EPFL

PVD summary MICRO-331 Microfabrication technologies

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& teams

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Fabrication steps

No mechanical parts

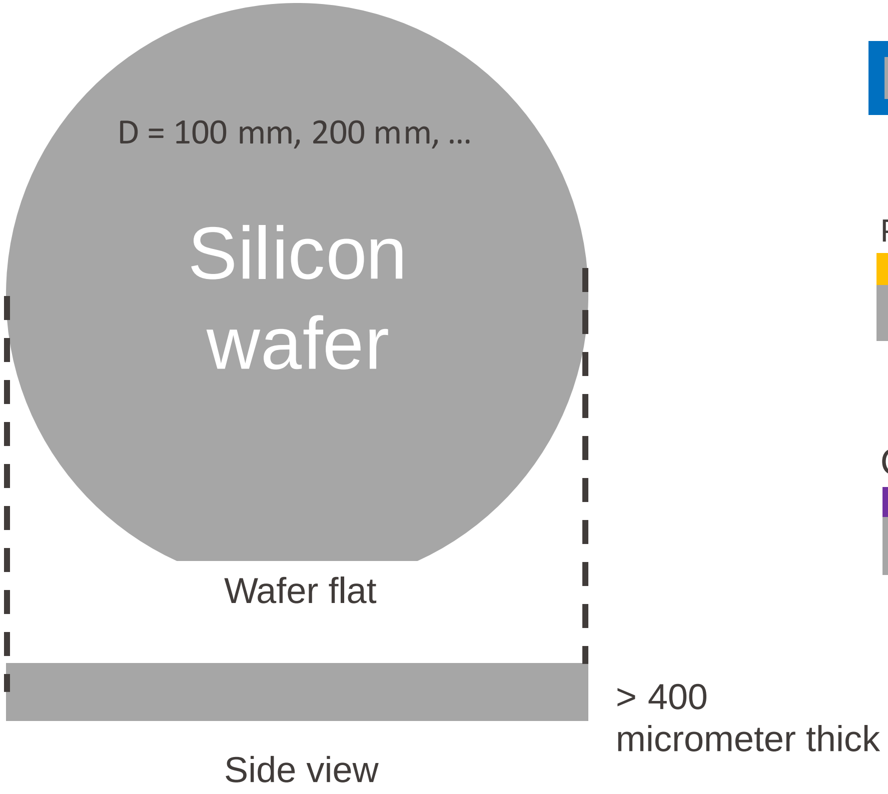
- Integrated Circuit, Microelectronics
  - Silicon doping
  - Silicon oxidation
  - Thin film deposition (CVD/PVD)
  - Photolithography
  - Thin film etching (dry/wet)
  - …

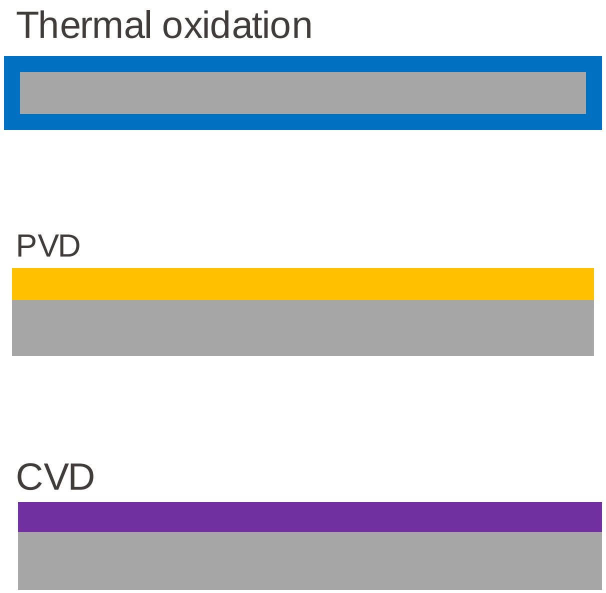
With mechanical parts

- MEMS, microsystems
  - All the steps for IC's
  - + sacrificial layer etching
  - + bulk silicon etching
- Create mechanically freestanding elements for physical sensing or actuation
  - Cantilevers, membranes

- PVD versus CVD
- PVD: Evaporation versus sputtering

Thin material layers on Silicon wafers





Condensed water film on ‘cold’ glass surface

Physical vapor deposition (PVD)

No chemical reaction involved

Purely physical film formation

Vapor condenses to a solid film (thin and uniform)

One side of the wafer (directionality)

- Evaporation (Thermal, E-beam)
- Sputtering (DC, RF, magnetron)
- Pulsed laser deposition (PLD)

Example questions

- *List the various techniques that are called 'Physical Vapor Deposition (PVD)', describe briefly their principle of operation, and list their advantages and disadvantages.*

Example questions

- *Describe the physical vapor deposition (PVD) called "thermal evaporation", its working principle, basic configurations, typical materials used, as well as advantages and limits*

Example questions

- *Describe the physical vapor deposition (PVD) called “sputtering”, its working principle, basic configurations, typical materials used, as well as advantages and limits.*

Example questions

- *Describe the uniformity of thin films on a flat substrate by thermal evaporation by analyzing the mass flow.*

Example questions

- *Describe the lift-off process to deposit for example a thin layer of Ti.*

Example questions

- *In which situation do you use sputtering instead of evaporation to form thin films on surfaces?*

Thermal oxidation

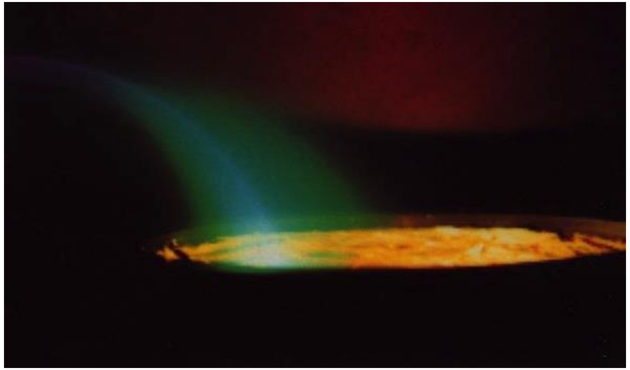
Oxidation process

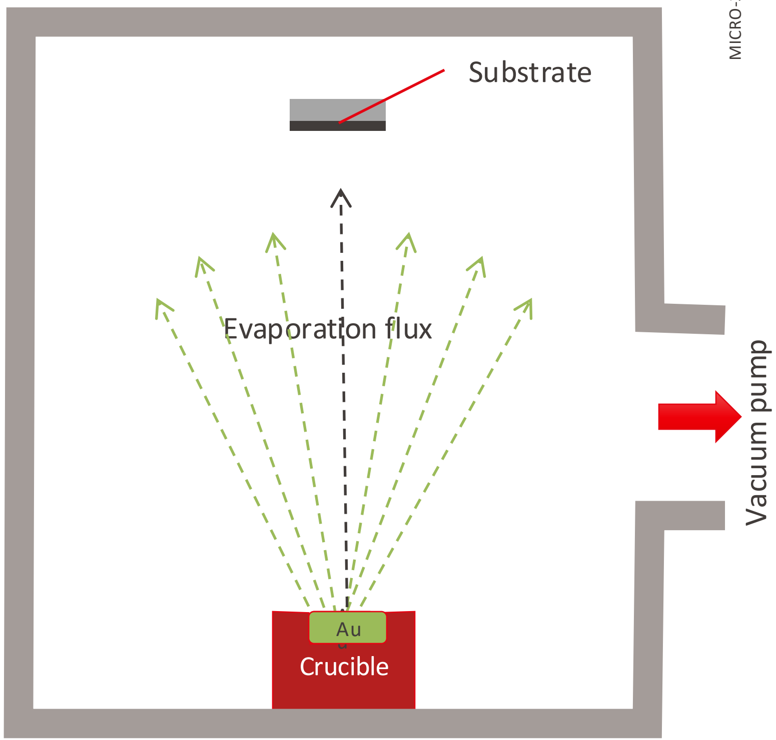
Strictly speaking NOT a deposition process
→ It consumes part of the substrate (silicon) to convert into a SiO_2 layer
Needs an oxygen-rich atmosphere + high temperature

→ LOCOS (local oxidation of silicon) using SiN mask (important for transistor fabrication)

How to heat up the evaporant?

- By resistive heater
  - + simple / - contamination
- By electron beam
  - - more complex / + control





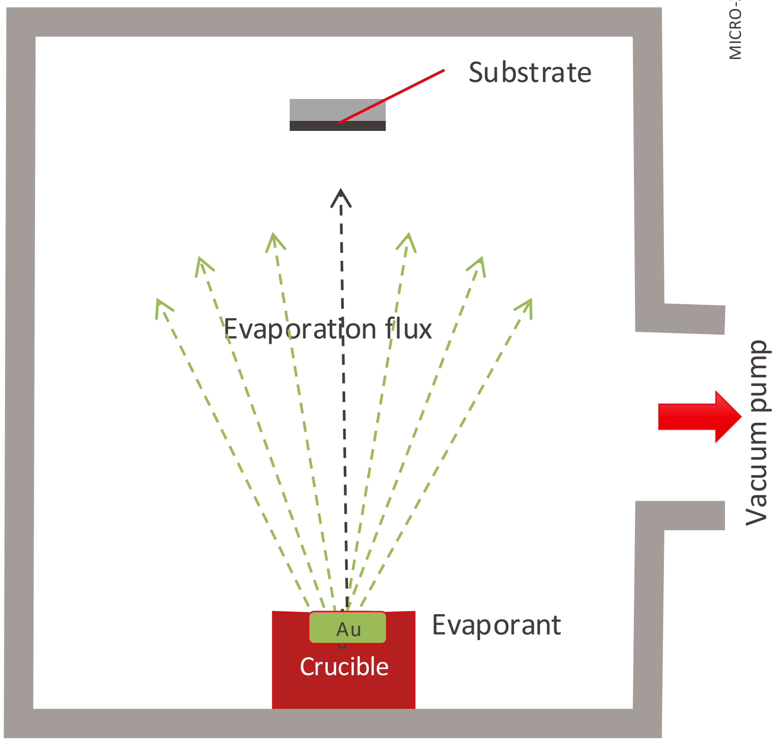
PVD: vapor creation

$$\Phi_e = \frac{1}{A_e} \cdot \frac{dN}{dt} = \frac{\alpha \cdot N_A \cdot (P_V - P)}{\sqrt{2\pi \cdot M \cdot R \cdot T}}$$

$$\Gamma_e = \Phi_e \cdot \frac{M}{N_A}$$

Φ_e = vapor flux [molecules/(m^2·s)]
A_e = source surface area [m^2]
N = number of gas molecules
α = sticking coefficient ($0<\alpha<1$)
N_A = Avogadro constant [mol^{-1}]

P_v = vapor pressure of the evaporant [Pa]
P = reactor pressure [Pa]
M = molar mass [kg/mol]
R = gas constant [J/(mol·K)]
T = temperature [K]
Γ_e = evaporation mass flux [kg/(m^2·s)]



Cosine law

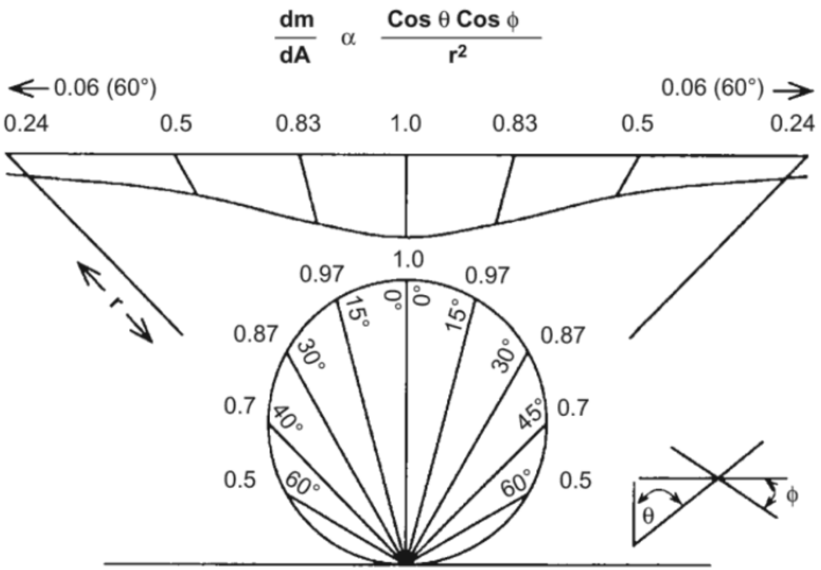
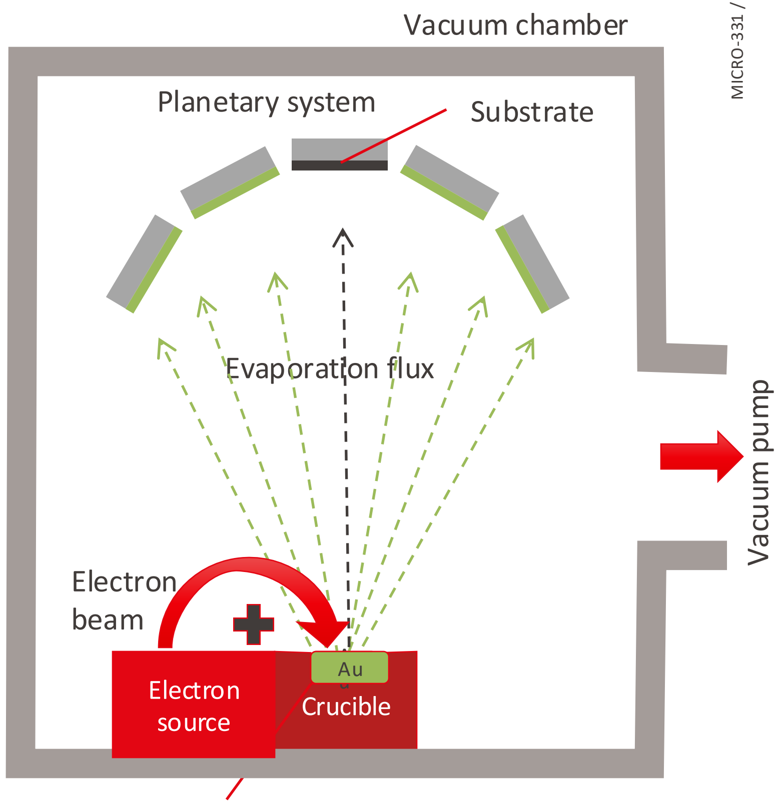


Figure 3.4: Cosine Distribution of Particles Leaving a Point on a Surface. Top: Relative Deposition on a Planar Surface from a Point Source of Vaporization. Bottom: Relative Vaporization as a Function of Angle from Normal

Handbook of Physical Vapor Deposition (PVD) Processing
By Donald M. Mattox

PVD: vapor flux towards substrate

- Uniformity issues on large & flat and for many substrates

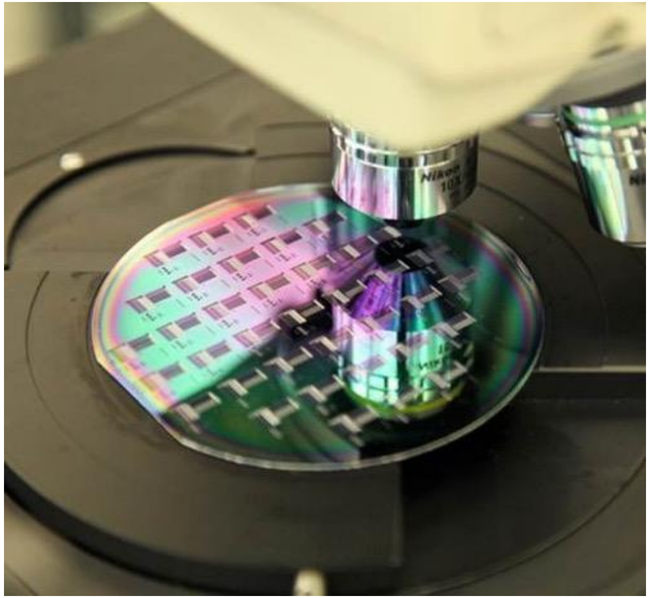


How to create a metal microstructure (e.g. wire)

There are 2 ways to reach this result:

1. PVD + lithography + etching + resist removal
2. Lithography* + PVD* + resist stripping (= Lift-off)

*special conditions must apply



PVD by evaporation wrap up

- Simple & Fast
- Pure materials (elements)
- High vacuum
- Long mean free path, micro-shadowing, grainy films
- But good for lift-off

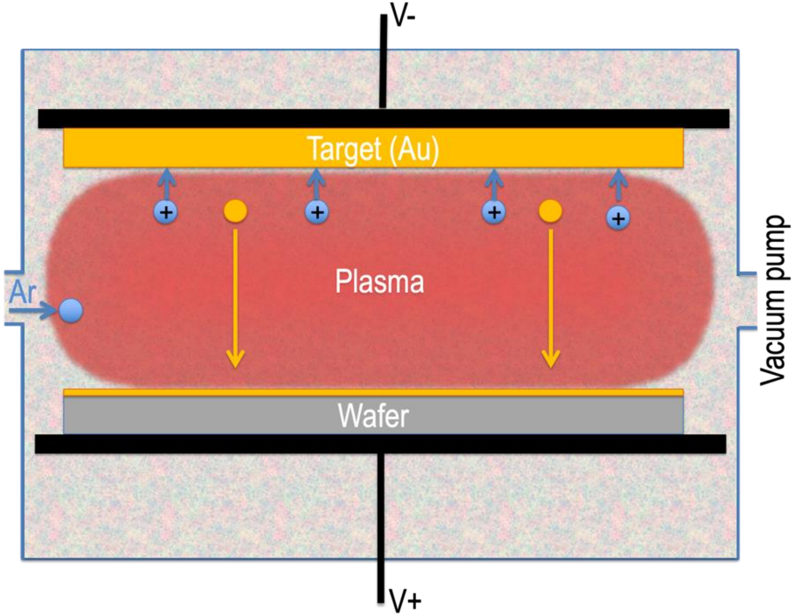
Does not allow depositing:

- Composite material, refractory metals

Sputtering principle

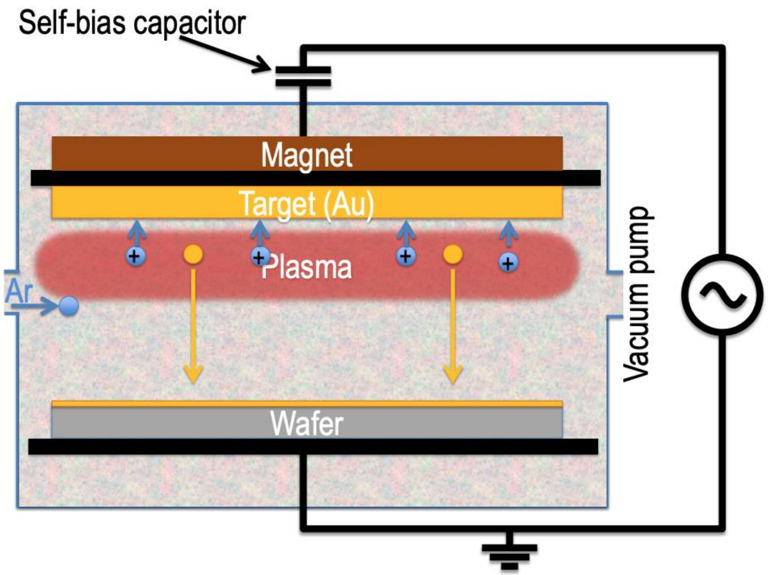
- Working principle
  1. Target made of material to deposit
  2. Plasma ions collide on target
  3. Atoms from target are ejected
  4. Atoms deposit onto the wafer

- Deposition of compounds
- Deposition of refractory materials
- Good adhesion
- Good step coverage
- Deposition of large amount of material



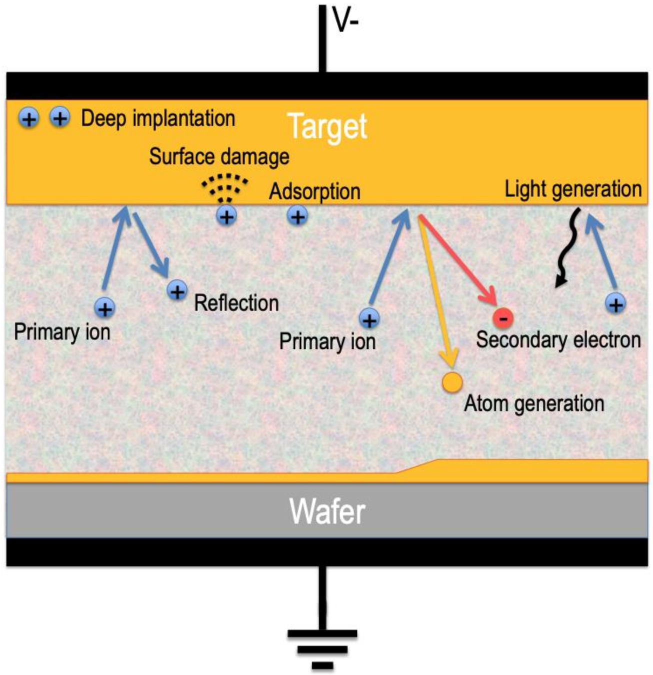
RF and Magnetron sputtering

- Target on cathode
- Substrate on anode
- RF voltage to create a plasma
- Capacitance for self-DC bias
- Magnet to confine the plasma



Sputter efficiency

- Ions-target interactions
  - Reflection, adsorption, surface damage, gas desorption
  - Secondary electrons, ions and atoms generation
  - Deep implantation
  - Photons and x-rays generation
- 95% of ions energy heats up the target
  - Target cooling is required
- Mechanical energy ejects atoms
  - Compounds and alloys deposition is possible



Ejection rate

Target ejection rate

$$W = \frac{k * V * i * S}{P * d}$$

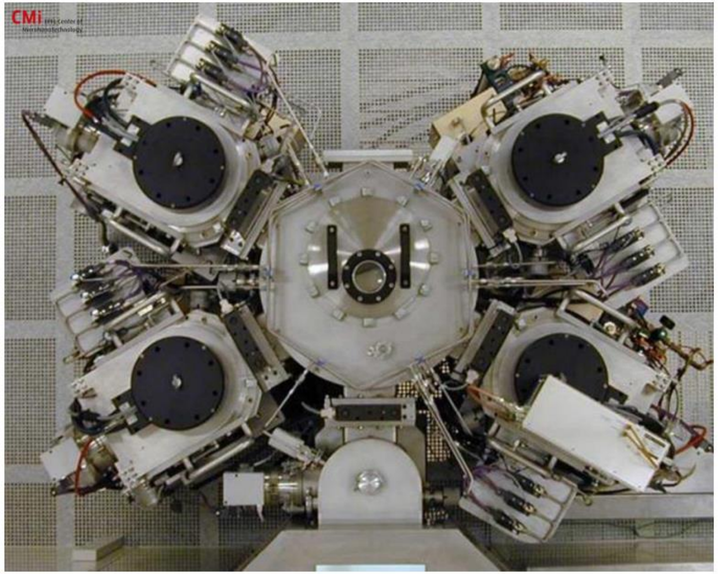
W = ejection rate in [molecule/$m^2 \cdot s$]
V = working voltage in [V]
i = discharge current in [A]
S = sputtering yield in [atom/ions]
P = gas pressure in the chamber in [Pa]
d = anode-cathode distance in [m]
k = proportionality constant in [m^{-4}]

→ Maximize V
→ Minimize P and d

Metal	Sputtering yield S*
Al	1.05
Cr	1.18
Au	2.4
Ni	1.33
Pt	1.4
Ti	0.51

* With 500 [eV] argon ions

Multi-material sputter tool

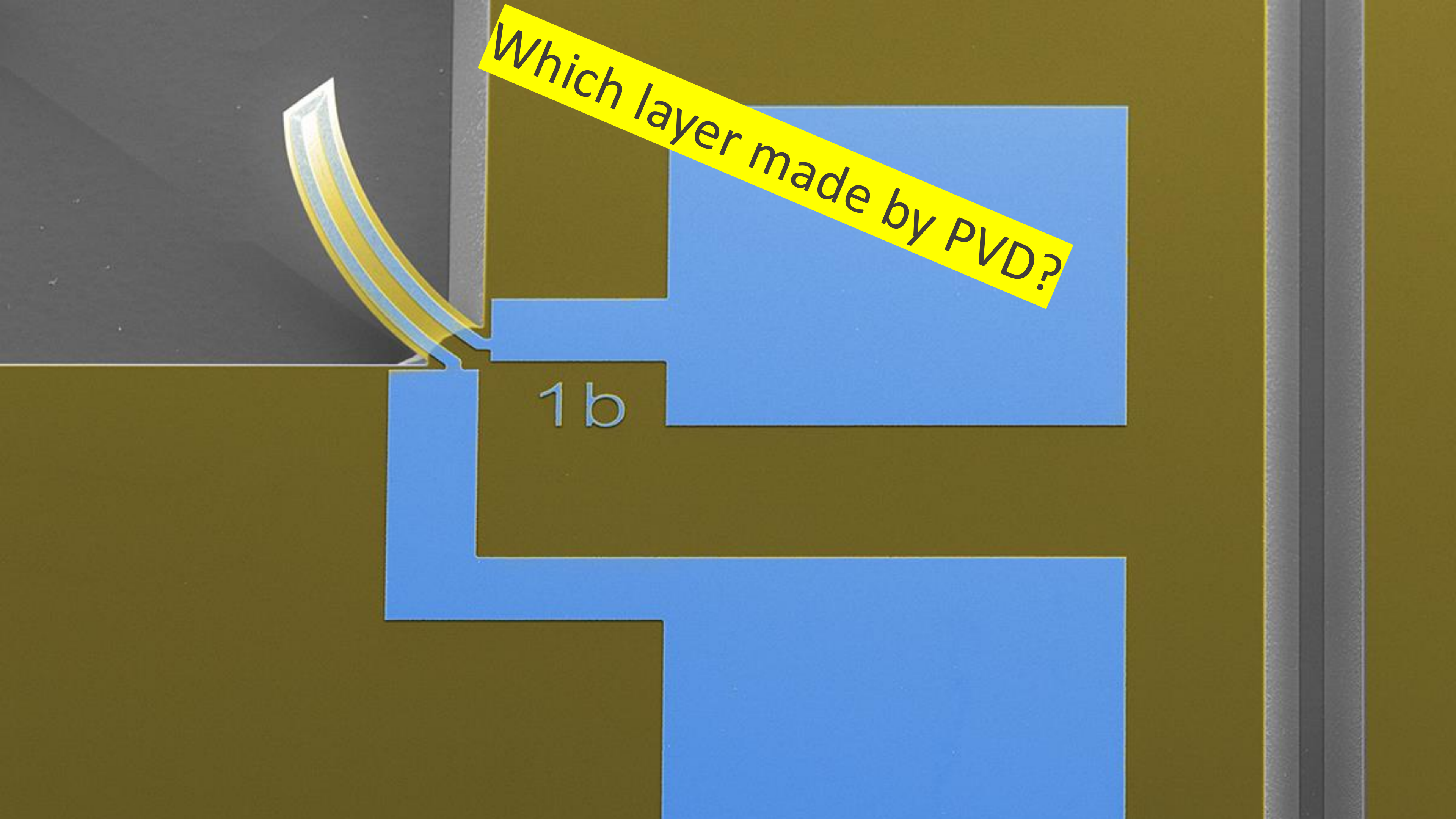


- **Pfeiffer Spider 600**
  - Sputter cluster system (25 wafers)
  - 2 x DC Magnetron: Al, AlSi, Mo, Nb, Pt, Ru, Si , Ta, Ti, W
  - 1x pulsed DC Magnetron: Al, AlSc
  - 1 x RF Magnetron: Al_2O_3,GeO_2, ITO, MgO, Ru, SiO_2, Ta_2O_5, Ti, TiO_2, V_2O_5
  - 1 x RF-etch for cleaning
  - 4 and 6 inches wafers
  - Deposition from RT to 350[ºC] (heaters)
  - Turbomolecular pump to reach high vacuum of 10^{-6} to 10^{-7} [Torr]
  - Deposition pressure is around 3 [mTorr]
  - Reactive sputtering in O_2 atmosphere

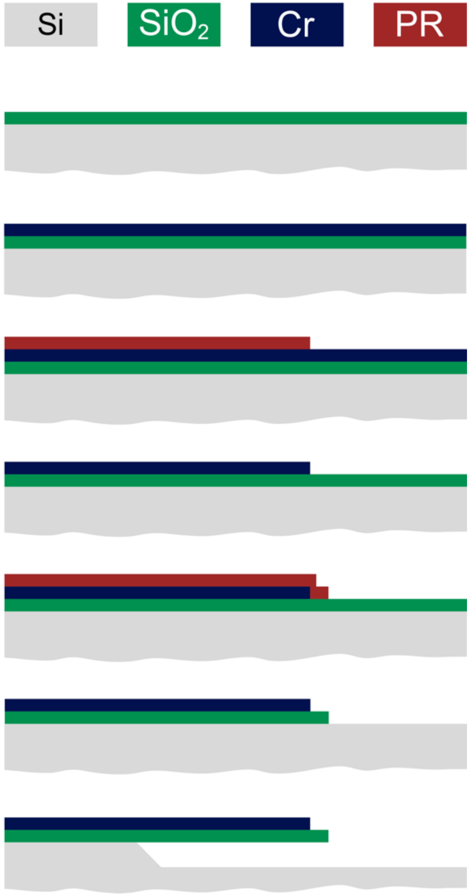
Pulsed laser deposition (PLD)

High energy UV excimer laser pulse ablates material from target forming high temperature vapor plume incident on sample

- Laser-target interactions:
  1. Short laser pulse: 10-30 [ns], 15 [pulses/s]
  2. Absorption at the target surface: ~10 [nm]
  3. Energy relaxation to the lattice through electrons-phonons interactions: 1-10 [ps]
  4. Heat diffusion, melting (tens of ns) and evaporation of a small amount of material
  5. Plasma creation
  6. Interactions of target and ablated species with plasma
  7. Cooling and resolidification between pulses


Which layer made by PVD?
1b

Overview of microfabrication sequence



1 Oxidation

2 Cr layer deposition

3 Lithography 1 (heater)

4 Cr etch

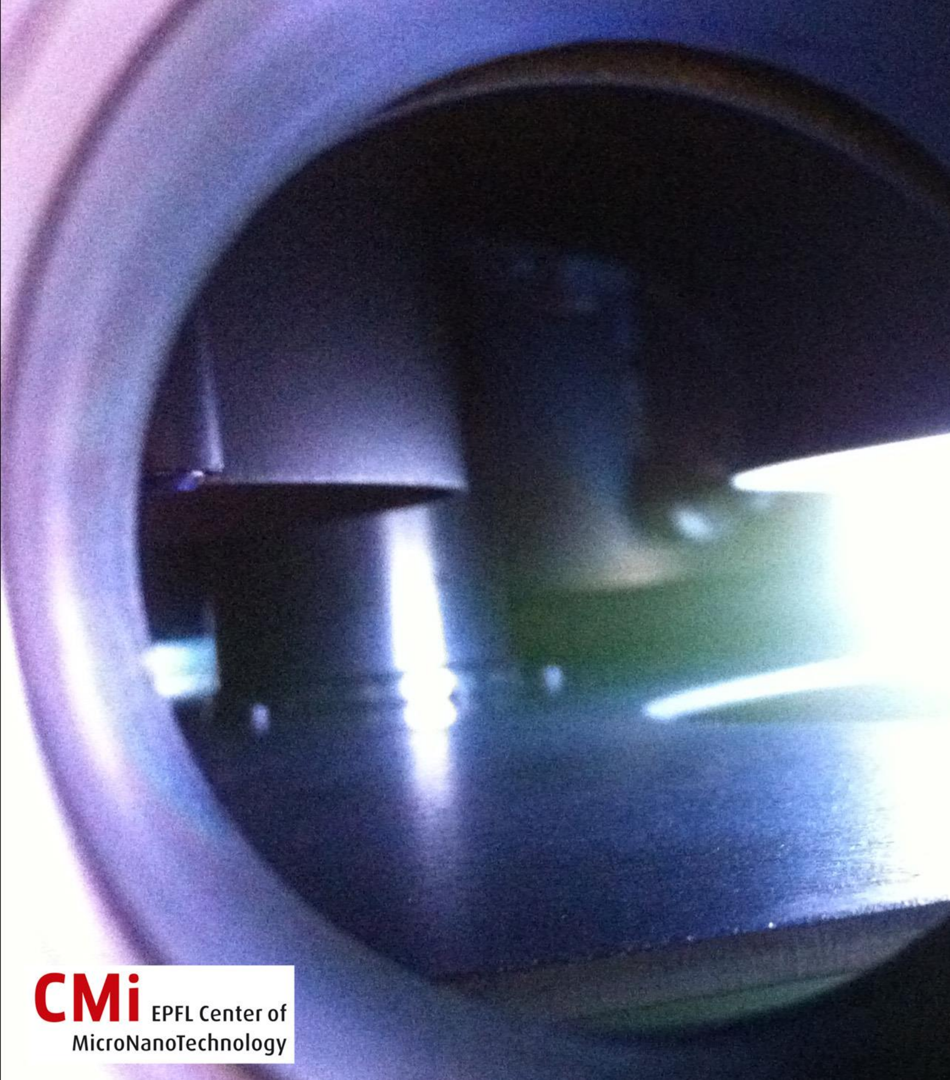
5 Lithography 2 (cantilever)

6 SiO2 etch in BHF

7 Silicon etch in KOH

- 7 steps for thermo-mechanical cantilever
- Color code for each material
- Process flow in cross section

Which step is PVD?



1. Low pressure chamber filled with argon
2. High voltage between electrodes
3. Breakdown of the gas
4. Current increases & voltage drops
5. Ar ions collide on the cathode
8. Secondary electrons are ejected
7. Secondary electrons sustain plasma
8. Plasma reaches steady state

CMi EPFL Center of MicroNanoTechnology

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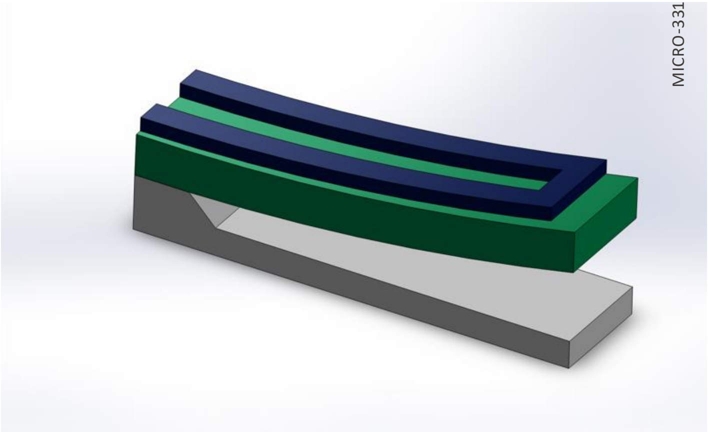
Simple example: the bi-morph micro-actuator

- Bi = 2; morph = shape
- Thermo-mechanical actuation
- Sandwich of two thin films
- Different thermal expansion coefficient α
- ΔT induces bending



$$\boxed{\frac{1}{r} = \beta \cdot \Delta\alpha \cdot \Delta T}$$

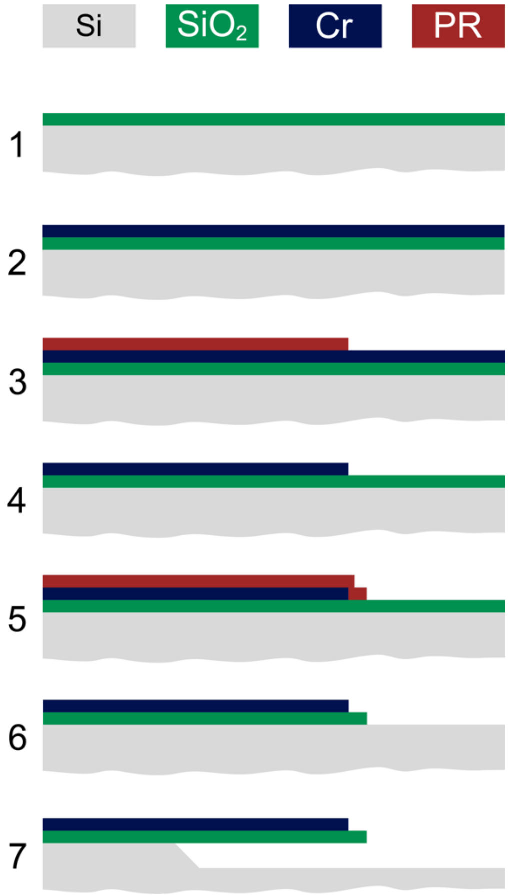
r: radius of curvature
β: constant, f(t, E)
α: thermal expansion coefficient [K^{-1}]
ΔT: temperature difference [K]

$$k = \frac{3EI}{L^3} \qquad \omega_{res} = \sqrt{\frac{k}{m_{eff}}}$$

I: area moment of inertia [m^4]
L: length of the beam [m]
t: thickness [m]
W: width [m]
m_{eff}: beam effective mass [kg]

k: spring constant [N/m]
E: Young's modulus [N/m^2]
σ: strain [Pa]
ω_{res}: resonant angular frequency [s-1]

Overview of microfabrication sequence



Oxidation

Cr layer deposition

Lithography 1 (heater)

Cr etch

Lithography 2 (cantilever)

SiO2 etch in BHF

Silicon etch in KOH

- 7 steps for thermo-mechanical cantilever
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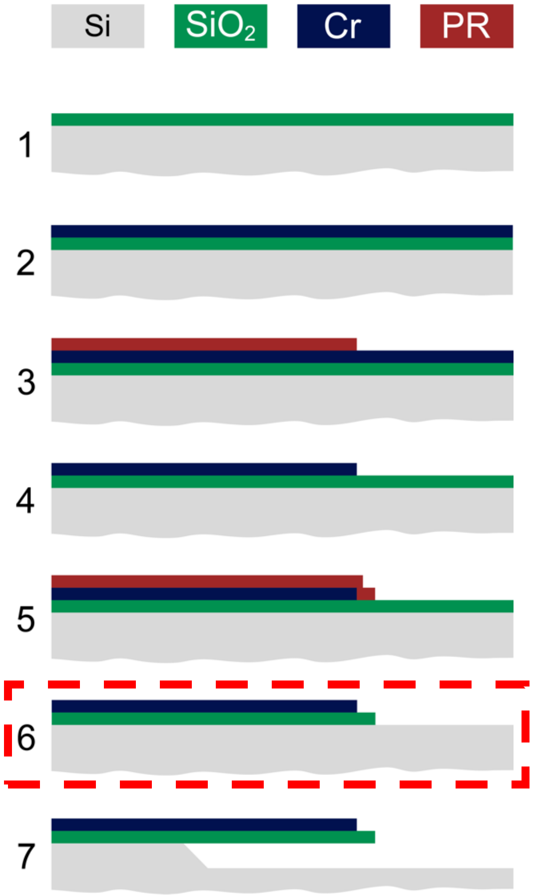
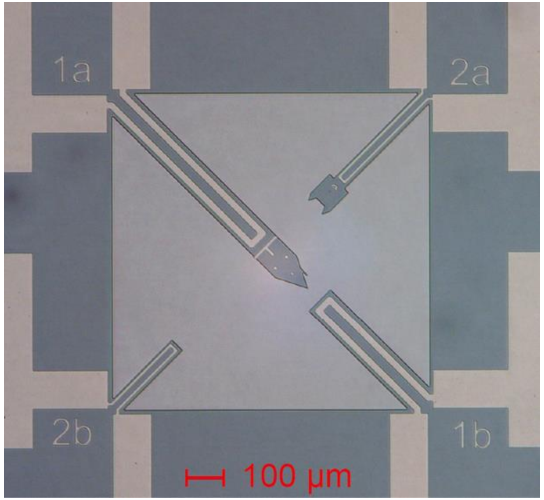
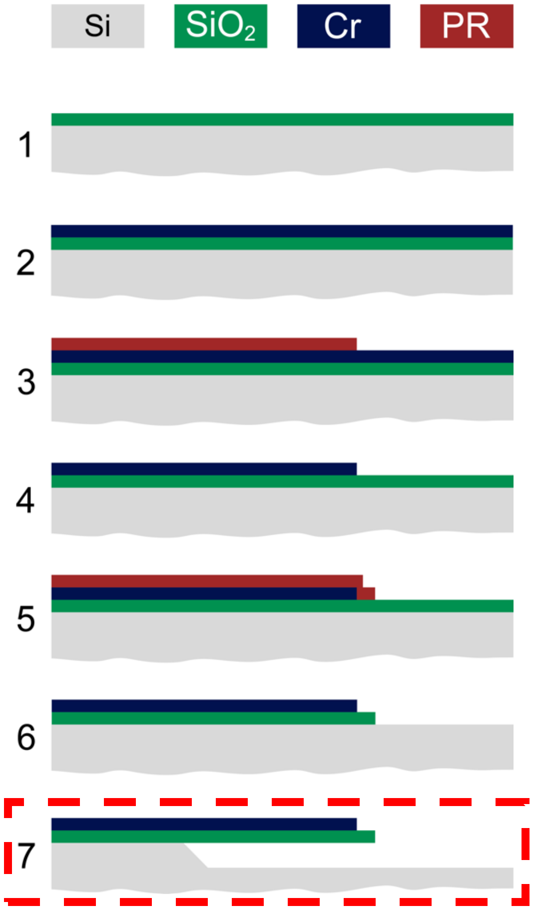
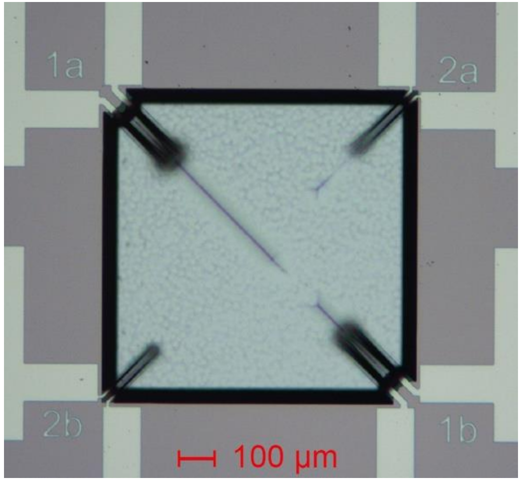
Step 6: SiO_2 etch



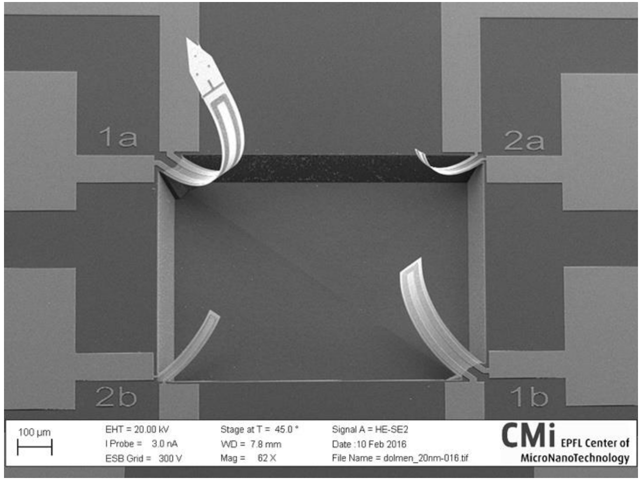


Step 7: Silicon etch





Optical microscope image



SEM image

Thermo-mechanical characterization