Lab demo process flow

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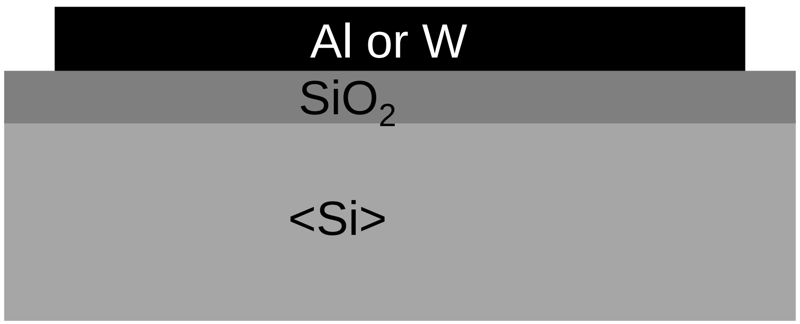
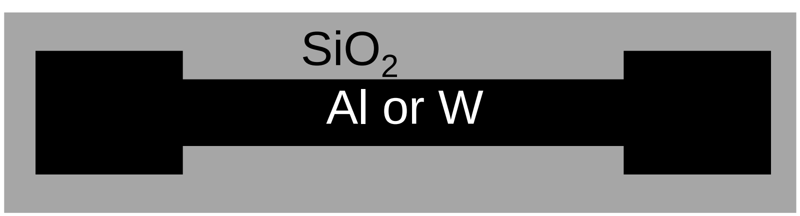
Lab device: metal resistor

Cross sectional view



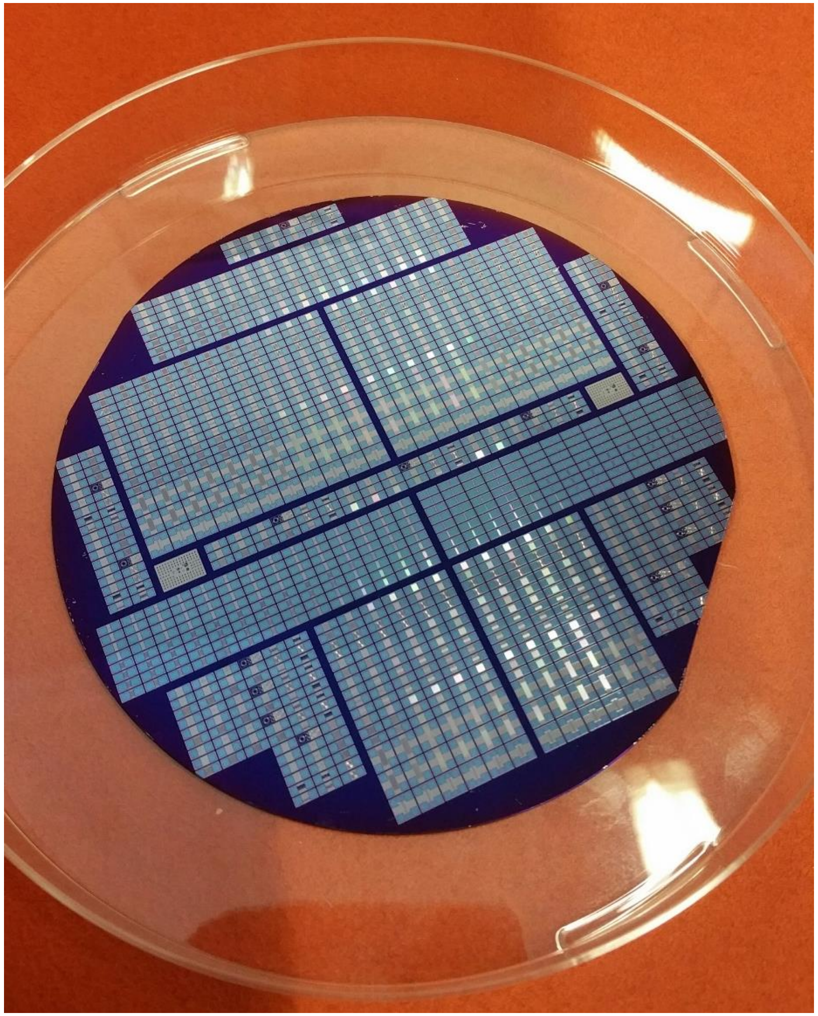
Layout/top view



Process flow:

Silicon wafer
Cleaning
Thermal oxidation
Al or W sputtering
Sheet resistance measurement
Lithography for resistor
Aluminum wet etching or
Tungsten plasma etching
Resist strip
Metal thickness measurement
Oxide thickness measurement
Resistance and TCR measurements

Resistor test wafer



A large number of test structures for 2-point resistance measurements:

-different widths
-different lengths
-straight and meandering lines

Silicon wafer selection

Wafer size: 100 mm

All Aalto Micronova equipment is geared towards 100 mm wafer size.

Some can handle 150 mm but not all.

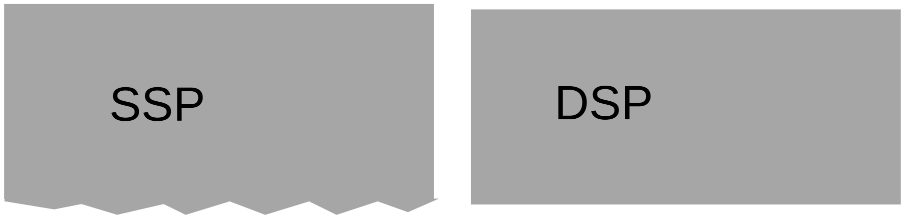
Silicon wafer selection: SSP

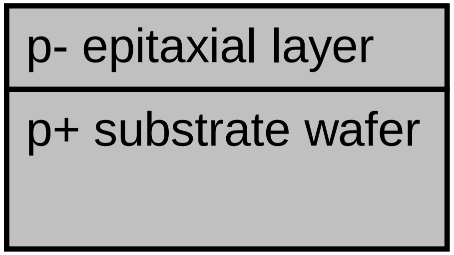
SSP=
Single side
polished

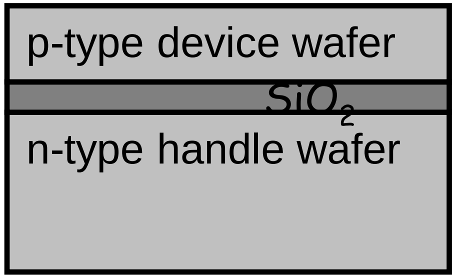
DSP =
double side
polished

Epi-wafer

SOI-wafer







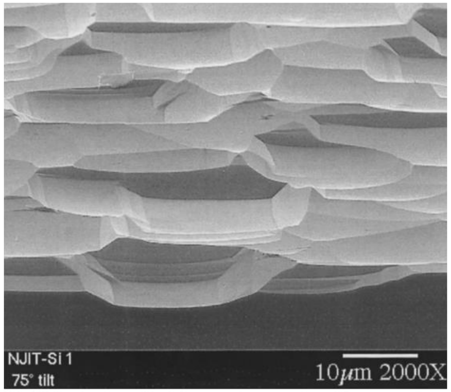
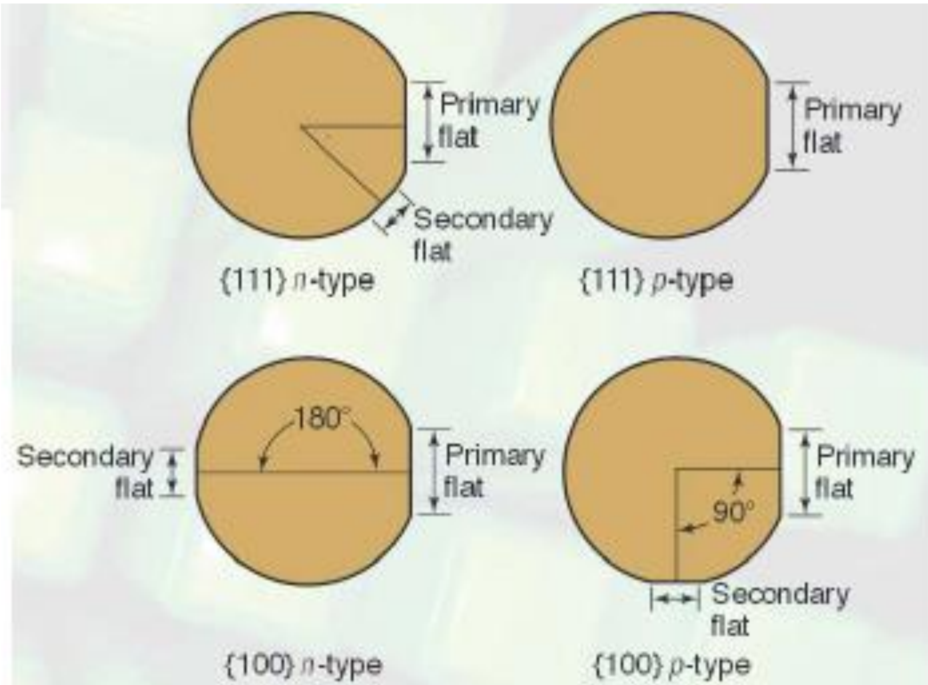


Fig. 2. SEM (2000X) picture of the rough side of *n*-Si.

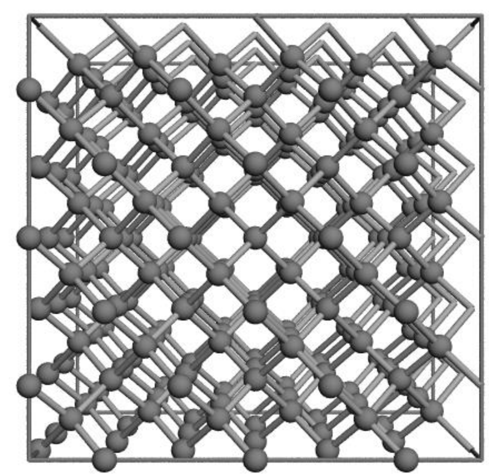
Our wafers:
cheap basic wafers

Wafer orientation



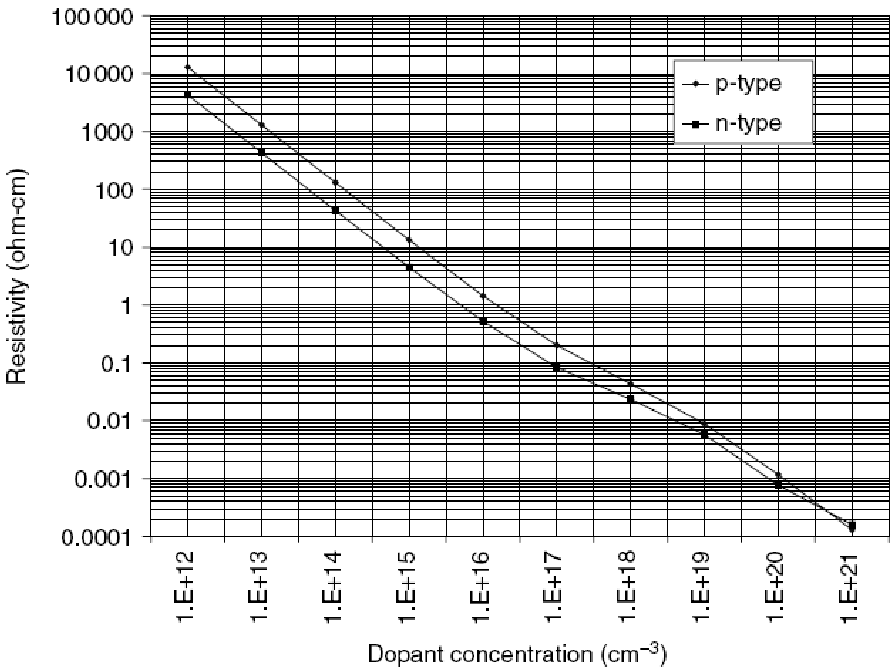
We always use <100> oriented wafers unless otherwise needed, because:

-most common
-break nicely for SEM



Check the flat and mark it in your lab notes.

Silicon wafer: doping



In this work, thermal oxide will completely isolate the resistor from the wafer ➔ no special need for certain silicon doping level.

Wafer cleaning in 3 steps

Name/alias	Chemical composition	Temp./time
RCA-1 SC-1, standard clean; APM; ammonia-peroxide mixture	$NH_4OH:H_2O_2:H_2O$ (1:1:5)	70-85^{o}C, 10-20 min
RCA-2 SC-2; standard clean-2; HPM, hydrogen chloride-peroxide mixture	$HCl:H_2O_2:H_2O$ (1:1:6)	70-85^{o}C, 10-20 min
DHF (dilute HF)	$HF:H_2O$ (1:100-1000)	room temp., 30 s

(and rinse and dry)

Cleaning functions

RCA-1:
Removes particles
Removes organics

RCA-2:
Removes metals

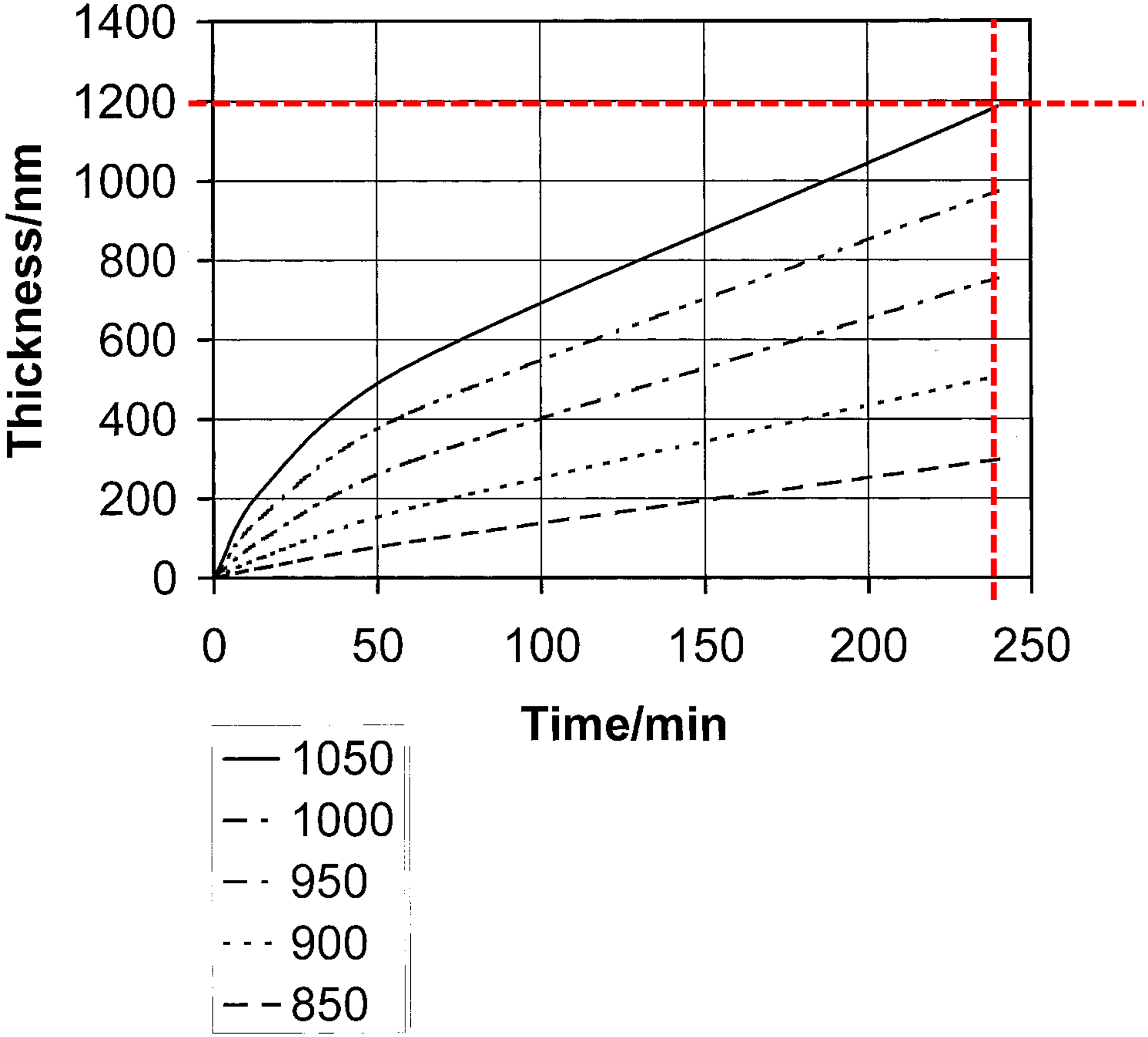
DHF: removes native oxide

Other reasons for cleaning:

-eliminates wait time differences
-eliminates previous step effects

Oxidation furnaces

Thermal oxide 1.2 µm thick



Obtained by 4 hour, 1200^{o}C wet oxidation.

The growth curves are simulations with a simple simulator.

Why thermal oxide ?

Because we can use thermal oxidation !!!!
No material on wafer prevents us from it !

Thermal oxide is better quality than CVD oxide.

What does oxide quality entail ?

Uniform (±1%)
Dense
Low interface charge density
Low defect density
➔High breakdown voltage

Why no cleaning before sputtering ?

Wafers coming from 1000^{o}C oxidation furnace are maximally clean.

No cleaning process can improve them.

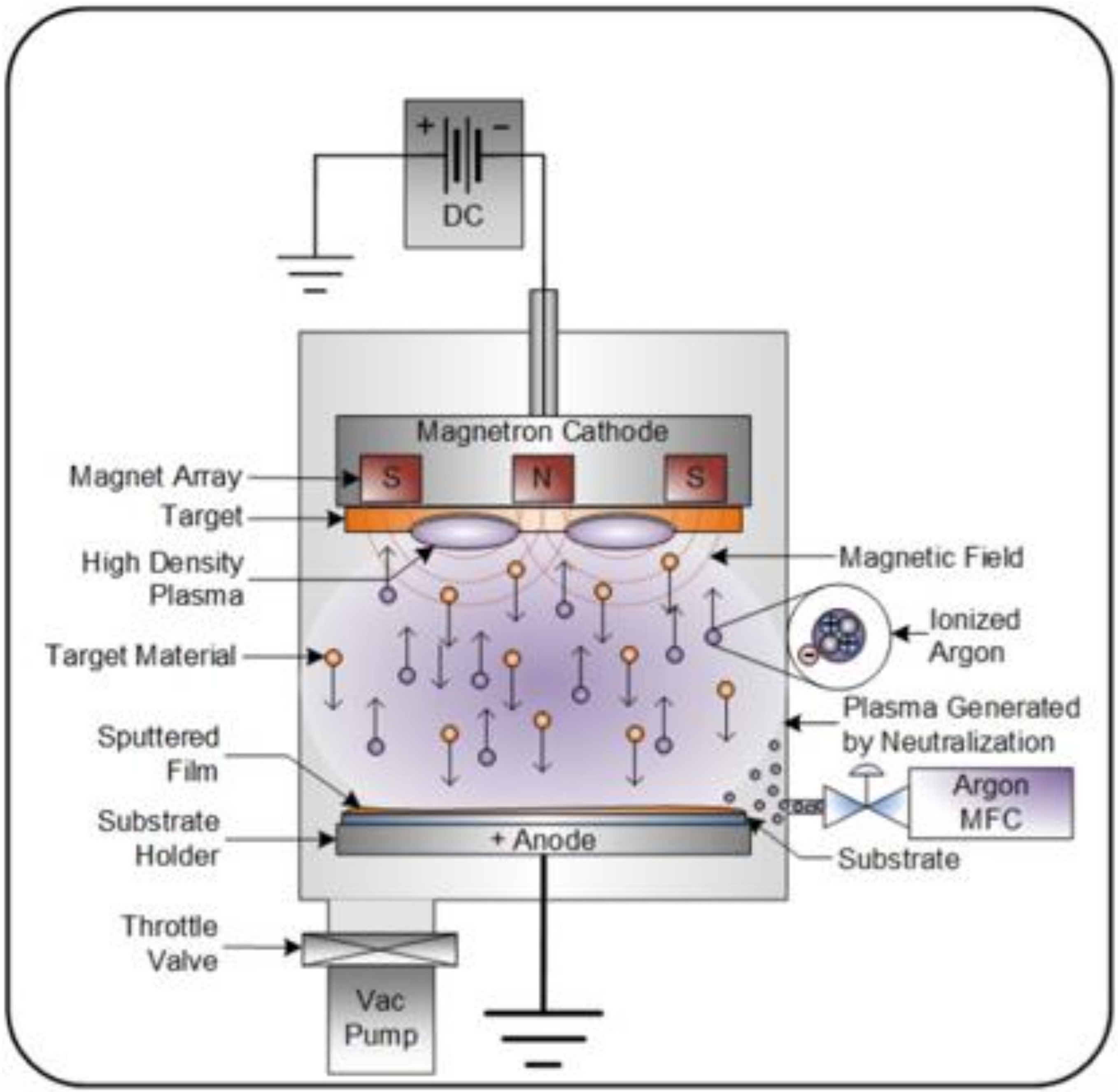
If there is a long wait between oxidation and sputtering, then it is wise to clean the wafers (with RCA-1).

Sputtering is a room temperature process, impurities not very mobile.

Sputter

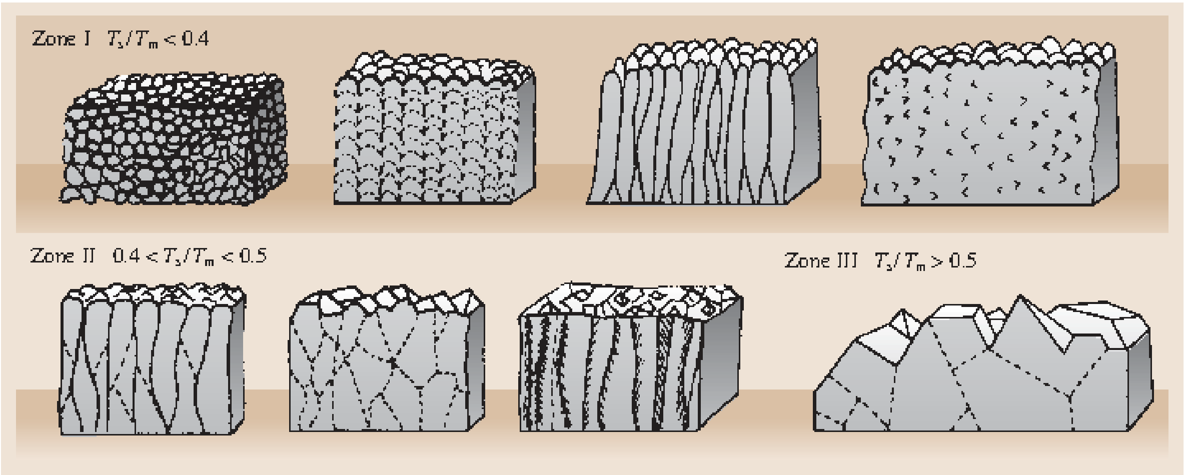
Ar+ ions hit metal atoms from target.

Ejected atoms fly in vacuum and condense on the wafer, forming a film (atom vapor to solid phase transition)



Sputtering tool parameters

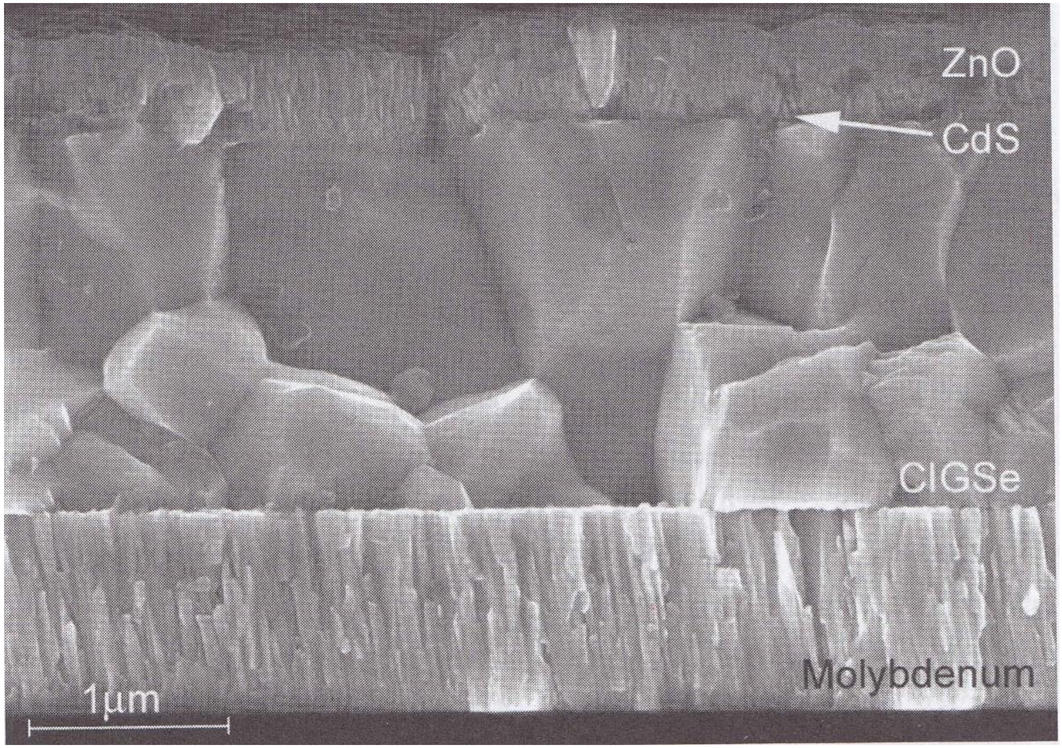
RF-power (deposition rate effect)
Base pressure (film purity issue)
Sputtering pressure (stress effect)
Wafer temperature (microstructure & purity effect)



Microstructure of the films depends strongly on temperature, but most often sputtering is RT process !

Gould R.D., Kasap S., Ray A.K. (2017) Thin Films. In: Kasap S., Capper P. (eds) Springer Handbook of Electronic and Photonic Materials. Springer Handbooks. Springer, Cham. https://doi.org/10.1007/978-3-319-48933-9_28

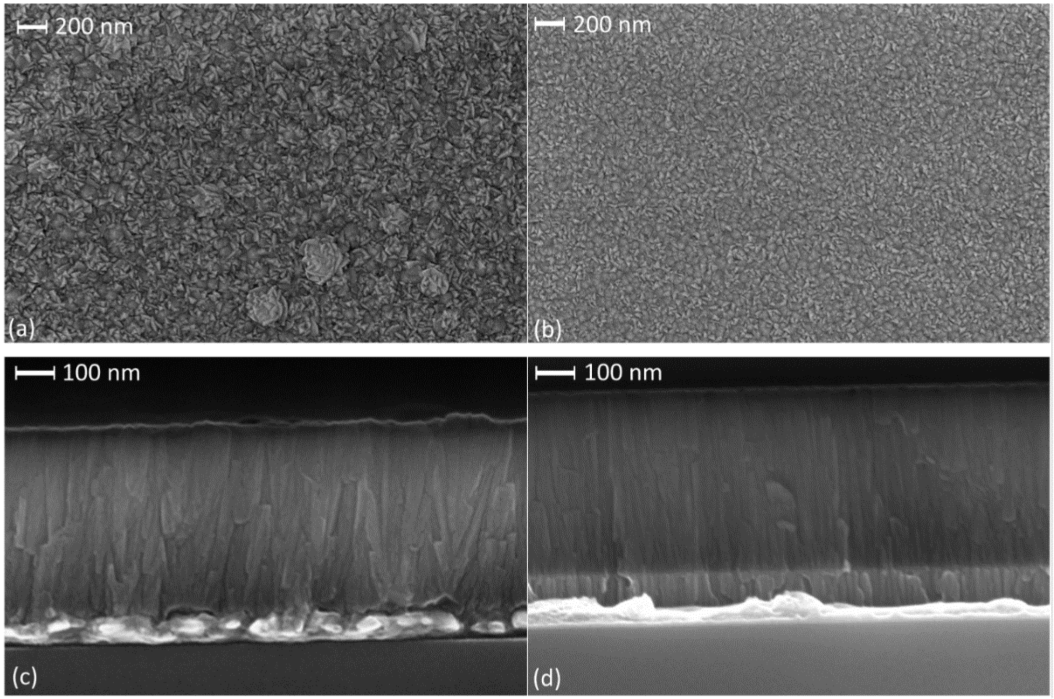
Other factor influencing film structure:



Material itself, underlying material, thickness
And of course sputtering parameters.

Poortmans: Thin film solar cells

Underlying material effect



Top view SEM

Cross sectional SEM

AlN grown on pure Al

AlN grown on AlMo

Texture inheritance: the growing film “inherits” crystal structure

Ramadan et al: PLOS ONE. https://doi.org/10.1371/journal.pone.0133479.g009

MRC vs. Oxford

Batch machine:
9 wafers in one run

Suitable for any wafer size and shape since wafers simply sit on a flat chuck.

No load lock ➔ have to pump longer to reach base pressure.

Single wafer load lock ➔ takes a long time to load (but up to 8 wafers sputtered simultaneously).

Fitted for one wafer size (100 mm at Aalto).

Load lock, quicker pump down

Sputtered metallization

Sputtering is the dominant metallization technique.

Evaporation has poor adhesion, poor step coverage and less parameters to tailor film properties.

Metallization thickness has to be $\geq$100 nm for conductors in order to have low enough resistance (resistor can be thin!)

1 µm is enough for most applications.
5 µm is used in power transistors and solar cells that carry large currents.

But: Aspect ratio is typically 1:1 (width ≈ height)

Aluminum pros and cons

Al has been used widely in the past and is still used

- Low resistivity (only Ag, Au and Cu lower)
- Ease of deposition (sputtering and evaporation)
- Wet and plasma etching
- Ohmic contacts to Si
- Excellent adhesion to dielectrics

Problems with Al

- Silicon is soluble to Al ➔ shallow junction pitting
- Electromigration ➔ current density limitations
- Stress relief by hillocks ➔ shorts between levels

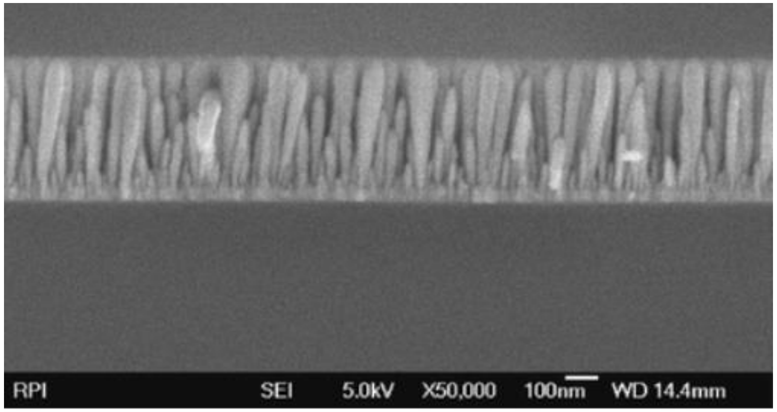
Tungsten pros and cons

Pros:

- Can be deposited by sputtering, evaporation and CVD
- Can be plasma and wet etched
- Makes Ohmic contacts to Si
- Excellent electromigration resistance (10^6 A/cm^2 no problem)

Problems with W

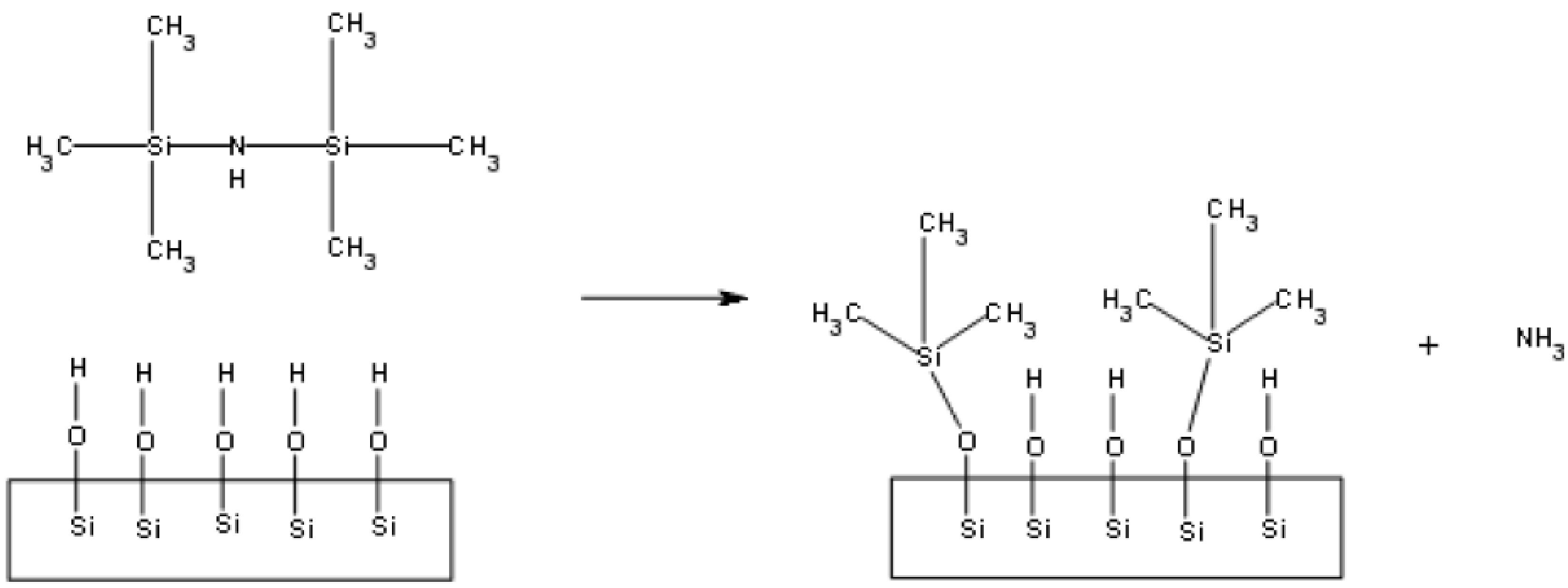
- Resistivity much higher than Al/Cu/Au (ca. 5-10X)
- Not so good adhesion (Ti/TiW/TiN adhesion layers often used)
- Sputtered films not dense (columnar grains with large intergrain voids, nanometers)



Karabacak et al: Applied Physics Letters 2003
DOI: 10.1063/1.1618944

Lithography: bake & prime

Bake at 120ºC for an hour to remove adsorbed water.
Treat with HMDS to make surface hydrophobic.



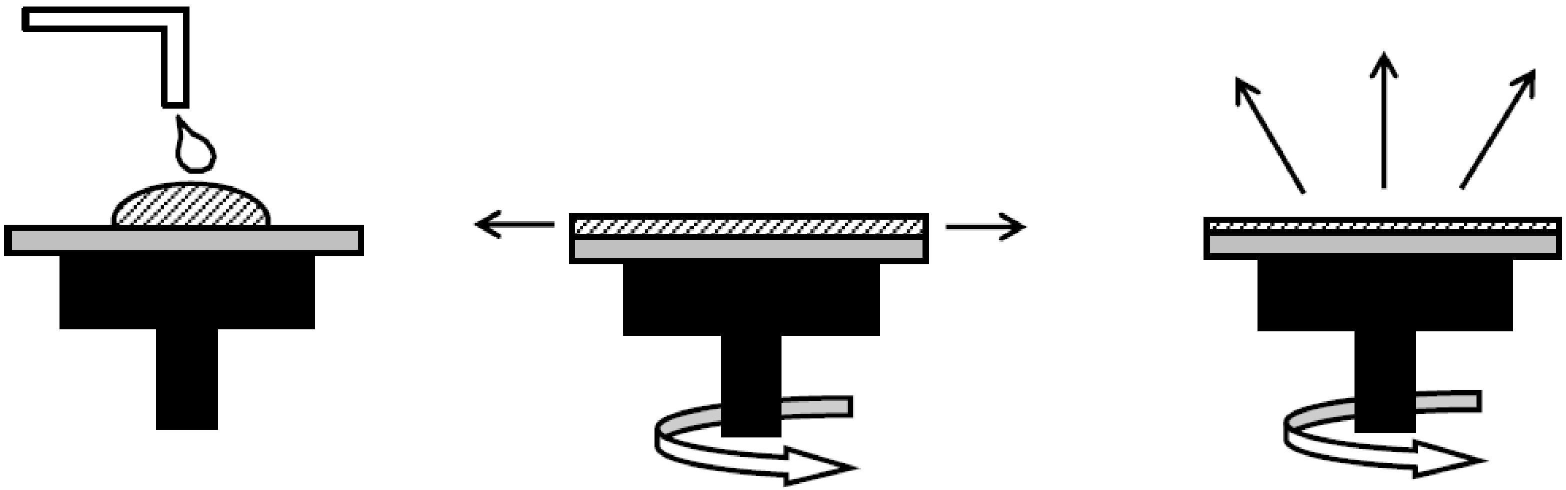
Lithography: resist choice

Positive resist AZ5214 is chosen.

Positive resists are:

-common
-developed in water-based solutions
-good enough adhesion
-easily stripped

Lithography: spinning



Resist dispensing
(a few milliliters)

Acceleration
(resist expelled)

Final spinning 4000 rpm
(partial drying via evaporation)

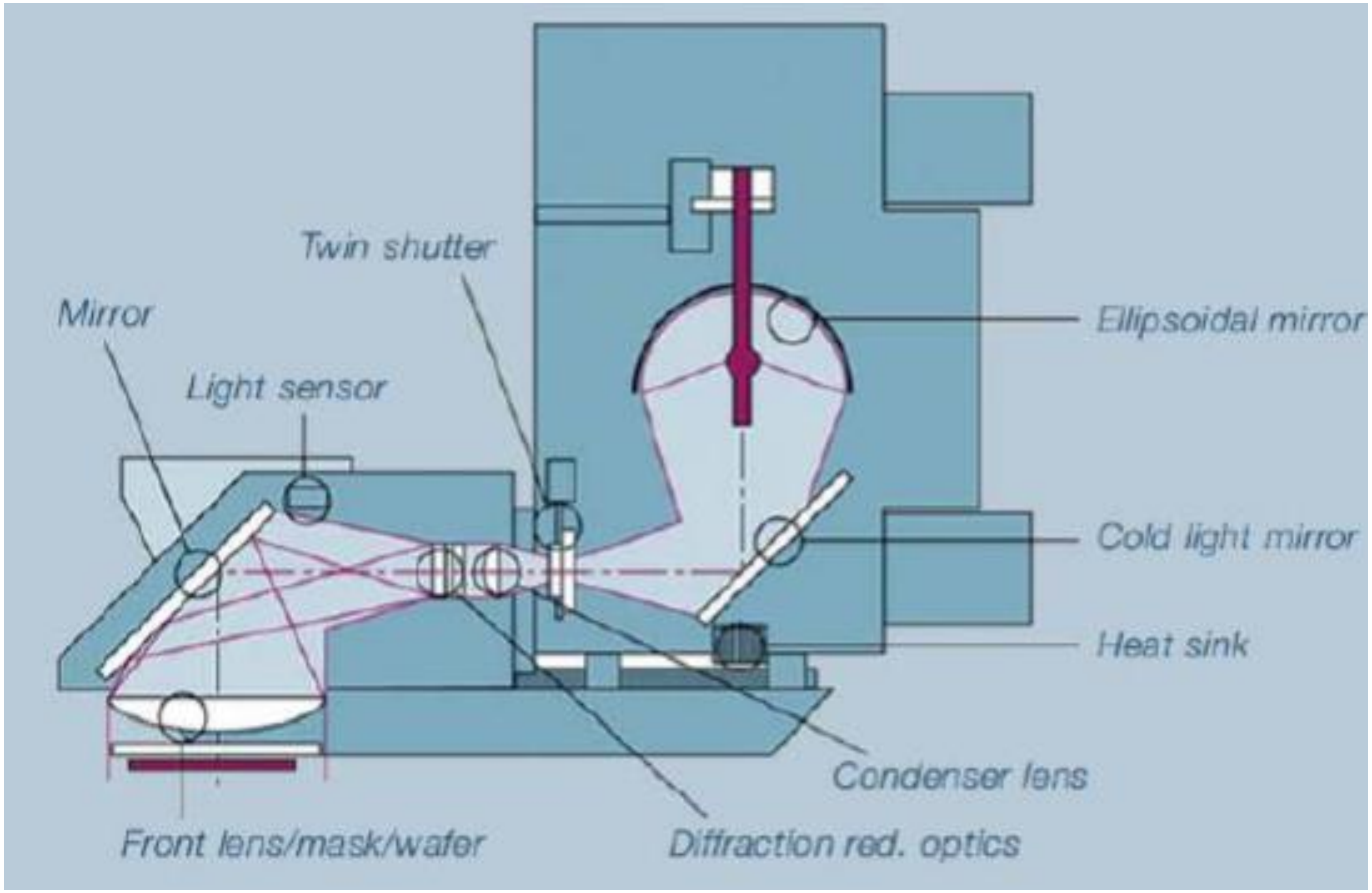
3 ml of AZ5214 is spin coated, resulting in 1.4 µm thick film.
What percentage of resist ends up on wafer ?

Bake on a hot plate

Ensure that solvent is gone.

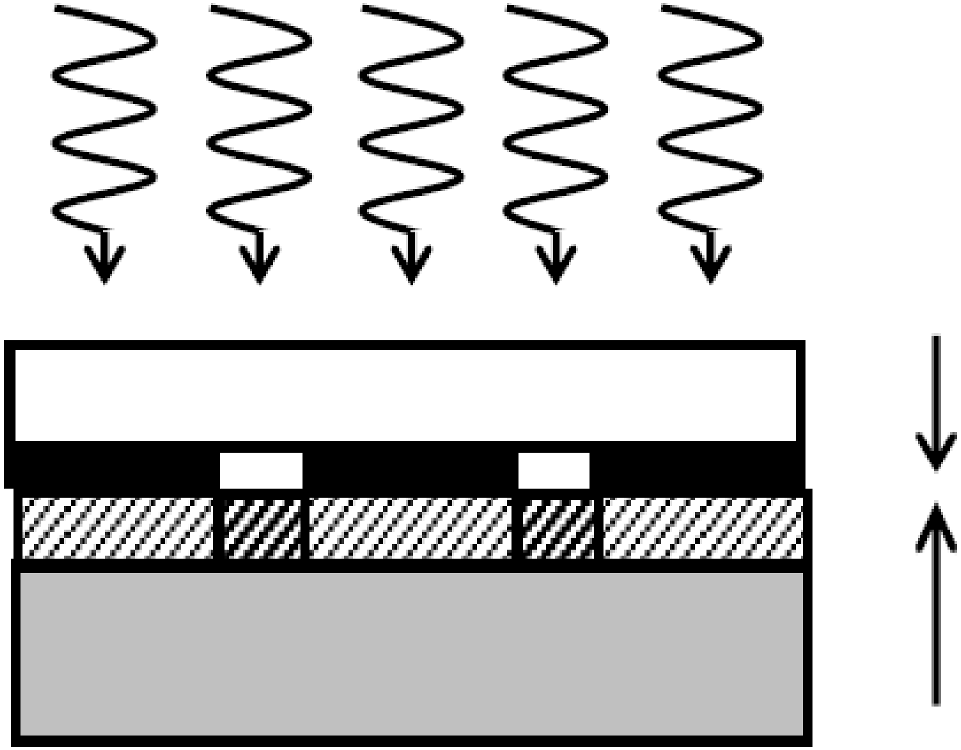
90°C.
Not too much heat, because the photoactive compound is destroyed at elevated temperatures !

Lithography: exposure tool



Lithography: exposure tool MA-6

Lithography: soft contact

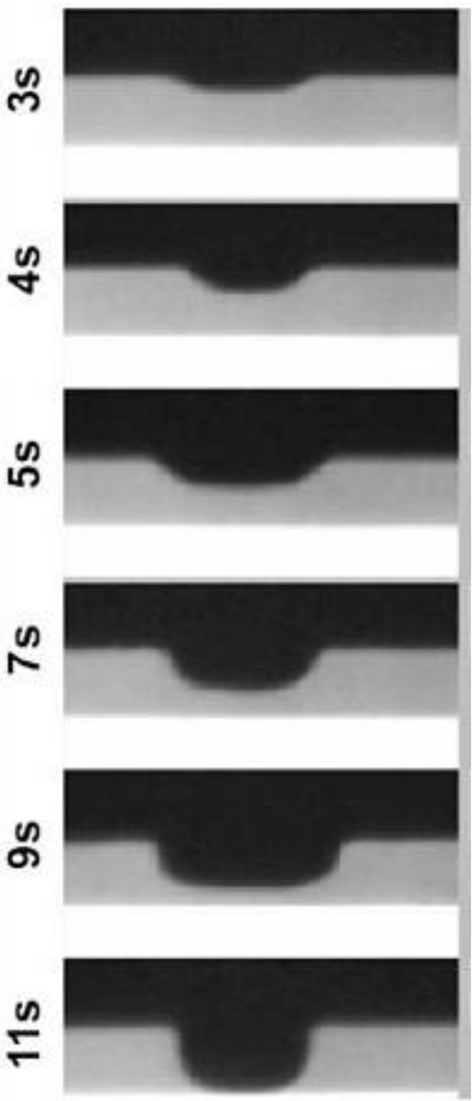


Soft contact:

-we make rather wide lines, no need to push performance to limit

-better linewidth control than with proximity litho

Development time effect



Optimal time depends on:

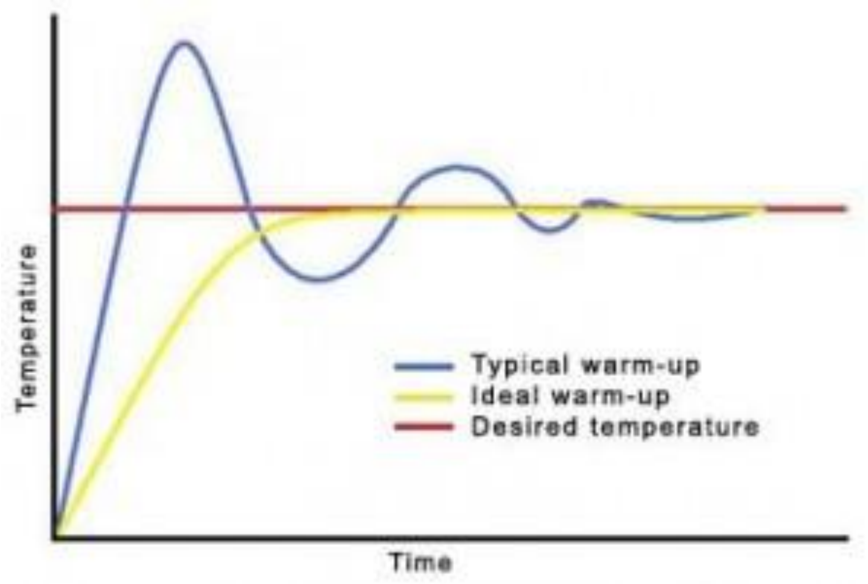
-resist thickness
-resist bake
-exposure dose
-developer concentration/age

Hard bake @ 120^{o}C

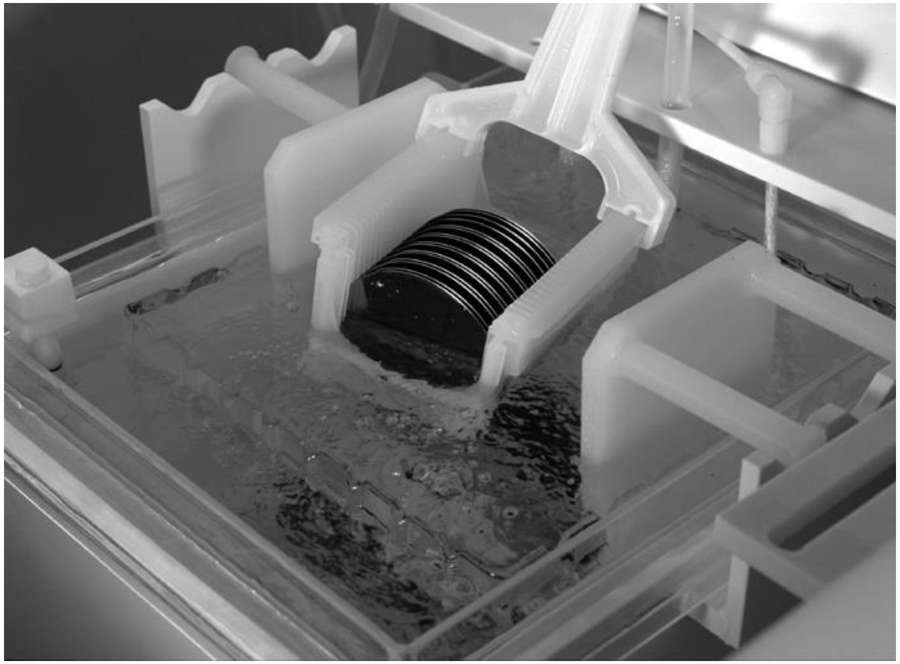
Completes the photochemical reactions

Improves adhesion

Tradeoff with ramp rate and overshoot.



Wet etching aluminum



H_3PO_4 -based etch

Heated to 50^{o}C to speed up the process

Etch rate ~500 nm/min

Plasma etching tungsten

Generation of active specie in plasma:
$SF_6 \rightarrow SF_5^* + F^- + F^* + SF_4^{2-}$
Overall reaction: $W + 6\ F^* \rightarrow WF_6$
Etch rate ca. 70 nm/min

Resist strip

Acetone is quick and dirty.
Rinsing and drying are essential steps connected to acetone stripping (and cleaning in general).

Other resist strips:

- Oxygen plasma
- Ozone @300^{o}C
- Ozonated water
- Organic amines
- Sulphuric acid (etches metals)

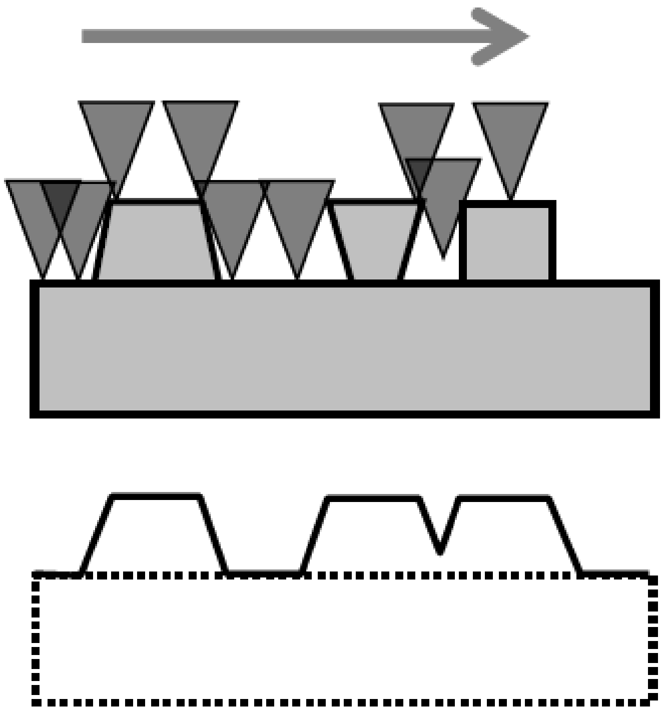
Metal thickness and linewidth

Profilometer Dektak

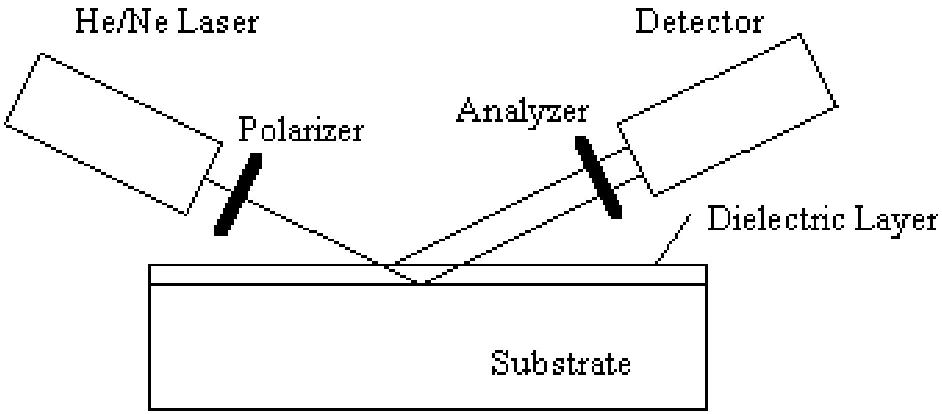
Mechanical needle is scanned over steps.

As seen in the figure, needle shape does not really allow profile measurement, but step height.

Width is also obtained, but it is just a ”side result”, and not very accurate.



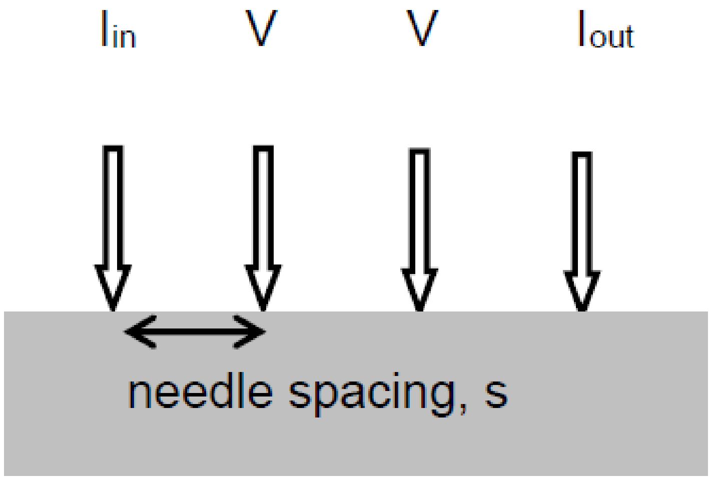
Ellipsometer



- The polarization change upon reflection is represented as an amplitude ratio, Ψ, and the phase difference, Δ.
- Refractive index assumed known (a very good assumption for thermal oxide; but not so good for e.g. PECVD films, or extremely thin films). For SiO_2 we use value 1.46
- If two wavelengths or two angles ➔ both thickness and refractive index can be measured.

Sheet resistance

Four-point probe (4PP)



$$R_s \equiv \rho/T$$

R_s is in units of Ohm, but it is usually denoted by Ohm/square (or $\Omega/\square$) to emphasize the concept of sheet resistance.

Resistance of a conductor line can now be easily calculated by breaking down the conductor into n squares: $R = nR_s$

Resistor sheet resistance

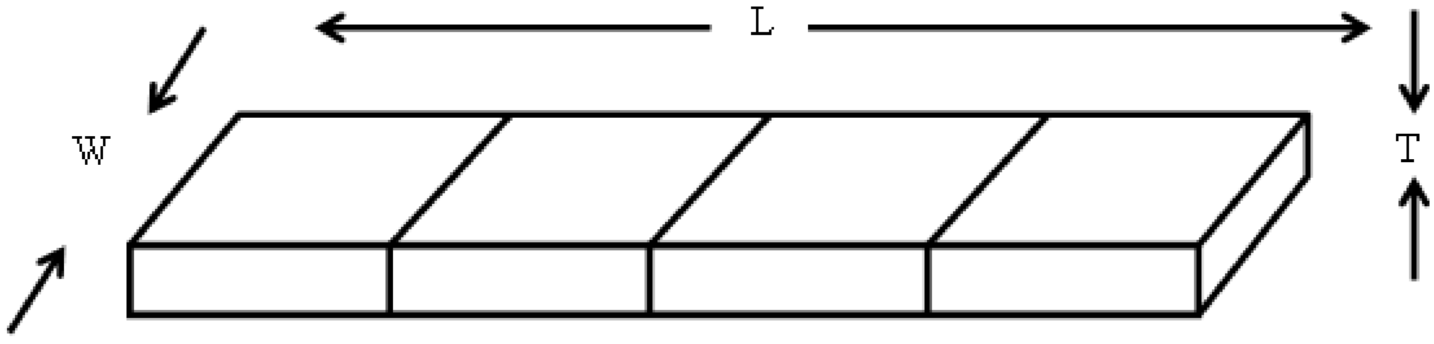


Figure 2.8: Conceptualizing metal line resistance: four squares with sheet resistance R_s in series gives resistance as $R = 4R_s$.

Sheet resistance example

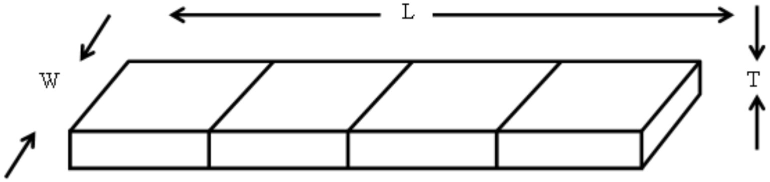
Copper film 1 µm thick, sheet resistance ?

ρ = 2 µΩ-cm,

$R_s \equiv \rho/T$

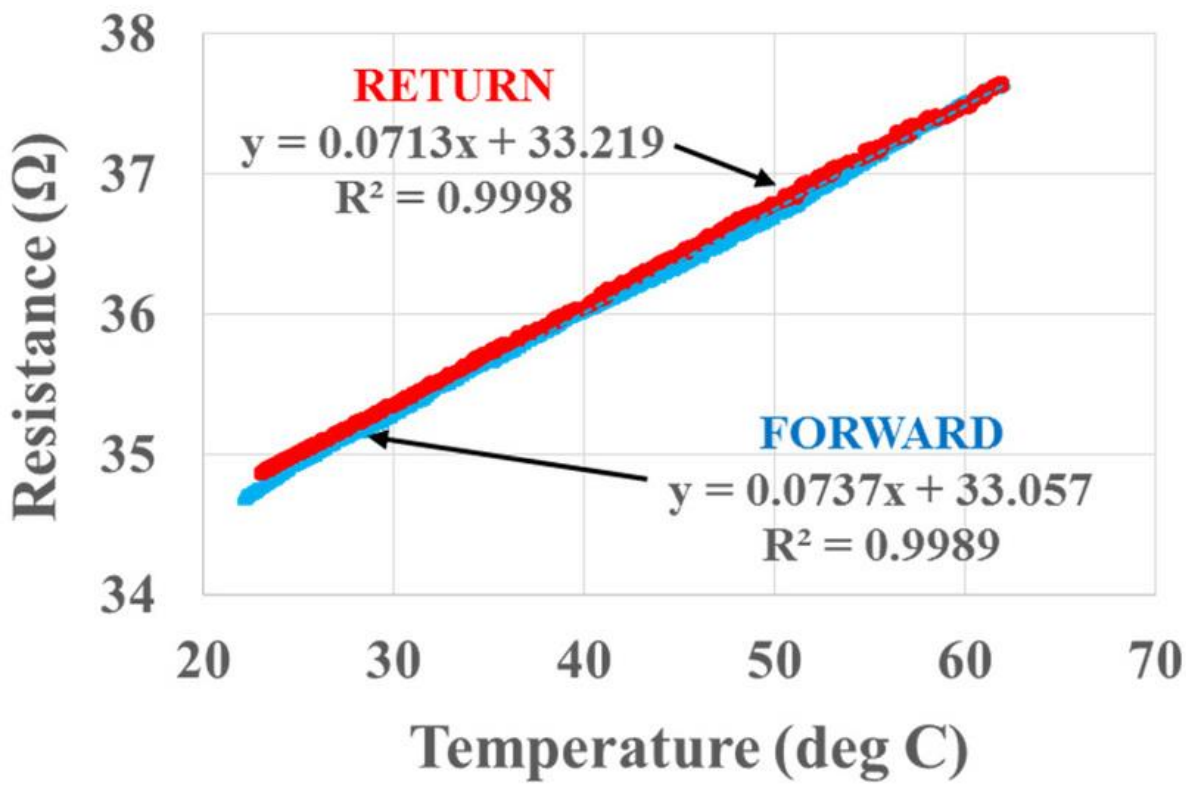
$R_s = 2\ \mu\Omega\text{-cm} / 10^{-4}\ \text{cm} = 20\ \text{m}\Omega = 0.02\ \Omega$

A resistor is 4L long ➔ n =4.



$R = n{*}R_s = 4{*}0.02\ \Omega = 0.08\ \Omega$

TCR: temperature coefficient of resistance



Looks nice, linear and reproducible, but it is only 22-63^{o}C !

You will measure up to 250^{o}C.

Do not burn yourself !

Electrical measurements

- Resistance measured at 20^{o}C (Multimeters)
- Calculate resistivity (profilometer thickness)
- Annealing on a hot plate @ 200^{o}C, measure
- Anneal at 450^{o}C for 20 min, measure
- Remeasure wire resistances at 20^{o}C
- Data is identical for the whole group
- But ***the report is personal***
  (return by April 2nd, 10 pm)
- Instructions in the lab data sheet