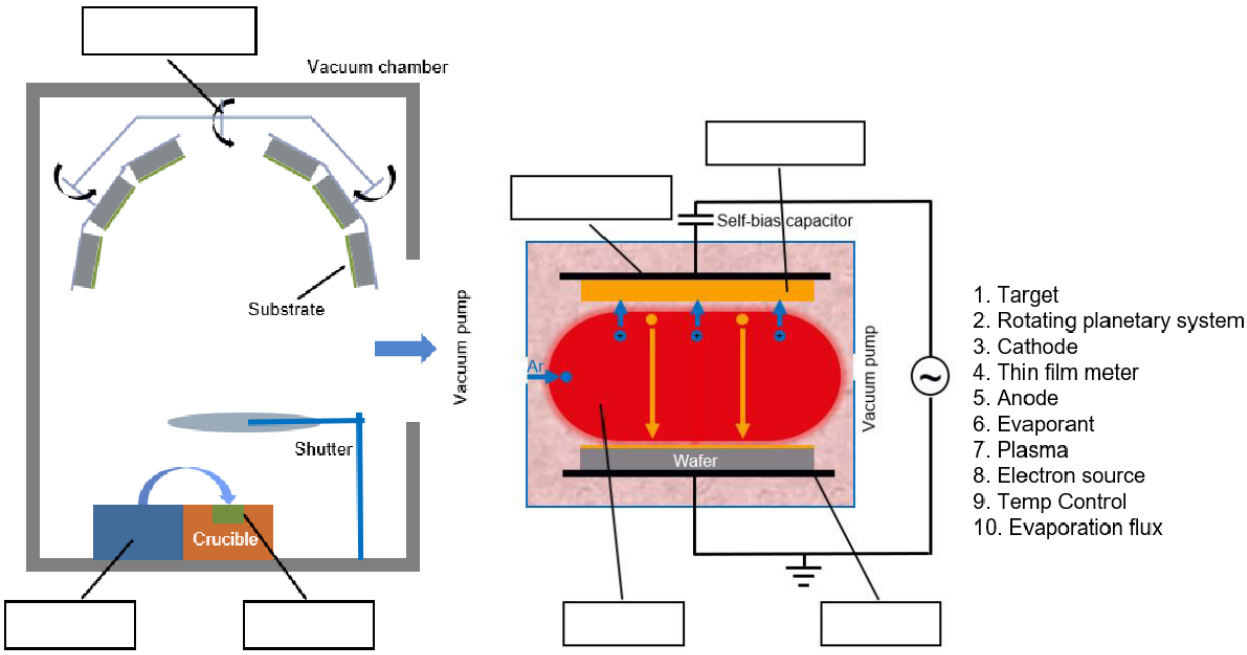
Série 2

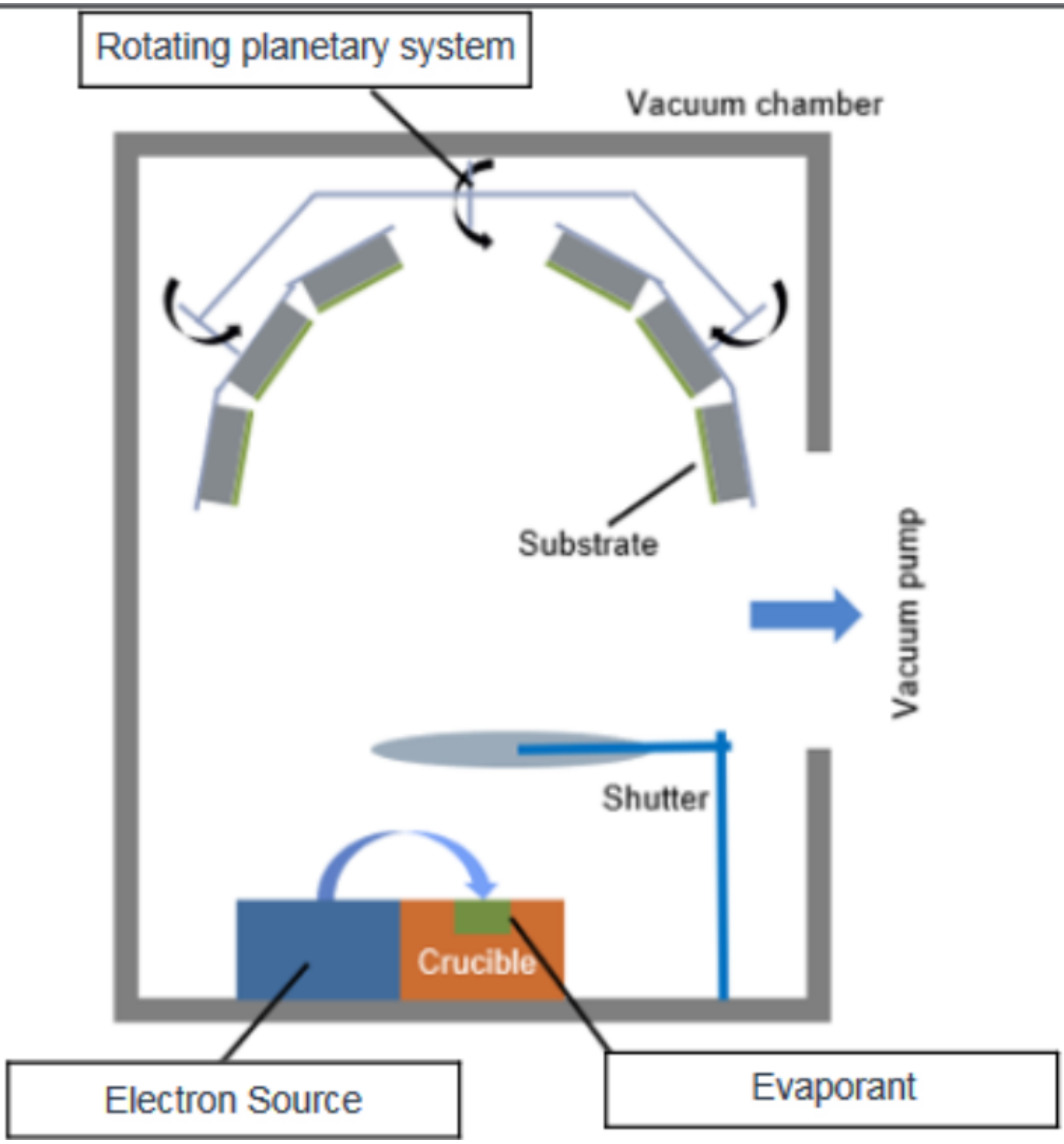
EXCERCISES 2a (PVD)

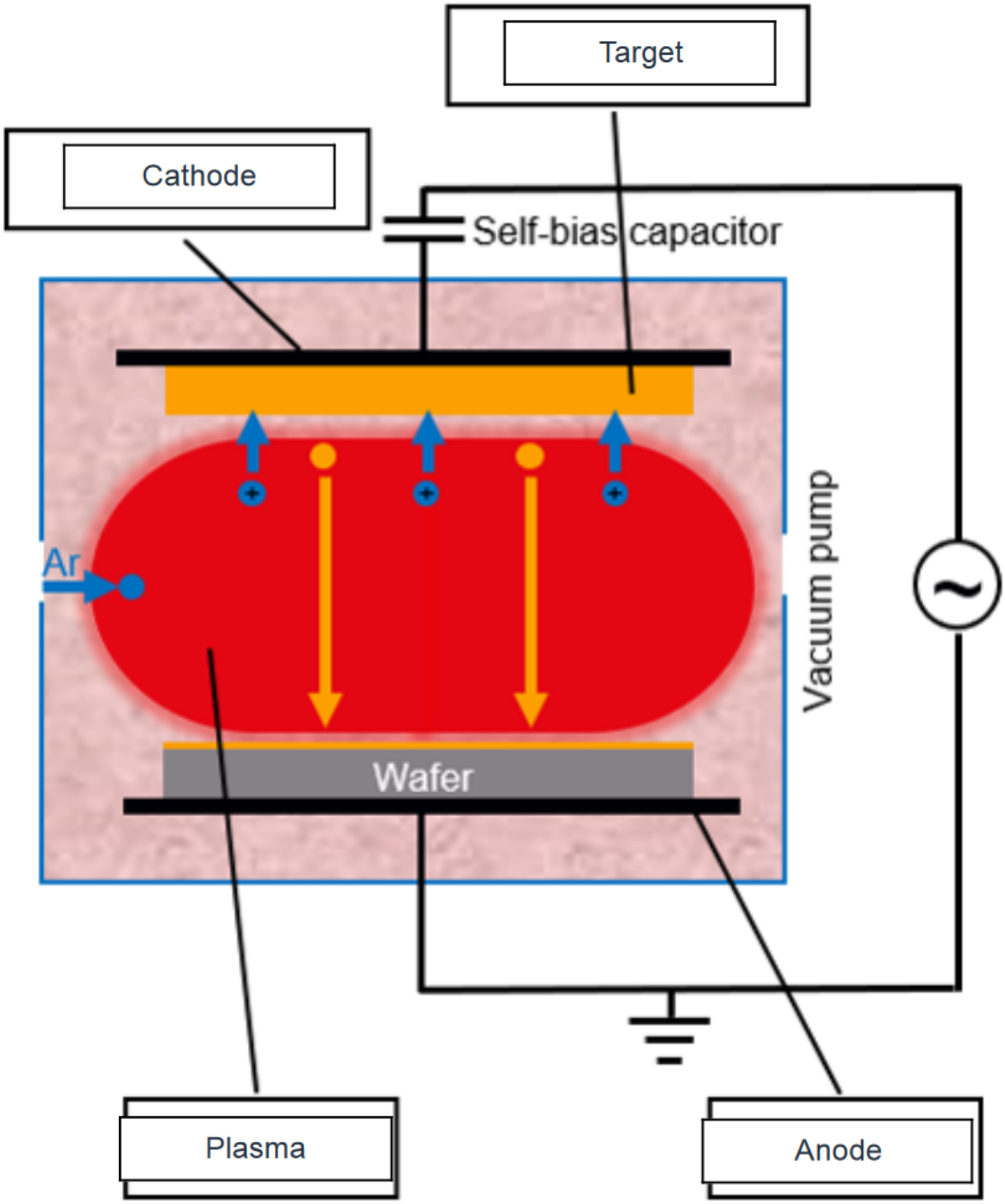
1) Topic: PVD

Let us compare an evaporation and a sputtering deposition system.

(a) Below are two schematic drawings: an evaporation tool and a sputtering tool. Some components are missing, and a list of the components are on the right. Fill in the blanks to complete the drawings.



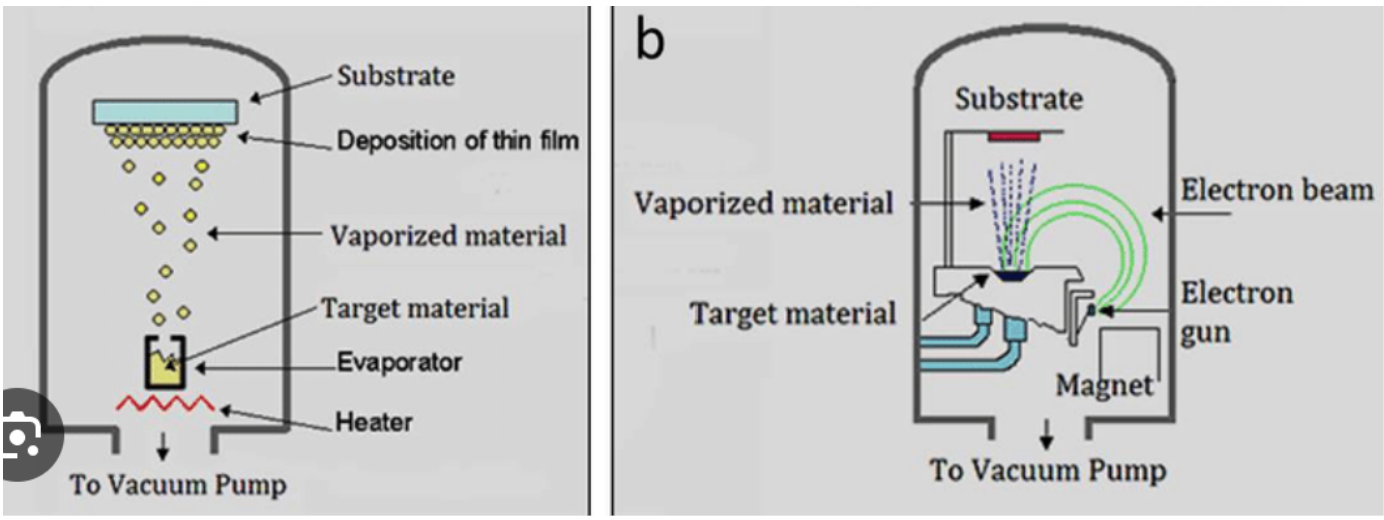

Rotating planetary system
Vacuum chamber
Substrate
Vacuum pump
Shutter
Crucible
Electron Source
Evaporant



(b) In a PVD evaporator tool, there can be two main types of heating principle for the sources: the resistive and electron heating principle. Draw and explain the differences between these two evaporation sources as well as the advantages and limitations of each of them.

resistive heating use electrical current inside a resistor to heat the evaporant

electron heating use the kinetic energy of the electron on the target to heat it



Advantages of resistive heating:

Uniform Heating: Resistive heating can provide relatively uniform heating to the source material or substrate, ensuring consistent deposition rates and film quality. This is important for producing uniform thin films in PVD processes.

Compatibility with Various Materials: Resistive heating can be used with a wide range of materials, including metals, ceramics, and semiconductors, making it versatile for different PVD applications.

Simplicity and Reliability: Resistive heating elements are relatively simple in design and operation, making them reliable and cost-effective. They have a longer lifespan and require less maintenance compared to some other heating methods.

Limitations of resistive heating:

Limited Temperature Range: Resistive heating has limitations in terms of the maximum temperatures it can achieve. For some high-temperature PVD processes, other heating methods like electron beam or laser heating may be more suitable.

Contamination Risk: In some cases, the resistive heating elements themselves can contribute to contamination of the deposition process, particularly if they degrade over time or release impurities during heating.

Limited to Solid Materials: Resistive heating is most suitable for solid materials. It may not be ideal for processes involving highly volatile or gaseous materials.

Advantages of electron heating:

High Temperature Capability: Electron heating is capable of achieving very high temperatures, making it suitable for processes that require extremely high deposition temperatures.

Rapid Heating and Cooling: Electron beams can be rapidly turned on and off, allowing for quick heating and cooling cycles during the deposition process, which can be advantageous in some applications.

Minimal Gas Contamination: Electron heating can be used in a low-pressure or vacuum environment, reducing the risk of gas contamination during the deposition process.

Limitations of electron heating:

Material Compatibility: the material need to be conductive

Complex Equipment: Electron beam heating systems are complex and require specialized equipment, which can be expensive to install and maintain.

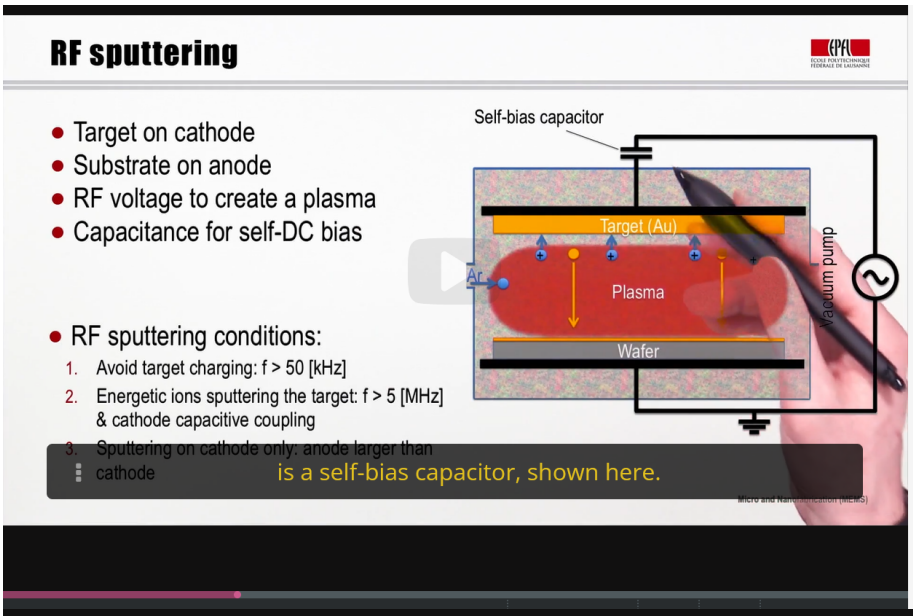
Limited Beam Size: The size of the electron beam is typically limited, which may require moving the beam or the substrate to achieve uniform heating in some cases.

High Power Consumption: Electron heating systems can consume a significant amount of electrical power, which can result in higher operational costs compared to other heating methods.

(c) In addition to DC sputtering, two other types of sputtering techniques are discussed in the lecture: These are RF sputtering and magnetron sputtering.

Explain the differences between these two sputtering techniques as well as the advantages and limitations of each of them and the advantage of using one technique or another depending on the material to deposit. Make some simple drawings.

magnetron sputtering use a magnetic field where RF sputtering use radio frequency like in a microwave.



instead of DC voltage

has the main advantage to avoid target charging

and thus allows the position of electrically insulating materials

such a dielectrics.

The key element to add to a system using an AC voltage

is a self-bias capacitor, shown here.

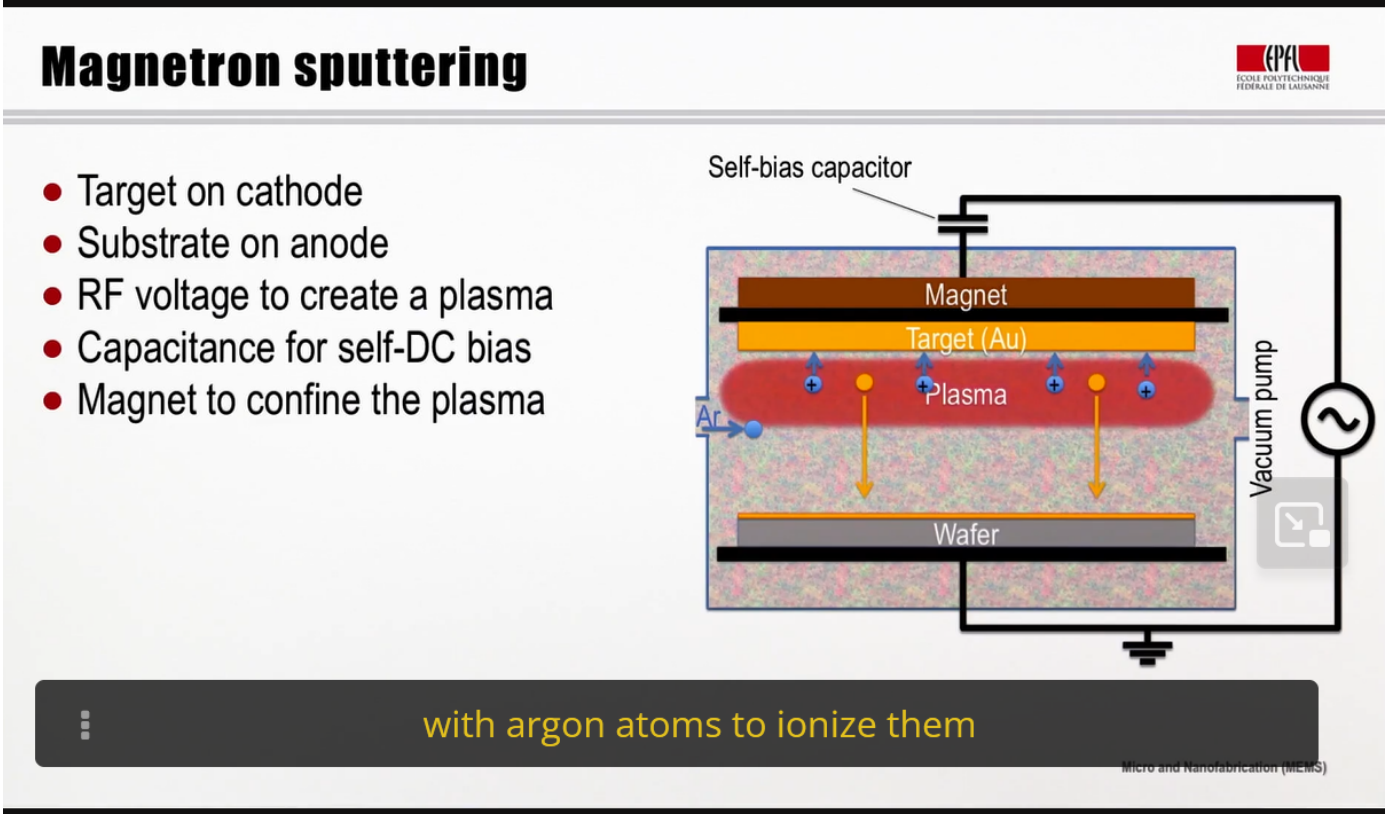
To enable RF sputtering, the following three conditions are required.

First, avoid target charging

as the cathode where the target is placed

will alternate between positive and negative voltages.

Both ions and electrons will accumulate on the target



RF avoid target charging but heat a lot especially insulating material and sputter the whole chamber

magnetron : use lower voltages and lower pressure, which allows
deposition of film with higher purity. less heating and less chamber sputerring but more complexe and target wear not uniform

(d) Below you will find a part of the Hertz-Knudsen equation. Fill in the remaining parameters to complete the equation (1.5 pt.) and explain what are the most important parameters.

$$\Phi_e = \frac{1}{A_e}\frac{d(\ )}{dt} = \frac{\alpha \cdot N_A \cdot (\qquad)}{\sqrt{2\pi \cdot R \cdot (\qquad)}}$$

Φ_e = vapor flux in [molecules/(m²·s)]
A_e = source surface area in [m²]
N = number of gas molecules
α = sticking coefficient (0< α <1 = ideal case)
N_A = Avogadro constant in [mol⁻¹]
P_v = vapor pressure of the evaporant in [Pa]
P = reactor pressure in [Pa]
M = molar mass in [kg/mol]
R = gas constant in [J/(mol·K)]
T = temperature in [K]
Γ_e = evaporation mass flux in [kg/(m²·s)]

Non-dissociative adsorption (Langmuirian adsorption) [edit]

The Hertz–Knudsen equation describes the non-dissociative adsorption of a gas molecule on a surface by expressing the variation of the number of molecules impacting on the surfaces per unit of time as a function of the pressure of the gas and other parameters which characterise both the gas phase molecule and the surface:[1][2]

$$\frac{\mathrm{d}N}{\mathrm{d}t} \equiv \varphi = \frac{\alpha p}{\sqrt{2\pi m k_\mathrm{B} T}} = \frac{\alpha p N_A}{\sqrt{2\pi M R T}},$$

where:

Quantity	Description
A	Surface area (in m^2)
N	Number of gas molecules
t	Time (in s)
φ	Flux of the gas molecules (in $m^{-2}\ s^{-1}$)
α	Sticking coefficient of the gas molecules onto the surface, $0 \le \alpha \le 1$
p	The gas pressure (in Pa)
M	Molar mass (in kg mol^{-1})
m	Mass of a particle (in kg)
k_B	Boltzmann constant
T	Temperature (in K)
R	Gas constant (J mol^{-1} K^{-1})
N_A	Avogadro constant (mol^{-1})

Since the equation result has the units of s^{-1} it can be assimilated to a rate constant for the adsorption process.

2) Jupyter Notebook exercise: PVD

You are expected to produce a metallic heater, and you have to choose materials and processes for the thin film depositions, as well as estimate the timing of the process.

Part 1: Thin film resistances and thickness

You are required to obtain a film with a total square resistance lower than 2.5 Ohm.
Remember that square resistance is calculated as:

$$R_{\blacksquare} = \frac{\rho}{t}$$

In the notebook you have some code that already can display some properties of typical metals available for the conductive layer, and also materials that can be used as adhesion layers.
Considering a 10 nm thick adhesion layer (only when needed), find the conductive layer thickness to achieve the resistance requirement, and fill in this table.

Required conductor thickness table		Conductor		
		Au	Cu	Al
Adhesion	Ti			
	Cr			

HINT: you can write code that will help you to find the required thickness of conductive layer running for cycles on the materials. Remember that the two stacked layers can be treated as resistances in parallel: $\frac{1}{R_{eq}} = \frac{1}{R_{cond.}} + \frac{1}{R_{adh.}}$.

	Material	Electrical Resistivity (ohm*m)
0	Au	2.21e-08
1	Cu	1.68e-08
2	Al	2.65e-08

	Adhesion Layer	Electrical Resistivity (ohm*m)
0	Ti	4.20e-07
1	Cr	1.25e-07

$$R_{Ti} = \frac{4.2 * 10^{-7}[\Omega m] * lenght}{thickness * widht}$$

$$R_{Ti} = \frac{4.2 * 10^{-7}[\Omega m]}{10 * 10^{-6}[m]} = 0.042[\Omega]$$

$$R_{Cr} = \frac{1.25 * 10^{-7}[\Omega m]}{10 * 10^{-6}[m]} = 0.0125[\Omega]$$

$$R = \frac{1}{\frac{1}{2.5} - \frac{1}{0.042}} = 0.042$$

$$R = \frac{1}{\frac{1}{2.5} - \frac{1}{0.0125}} = 0.0125$$

$$t_{TiAu} = \frac{\rho}{R} = \frac{2.21 * 10^{-8}}{0.042} = 5.261 \times 10^{-7}[m]$$

$$t_{CrAu} = \frac{\rho}{R} = \frac{2.21 * 10^{-8}}{0.0125} = 1.768 \times 10^{-6}[m]$$

$$t_{TiCu} = \frac{\rho}{R} = \frac{1.68 * 10^{-8}}{0.042} = 4 \times 10^{-7}[m]$$

$$t_{CrCu} = \frac{\rho}{R} = \frac{1.68 * 10^{-8}}{0.0125} = 1.344 \times 10^{-6}[m]$$

$$t_{TiAl} = \frac{\rho}{R} = \frac{2.651 * 10^{-8}}{0.042} = 6.311 \times 10^{-7}[m]$$

$$t_{CrAl} = \frac{\rho}{R} = \frac{2.65 * 10^{-8}}{0.0125} = 2.12 \times 10^{-6}[m]$$

	Conductor = Au	Cu	Al
Adhesion = Ti	-83.14	1.49e+18	-99.69
Cr	-70.72	1.49e+18	-84.80

Part 2: Gathering deposition rate data

Using the CMi recipe data for the evaporator LAB600 and the sputtering tool DP650, find the fastest deposition recipes available for each material, and complete the line of code that stores the deposition rates (in nm/min). With this, find the total deposition times of the (bi-)layers of Part 1 by the two methods, and complete the table:

Remember: 10 Angstrom = 1 nm.

Deposition time Evaporation		Conductor		
		Au	Cu	Al
Adhesion	Ti			
	Cr			

Deposition time Sputtering		Conductor		
		Au	Cu	Al
Adhesion	Ti			
	Cr			

```
#Fill here the evaporation deposition rates for the materials
Au_deposition_rate = 4 #[A/s]
Cu_deposition_rate = 0 #???
Al_deposition_rate = 4

deposition_rates_evap = [Au_deposition_rate, Cu_deposition_rate, Al_deposition_rate]

#Fill here the sputtering deposition rates
Au_deposition_rate = 21.7
Cu_deposition_rate = 30.5
Al_deposition_rate = 14.7

deposition_rates_sput = [Au_deposition_rate, Cu_deposition_rate, Al_deposition_rate]
```

Part 3: Uniformity by evaporation.

The evaporation process can be advantageous in some cases, due to its directionality. Let us look at this process in detail.

By using the interactive plots and completing the missing parts of code, estimate the non-uniformity U in % for all possible combinations of wafer size and distance to source.

Hint: Some formulas that you might want to consider.

$$U = \left(\frac{t_{max}}{t_{average}} - 1\right) \times 100\%$$

$$t_{average} = \frac{\iint_{wafer} t\, dx\, dy}{\pi R^2} \cong \frac{\sum_{x_i^2+y_j^2<R^2} t(x_i, y_j)}{N_{\left(x_i^2+y_j^2<R^2\right)}}$$

Where $x_i^2 + y_j^2 < R^2$ refers to those points of the grid that are inside the wafer. Note that in the code, the matrix "points_outside" contains Boolean values of true for the indices that are in the outside region. $N_{\left(x_i^2+y_j^2<R^2\right)}$ is the number of grid elements that are inside the wafer (i.e. that have a false "points_outside" value) . Consider built-in methods for vector (like max, min, sum, mean) and use the "points_outside" matrices defined in the code to select wisely the indices you need.

Non-uniformity		Wafer Size			
		5 cm	10 cm	15 cm	20 cm
Distance (cm)	20				
	40				
	60				
	80				
	100				

Part 4: Vacuum in evaporation chambers

It is necessary to pump a vacuum in the deposition chamber. Adding the necessary code to the plotting function to calculate exactly the required time to reach a sufficiently good vacuum and display it on the plot with vertical and horizontal intersecting lines.
The required mean free path needs to be greater than 100 times the distance between source and wafer. The pumping time in seconds is by rule of thumb 75 times the mean free path in m, for each of the possible distances.

Distance (cm)	Pumping time required
20	
40	
60	
80	
100	

Part 5: Process duration

a. What would be the total duration of an evaporation process for all the films proposed in the previous parts? What fraction of the time is actually employed for the deposition?

b. Assuming that the sputtering process can be done on a single wafer at a time, and it takes 15 minutes to process one wafer, how many wafers have to be processed identically so that using evaporation starts to make more sense (of course, ignoring any details about process-dependent differences in thin film quality)?

Part 6: Deposition on tapered walls

Follow the last part of the notebook to appreciate the effects of depositing on a substrate with topography and tapered sidewalls.