Thin films growth and applications

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Outline

- Why thin films?. Motivation
- Growth techniques
- Deposition mechanisms
- Epitaxy
- In-situ characterization: RHEED
- Examples

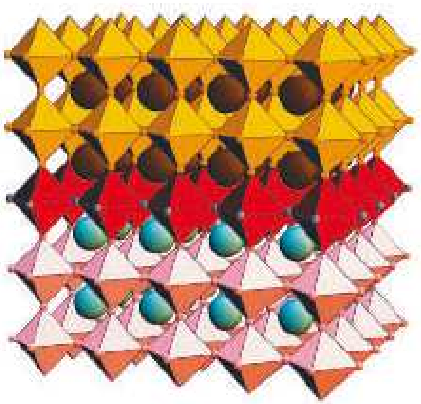
Why thin films?

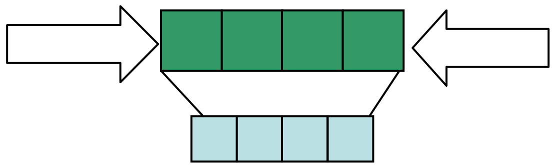
• Possibility of growth metastable phases, difficult or impossible to obtain in bulk/single crystals

• Possibility of obtain materials with improved properties (strain effects, finite size effects)

• Combine different materials in multilayers/composites, with improved functionalities

• This is the form needed for applications



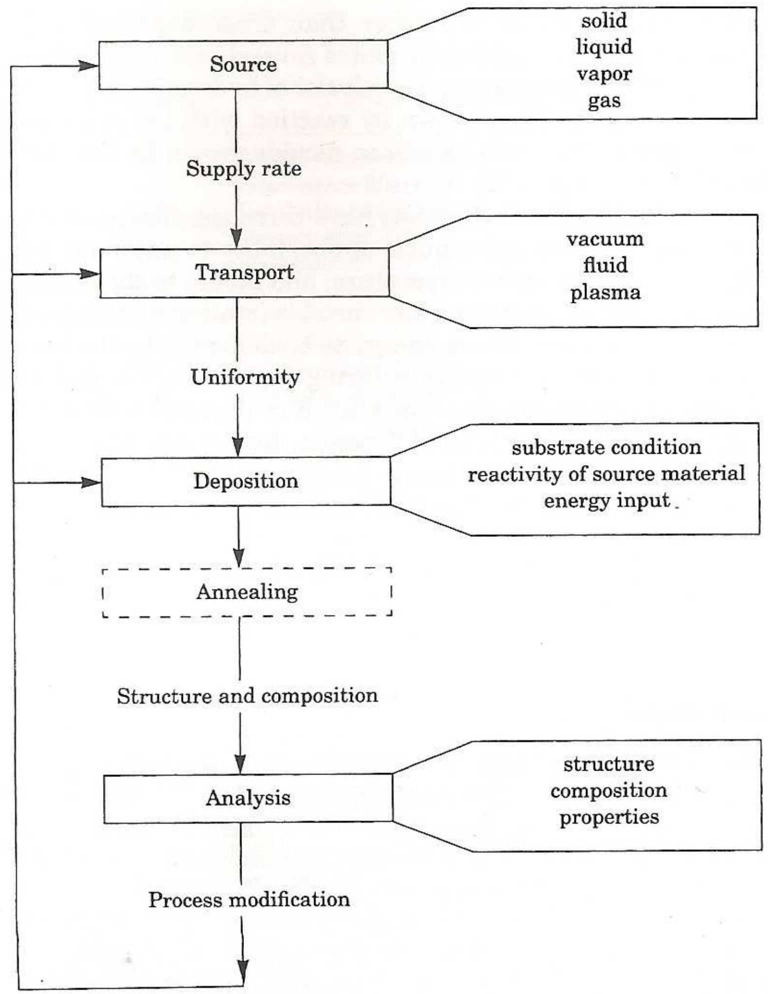


Thin Film Applications

TABLE 1.1 Thin-Film Applications

Thin-film property category	Typical applications
Optical	Reflective/antireflective coatings Interference filters Decoration (color, luster) Memory discs (CDs) Waveguides
Electrical	Insulation Conduction Semiconductor devices Piezoelectric drivers
Magnetic	Memory discs
Chemical	Barriers to diffusion or alloying Protection against oxidation or corrosion Gas/liquid sensors
Mechanical	Tribological (wear-resistant) coatings Hardness Adhesion Micromechanics
Thermal	Barrier layers Heat sinks

Thin film process steps



Vacuum technology

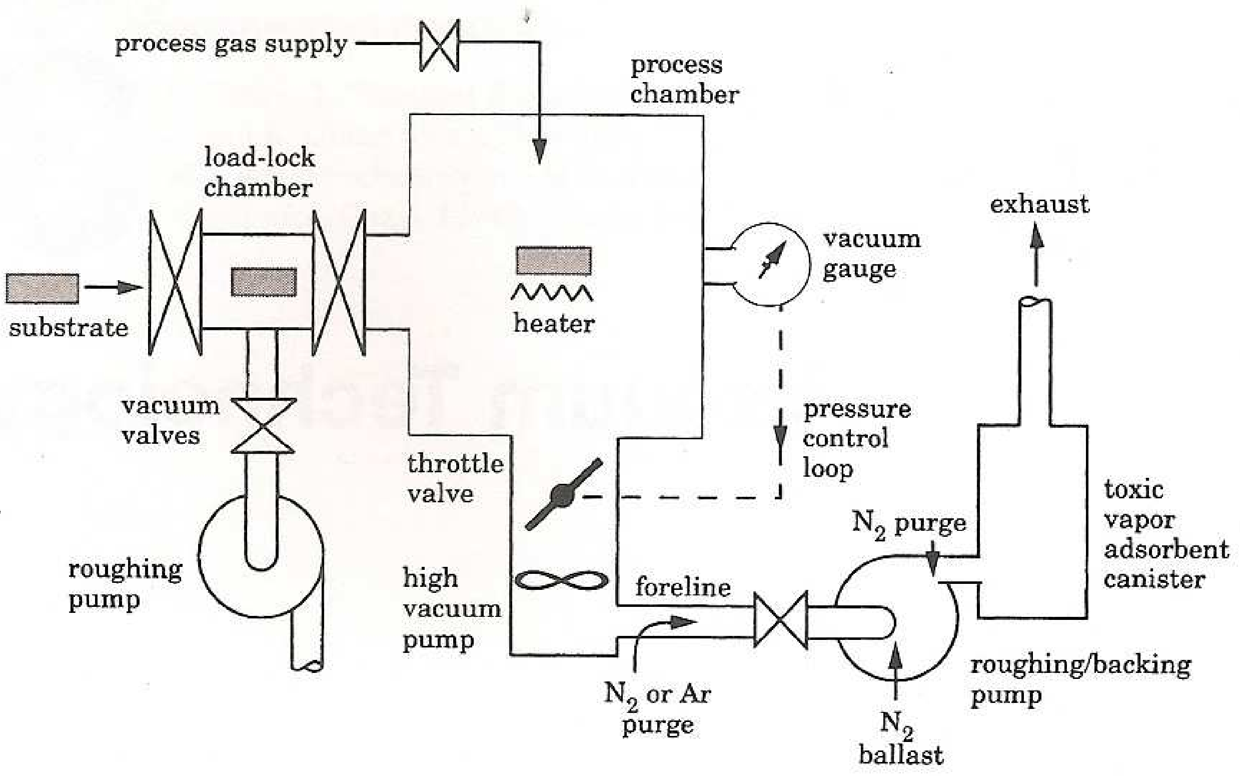
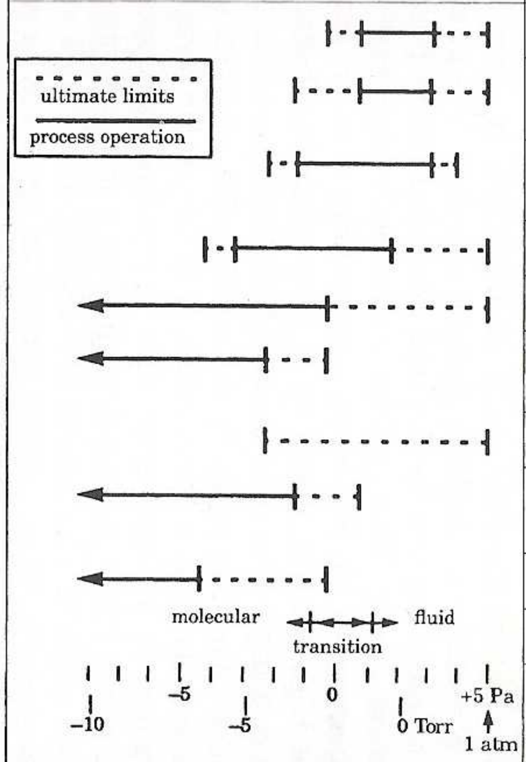


Figure 3.1 Typical vacuum-system components for thin-film deposition.

Vacuum technology

TABLE 3.1 Vacuum Pump Characteristics



Name	Category	Approx. $/(l/s)	Backing pump req'd?	Oil present? Inlet	Oil present? Outlet	Problematic gases and vapors	Other comments
Dry rotary	Displacement	1000	No	No	Yes	Condensables require gas ballasting; see text	
Oil-sealed rotary	Displacement	300	No	Yes	Yes		Common for roughing/backing
Roots blower	Displacement	70	Yes	No	Yes		Oil contam. unless foreline purged
Molecular drag	Displacement	35	Yes	No	Yes*	Low compression ratio for H_2 and He	
Turbo-molecular	Displacement	40	Yes	No	Yes*		
Oil diffusion	Displacement	5	Yes	Yes	Yes		Greatest risk of oil contam.
Cryosorption	Trapping	450	No	No	(No outlet)	Explosion danger with flammables	For dry roughing
He-cycle cryopump	Trapping	7	No	No	No†		Low capacity for He, H_2
Sputter-ion	Trapping	25	No	No	(No outlet)	Poor for inerts	

Pressure ranges chart rows: Flow regime for 5 cm diameter tube; log of pump inlet pressure

*except magnetically levitated bearing types, which use no lubrication

†Purge roughing pump line to avoid oil contamination during warmup regeneration cycle.

Thin film techniques

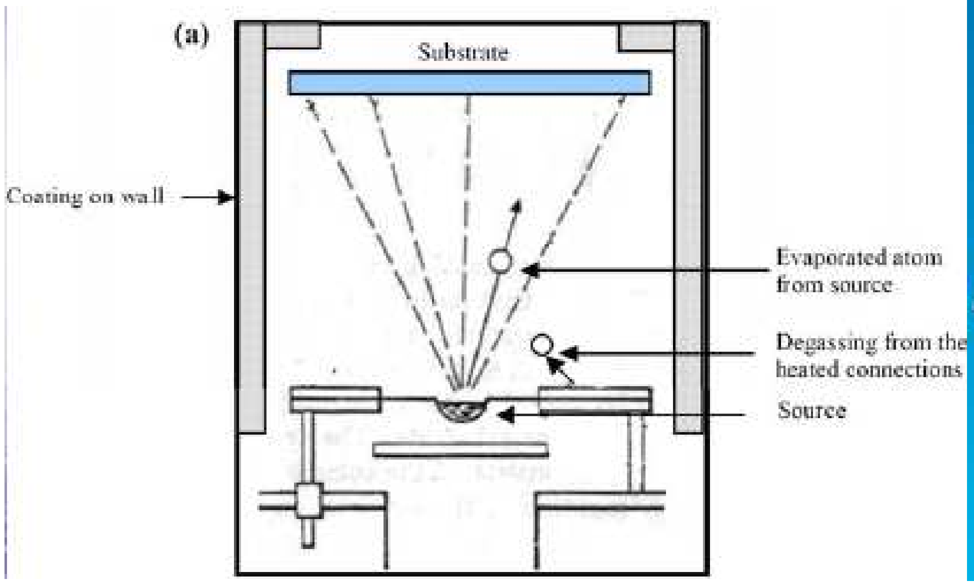
Physical Vapor Deposition (PVD)

- Thermal evaporation
- Electron beam evaporation
- Sputtering
- Molecular beam epitaxy
- Pulsed laser deposition

Chemical Vapor Deposition (CVD)

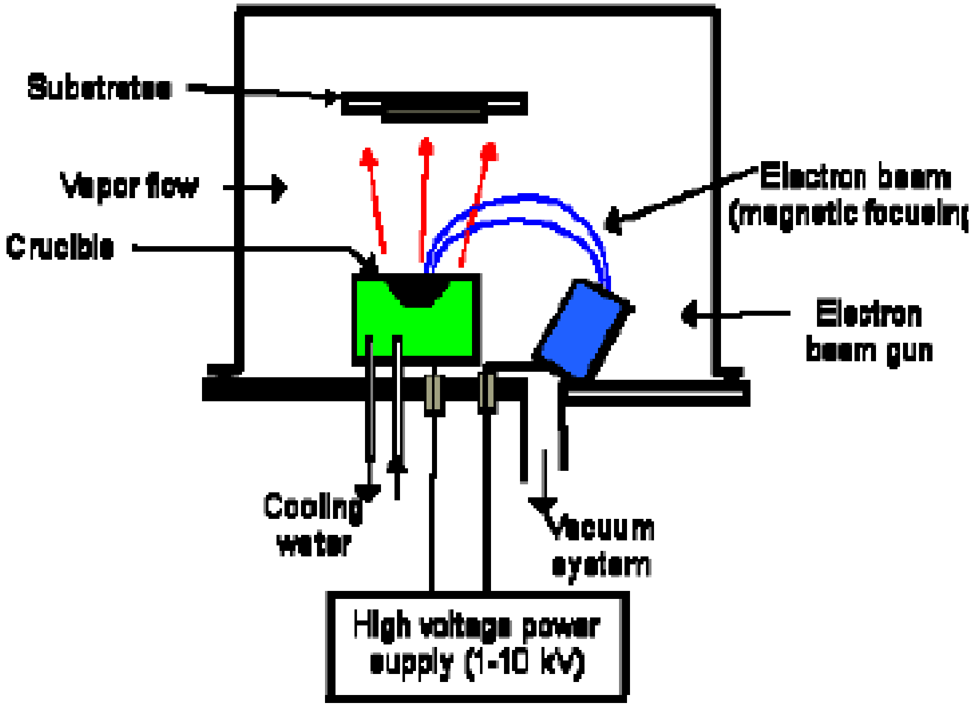
Other (spin coating, dip coating, atomic layer deposition…)

Thin film techniques: Thermal evaporation



- The coating material is evaporated in vacuum with the help of resistive heating.
- Advantages: Good purity and good surface quality
- Disadvantages: non-uniformity of the deposit, poor adherence sometimes, evaporation of complex compounds is problematic (different evaporation rates)

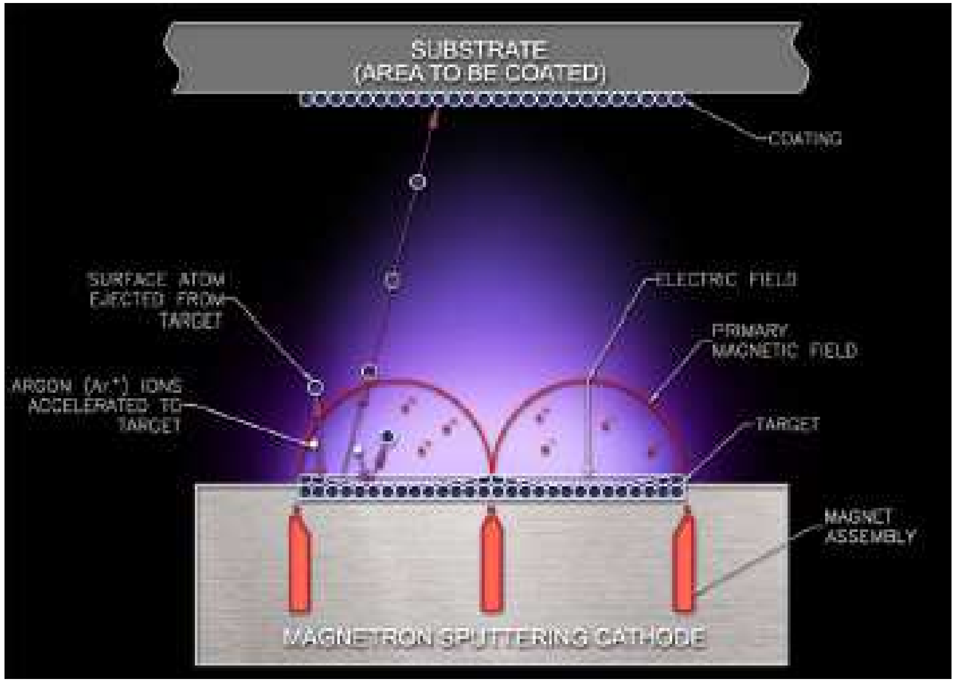
Thin film techniques: Electron beam evaporation



• A target anode is bombarded with an electron beam given off by a charged tungsten filament under high vacuum. The electron beam causes atoms from the target to transform into the gaseous phase. These atoms then precipitate into solid form, coating everything in the vacuum chamber with a thin layer of the anode material

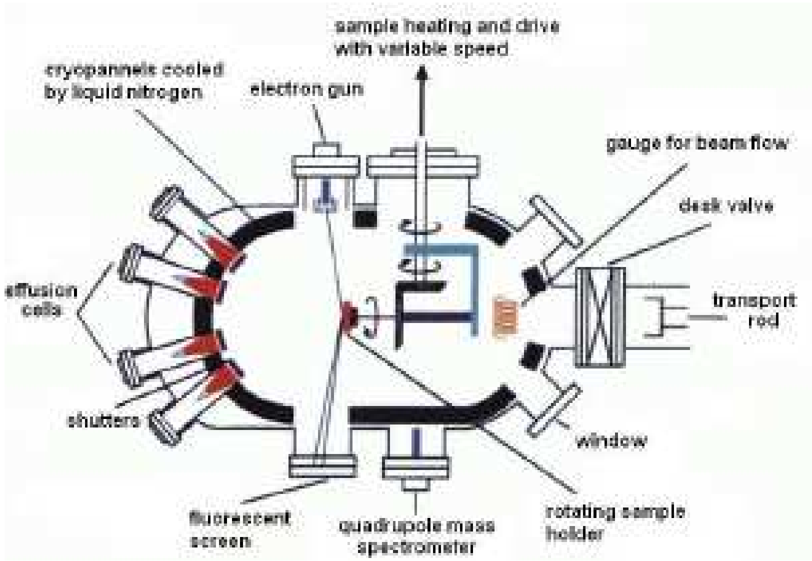
• Multiple electron guns can be used simultaneously in a single system.

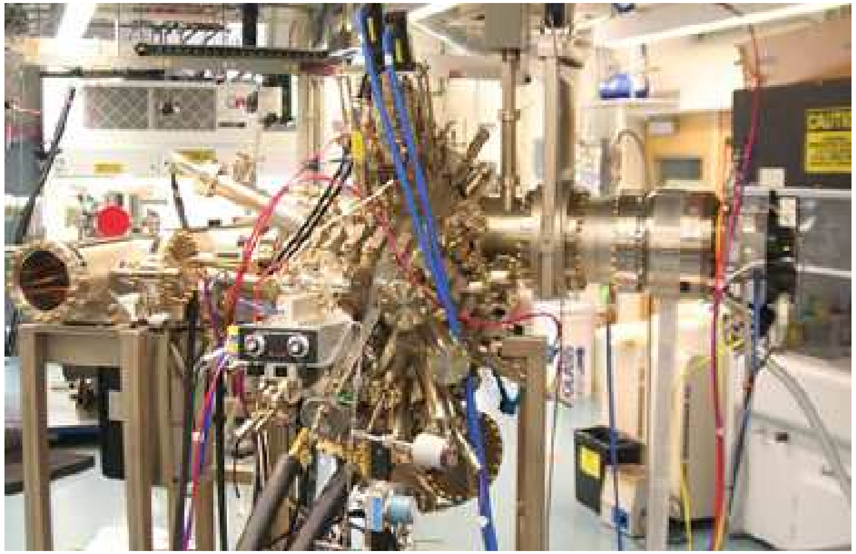
Thin film techniques: Sputtering



- Atoms are ejected from a solid target material due to bombardment by energetic particles.
- The primary particles for the sputtering process can be supplied in a number of ways, for example by a plasma or an ion source.
- Sputtering sources often employ magnetrons that utilize strong electric and magnetic fields to confine charged plasma particles close to the surface of the sputter target.
- Charge build-up on insulating targets can be avoided with the use of RF sputtering.
- Advantages: good uniformity in thickness, good adhesion, stochiometry preservation

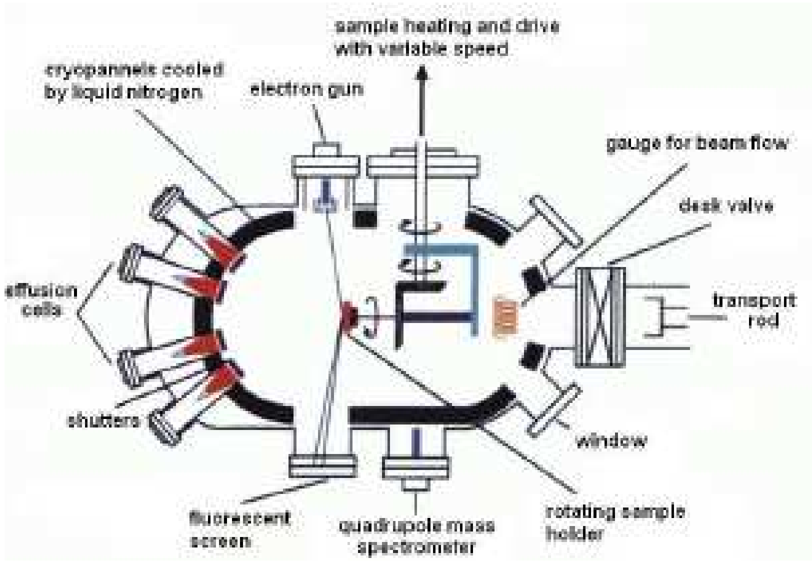
Thin film techniques: Molecular beam epitaxy

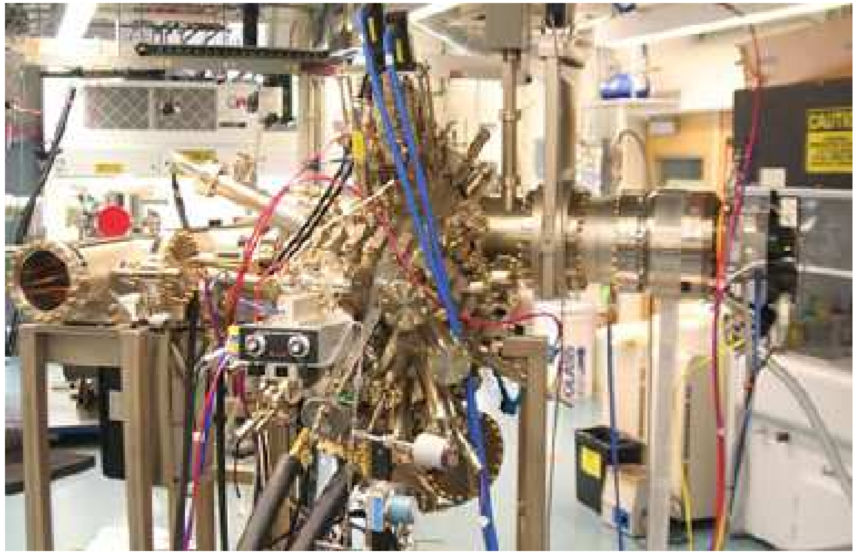




- Intricate structures of layers of different materials may be fabricated this way.
- Typically used to grow high quality semiconductors (i.e. solar cells)
- More recently has been used to deposit oxide materials for advanced electronic, magnetic and optical applications. For these purposes, MBE systems have to be modified to incorporate oxygen sources.

Thin film techniques: Molecular beam epitaxy

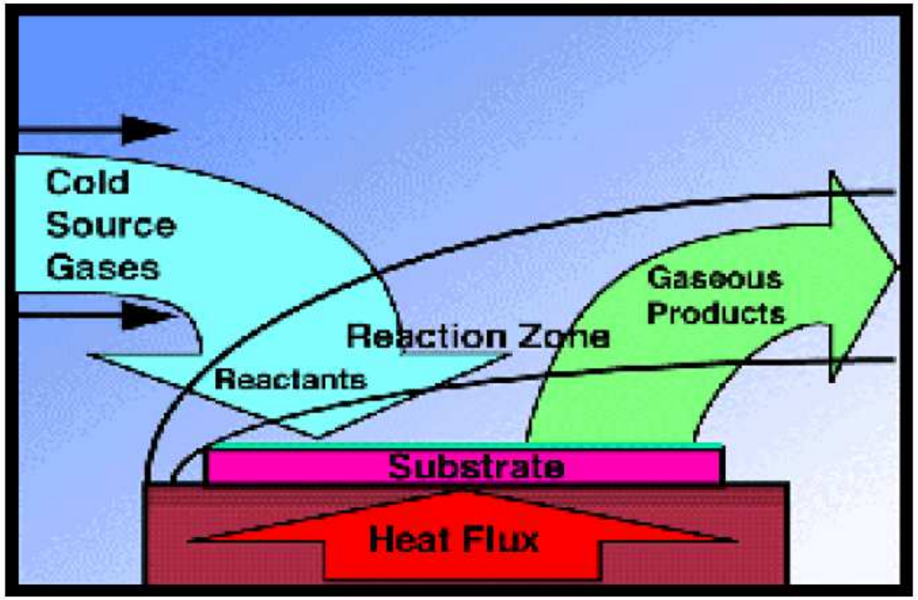


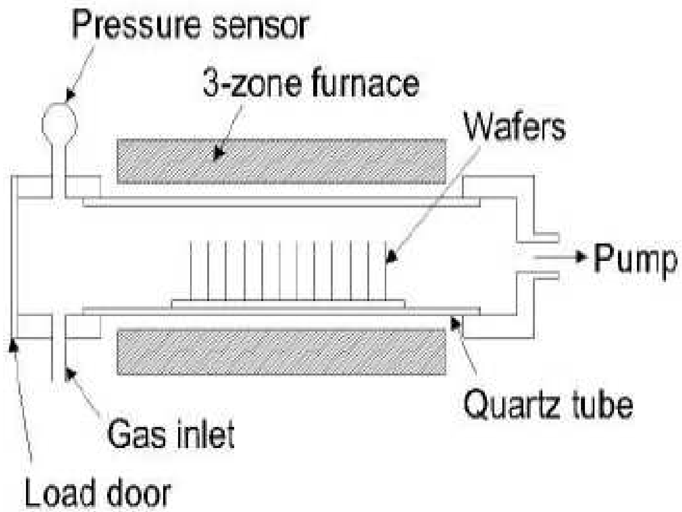


• MBE takes place in ultra-high vacuum (10^{-8} Pa). The deposition rate (typically less than 3000 nm per hour) allows the films to grow epitaxially. The absence of carrier gases as well as the ultra high vacuum environment result in the highest achievable purity of the grown films.

• In solid-source MBE, elements in ultra-pure form, are heated in separate Knudsen effusion cells until they sublime. The gaseous elements then condense on the wafer, where they may react with each other. The evaporated atoms do not interact with each other or vacuum chamber gases until they reach the wafer, due to the long mean free paths of the atoms.

Thin film techniques: Chemical Vapor Deposition





• Reactive gaseous precursos are brought onto the substrate at high temperatures. The reagents are decomposed and adsorbed, and the film is formed as a result of the chemical reaction between the precursos. By products are desorbed from the substrate and removed by a gas flow.

• Advantages: good quality films, uniformity in thickness.
• Disavantages: high temperature of the substrate

Thin film techniques: Pulsed Laser Deposition

<u>History</u>:

- **First experiments in the 1960's**
- **Limited efforts in the 1970's and 1980's**
- **Boom in late 1980's → thin films of HTS**
- **Today, PLD is used for:**
  - **insulators**
  - **semiconductors**
  - **metals**
  - **polymers**
  - **biological**

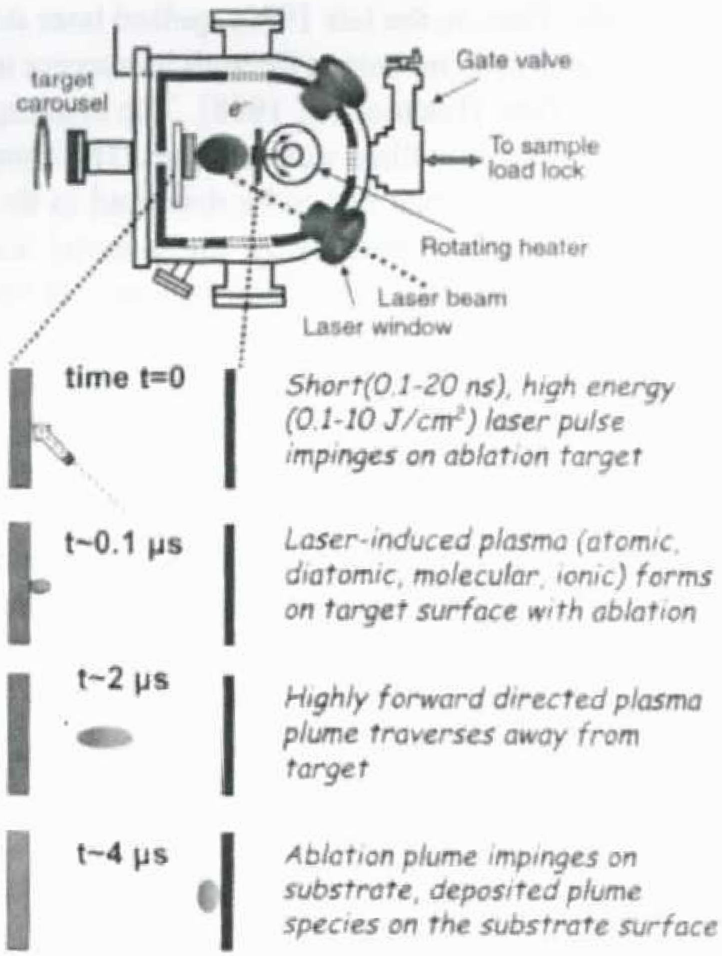


Figure 1.1 Schematic of the PLD process.

Thin film techniques: Pulsed Laser Deposition

Advantages:

- **Congruent deposition → highly non-equilibrium process**
- **Deposition under reactive gases**
- **Multilayer growth**

Deposition parameters:

- **Laser fluence → minimum threshold to avoide heating/evaporation**
- **Laser wavelenght → UV, good absorption**
- **Gas pressure during growth → participation on the chemistry of film growth + control of the kinetic energy of the ablated species**
- **Substrate temperature → difusson of species on substrate surface**
- **Target-substrate distance → growth rate, particulate**

Thin film techniques: Pulsed Laser Deposition

Targets → high optical absorption at laser wavelenght

In general, only cation stochiometry matching is required

Ceramics (dense!!), single crystals, soft materials (bio) → material of interest embedded in a matrix of optically absorbing material

Reactive PLD → metal targets → low efficiency process (metals reflect!) + particulate due to molten droplets. Solution: liquid metal targets.

Growth rate: 1 pulse → usually 1 sub-monolayer → layer-by-layer growth monitored by RHEED

Deposition rates: 0.001 to 1Å/pulse

Thin film techniques: Pulsed Laser Deposition

<u>Scaling</u> → industry requires large areas → manipulation of plume-substrate positioning → substrate rotation + rastering of ablation beam over a large target area

<u>Drawbacks</u> → changes in plume energy and stochiometry as one moves to the edge of the plume

<u>Volatile species</u> → non-stochiometric films due to evaporation → cation excess in the target or mosaic target

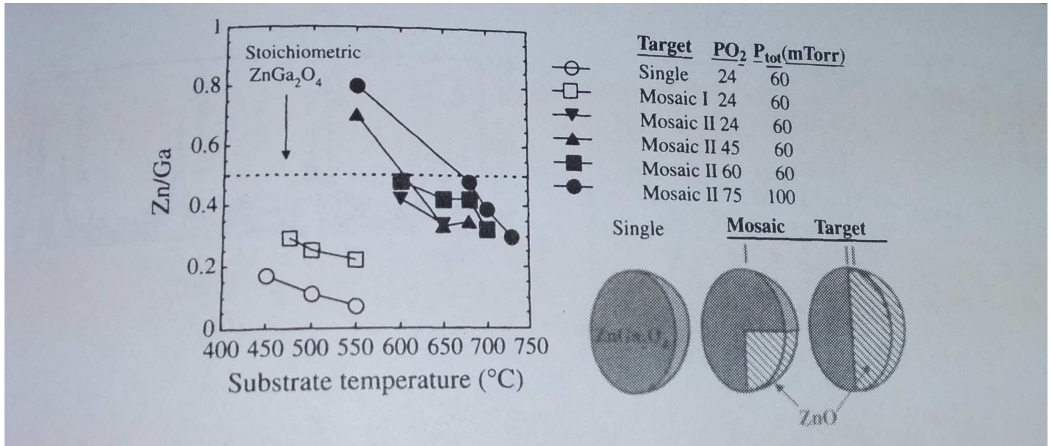
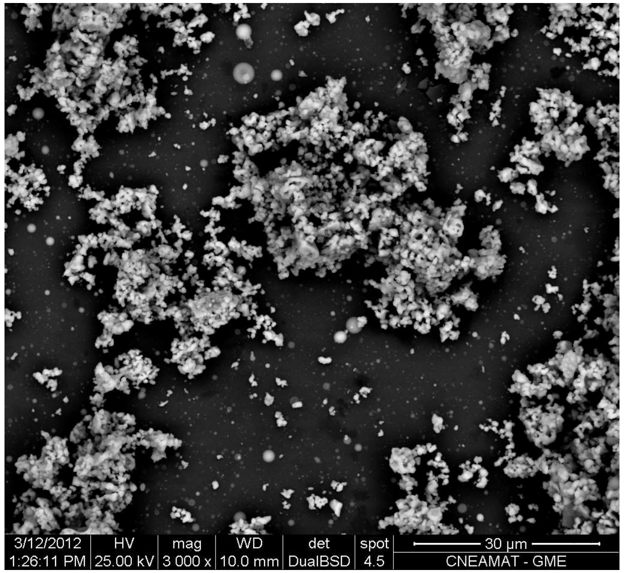


Figure 1.5 Plot of the Zn/Ga ratio for $ZnGa_2O_4$ films deposited using mosaic ablation targets.

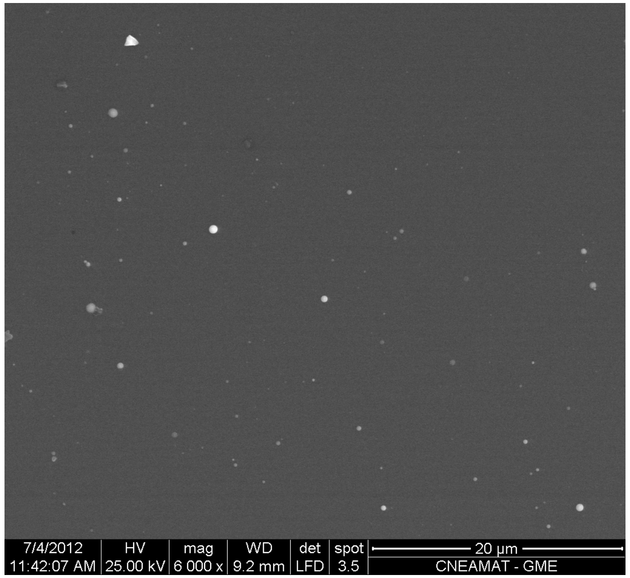
Thin film techniques: Pulsed Laser Deposition

<u>Main disadvantage</u>:

• Particulate formation (problem for multilayers!) → large penetration depth of the laser inside the target. High density targets should be used!



LCMO/Si
6 Ton



LCMO/Si
10 Ton

Thin film techniques: Pulsed Laser Deposition

• **Mechanical techniques can minimize particulate formation → velocity filters, off-axis laser deposition**

• **Nucleation during flight can also produce particulate → background pressure sufficiently high for particle nucleation. Substrate-target distance is also important.**

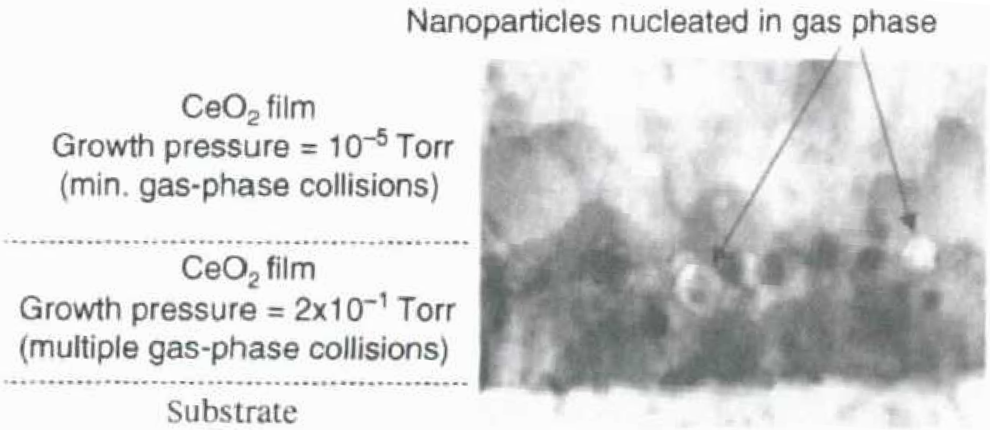
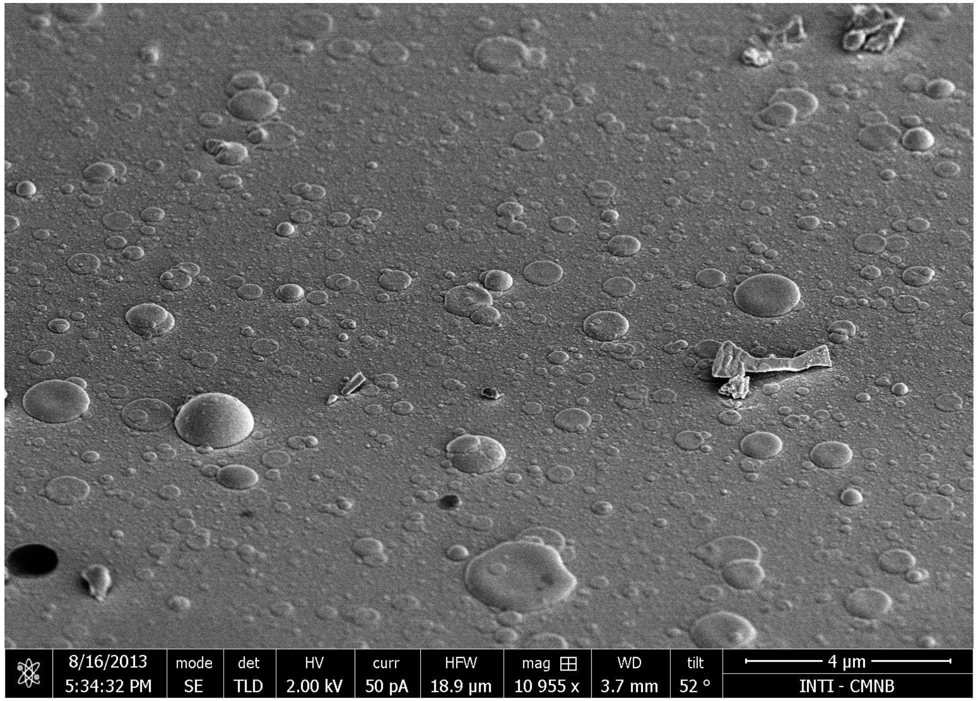


Figure 1.4 Cross-section TEM image of a CeO_2 film grown at high and low pressure, with CeO_2 nanoparticles forming at the high background pressure.

Thin film techniques: Pulsed Laser Deposition

• **Different types of particulate**



LCMO/Si

Thin film techniques: Pulsed Laser Deposition

Applications of PLD

• Complex oxides thin films growth → stochiometry transfer is critical! → $YBa_2Cu_3O_7$, manganites $A_xA'_{1-x}MnO_3$

Even more sophisticated oxides → magnetoplumbite $Ba_2Co_2Fe_{12}O_{22}$ → extremely complex crystal structure

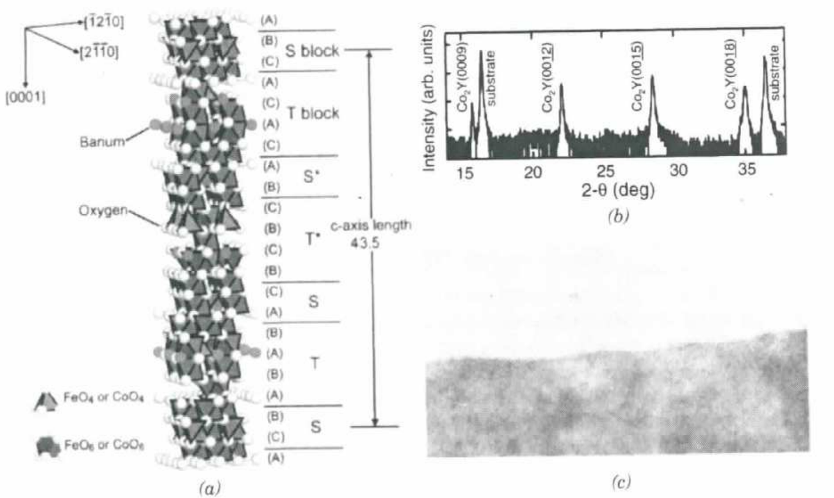


Figure 1.6 Crystal structure, X-ray diffraction data, and TEM image of a $Ba_2Co_2Fe_{12}O_{22}$ film grown by PLD [Ohkubo et al., 2003].

Thin film techniques: Pulsed Laser Deposition

Applications of PLD

• **Epitaxial interfaces and superlattices, even chemically dissimilar materials (i.e. metal-oxide CeO_2/Ge) → investigation of reduced dimensionality effects**

$KTaO_3$/$KNbO_3$ → individual layers as thin as 1 u.c. → sharp interfaces (atomic scale). PLD is competitive with MOCVD and MBE

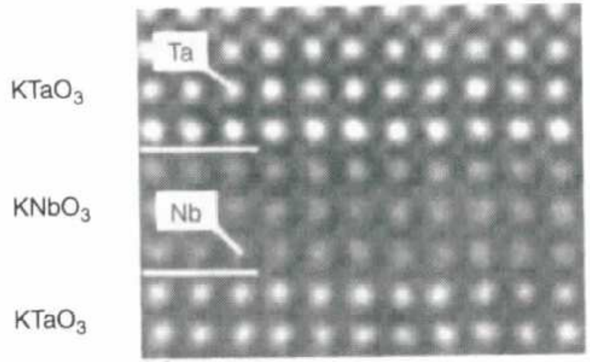


Figure 1.7 Cross-section Z-contrast STEM image of a $KTaO_3$/$KNbO_3$ superlattice structure grown by pulsed laser deposition.

Thin film techniques: Pulsed Laser Deposition

Applications of PLD

• Superconducting Electronic Devices → high freq. electronics for RF/microwave communications and SQUIDS

• Supercoduncting wires for viable HTS technology. RABiTS → substrate tape with appropiate texture + epitaxial YBCO growth. The integrity of the epitaxial layer should be maintended allong the conductor (~kms!!).

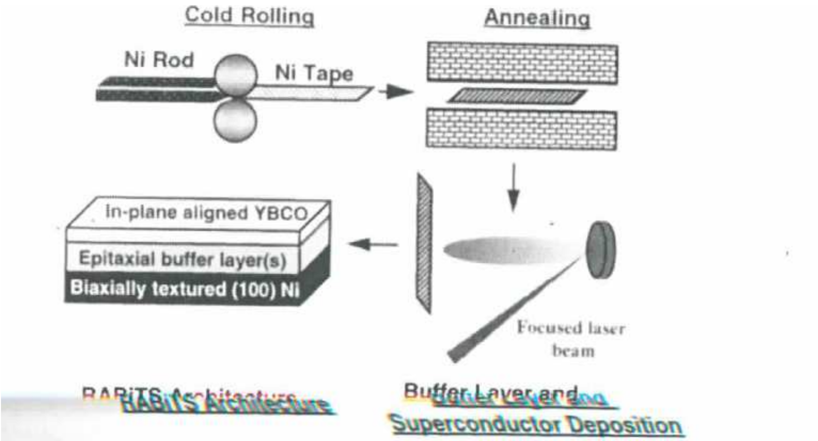


Figure 1.11 Schematic of the RABiTS process for HTS-coated conductor fabrication.

Thin film techniques: Pulsed Laser Deposition

Applications of PLD

• **Novel oxide devices concepts**

• **High-k dielectrics for Si microelectronics (miniaturization → replacement of SiO_2) → increase of gate capacitance in transistors → epitaxial, polycristalline and amorphous dielectrics (i.e. HfO_2)**

• **Memory devices based on FE → Au/PZT/$Bi_4Ti_{13}O_{12}$/p-Si diode → memory is accomplished via polarization hysteresis related to FE switching**

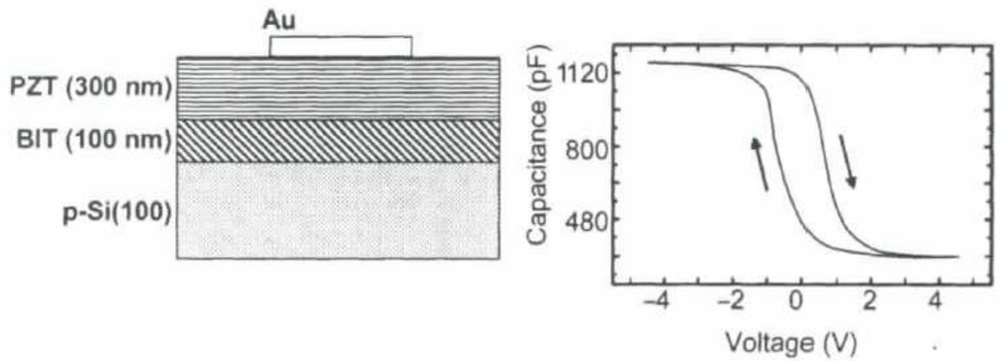


Figure 1.13 Capacitance versus bias voltage characteristics of Au/PZT/BIT/p-Si diode between −4.5 and 4.5 V bias voltage at a bias frequency of 100 kHz. The thickness of PZT and BIT were 300 and 100 nm, respectively [Yu et al., 2001].

Thin film techniques: Pulsed Laser Deposition

Oxide sensor devices

• **Chemical detectors based on semiconducting oxides (i.e. gas sensors, electronic noses → SnO_2 for NO_2 detection). Uncooled bolometers for infrared detection (VO_2, I-M transition and high temperature coefficient).**

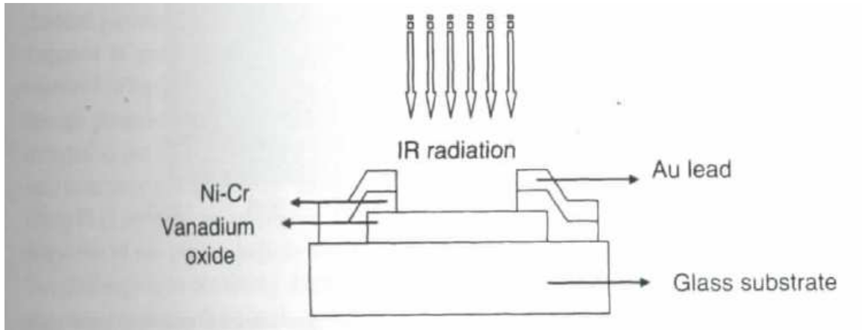
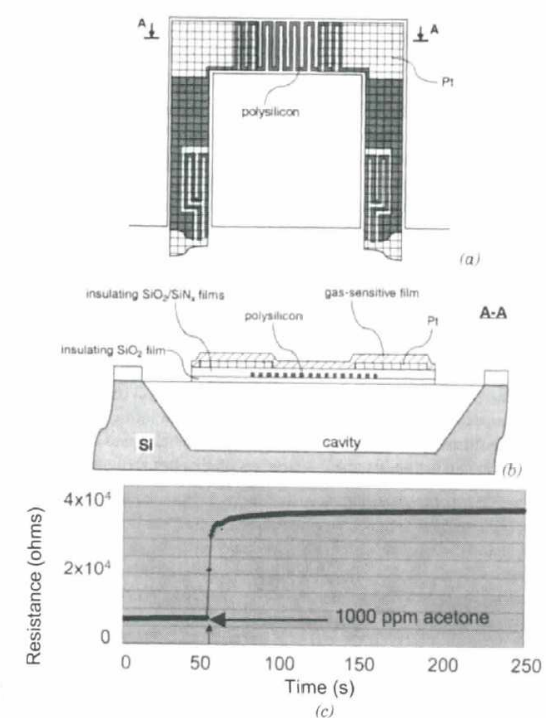


Figure 1.21 Microbolometer element, without air-gap thermal isolation, was fabricated using pulsed laser deposited vanadium oxide as the IR sensing layer [Kumar et al., 2003].

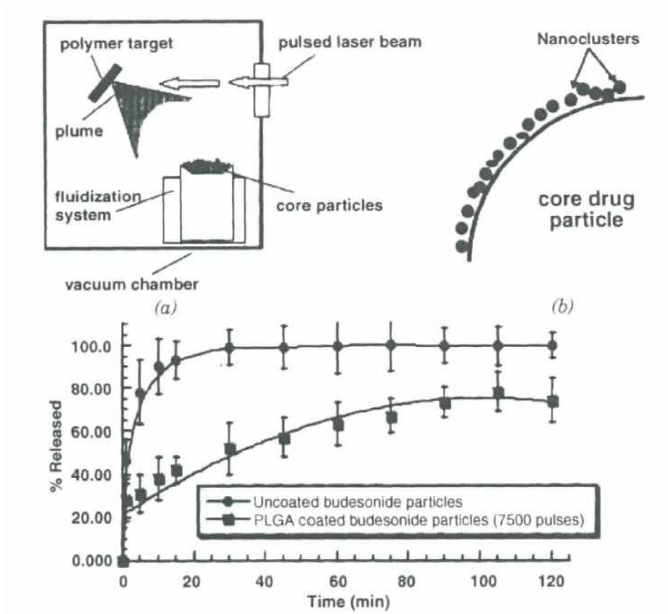


Thin film techniques: Pulsed Laser Deposition

Protective coatings and barriers → borides, nitrides, carbides. Diamond-like carbon can deposited by PLD.

- **Biocompatible coatings → dental and orthopedic implants (hydroxilapatite, calcium orthoposphate), similar to bone tissue**

- **Particle coatings for drug delivery → Budenoside (asthma treatment) covered with a polymer**



Thin film techniques: Pulsed Laser Deposition

Nanosystems synthesis: nanocrystals, nanowires, nanocomposites for nanotransistors, nanosensors study of quantized electronic systems.

For example, an hybrid PLD/CVD was used to synthesize NW with periodic composition

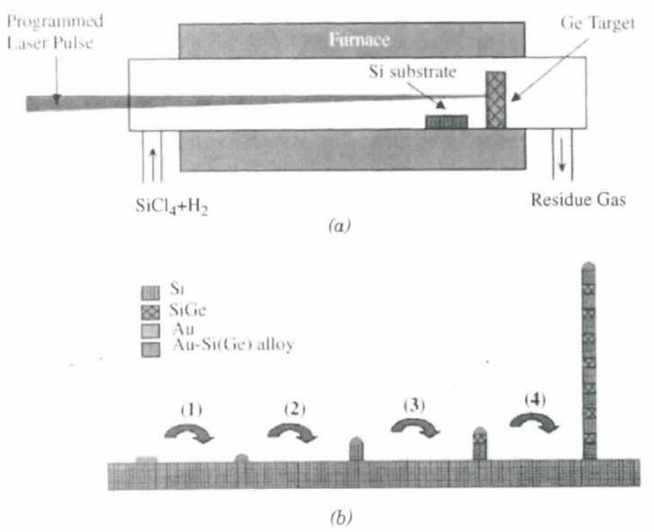


Figure 1.24 Film growth process that is a hybrid of pulsed laser ablation and chemical vapor deposition was used to synthesize semiconductor nanowires with periodic longitudinal heterostructures [Wu et al., 2002].

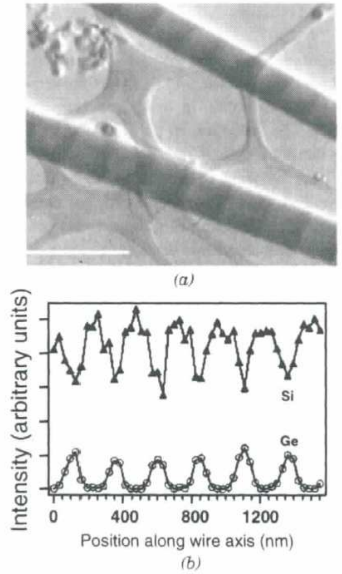


Figure 1.25 Cross-sectional transmission electron microscopy image of a single-crystal compositionally modulated nanowire with a Si/SiGe superlattice structure along the length of the wire [Wu et al., 2002].

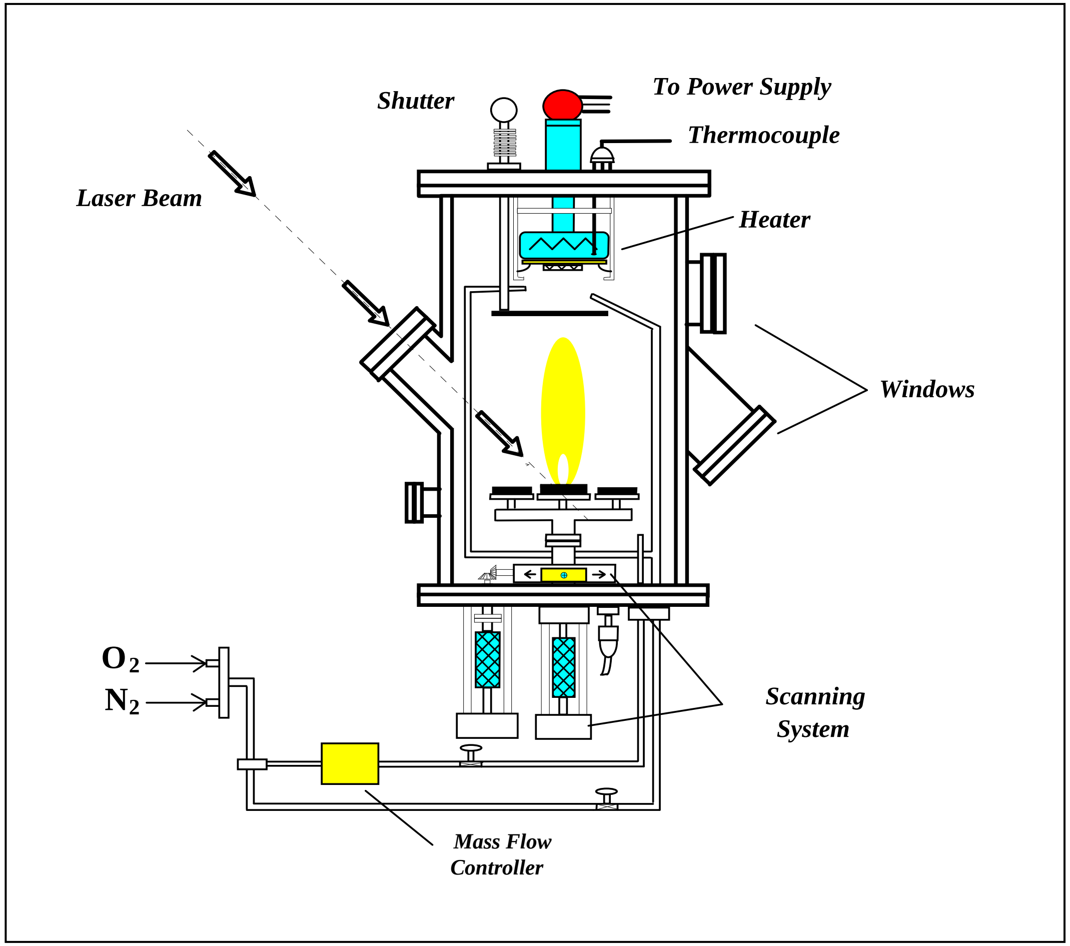
Thin film techniques: Pulsed Laser Deposition

Polymer and organic thin films

Teflon can be deposited on metallic surfaces by PLD (protective coatings for bio applications: metal implants, tooth fillings, jewerly). PMMA can also be deposited by PLD. Effective PLD should avoid organic molecules decomposition. Also, light-induced descomposition should be avoid during ablation → a photosensitizer is added to the target → excitation of the latter

DNA thin films can be grown by PLD, for microfluidic biosensors, biocompatible coatings, gene recognition microarrays.

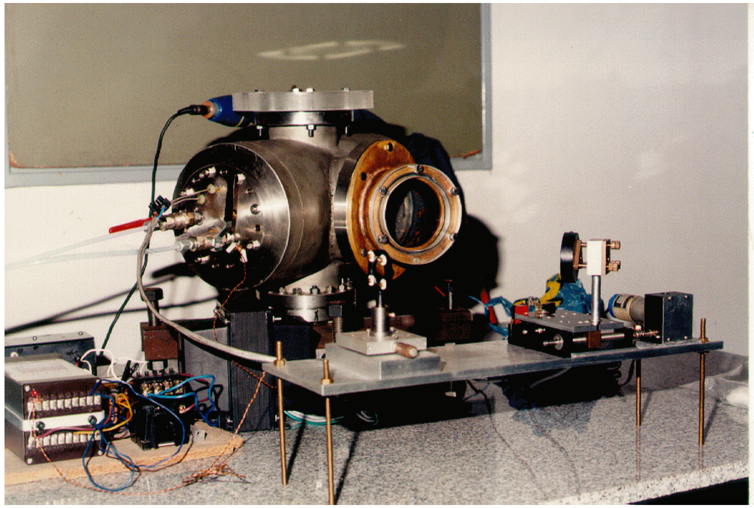
Thin film techniques: Pulsed Laser Deposition



Typical PLD chamber

Thin film techniques: Pulsed Laser Deposition

FI-UBA: home made PLD system



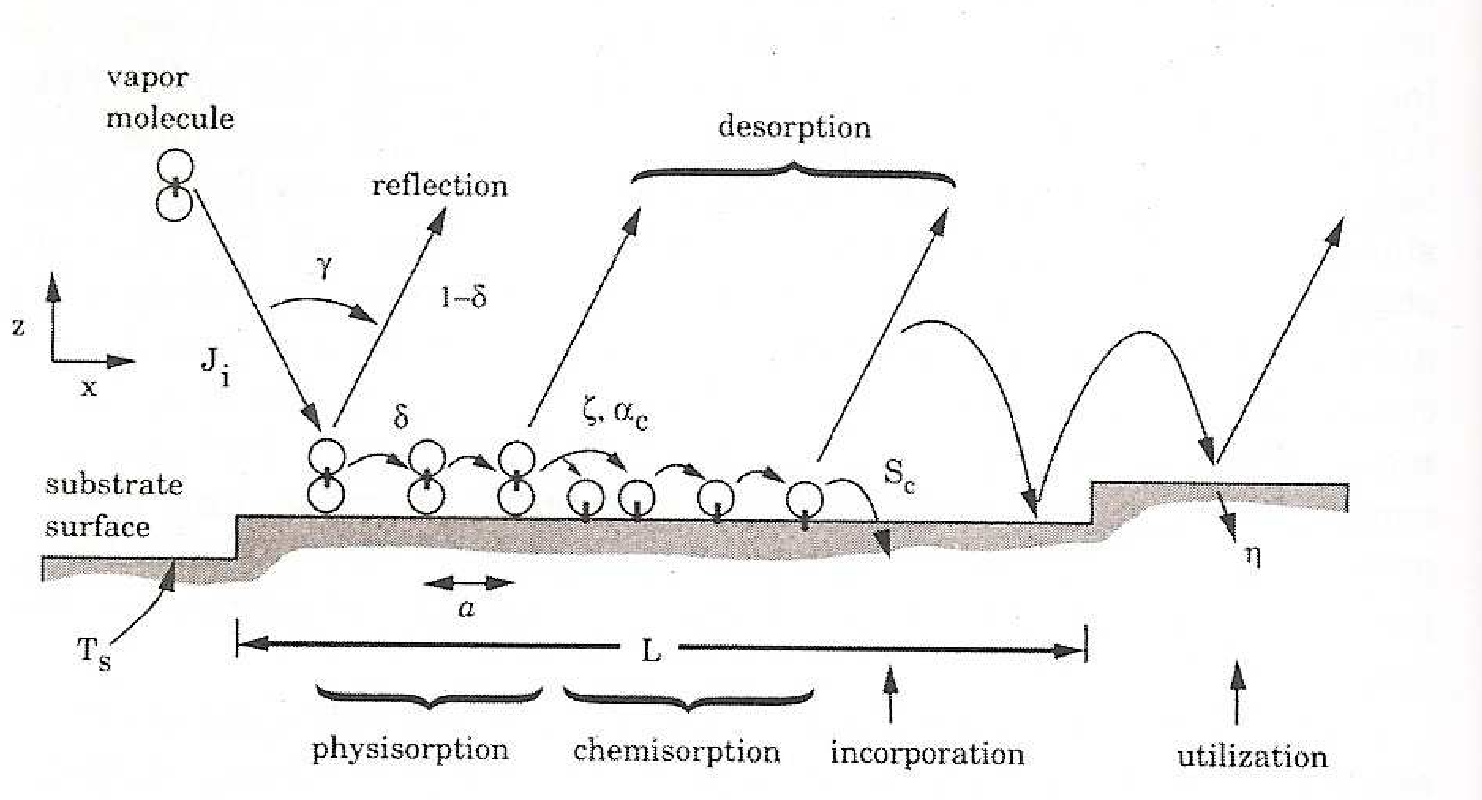
CAC-CNEA: NBM PLD commercial system

Deposition

(1) Arriving atoms are adsorbed on the substrate surface
(2) Diffuse some distance before becoming incorporated into the film
(3) Reaction to form the bonds (with other species + surface)
(4) Nucleation (initial agregation of the film)
(5) Development of a structure or morphology, including topography and crystallography
(6) Diffusional interactions within the bulk of the film and with the substrate

Adsorption

- Physisorption (van der Waals interaction)
- Chemisorption (chemical bonds are created)



Nucleation

γ → surface energy per unit area of surface (N/m)

Surface diffusion → minimization of surface energy

γ depends on chemical composition, crystallographic orientation, atomic-scale roughness, etc.

γ is usually anisotropic → low energy facets

For deposition onto a foreign substrate, one must take into account γ_S (substrate free surface), γ_I (substrate-film interface) and γ_F (film free surface).

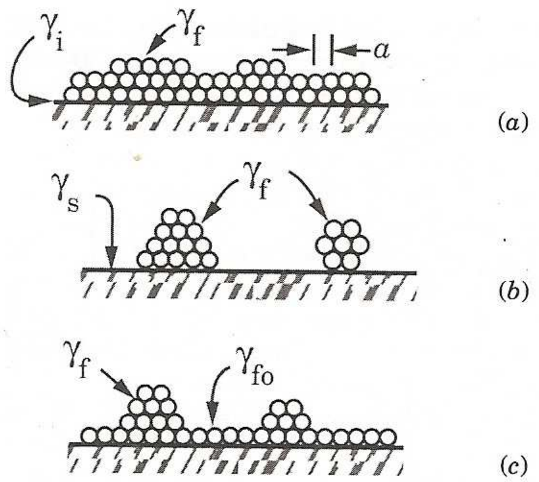
γ_I is tunable → decreases when film-substrate bonding increases

Nucleation

(a)layer-by-layer growth (Frank-van der Merwe) if $\gamma_F+\gamma_I<\gamma_S$ (surf. energy is lower for the wetted substrate than for the bare one)

(b) 3D-islands (Volmer-Weber)

(c) Stranski-Krastanov (Elastic energy is accumulated as the film grows 2D. At some critical height, the free energy of the film can be lowered if the film breaks into isolated islands, where the tension can be relaxed laterally.)



Epitaxy

Epitaxy occurs when the bonds of the film crystal align with the bonds of the substrate surface, making the interfacial energy γ_I very small. So, it is energetically favourable for the film material to crystallography align itself with the substrate

- Structural matching with the substrate

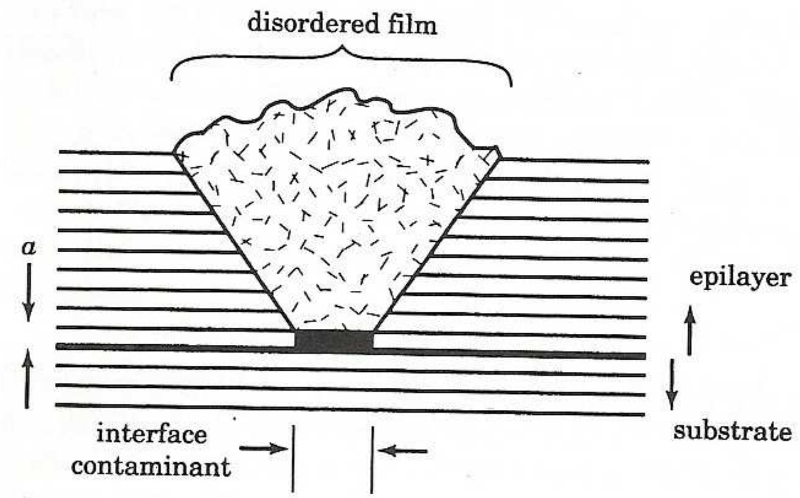
$$\frac{\Delta a}{a} = \frac{(a_{pel} - a_{subs})}{a_{subs}} * 100$$

- Substrate temperature window (interdifusion with the substrate, difussion on the surface)

Epitaxy improves interface quality in multilayered structures and results in films with few grain boundaries

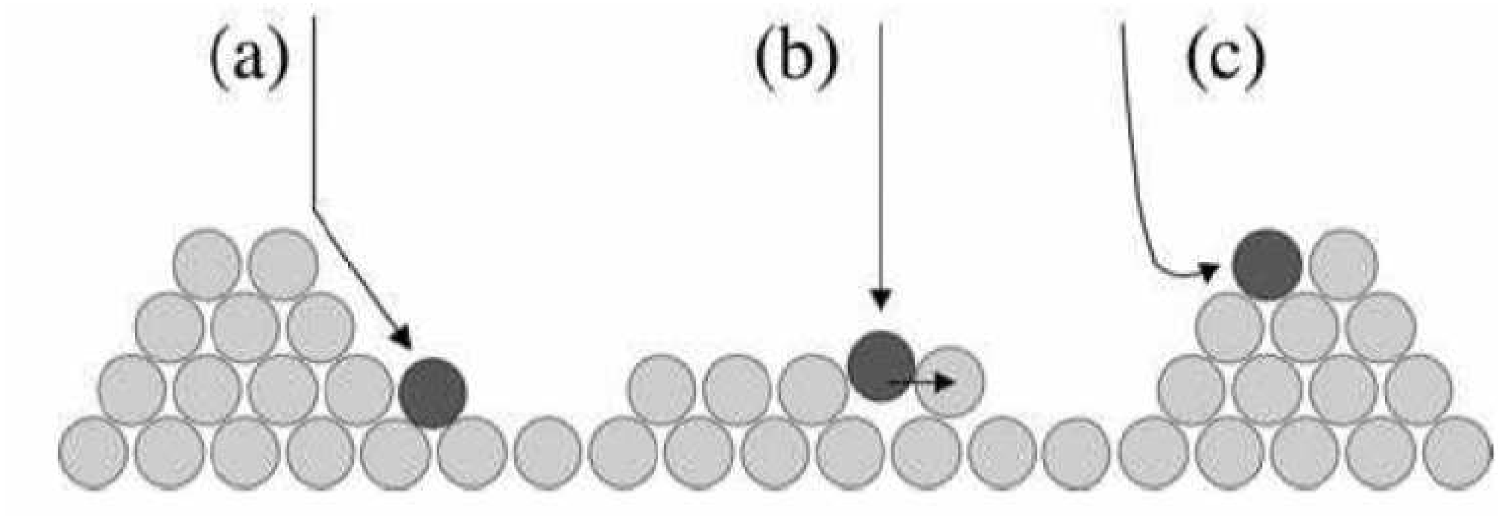
Disruption of epitaxy

Epitaxy is particulary sensitive to degradation by impurities and defects. Even one monoloayer of disordered contaminant disrupts epitaxy.



Substrate requirements to obtain epitaxy: crystallographic order, sub-monolayer surface cleanless and chemical inertness toward the depositing species.

Kinetics of thin film growth



Kinetic effects may play a role in adatom incorporation:

(a) Downhill funneling: the deposited particle slides down a slope until a local minimum of the surface height is reached
(b) Knockout process: the momentum of the arriving particle suffices to push out a surface adatom at a terrace edge
(c) Steering effect: attractive forces can influence the trajectory of the arriving particle significantly

Thin film characterization: RHEED

RHEED: Reflection High Energy Electron Diffraction

In-situ characterization → Electron diffraction in grazing incidence:
surface effect (a few nm)

Electrons energy ~ 10-50keV

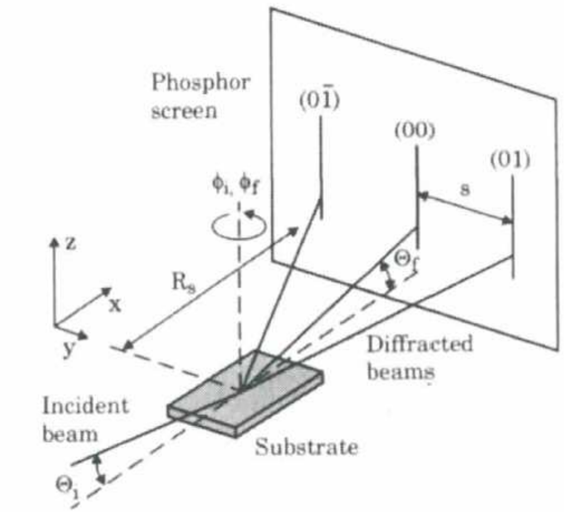
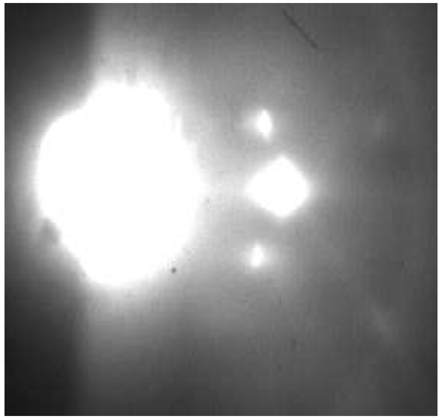


Figure 4.1 Schematic view of the RHEED geometry. $\Theta_I(\Theta_F)$ and $\phi_I(\phi_F)$ are the incident and azimuthal angles of the incident (diffracted) beam. R_S is the distance between substrate and phosphor screen and S the distance between the diffraction spots or streaks.

Electrons energy ~ 10-50keV
λ(Å)=$(150/E)^{1/2}$ ~ 0.05-0.1 Å

Incidence angle ~ 0.1º-5º



Thin film characterization: RHEED

RHEED: Reflection High Energy Electron Diffraction

Weakly interacting diffraction techniques → kinematic scattering theory
RHEED → strong interactions! → no quantitative description

$$K_S - K_0 = G$$

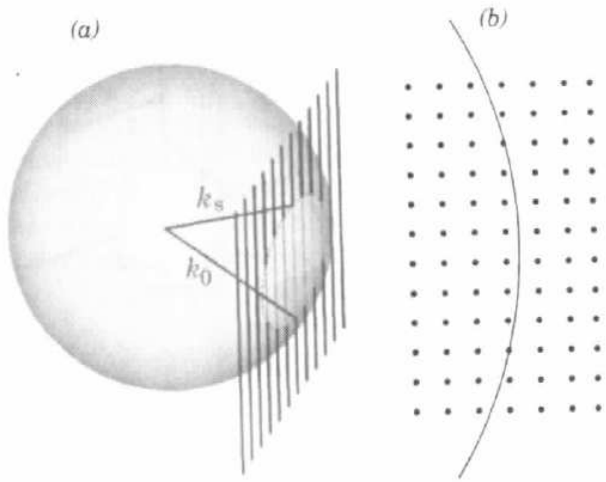


Figure 4.2 Ewald sphere construction in (a) three dimensions and (b) a section of the horizontal $z = 0$ plane.

Reciprocal lattice of a 2D surface → lattice of thin rods, perpendicular to the surface. High electronic energy → Ewald sphere is large → few sport are seen

Thin film characterization: RHEED

RHEED: Reflection High Energy Electron Diffraction

Kikuchi lines → multiple scattering

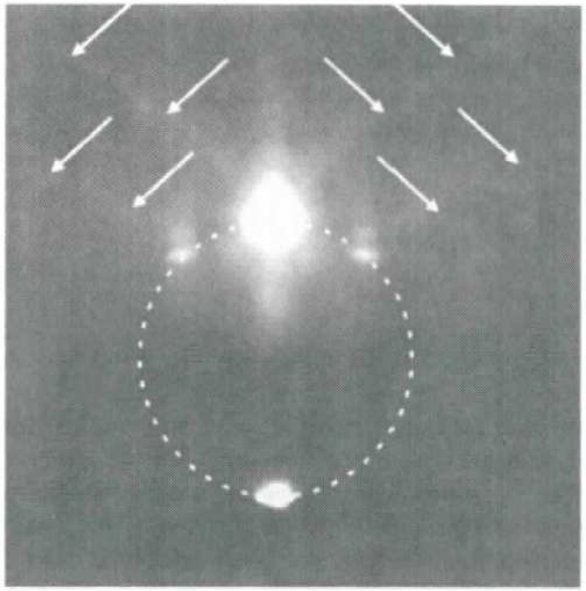


Figure 4.3 Typical RHEED pattern as recorded from a perfect $SrTiO_3$ surface.

Clear and sharp Kikuchi lines → indication of flat and crystalline surface

Thin film characterization: RHEED

RHEED: Reflection High Energy Electron Diffraction

Utility of RHEED

- **Determination of lattice parameters**

$$n/d_x = 1/\lambda(\cos\theta_f - \cos\theta_i)$$

$$n/d_y = 1/\lambda(\cos\theta_f * \sin\phi_f)$$

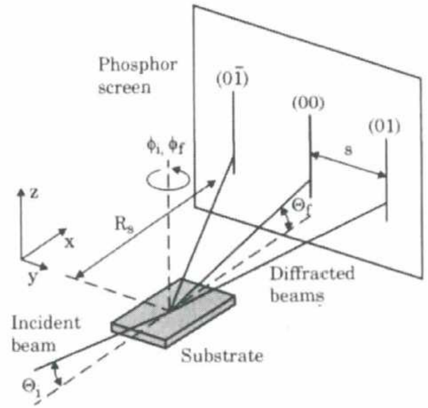


Figure 4.1 Schematic view of the RHEED geometry. $\Theta_I(\Theta_F)$ and $\phi_I(\phi_F)$ are the incident and azimuthal angles of the incident (diffracted) beam. R_S is the distance between substrate and phosphor screen and S the distance between the diffraction spots or streaks.

θ and ϕ → incident and azimuthal angles of electron beam
d_x and d_y → lattice parameters parallel and perpendicular to incident beam

Thin film characterization: RHEED

RHEED: Reflection High Energy Electron Diffraction

Utility of RHEED

- **Determination of vicinal angle**

Diffracted intensity → diffraction due to in-plane lattice constant times diff. due to additional periodicity of step-terrace structure.

Out of phase condition → splitting angle

$$\Delta\theta_f=(2\pi/kd)\ (\beta\cos\phi_{p,i})\ /\ (\beta\cos\phi_{p,i} + \langle\theta_f\rangle)$$

$\beta\cos\phi_{p,i}$ → projection of vicinal angle along beam direction

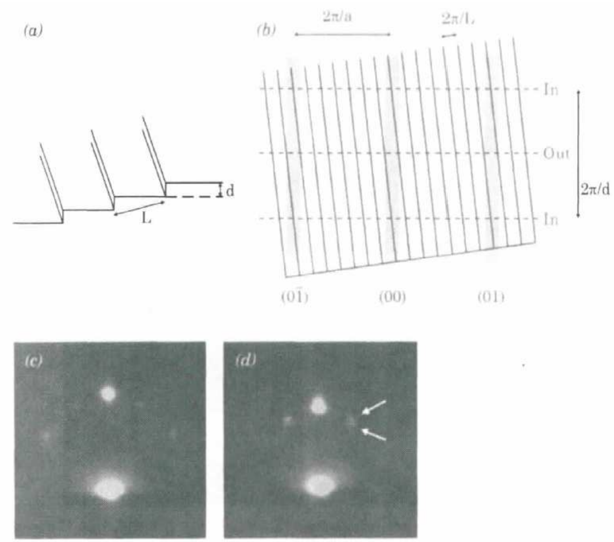
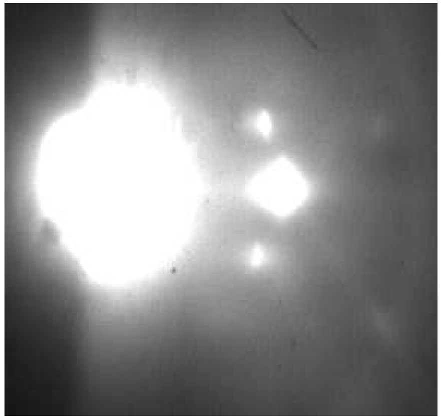


Figure 4.4 (a) Real space and (b) reciprocal space of a vicinal surface with a the in-plane lattice parameter, d the step height, and L the terrace width. RHEED patterns as recorded from a vicinal $SrTiO_3$ surface with incident beam perpendicular to the step ledges: (c) in-phase condition and (d) out-of-phase condition.

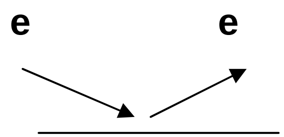
Thin film characterization: RHEED

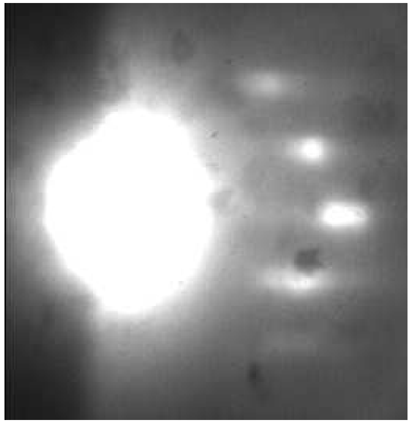
RHEED: Reflection High Energy Electron Diffraction

+ roughness

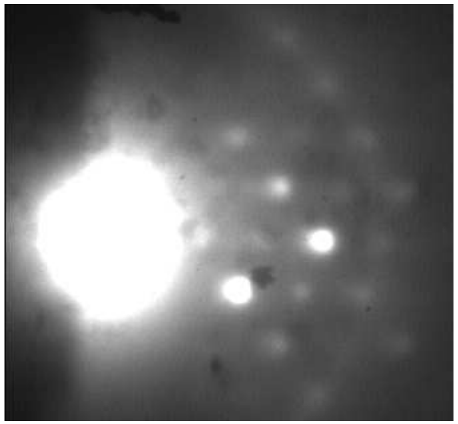


Spots (2D surface)

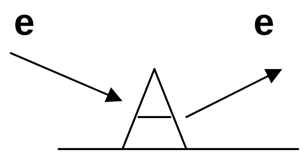




Stripes

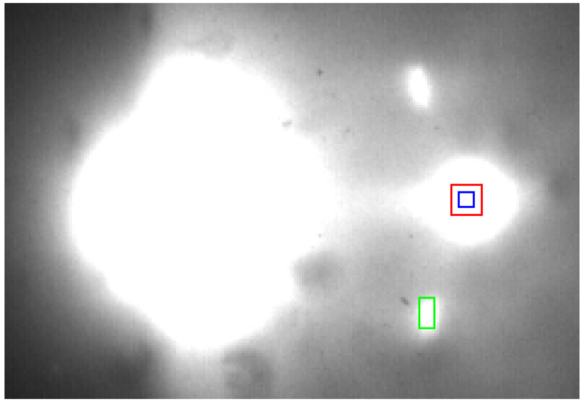


Transmission pattern (3D surface)

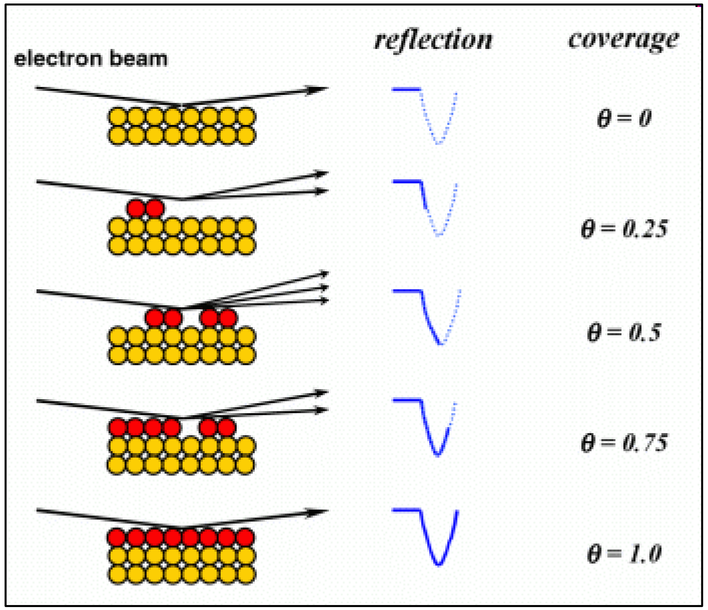


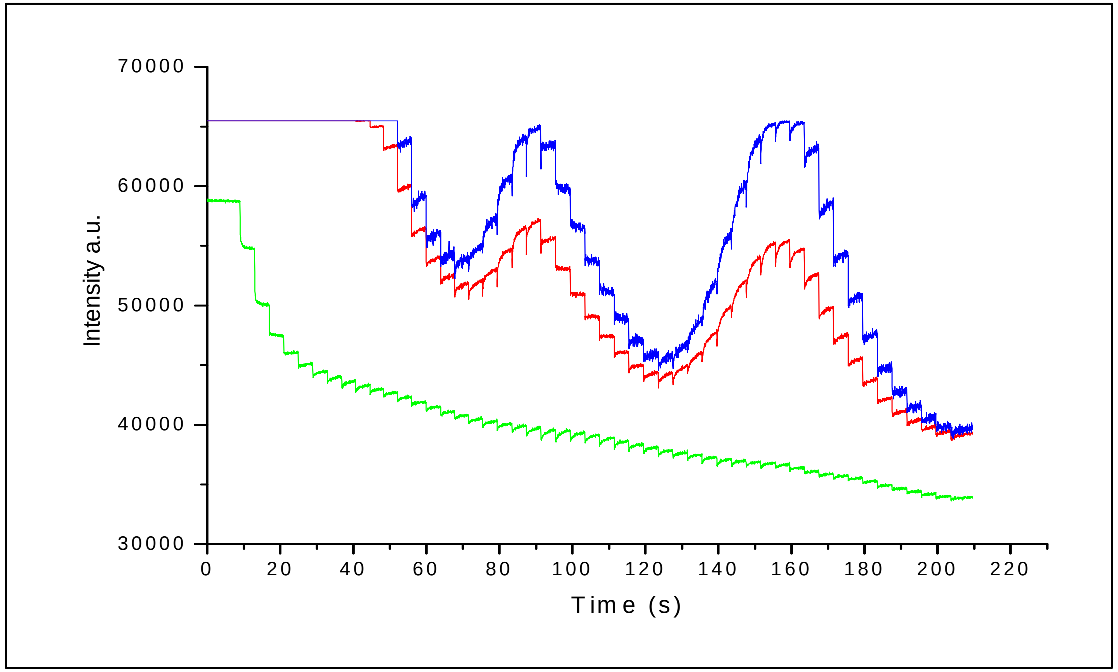
Thin film characterization: RHEED

RHEED: Reflection High Energy Electron Diffraction



Layer by layer growth





Thin film characterization: RHEED

RHEED: Reflection High Energy Electron Diffraction

High pressure RHEED

$I/I_0 = \exp(-l/L_E)$ L_E → mean free path, l → path distance

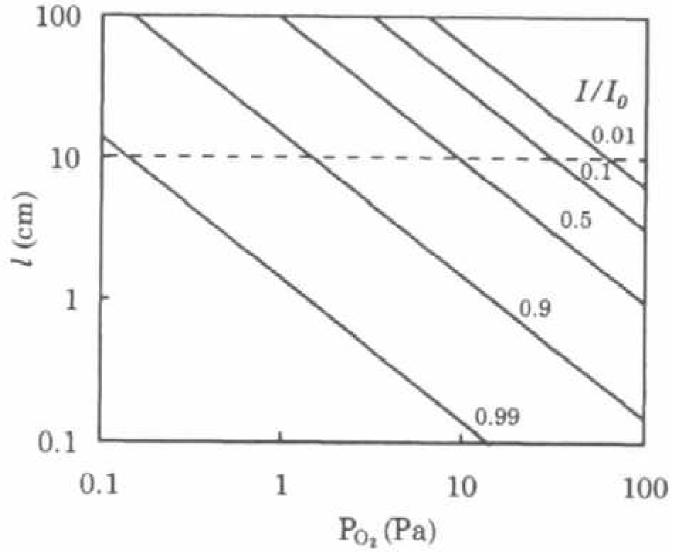


Figure 4.6 Attenuation I/I_0 of a 10-keV electron beam as a function of the oxygen pressure P_{O_2} and penetration length l. The dashed line represents the traveling distance in the high-pressure RHEED setup.

Travelling distance has to be minimized

Thin film characterization: RHEED

RHEED: Reflection High Energy Electron Diffraction

High pressure RHEED

Differential pumping system. The travelling distance is reduced to 100mm (I/I_0~0.01)

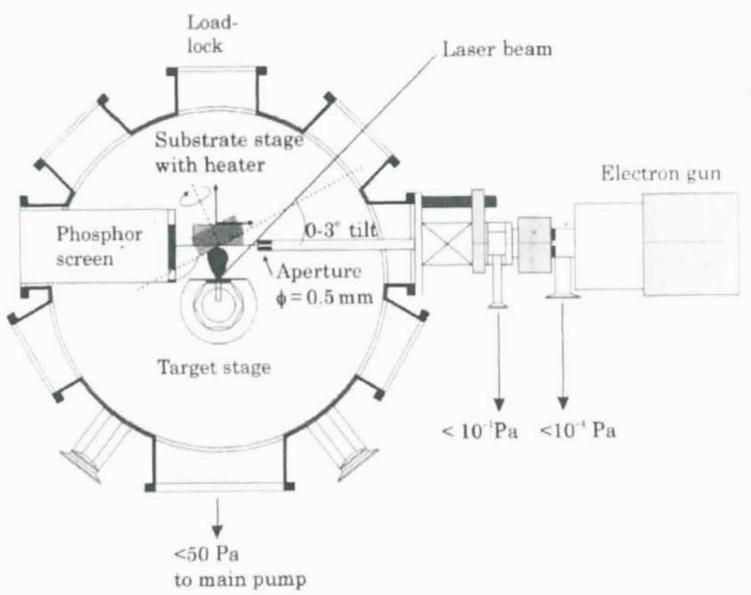


Figure 4.7 Schematic view of the deposition chamber, including the electron source assembly. The system is fully computer controlled including selection of the targets allowing for automated multilayer deposition.

Thin film characterization: RHEED

RHEED: Reflection High Energy Electron Diffraction

Growth kinetics → PLD is a non-equilibrium technique and kinetics effect could be relevant. High supersaturation → large nucleation rates → kinetic effects control growth mode

Homoepitaxy → 2D growth modes are expected (no lattice misfit and thermal coefficient differences). Relevant parameters: surface difussion coeficient (D_S), sticking coeficient of adatom to a terrace, energy barrier for adatoms to descend to a lower terrace (E_S).

$l_D=(D_S\tau)$, where l_D is surface diff. lenght and τ is reevap. time

$D_S=\nu a^2 \exp(-E_A/k_BT)$, E_A activation energy

The difussion is controlled by the temperature!!

Two processes should be considered: intralayer mass transport and diffusion to a lower terrace

Thin film characterization: RHEED

RHEED: Reflection High Energy Electron Diffraction

Fast intralayer mass transport → step flow on a vicinal substrate (l_D large). Steps act as sinks of deposited atoms and nucleation on terraces is prevented → step propagation

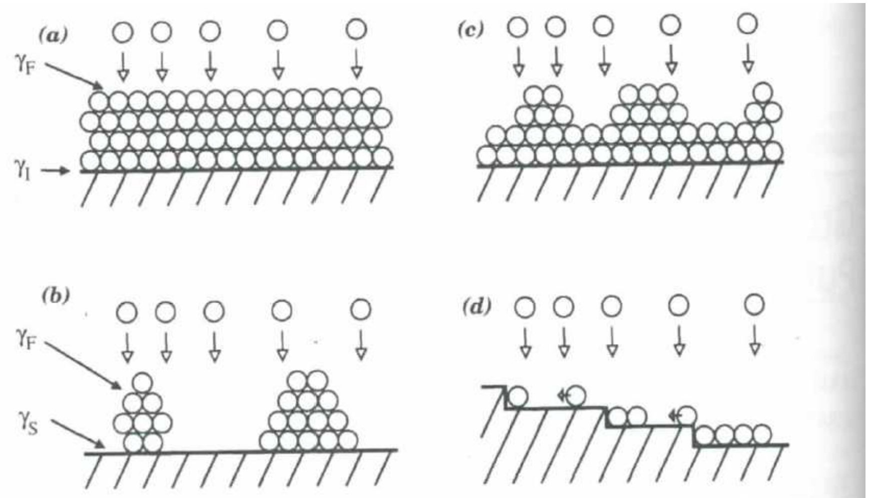


Figure 8.1 Film growth modes—layer-by-layer: (a) Frank-Van der Merwe, island; (b) Volmer–Weber (c), Stranski–Krastanov, (d) and step flow.

Slow intralayer mass transport → nucleation at terraces. If interlayer transport is high → layer by layer growth. Otherwise, 3D islands are formed

Thin film characterization: RHEED

RHEED: Reflection High Energy Electron Diffraction

Homoepitaxial $SrTiO_3$

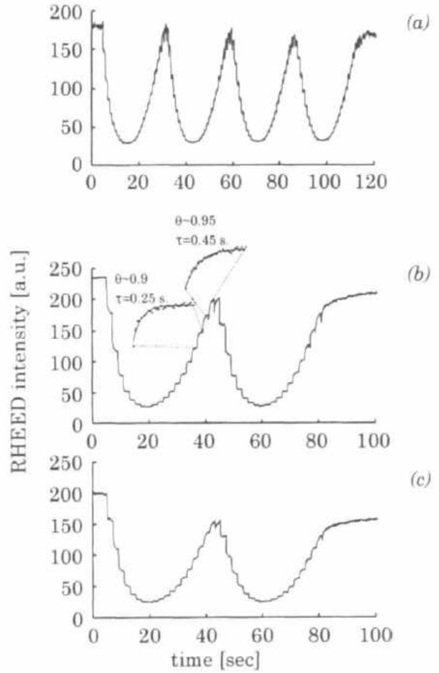


Figure 8.2 Specular RHEED intensity oscillations during homoepitaxial growth of $SrTiO_3$ at (a) 3 Pa, 850°C, (b) 750°C, and (c) 650°C. The insets in (b) show the enlarged intensities after a laser pulse at different coverage.

Layer-by-layer growth. RHEED relaxations related to adatoms diffusion
$I \sim I_0(1-\exp(-t/\tau))$, diffusion times, activation energies can be obtained

Thin film characterization: RHEED

RHEED: Reflection High Energy Electron Diffraction

Homoepitaxial $SrTiO_3$

Transition from 2D to step flow (constant RHEED intensity) → adatom diffusion lenght

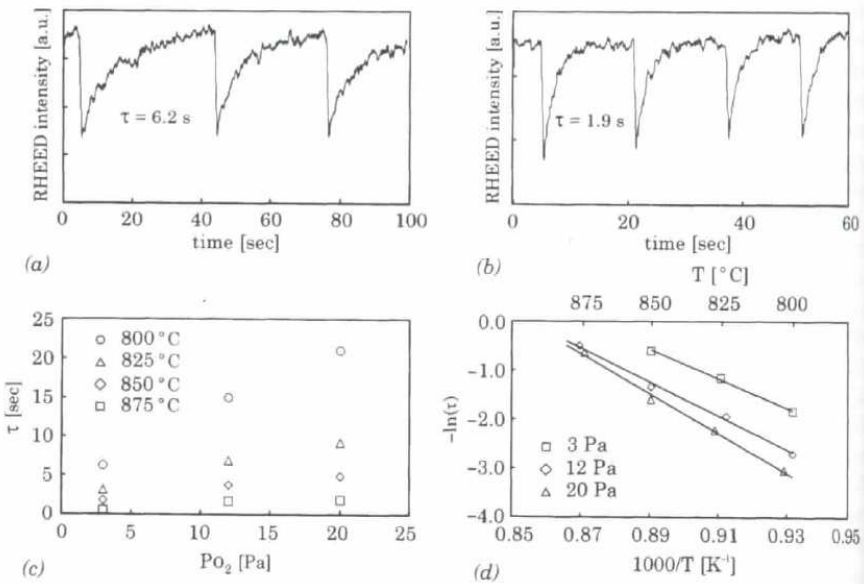


Figure 8.7 Specular RHEED intensity variations during homoepitaxial step flow growth of $SrTiO_3$ at oxygen deposition pressure of (a) 3 Pa and 800°C and (b) at 20 Pa and 875°C. Relaxation times obtained from a fit with Eq. (8.13) for (c) different temperature and oxygen deposition pressure and (d) the same values in the Arrhenius form.

Thin film characterization: RHEED

RHEED: Reflection High Energy Electron Diffraction

Atomically smooth surfaces are desired → layer-by-layer growth. Roughening is usually observed (especially at low temperatures and high deposition pressures), related to limited interlayer mass transport. How to avoid this problem? → fast deposition of the amount of material necessary to complete a unit cell in a short interval (supersaturation is achieved for longer times)

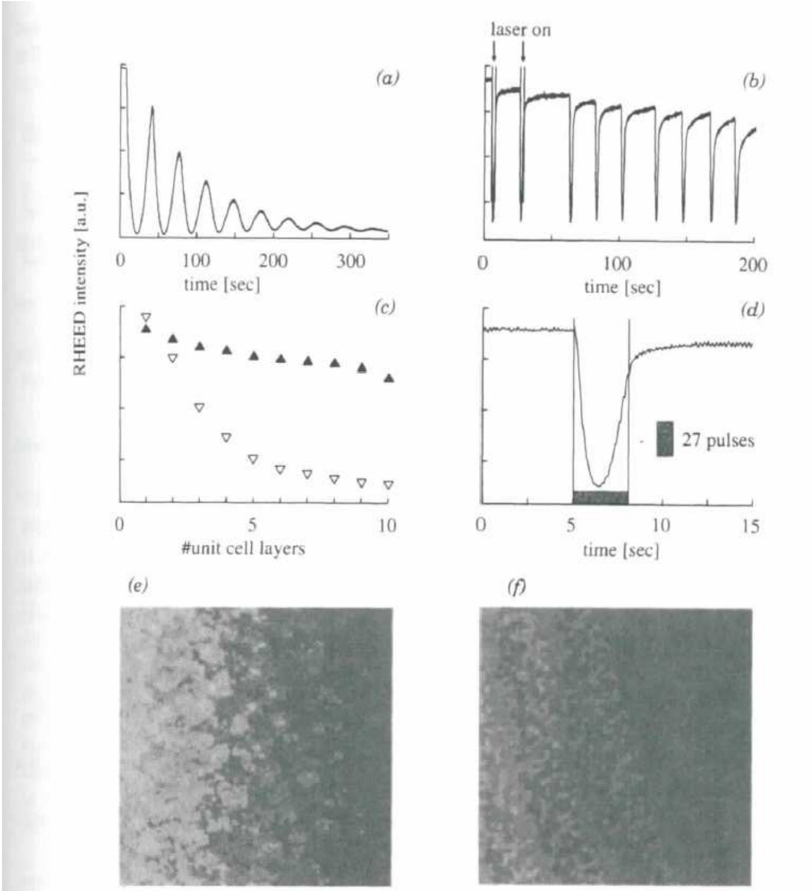


Figure 8.8 Specular RHEED intensity recorded during homoepitaxial growth of $SrTiO_3$ at 10 Pa and 8(using (a) "standard" PLD and (b) interval PLD. Intensity maxima using (c) "standard" PLD, ▽, and inte PLD, ▲. (d) Intensity variation during one deposition interval. The surface morphologies of ~30-nm-t $SrTiO_3$ films are depicted in the atomic force microscopy (AFM) micrographs (1 × 1 μm^2): (e) "standard" and (f) interval PLD.

Remarks

- The importance of thin films and their applications in current research was shown

- Approach to different thin films growth techniques

- Growth mechanisms

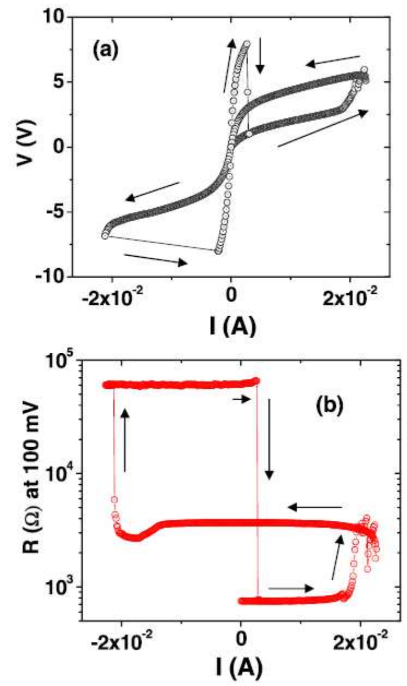
- In-situ characterization

- Examples of applications: influence of strain effects on functional properties (magnetic, transport), ReRAM devices, etc.

Laboratorio de Ablación Láser – CAC - CNEA

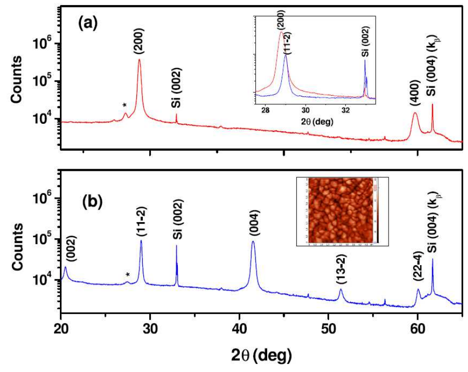
Líneas de Trabajo

- Memorias resistivas (memorias ReRAM)
- Oxidos ferroeléctricos
- Gases electrónicos 2D en sup. e interfaces
- $LiMn_2O_4$ para electroquímica



¿Qué hacemos?

- Crecimiento`por PLD+RHEED
- XRD, AFM, SEM
- Espectroscopías XPS y Raman
- Micro y nanofabricación en Sala Limpia
- Caracterización eléctrica y magnética
- Modelado



Producción: 20 publicaciones en los últimos 5 años

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