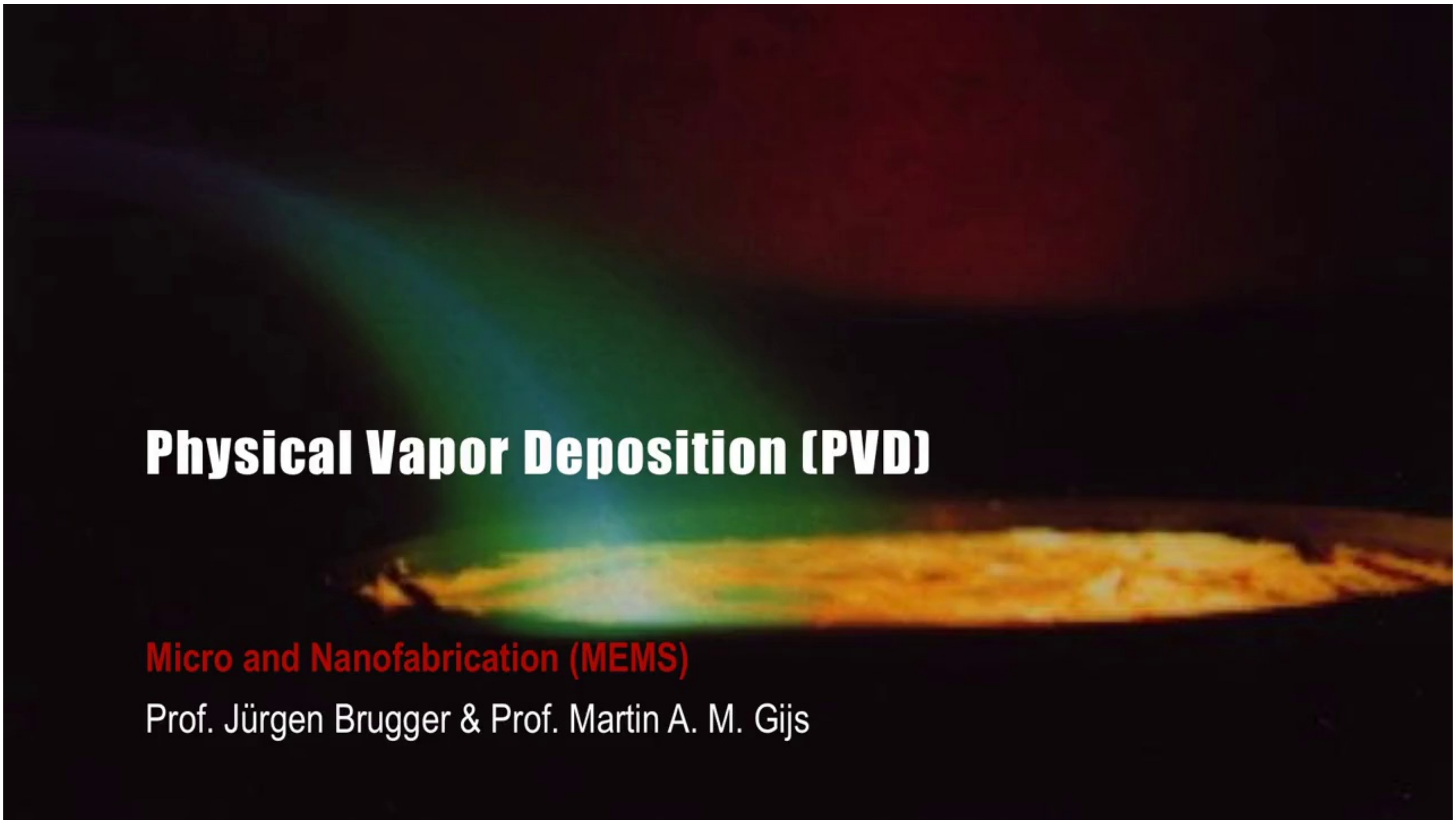
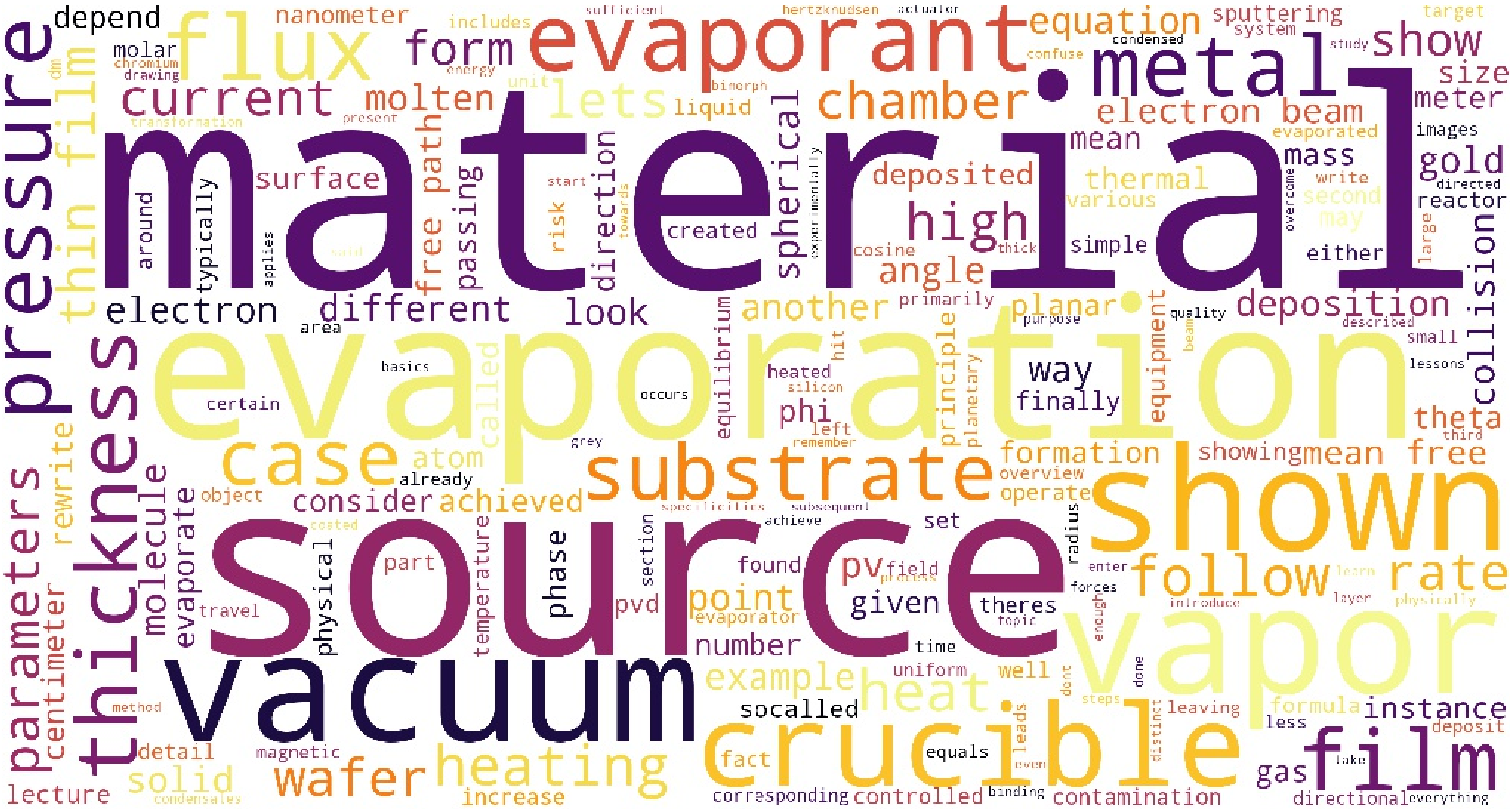


Physical Vapor Deposition (PVD)

Micro and Nanofabrication (MEMS)

Prof. Jürgen Brugger & Prof. Martin A. M. Gijs



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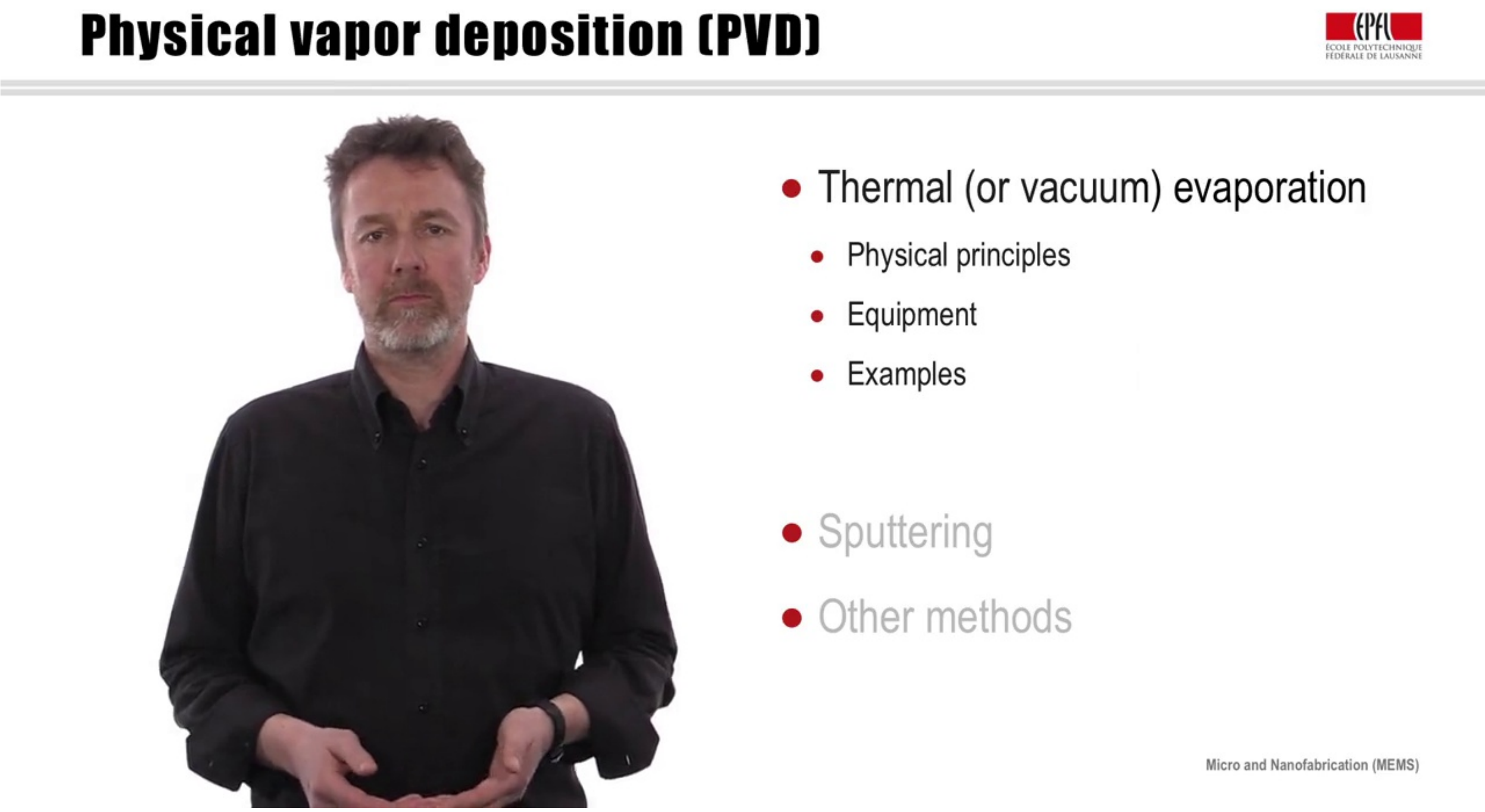
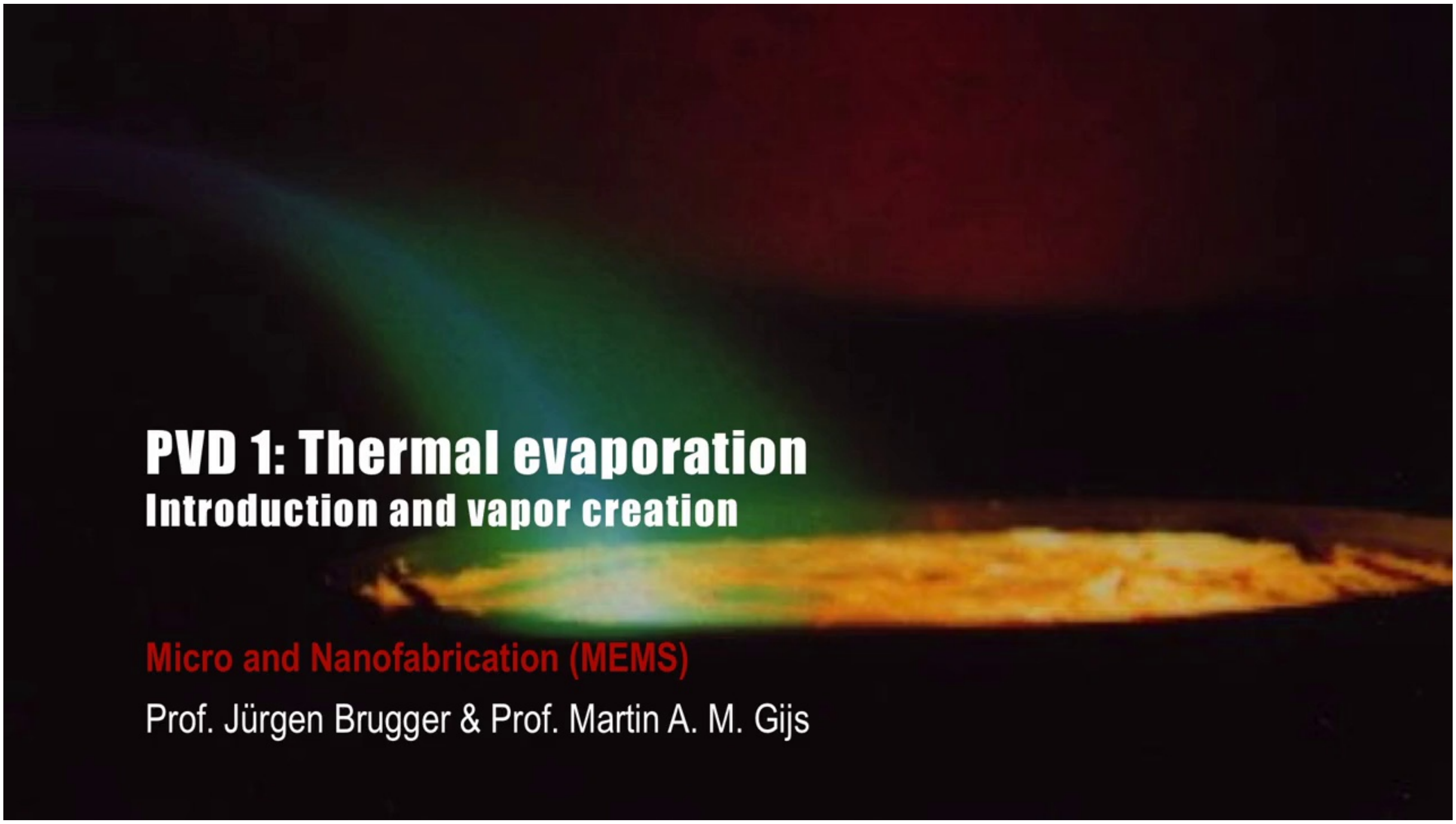


Physical vapor deposition (PVD)

- Thermal (or vacuum) evaporation
  - Physical principles
  - Equipment
  - Examples
- Sputtering
- Other methods

Micro and Nanofabrication (MEMS)

In this lecture, I will show you how we can form a high quality thin film on a substrate. You may remember the case study of the bimorph thermal actuator beam where we deposited a 500 Nanometer thick layer of chromium on a SiO2 coated silicon wafer. Such thin films in metals are deposited by so-called physical vapor deposition or PVD. In this lecture, you will learn the basics of vacuum evaporation. I will start by showing the physical principle, then show how the equipment looks like, and finally present some examples. Don’t confuse thermal evaporation with sputtering, which is another PVD method and that will be shown in the subsequent lessons part two.



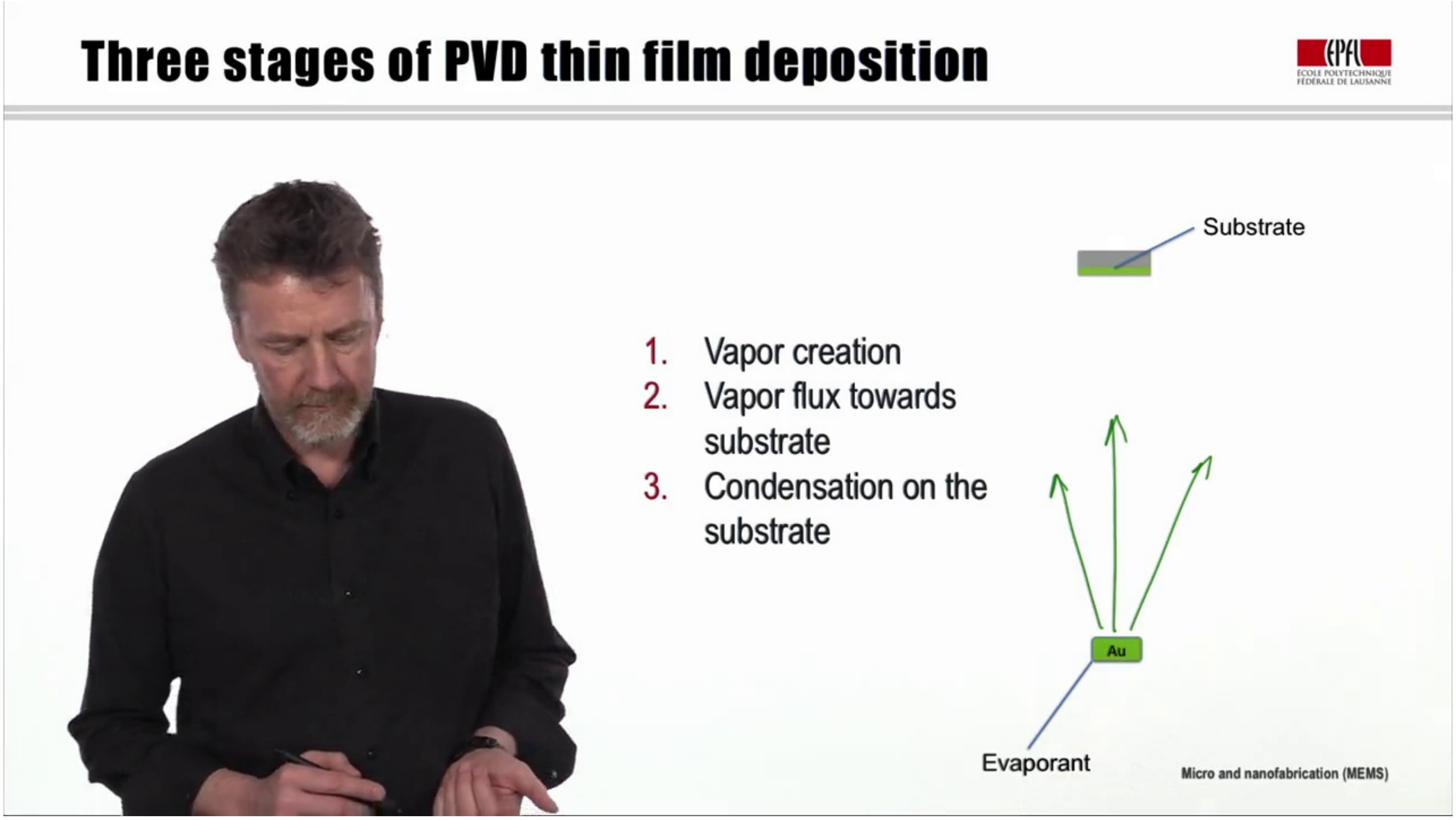
PVD 1: Thermal evaporation

Introduction and vapor creation

Micro and Nanofabrication (MEMS)

Prof. Jürgen Brugger & Prof. Martin A. M. Gijs

So in this first part, let’s have a look at thermal evaporation, also called vacuum evaporation. I will introduce the topic and show how the vapor is created.

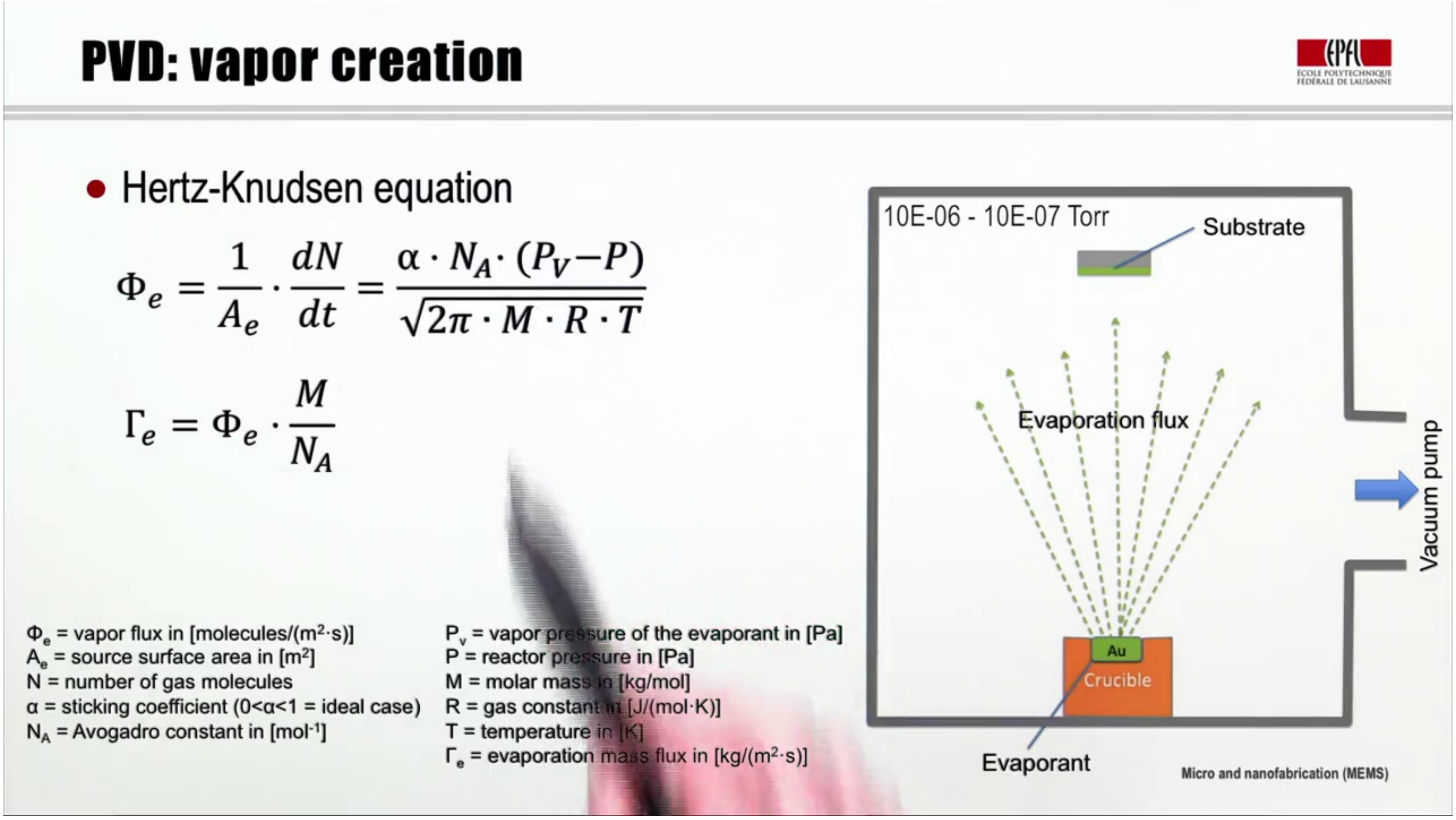


Three stages of PVD thin film deposition

1. Vapor creation
2. Vapor flux towards substrate
3. Condensation on the substrate

Micro and nanofabrication (MEMS)

So how do we get from the source of metal to a well controlled thin film on the wafer like shown here in grey. This is done by so called evaporation. Let’s take gold as an example. Evaporation occurs when the atoms of the evaporant achieve sufficient energy to overcome the solid and liquid binding forces and enter the gas phase. By drawing here. This is physically achieved by heating the material, but just heating is not enough for our purpose even at very high as you will see. In this process, we have to consider three distinct phases as follows. First of all, how is the vapor created? Second, how the vapor flux is directed towards the substrate? And third, how the material condensates on the substrate to form a thin film. So let’s look at these steps one by one in detail now. As said, we will set gold as an example material but everything applies to other materials as well, just with different parameters and specificities.



PVD: vapor creation

- Hertz-Knudsen equation

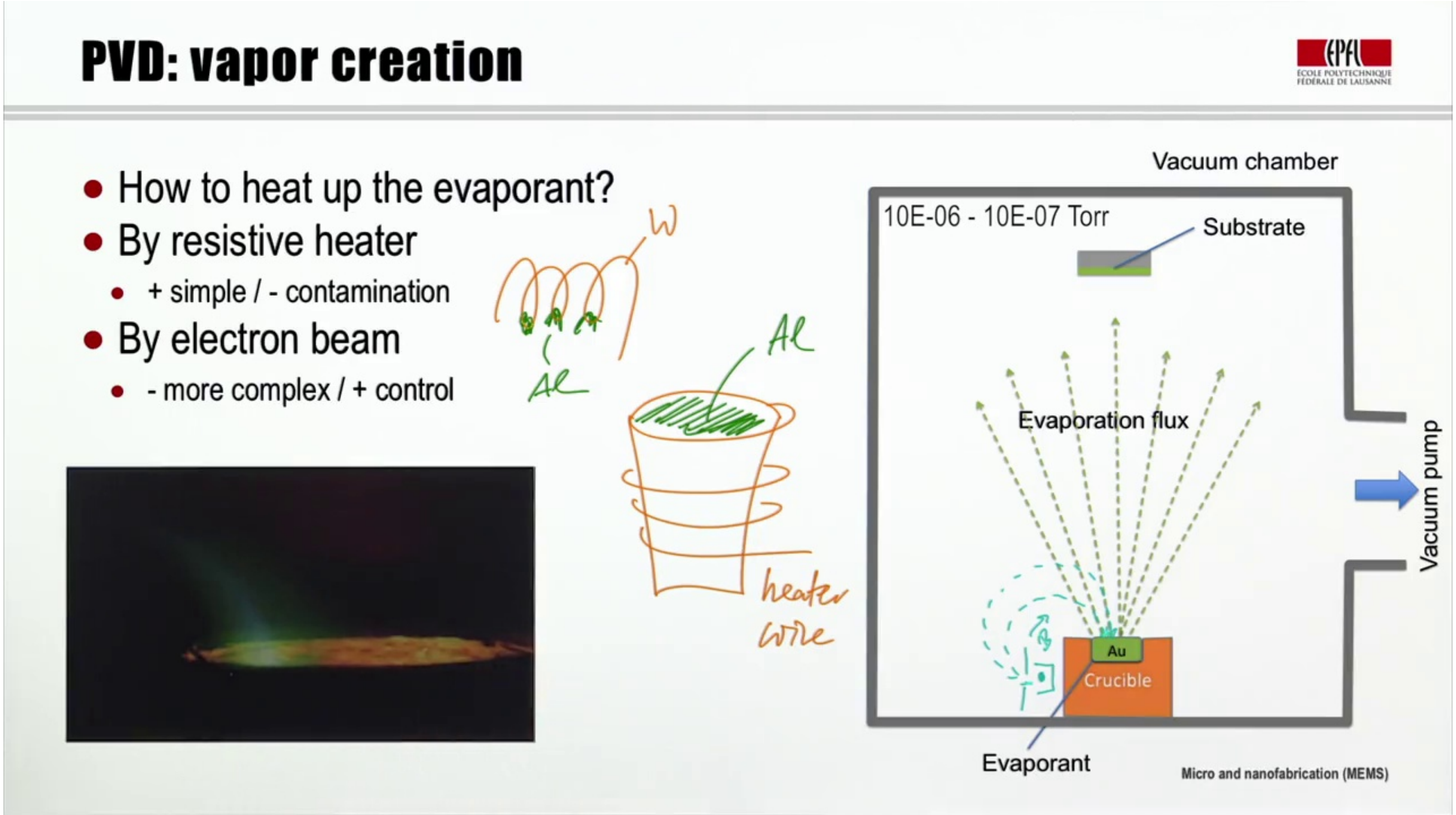
$$\Phi_e = \frac{1}{A_e} \cdot \frac{dN}{dt} = \frac{\alpha \cdot N_A \cdot (P_V - P)}{\sqrt{2\pi \cdot M \cdot R \cdot T}}$$

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

Φ_e = vapor flux in [molecules/(m^2·s)]
A_e = source surface area in [m^2]
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/(m^2·s)]

Micro and nanofabrication (MEMS)

The transformation of a material from condensed phase, either solid or liquid into vapor is described by the Hertz-Knudsen equation. In fact, it was found experimentally that the vapor flux Phi is proportional to the difference between Pv and P. Where Pv is the equilibrium vapor pressure of the evaporant at temperature T, and P is the reactor pressure. It further depends on a series of parameters that are all listed here below. Another convenient way to quantify the deposition parameters is to use the evaporation mass flux in gamma, which is the vapor flux multiplied by the molar mass divided by the Avogadro number. It was found that the evaporation rate does not increase further by supplying more heat unless the equilibrium vapor pressure is also increased by this action. Thus, there is a maximum evaporation rate set by Pv and can only be achieved in a vacuum where P approaches 0. For highest vapor flux, one therefore operates the evaporation in a vacuum chamber and by heating up the material in the Crucible. Another advantage to operate in a vacuum is to avoid any contamination of the evaporant with residual gases. Please note that according to the formula, heating up should actually decrease the flux because T is in the denominator but this is compensated by the fact that Pv also increases with T.

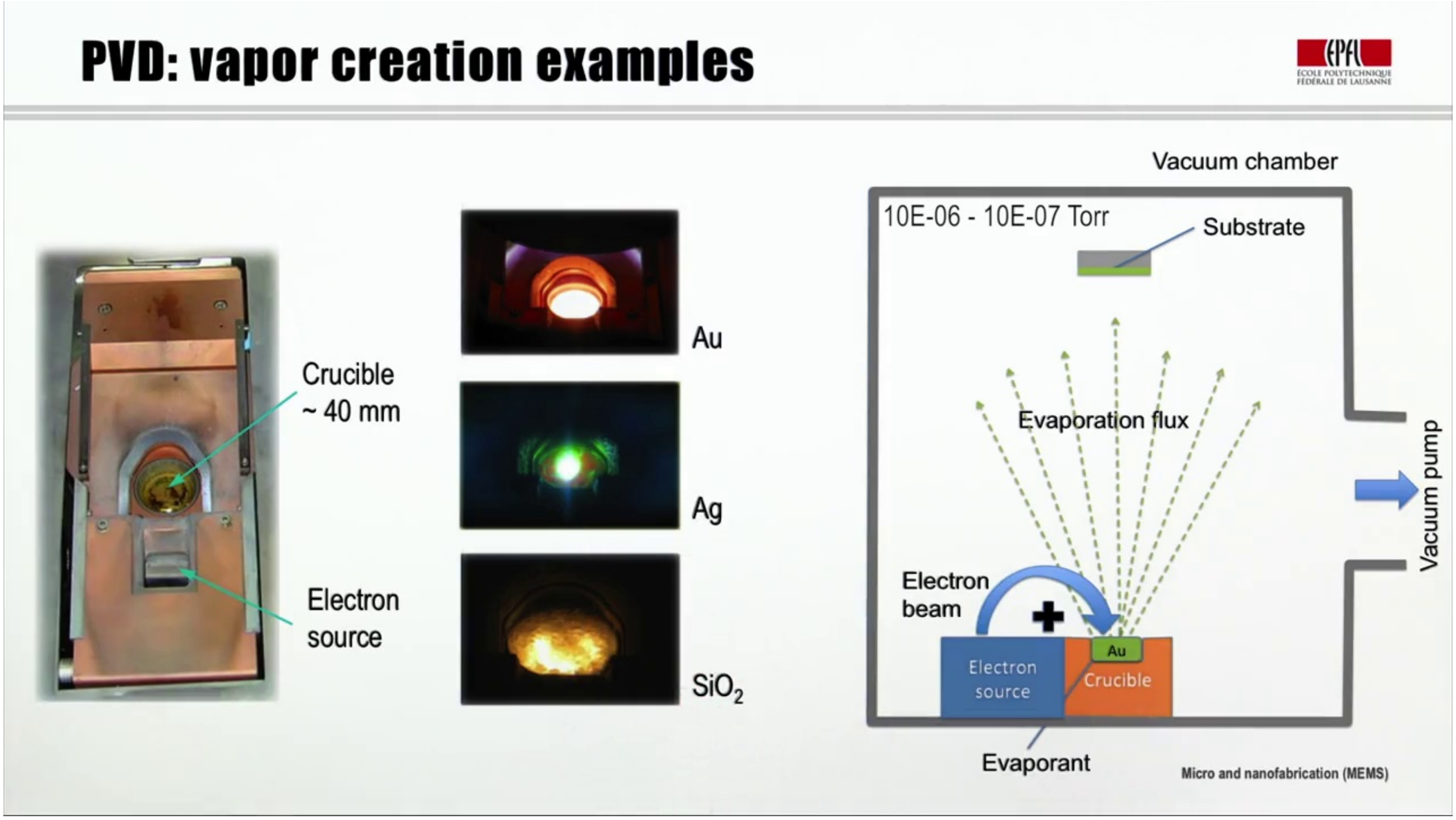


PVD: vapor creation

- How to heat up the evaporant?
- By resistive heater
  - + simple / - contamination
- By electron beam
  - - more complex / + control

Micro and nanofabrication (MEMS)

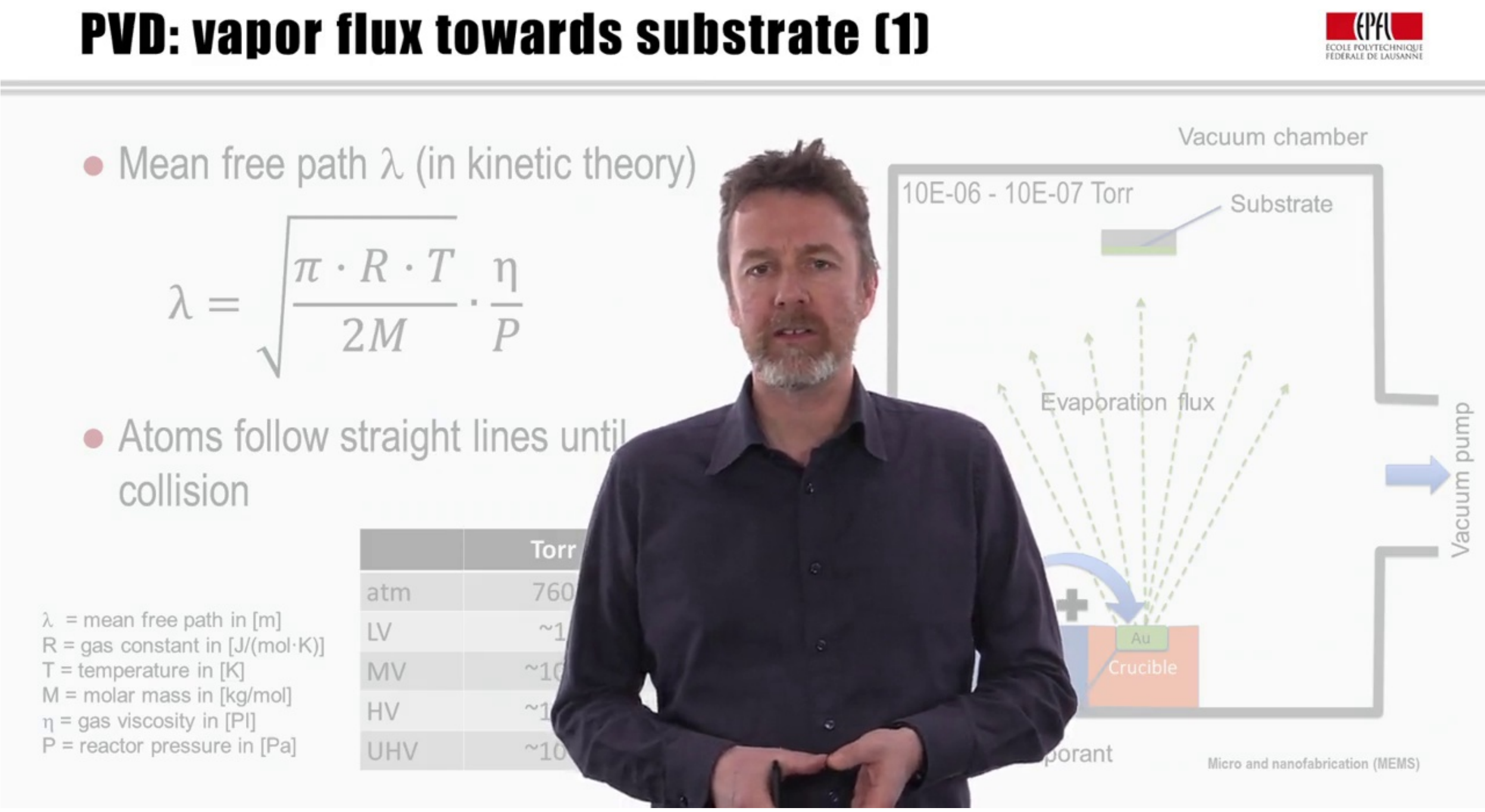
There are various ways to heat up the material to evaporate. One simple way is to wrap some evaporant material around a tungsten wire like shown here but which has a limited source lifetime. Therefore, one typically places the evaporant material in a so-called crucible or boat, which is made of a robust material that resists to very high temperature, meaning that it is not evaporating itself. Heating can be achieved by passing a current either around the bolt or by directly passing a current through the crucible that warms up and evaporates then the metal. This technique is simple, but has the drawback that there's a possible risk of alloy formation and contamination as we heat the entire container. Therefore another way has been developed which is based on the use of an electron beam to create the current that heats up the evaporant. So assuming here is an electron emitter, with a corresponding anode that accelerates the electrons, now the electrons are... have a trajectory that can be controlled by a magnetic field so that they hit the metallic target and close the current loop. So this induces the heat that melts the metal in the crucible. By changing magnetic field, one can scan the electron beam to uniformize the heat generation on this molten metal. On this photograph you see nicely, and the electron beam coming from the left and heating the molten metal here, in this crucible. The size of this crucible is in the order of four centimeters.



PVD: vapor creation examples

Micro and nanofabrication (MEMS)

The library of materials that can be evaporated is quite extensive and includes not only refractory metals but also dielectric and organic material. See the accompanying documents for an overview of operation material and their corresponding specific parameters. On the left, you can see a crucible with the electron source. As we use it in our cleaning room evaporator, the typical size of the crucible here, shown here is about 40 millimeter and may depend on the equipment parameters. In the center you can see three optical images showing different materials being heated with the electron beam. This images has been taken from outside the vacuum chambers through a glass window. It is worthwhile mentioning that each material has a very different structure in the crucible. For instance, SiO2 is in forms of beads shown here whereas gold and silver are completely molten under the e-beam current.



PVD: vapor flux towards substrate (1)

- Mean free path λ (in kinetic theory)

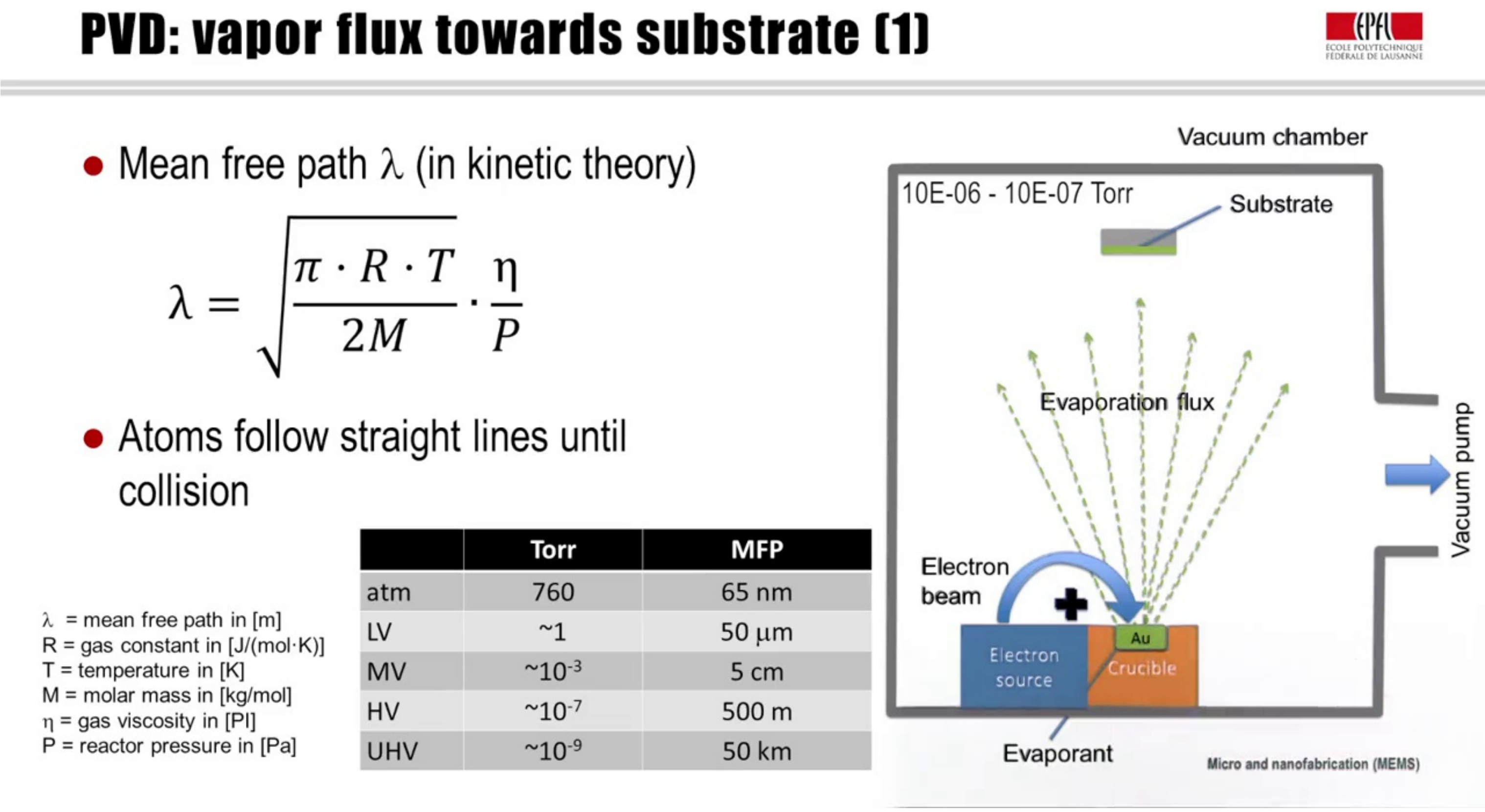
$$\lambda = \sqrt{\frac{\pi \cdot R \cdot T}{2M}} \cdot \frac{\eta}{P}$$

- Atoms follow straight lines until collision

λ = mean free path in [m]
R = gas constant in [J/(mol·K)]
T = temperature in [K]
M = molar mass in [kg/mol]
η = gas viscosity in [Pl]
P = reactor pressure in [Pa]

	Torr
atm	760
LV	~1
MV	~10
HV	~1
UHV	~10

This photo shows for instance how gold looks like as evaporant material when it is placed in the crucible before it is heated and molten. Atoms leaving the evaporant source into the vacuum follow straight line paths until they collide with other gas molecules or strike the substrate or the wall of chamber, condense there, and form a solid thin film. In Kinetic theory, one can define a distance that an object travels between collisions with other moving objects.



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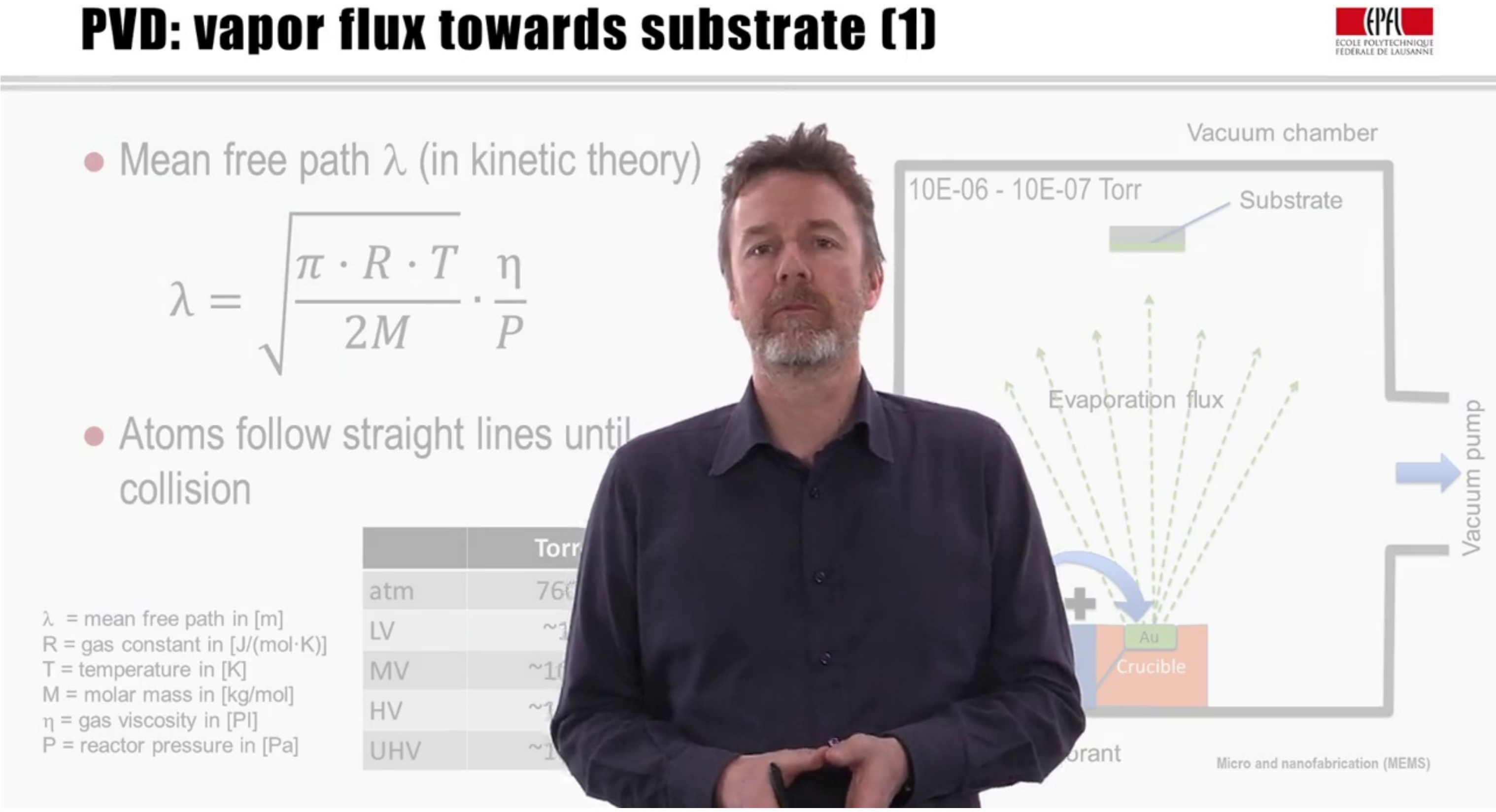
P = reactor pressure in [Pa]

	Torr	MFP
atm	760	65 nm
LV	~1	50 µm
MV	$\sim 10^{-3}$	5 cm
HV	$\sim 10^{-7}$	500 m
UHV	$\sim 10^{-9}$	50 km

Micro and nanofabrication (MEMS)

This leads a mean free path, expression of lambda that is shown here, which primarily depends on the gas viscosity the molar mass, and last but not least, on the reactor pressure. So if we have less collisions, that means the deposit is more directional. This is one of the primarily characteristic of the vacuum evaporation and has some consequences for particular cases as you will see. One of them is that there's a certain risk of shadow formation. This table give an overview of various mean free path values as a function of chamber pressure. At atmospheric pressure, we have very short mean free path, and so the molecules are bouncing into each other and the average, every 65 Nanometer of travel if you go to low vacuum, or medium vacuum and high vacuum for example, we can already gain mean free path of several meters. So our chamber that we built is typically a half meter, one meter, in size. So an atom or molecule leaving the evaporant's source, will not have any collision before it hits the substrate surface. That means this is a very directional flux from the source to the substrate.



PVD: vapor flux towards substrate (1)

- Mean free path λ (in kinetic theory)

$$\lambda = \sqrt{\frac{\pi \cdot R \cdot T}{2M}} \cdot \frac{\eta}{P}$$

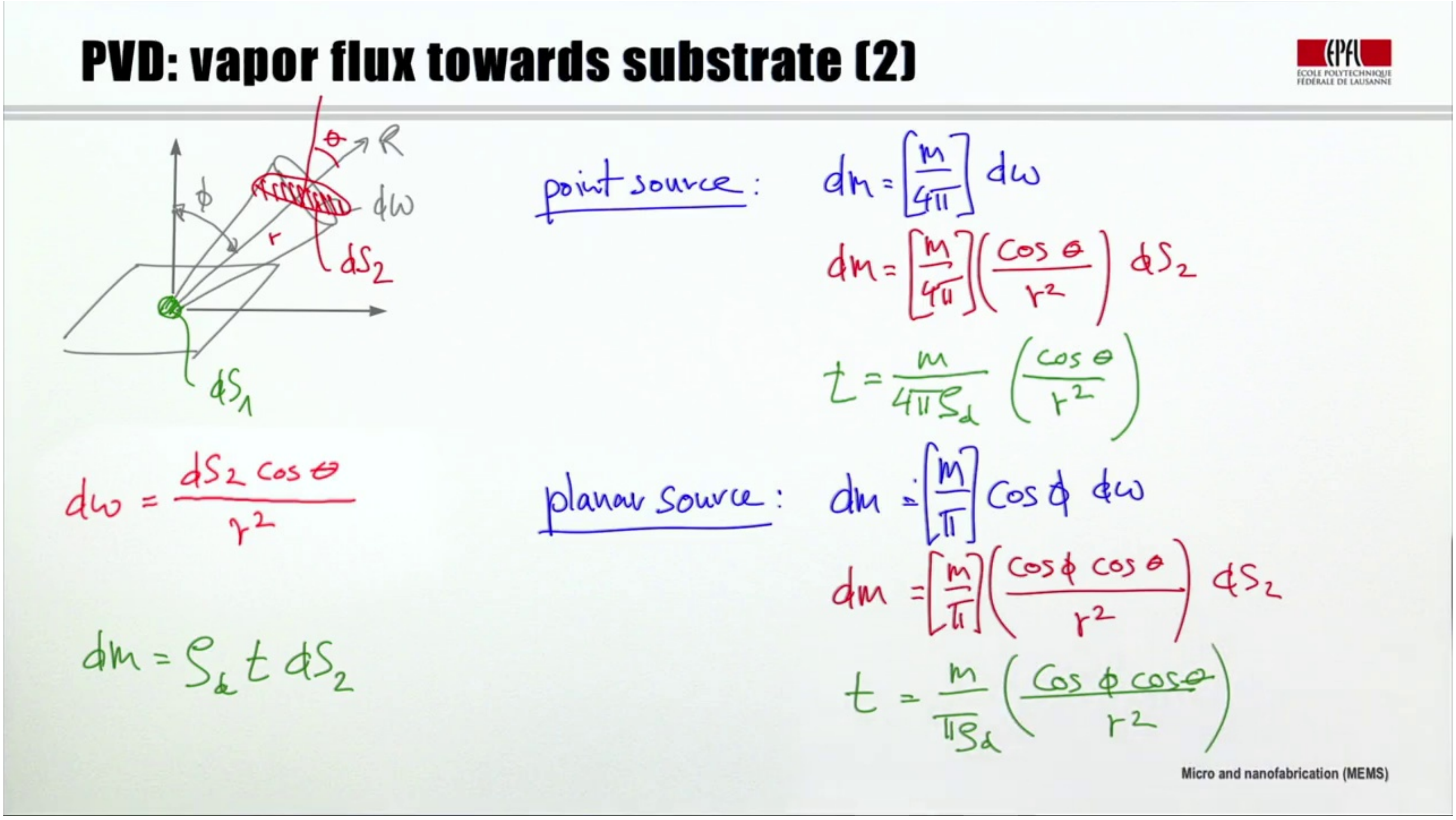
- Atoms follow straight lines until collision

λ = mean free path in [m]
R = gas constant in [J/(mol·K)]
T = temperature in [K]
M = molar mass in [kg/mol]
η = gas viscosity in [Pl]
P = reactor pressure in [Pa]

	Torr
atm	76
LV	~1
MV	~1
HV	~1
UHV	~1

Micro and nanofabrication (MEMS)

In contrast as you will see later, sputtering is performed at higher pressure and involves more collisions of target molecules and ions before deposition. This leads to a very different film morphology. For instance, much less shadowing, which favors smooth film formation.



PVD: vapor flux towards substrate (2)

$$d\omega = \frac{dS_2 \cos\theta}{r^2}$$

$$dm = \rho_d\, t\, dS_2$$

point source:

$$dm = \left[\frac{M}{4\pi}\right] d\omega$$

$$dm = \left[\frac{M}{4\pi}\right]\left(\frac{\cos\theta}{r^2}\right) dS_2$$

$$t = \frac{M}{4\pi\rho_d}\left(\frac{\cos\theta}{r^2}\right)$$

planar source:

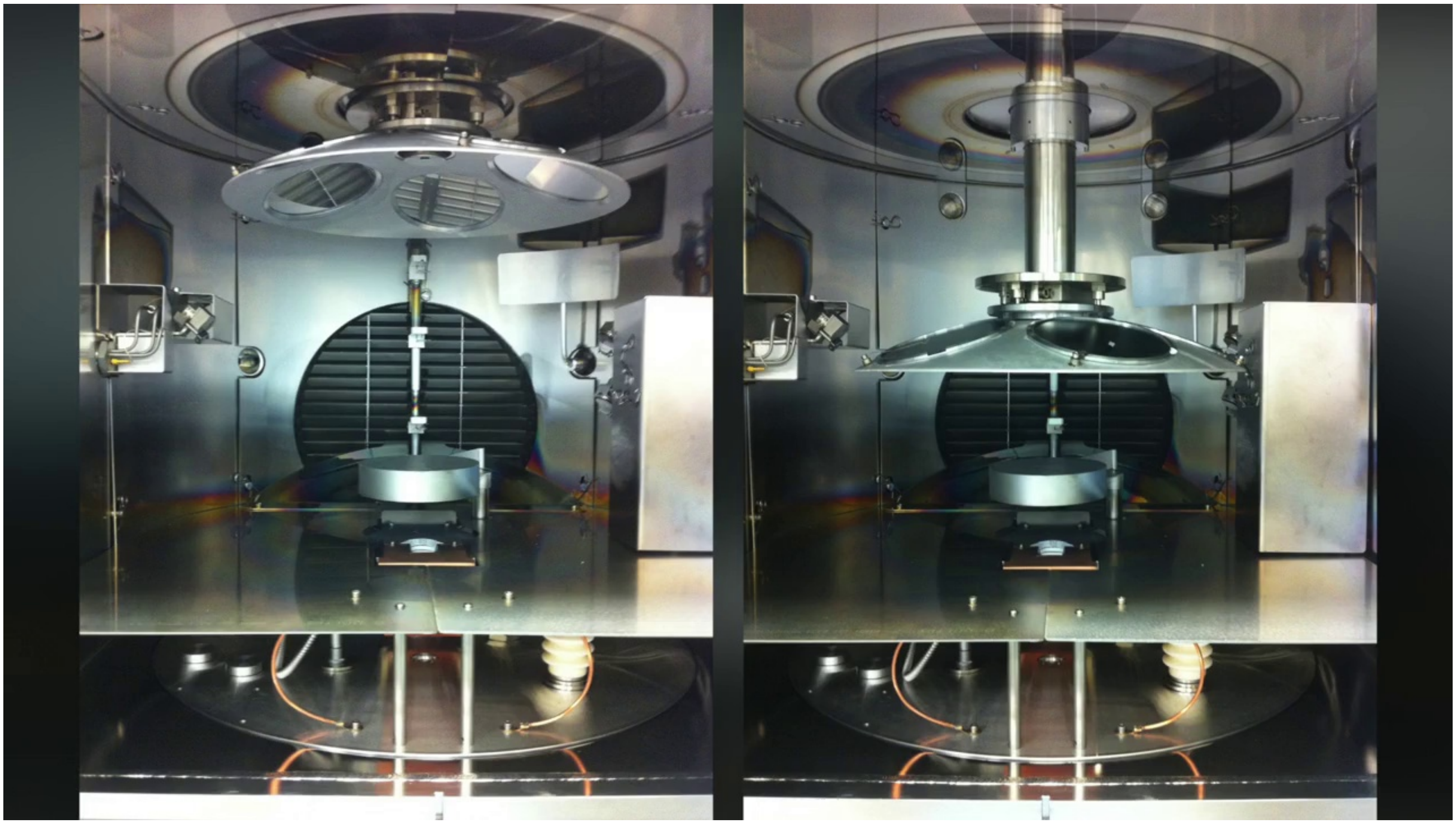
$$dm = \left[\frac{M}{\pi}\right] \cos\phi\, d\omega$$

$$dm = \left[\frac{M}{\pi}\right]\left(\frac{\cos\phi\cos\theta}{r^2}\right) dS_2$$

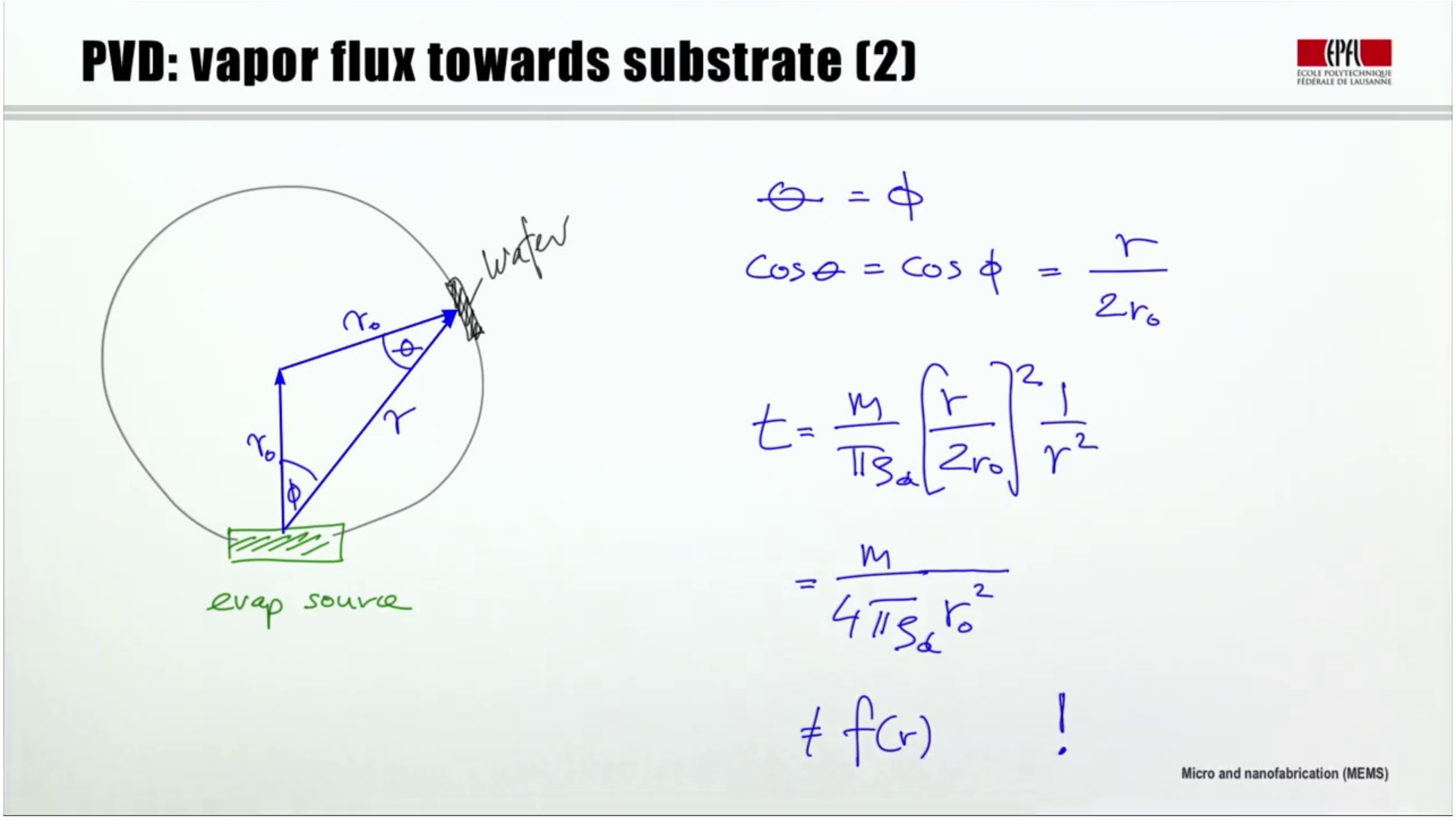
$$t = \frac{M}{\pi\rho_d}\left(\frac{\cos\phi\cos\theta}{r^2}\right)$$

Micro and nanofabrication (MEMS)

Let’s now consider how we can derive the thickness of the film, deposited from an evaporation source. Consider a small sphere dS1 that evaporates material in all direction at a given rate as shown here. We call such an evaporation source, a point source. In this case, the material passing through a solid angle d_omega, in any direction per unit time is given by this equation. In reality, the evaporation comes from a plane source with the area dS1, and the material is evaporated from one side with a certain rate. In this case, dm can be written as the following. In the case, the material flux arrives at a small area dS2 on a surface that is inclined by an angle theta with respect to the normal to the direction of the vapor stream as shown here, we can write the equations as follows. And we can rewrite the two equations for the point source and the planar source as follows. So how can we now get to the thickness of the film, let’s assume that the material has a density rho_d, in grams per cubic centimeter and the film thickness per unit time is T in centimeter per second. Then the volume of the deposit on dS2 must be T times dS2, and we can rewrite dm as follows. Then our two formula for the planar source and the point source can be rewritten finally as shown here in green.



For high throughput integrated circuit and MEMS processing, we need to be able to coat large numbers of wafers, each requiring a uniform film thickness. In this case, we use a planetary system that consists of rotating spherical sections. The principle behind is shown here.



PVD: vapor flux towards substrate (2)

$$\theta = \phi$$

$$\cos\theta = \cos\phi = \frac{r}{2r_0}$$

$$t = \frac{m}{\pi \rho_d}\left[\frac{r}{2r_0}\right]^2 \frac{1}{r^2}$$

$$= \frac{m}{4\pi \rho_d r_0^2}$$

$$\neq f(r) \qquad !$$

Micro and nanofabrication (MEMS)

The receiving service is spherical, having a radius r0 that includes also the planar source. We can already state that the angle phi equals the angle theta and we can write cosine phi equals cosine theta is given by r over 2r0. Taking what we did use in the previous slide, we can rewrite now the thickness like follows. So the thickness is independent from the radius r. That means that the deposition rate is the same for each point on the spherical surface. Thereby, a uniform film thickness can be obtained also for a large number of wafers. In a real evaporator system, the wafers are arranged therefore in a spherical holder called planetary, as you will see in the next section of this chapter in more details.
