodi chimici:

- scarso controllo di omogeneità chimica, strutturale e morfologica
- applicabilità limitata ad alcune classi di materiali
- necessità di vari passaggi intermedi e scarsa integrabilità

Da M. Ohring, The Materials
Science of Thin Films,
Academic (1992)

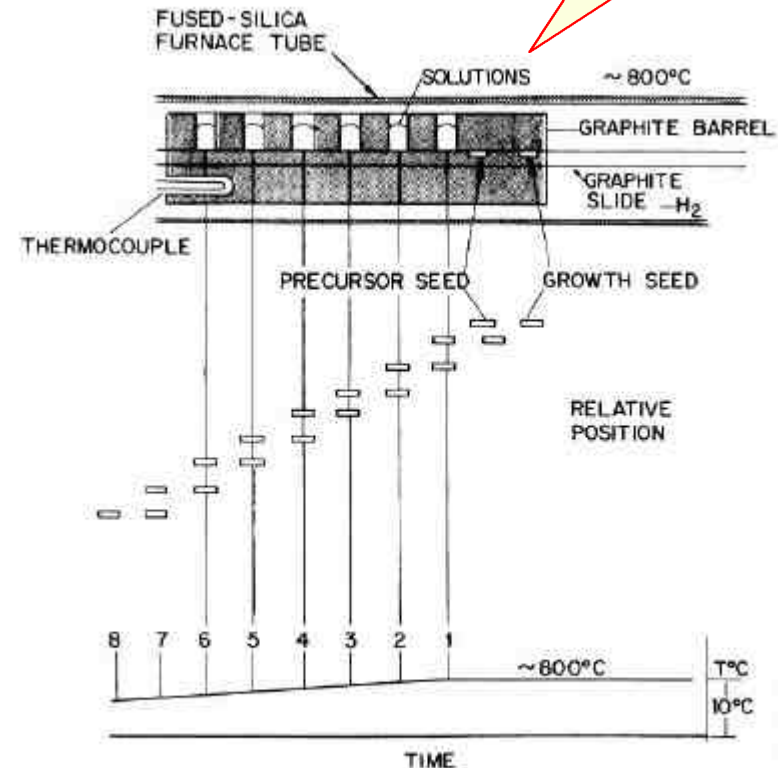


Figure 7-17. Schematic of LPE reactor. (Courtesy of M. B. Panish, AT&T Bell Laboratories.)