EPFL

MICRO-331

Microfabrication technologies

Lecture 4

Yujia Zhang

2025 edition

Today's program

- 1st hour:
  - Mid-term feedback (8')
  - Responses to previous questions (2')
  - Recapitulation: PVD (20')
  - Mid-term summary (5')
  - A brief introduction of lithography (10')

- 2nd hour:
  - Guest lecture by Prof. Minshen Zhu, from TU Chemnitz, Germany (40')
  - Q&A (5')

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Congrats on getting through the first half of the fall semester

- Please form into small groups with your neighbouring students
- Introduce yourself
- And discuss (5’):

1. In your opinion, what is the most **interesting** part of this course?
2. Which part of this course do you **not like** and want to improve?
3. Until now, please rank the following topics based on your confidence level: MEMS & Cleanroom, CVD, and PVD.

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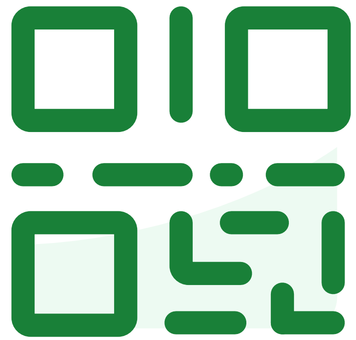

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In your opinion, what is the most interesting part of this course?

ENT / NAME PRESENTATION

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Which part of this course do you not like and want to improve?

ENT / NAME PRESENTATION

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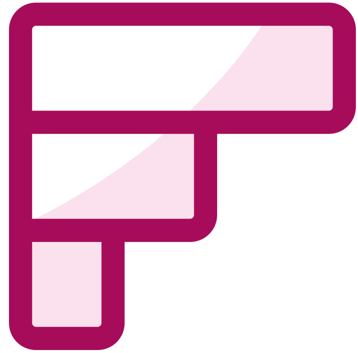

Until now, please rank the following topics based on your confidence level: MEMS & Cleanroom, CVD, and PVD.

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Open Q&A

- Low use rate of the A.I. Tutor Bot (ED Discussion)
- Please register your availability before the SLTs
- Other questions?

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Audience Q&A

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Recapitulation: PVD

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Basic principles of PVD

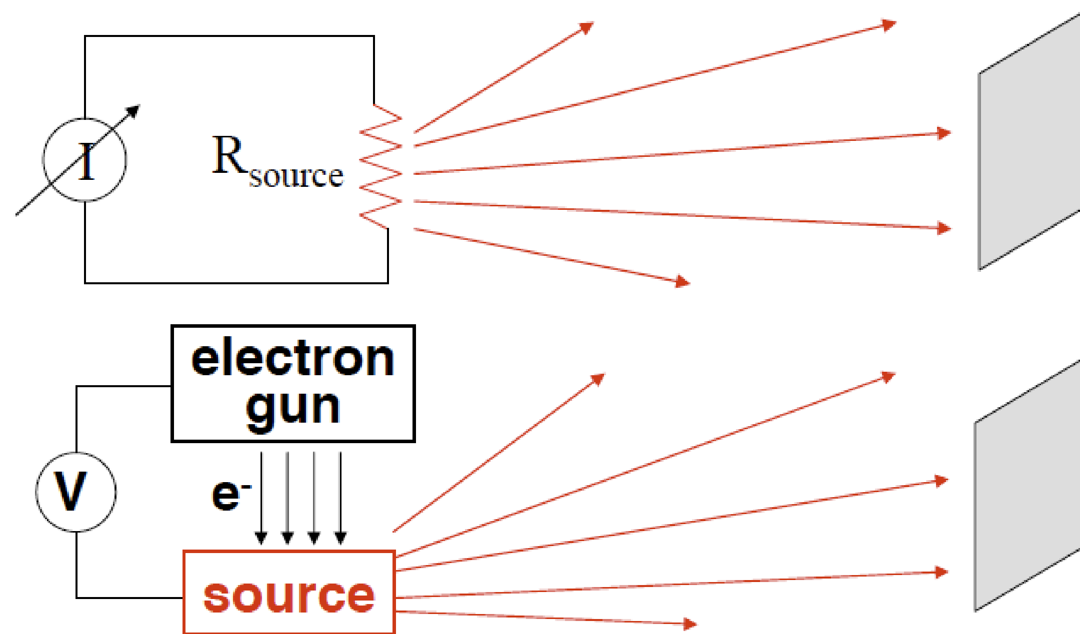
- Remove material from a solid source
- Transport material to substrate
- Deposit material on substrate
- Differences among PVD techniques
  - How material is removed from the source
  - Directionality when it arrives at the substrate
  - Cleanliness of deposition
  - **Evaporation (Thermal, E-beam)**
  - **Sputtering (DC, RF, magnetron)**
  - …

See MOOC:
Thermal evaporation, Sputtering, and Other PVD methods

Thermal and e-beam evaporation

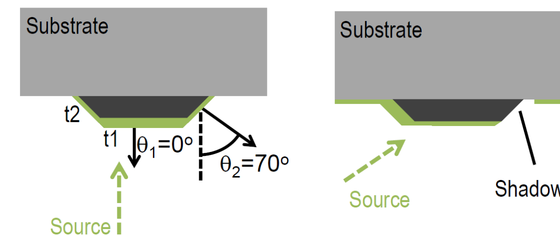
SLT 3.1

- Source is resistively heated
- or Electron beam heats the source in a **high vacuum**
  - Typical source: metal
- Hot source atoms are emitted in all directions and stick where they land
- Substrate receives a **directional flux** of source material (uniformity issue)
- Good for lift-off processes, otherwise **poor conformality**
  - Possible contamination from generalised heating
  - Heating is less generalised ➔ Less contamination

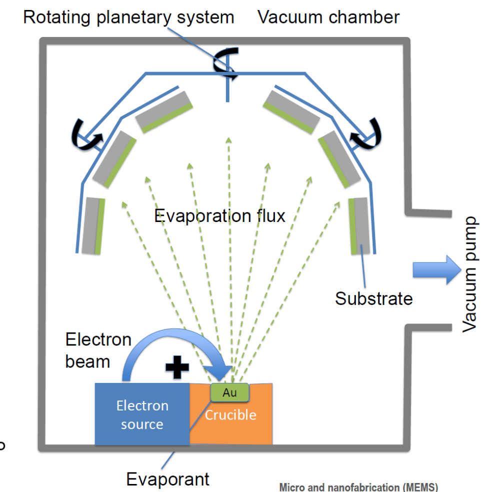


PVD: vapor condensation on the substrate

- Uniformity issues by topographical surfaces and by shadowing



$$\frac{t_1}{t_2} = \frac{\cos(\theta_1)}{\cos(\theta_2)} \approx 3, when\ \phi = 0°, \theta_1 = 0°, \theta_2 = 70°$$



Micro and nanofabrication (MEMS)

Sputtering

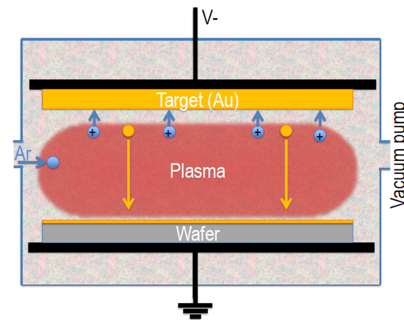
- Unreactive ions (i.e., **Ar**) knock material off a target by momentum transfer
  - Targets: metals, dielectrics, piezoelectrics, etc.
- Low pressure, but not high vacuum
- Less directional and faster than evaporation
- Different methods of obtaining energetic ions
  - DC: Only for electrically-conductive materials
  - RF: Dielectric deposition
  - Magnetron with RF and DC sputtering

SLT 3.2

SLT 3.3

DC sputtering

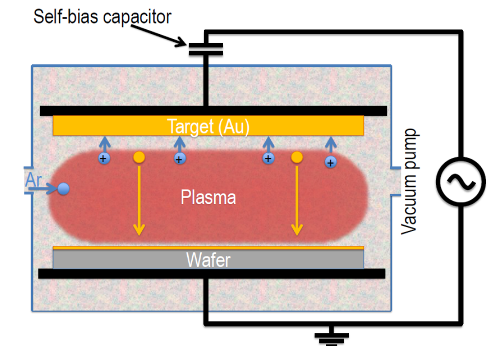
- Target on cathode
- Substrate on anode
- High DC voltage to create a plasma



- Advantages
  - Simple setup
- Limitations
  - Substrate cooling is required
  - Only for electrically-conductive materials

RF sputtering

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



- Advantages
  - Dielectric deposition
  - Higher deposition rate than DC sputtering
  - Lower power consumption than DC sputtering
- Limitations
  - Target cooling is required
  - Substrate cooling is required

Evaporation versus sputtering

Evaporation

- Simple & Fast
- Pure materials (elements)
- Does not allow depositing: composite and refractory materials
- High vacuum: long mean free path, micro-shadowing, grainy films
- Weak adhesion but good for lift-off

Sputtering

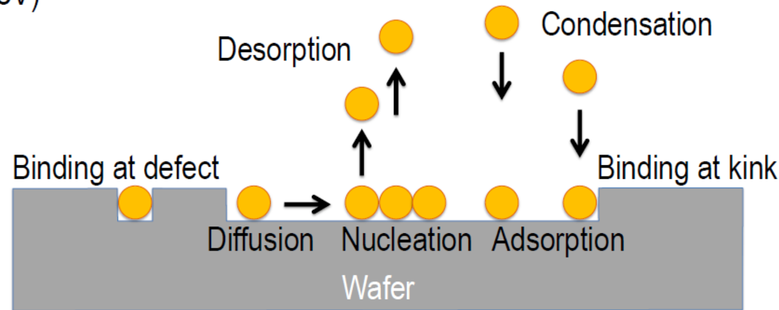
- Deposition of compounds and refractory materials
- Good adhesion and step coverage
- Deposition of a large amount of material

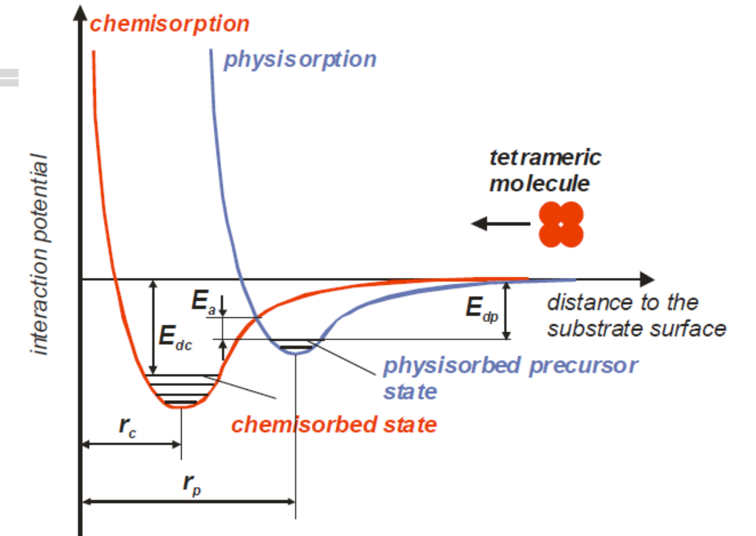
Type of Material: Examples
Metals: Al, Cu, Zn, Au, Ni, Cr, W, Mo, Ti
Alloys: Ag-Cu, Pb-Sn, Al-Zn, Ni-Cr
Nonmetals: graphite, MoS_2, Ws_2, PTFE
Refractory oxides: Al_2O_3, Cr_2O_3, SiO_2, …
Refractory carbides: TiC, ZrC, HfC, NbC
Refractory nitrides: TiN, Ti_2N, ZrN, HfN, …
Refractory borides: TiB_2, ZrB_2, HfB_2, CrB_2, …
Refractory silicides: $MoSi_2$, WSi_2, Cr_3Si_2

Physisorption and chemisorption

Atoms arrival

- Atoms adsorption on the surface
  - Chemisorption = chemical bond (≈ 1 eV)
  - Physisorption = van der Waals forces (≈ 0.3-0.5 eV)
- Once on the surface, atoms can:
  - Stay: when chemisorbed
  - Diffuse: when physisorbed
  - Desorb: when physisorbed and high energy





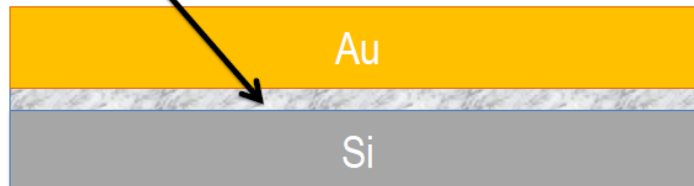
See MOOC:
PVD 8: Film growth

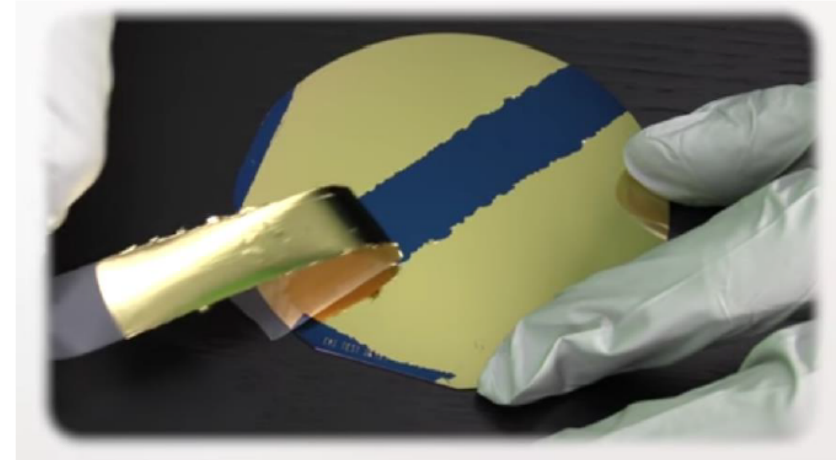
When physisorption is poor

Adhesion

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

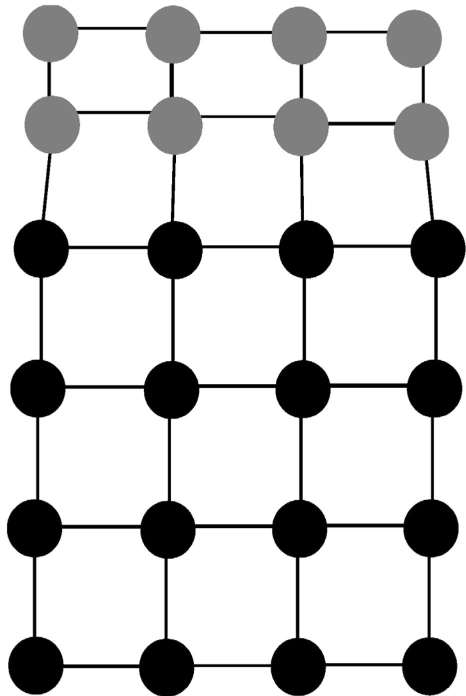
- Substrate cleanliness is primordial
- Process parameters affect adhesion
  - Sputtering is better than evaporation
- Noble metals adhesion is poor
  - Adhesion layer of a few nanometers
- "Tape pull test" adhesion test

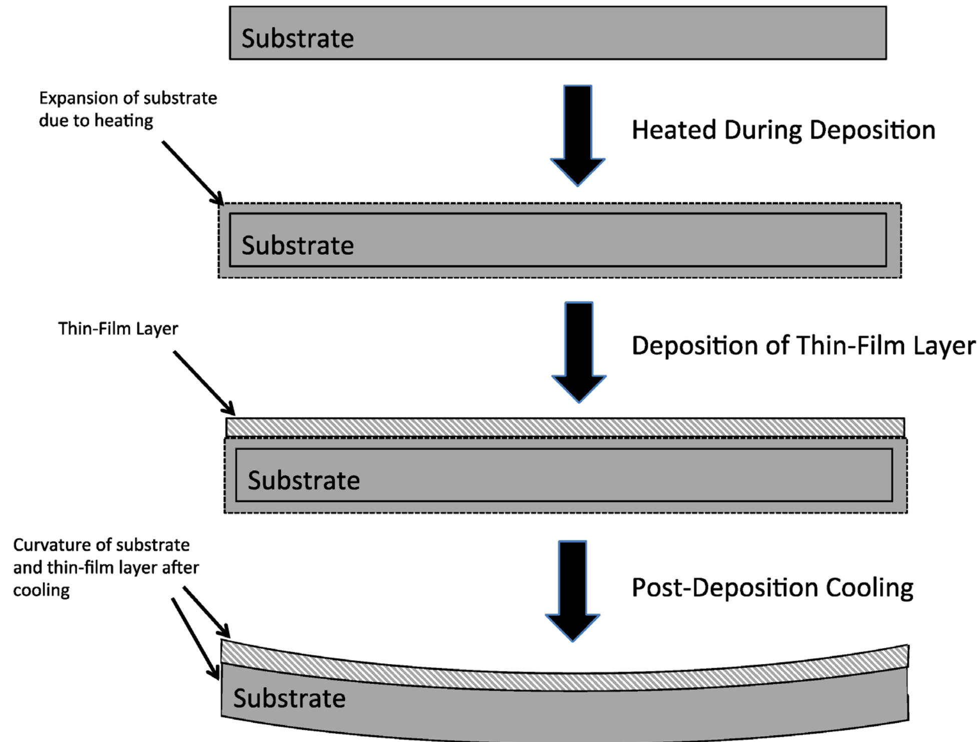




Residual stress

- **Thermal expansion coefficients (TCE)**



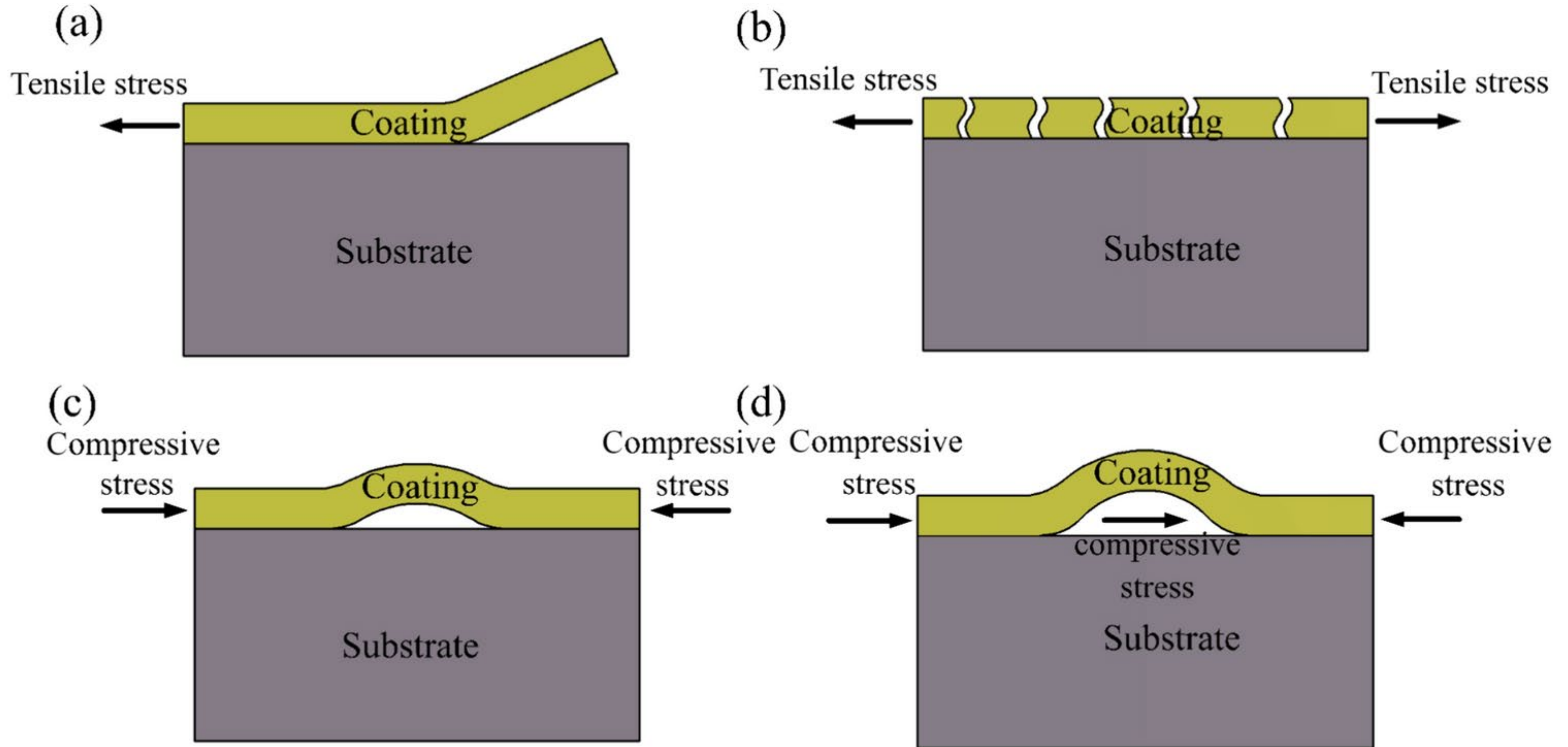


In this case, the thin film material layer would be in a state of tensile stress.

Micromachines **2022**, *13*, 2084.

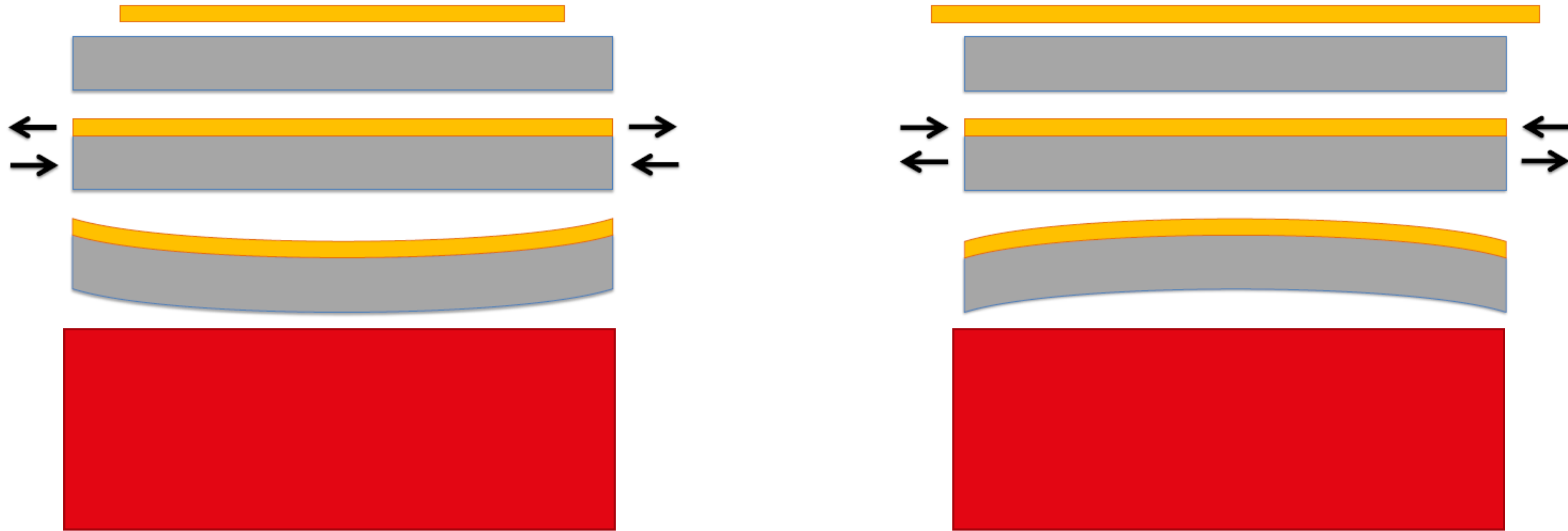
Failure modes of coating under residual stress

(a) delamination, (b) cracking, (c) buckling, (d) delamination and buckling

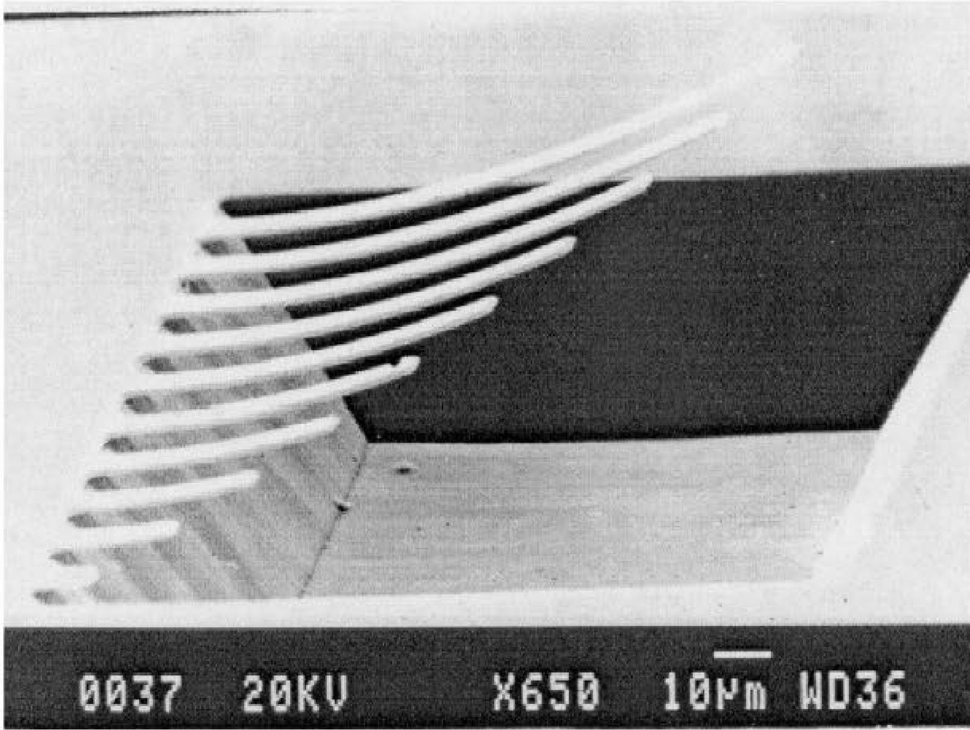


J Coat Technol Res **22**, 581–603 (2025).

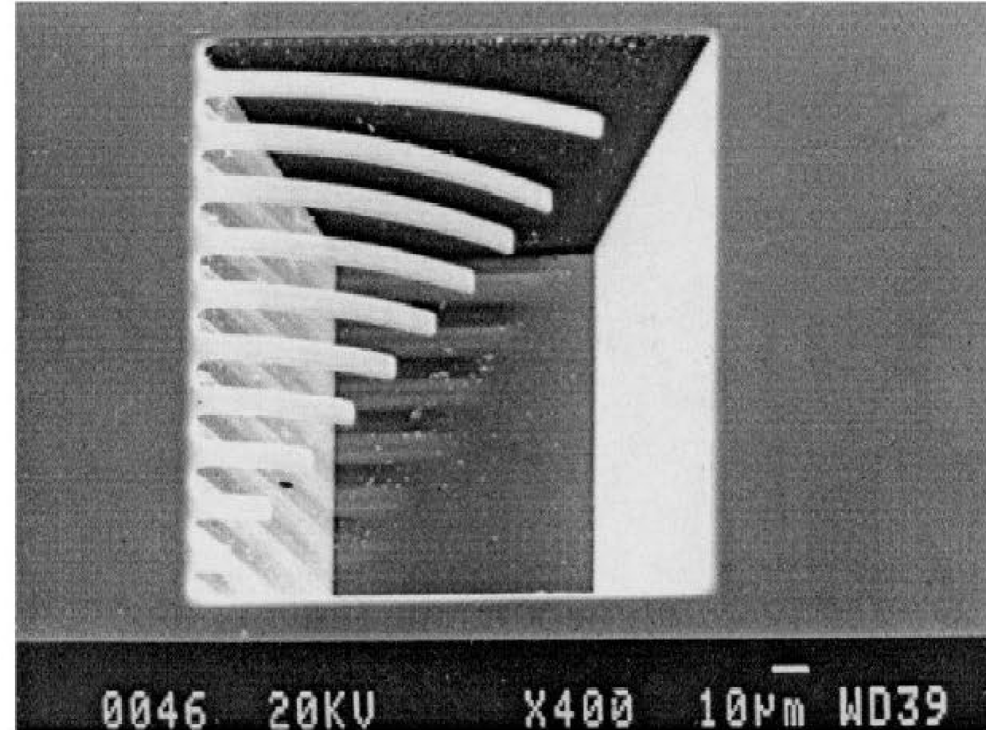
Tensile and Compressive stresses



When residual stresses are useful



- Ti/SiO_2 cantilever
  - Bends upward



- Al/SiO_2 cantilever
  - Bends downward

Weileun Fang et al., "On the thermal expansion coefficients of thin films", Sensors and Actuators A: Physical, Volume 84, Issue 3, 1 September 2000, Pages 310–314, with permission from Elsevier
http://www.sciencedirect.com/science/article/pii/S0924424700003113

Mid-term summary

YZ

What have we learnt so far?

- Why, how, and what?
- MEMS and Cleanroom
- CVD techniques and PVD techniques
  - Differences between techniques
  - Differences between CVD and PVD

SLT 3.4

- What are the connections, and what will we learn next?
- 3 most important processes of manufacturing:
  - Addition (CVD & PVD)
  - Patterning (Lithography)
  - Subtraction (Dry & Wet etching)

What we have not covered?

- Other approaches to add materials (thin films):
  - Spin-coating: target material mixed in a solution, spin it onto the surface, and bake out the solvent (spin rate affects the film thickness)
  - Other forms of vapour deposition designed for a particular purpose (depositing the inert polymer parylene by vapour deposition, followed by polymerisation)
  - Lamination of free-standing resist films onto surfaces
  - Self-assembled monolayers
- …

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Course plan

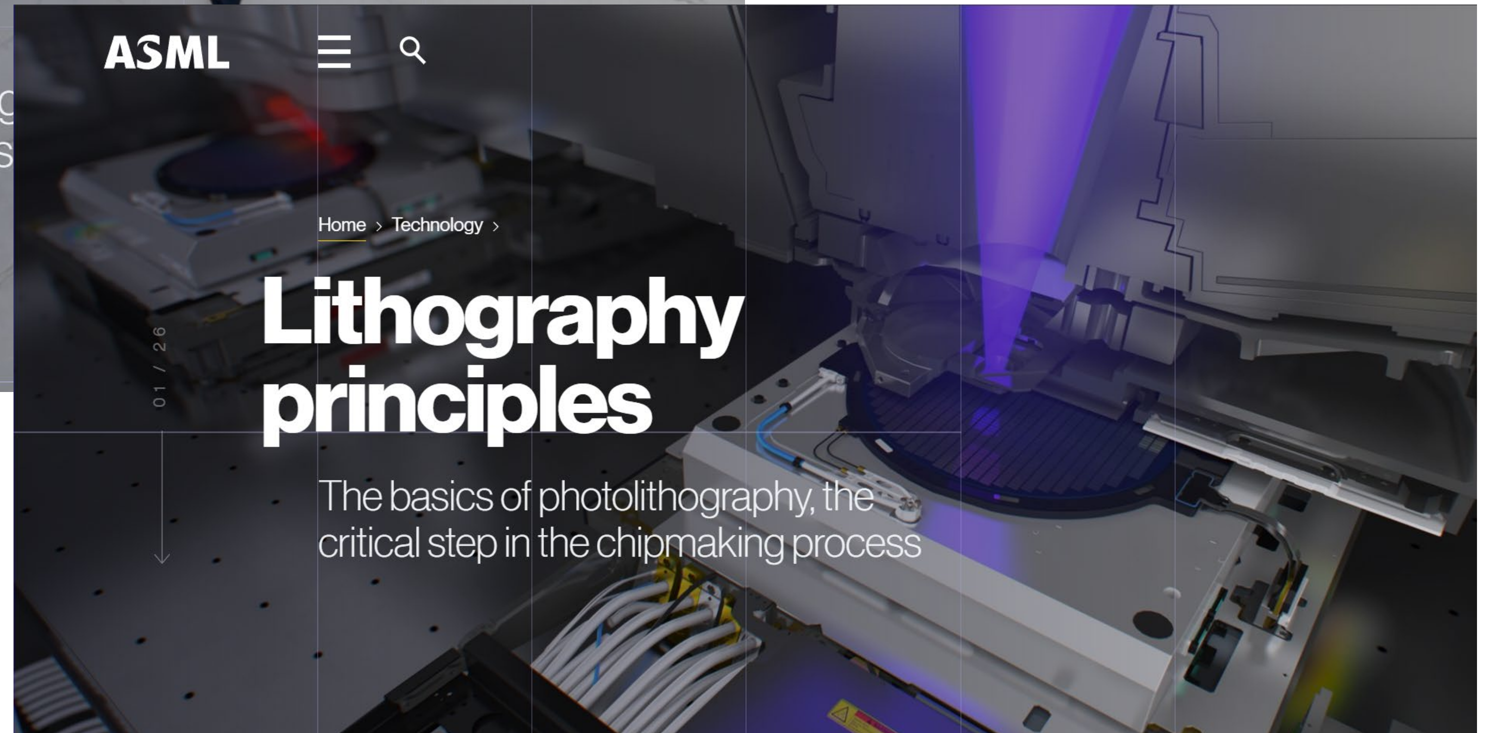
- Tomorrow (Thu / 6 Nov):
  - MOOC self-study, lecture room is available, MOOC: **Lithography**
- Wed / 12 Nov
  - SLT_#4 in groups, Topic: **Litho**
  - **The questions are already on Moodle**
- Thu / 13 Nov
  - MOOC self-study, lecture room is available, MOOC: **Lithography & Dry Etching**
- Wed / 19 Nov
- **Lecture**, Topic: Litho recap and Dry Etching, by Prof **Jürgen Brugger**

- I’ll be back on December 17/18 and I am available by email the entire time

A brief introduction of lithography

Lithography principles

ASML
Changing the world, one nanometer at a time
01 / 32
ASML gives the world's leading chipmakers the power to mass patterns on silicon
QUICK LINKS

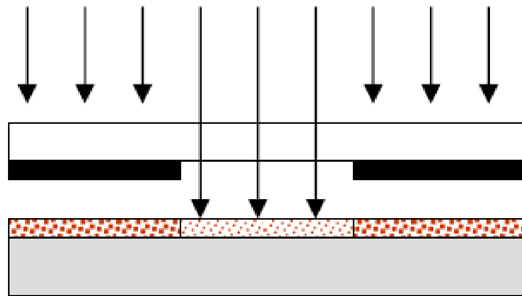


https://www.asml.com/en; https://www.asml.com/en/technology/lithography-principles;

Optical Lithography

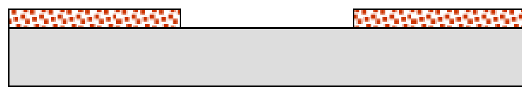
- How do we create a microscale pattern?

Spin-cast a photosensitive resist layer; bake out solvent

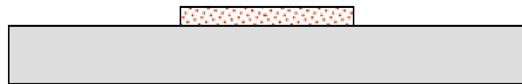


Collimated UV exposure through a mask; resist either cross-links or becomes soluble

positive



negative



Develop by dissolving the exposed/unexposed (positive/negative) resist; can now transfer pattern to substrate

Reference: Design and Fabrication of MEMS Devices, Spring 2007. MIT

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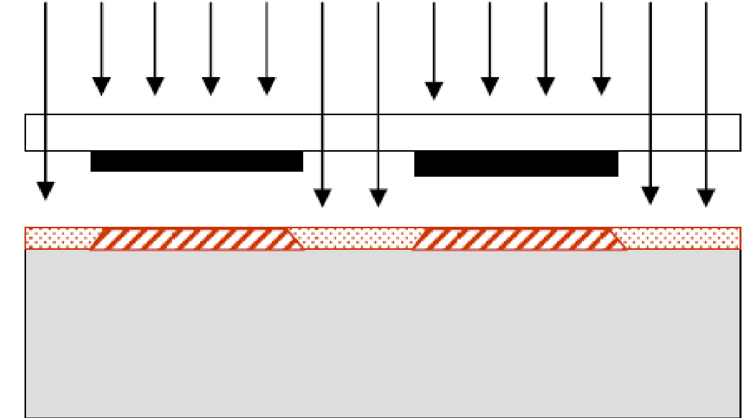
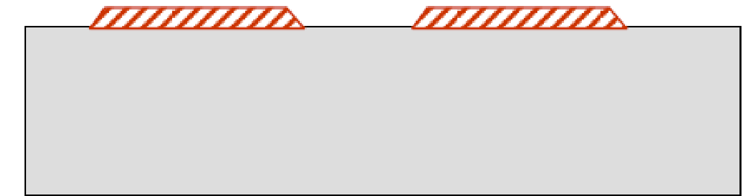
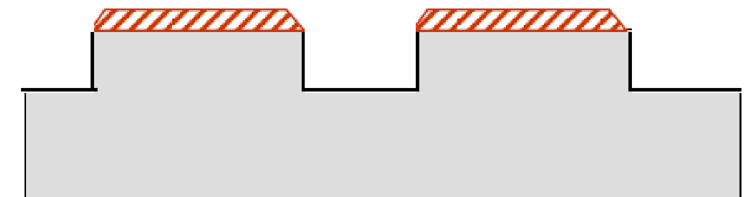
Positive photoresists

- Spin cast
- Thickness of order 1 µm
- Developer removes exposed resist
- Creates a sloped profile at the resist edge
- Some applications
  - Wet etching
  - Shallow dry etching

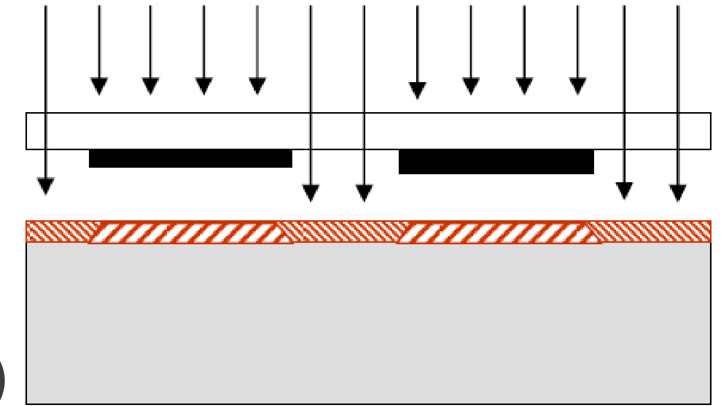


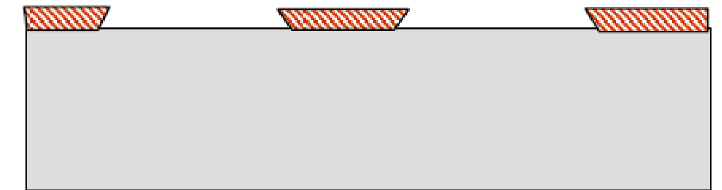


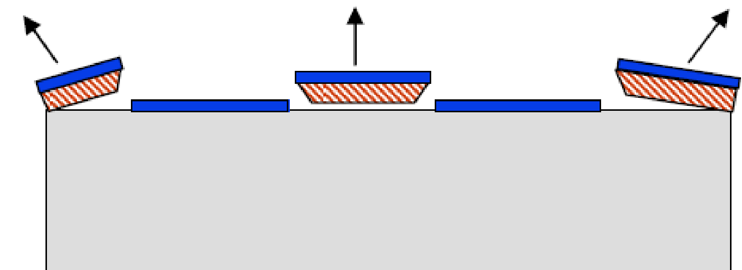


Negative photoresists

- Spin cast
- Thickness of order 1 µm
- Developer removes unexposed resist
- Creates a re-entrant profile
- Typical application: lift-off processes (e.g., acetone)
  - Rule of thumb: the resist thickness should be 3x the thickness of the layer to be lifted off







Take home messages

- The rationale behind different PVD microtechniques
- Comparison of various approaches
- CVD and PVD
- Residual stress
- 3 most important processes of manufacturing

Guest lecturer
Prof Minshen Zhu
TU Chemnitz

There will also be another seminar today at 12:15-13:00 @ BM 5202

IEM Distinguished Lecturers Seminar:
Micro-Origami Meets Batteries: Pushing Energy Storage Boundary below 1 mm^2