

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



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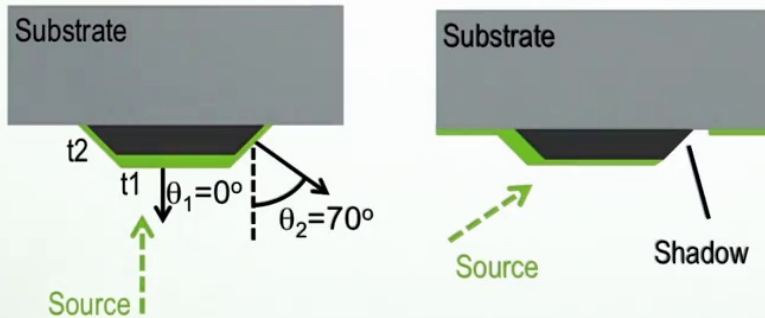
- Thermal (or vacuum) evaporation
 - Physical principles
 - Equipment
 - Vapor creation
 - Vapor flux
 - Film formation
 - Examples

Micro and Nanofabrication (MEMS)

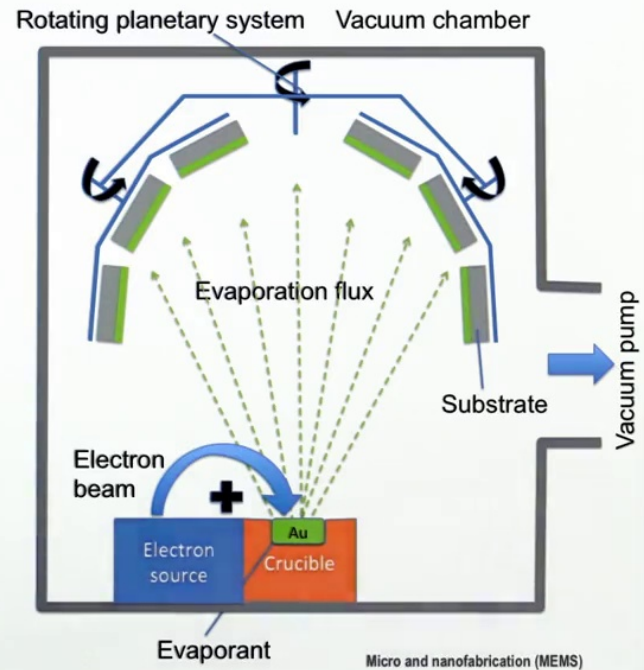
Now let's have a look in detail how the film forms on the surface. As mentioned before, the long mean free path allows for very directional flux of evaporant. This has an effect for surfaces that are not perfectly flat as often encountered in MEMS and microfabrication with 3D surface features.

PVD: Condensation on the substrate

- Non-uniform step coverage
- Shadowing



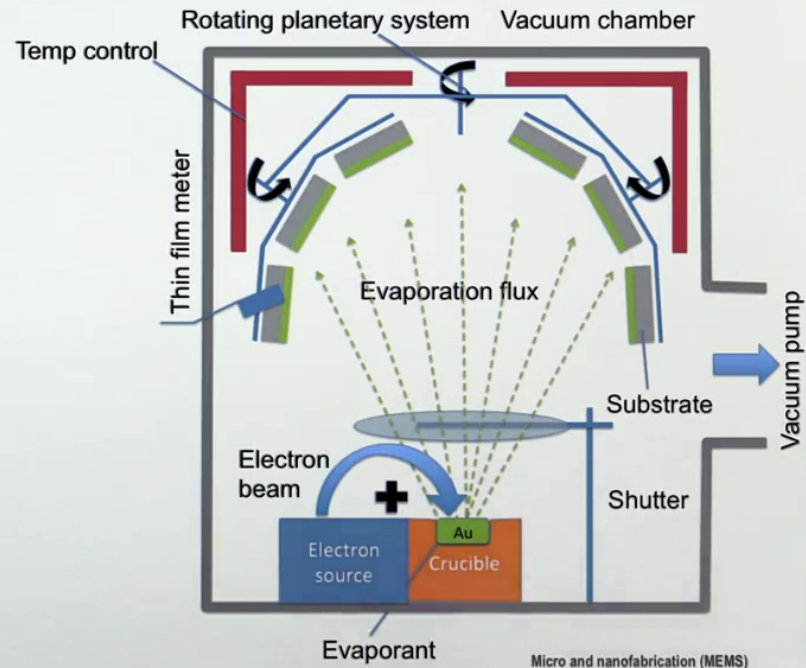
$$\frac{t_1}{t_2} = \frac{\cos(\theta_1)}{\cos(\theta_2)} \approx 3, \text{ when } \phi = 0^\circ, \theta_1 = 0^\circ, \theta_2 = 70^\circ$$



The left image shows a situation for a tapered surface structure in grey, that has to be coated by the thin film in green with the source coming from the bottom. Now, by simple geometrical consideration, one can already see that on the flat part, that is facing the source, we obtain the target of thickness t_1 , whereas on the sloped part of the structure, we have a thickness of only about one third of the target thickness in the case of an angle of 70 degrees like shown here. This can be calculated simply by geometrical considerations. Another important case is the off-axis position of the wafer, which we always have in this sort of arrangement, is that if we have surface features we can create a shadow effect because of the directionality of the beam, which can not deposit on the lee side of this structure. Consequently, there is a much thicker film deposited on the slope, facing the source, than on the slopes that are under an angle to the source or actually invisible to the source. To overcome this important drawback, modern evaporator tools are equipped with rotating planetary systems as shown here which repositions the wafers during the evaporation and cancels the aforementioned effects. Thus, every wafer in the planetary system receives the exact same amount of material under various angles which yields a well controlled film thickness across a wafer's surface, and from wafer to wafer in a batch.

PVD: other equipment specs

- Shutter
- Thickness monitor
- Temperature control
- Pressure control
- Gas inlets for reactive evaporation
- Stress optimization



In addition to the basic configuration of a thermal evaporator, there are some other features that have been incorporated for better control and monitoring. One of them is the mechanical shutter shown here that blocks the flux between the crucible and the wafers and allows for very precise timing of the deposition. It's much more precise than switching on and off the heat source. Another important feature is the thin film monitor, typically a quartz crystal microbalance that measures the added mass which can then be used to deduce the thickness that has been added on each of the wafer. We can furthermore control the temperature of the substrate either by cooling or heating which has an important influence on the film morphology as the thin film grows. Further, we can always control the pressure in the chamber and also inlet some specific gases for reactive evaporation. All these features have an influence on the stress of the thin-film as it grows on the surface and can be optimized if one knows how they influence the growth mechanism.



Here on this photograph, you can see the inside of one of our clean room thermal evaporators. On the bottom you can see the crucible with the mechanic shutter, and on top, you can see the wafer holder system that holds a couple of wafers for thin film coating.



And here you can see a close up photograph of the crucible area with the mechanical shutters. More details of these equipment aspects will be shown later in a dedicated video taken in our clean room.



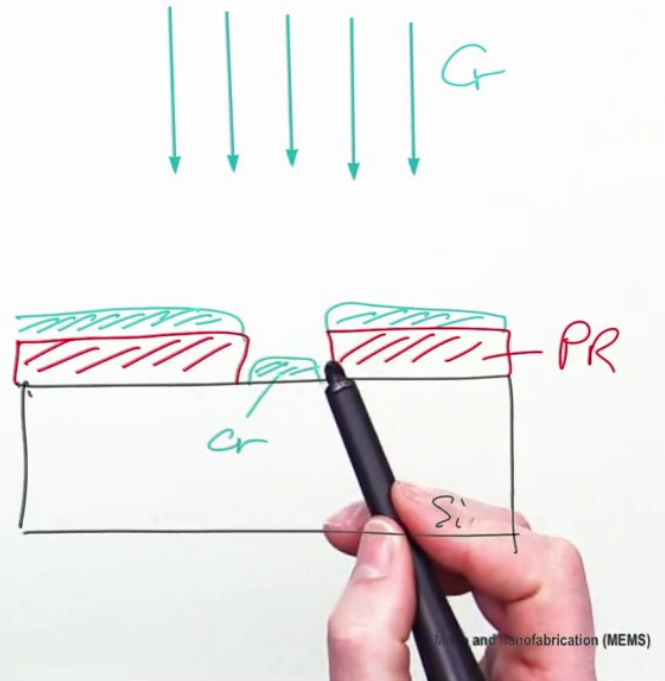
- Thermal (or vacuum) evaporation
 - Physical principles
 - Vapor creation and vapor flux
 - Film formation
 - Condensation on the substrate
 - Examples
 - Lift-off and Stencil lithography
- Sputtering
- Other methods

Micro and Nanofabrication (MEMS)

So now that we have seen the basic principles and equipment aspects of thermal evaporation, let's have a look at some characteristic examples. I want to show you in particular the so-called lift-off technique and then stencil lithography. They both rely and benefit from the long mean free path and shadowing effect that we can obtain in thermal PVD.

PVD: particular example LIFT-OFF

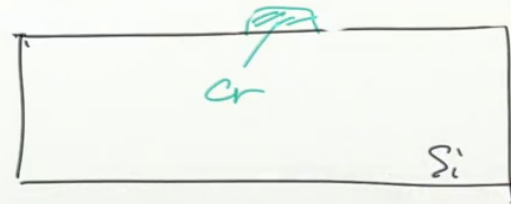
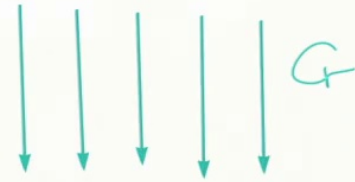
1. Photoresist patterning (Slope!)
2. PVD with shadow effect (directional)
3. Photoresist stripping



Let's have a look at the lift-off which is a particular example where thermal evaporation PVD is very useful. Lift-off is done typically on a substrate like shown here, like a silicon wafer that has been coated with a layer of photoresist and patterned by lithography, it is a photoresist layer that has an opening by lithography and development and now we come with the source that is far away, that emits chromium as material in a vacuum chamber, which deposits now all over the surface and forms a film which has more or less this shape. Where this is chrome. You notice now that the photoresist was designed to have a certain sloped angle which prevents that the directional flux of material creates a bridge from the part of the film that is on the photoresist and part that is directly on the substrate. Now the actual lift-off is then the stripping of the photoresist, which is a liquid, a solvent, that can penetrate

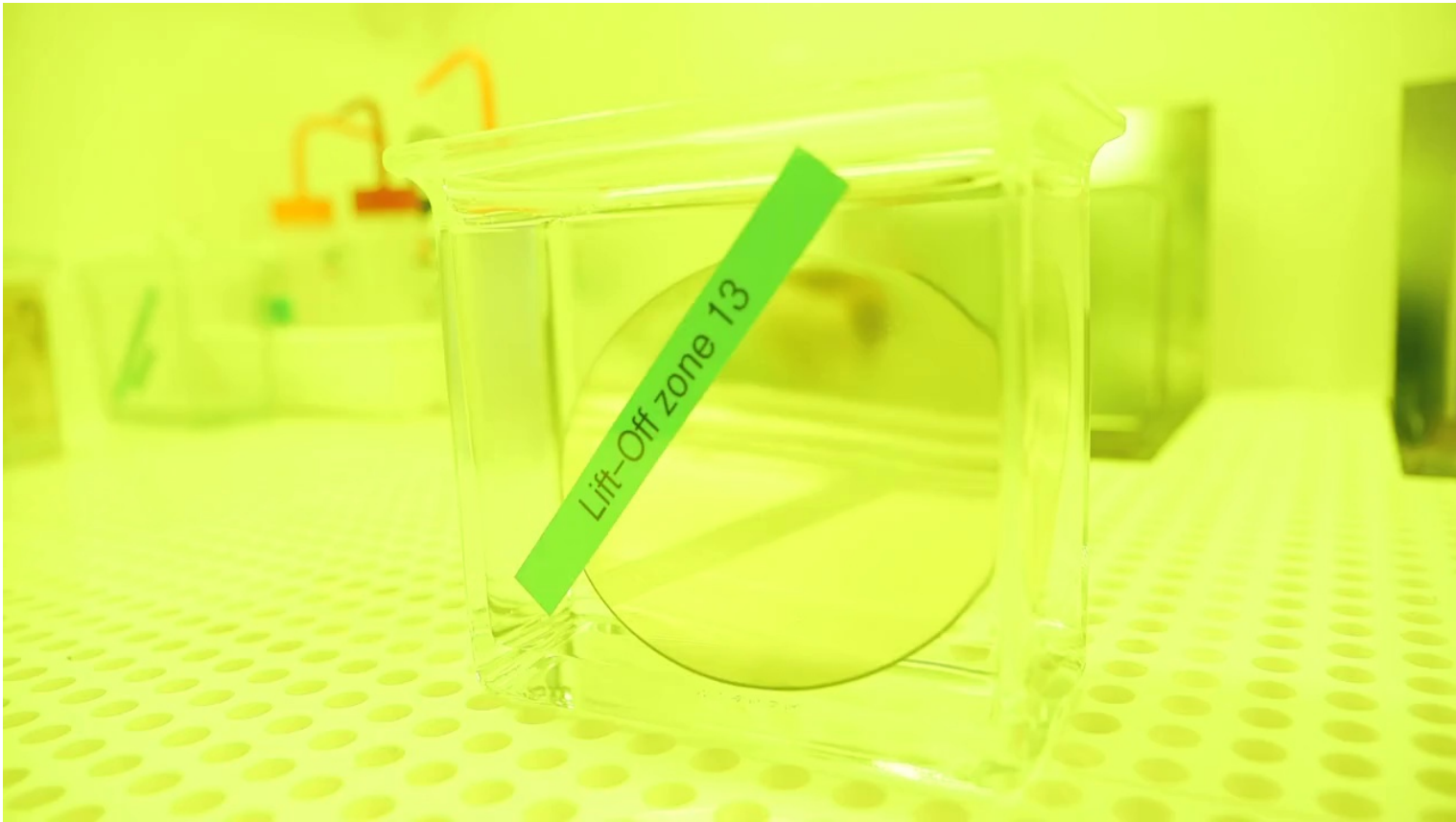
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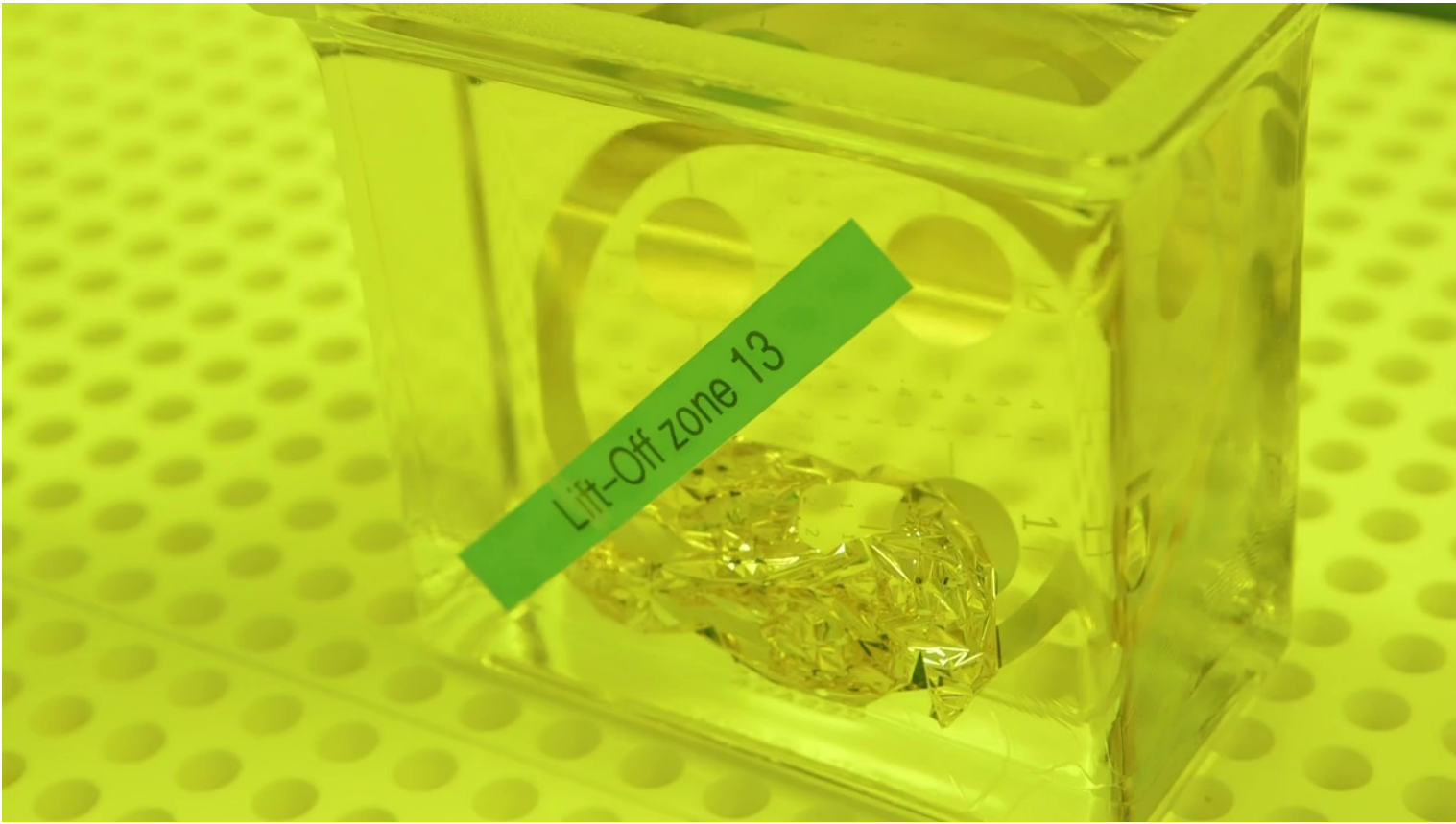


Micro and nanofabrication (MEMS)

through the openings and start to remove the photoresist from this part and removes everything that is also on top of it. And the same on this side. Which leaves us at the end... the chrome pattern that we want and this chrome pattern now has been made simply by one lithography and deposition without the need for etching. Some materials are indeed very difficult to etch so the lift-off is a very convenient way to create micro and nano patterns by this technique.



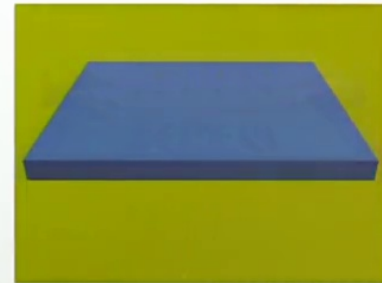
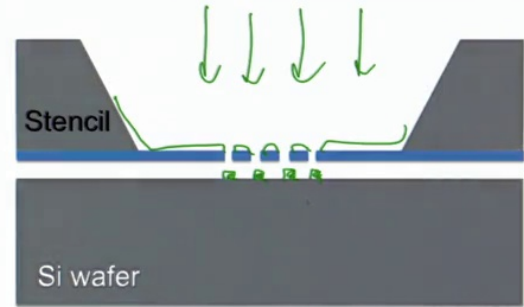
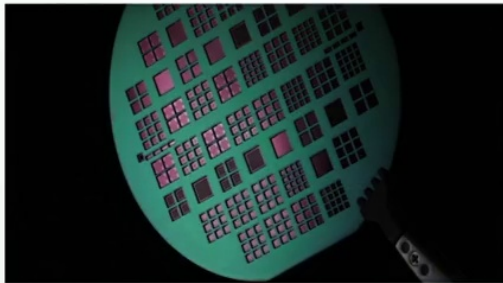
Here you can a live demonstration of a lift-off step in our clean room. A glass wafer has previously been patterned with a photoresist and then coated by PVD evaporation with a thin film of chrome. When placing the wafer in a solvent, for example, Acetone,



that photoresist dissolves after some time and also removes the metal layer on top of it. This lift-off process takes a few seconds depending on the materials involved and the dimensions. It helps to mechanically move the wafer in the bath. Also ultrasound can be applied in some cases . In this step, the appearance of the patterned metal structures

PVD: particular example STENCIL Lithography

1. Align and position stencil
 2. PVD with shadow effect (Long mean free path)
 3. Third: remove stencil
- No heat and chemical process

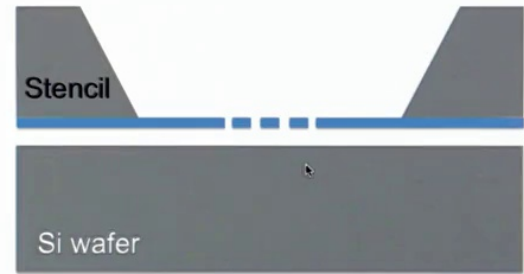
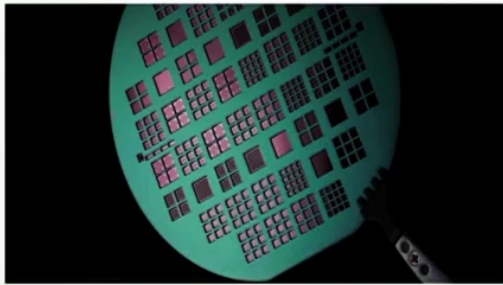


Micro and nanofabrication (MEMS)

The second example that benefits from the long mean free path and the shadow effect in PVD is stencil Lithography which is shown here where a very thin membrane with apertures is approached close to the surface to be coated and then when we get material evaporated with a very directional flux, there is the deposition of the material on the stencil but also through the apertures on the substrate like shown here. The third step would then be to remove the stencil simply mechanically and the surface features are created without any further heat or chemical processes which makes this technique very suitable for patterning fragile substrates.

PVD: particular example STENCIL Lithography

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Micro and nanofabrication (MEMS)

In the animation, you can see now how the, material is deposited through the stencil on the surface leaving their features and the second step here also shows that this stencil technique can be used for local etching.

Evaporation setup details



● Leybold Optics LAB 600H

- 1 x e-beam, 6 pockets
- 1 x resistive heating
- 1 x ion source for IAD + cleaning
- Ag, Al, Au, Cr, Ge, In, Mo, Ni, NiFe, Nb, Pd, Pt, Ta, Ti, Y, Al_2O_3 , ITO, La_2O_3 , MgO , SiO_2 , Ti_2O_3 , Ti_3O_5 , Y_2O_3 , ZrO_2 , MgF_2
- 4 and 6 inches wafers
- Large source-substrate (1010 [mm]) distance for lift-off
- Deposition from RT to 200 [°C] (heaters)
- Cryopump to reach high vacuum of 10^{-6} to 10^{-7} [Torr]
- Quartz-crystal deposition rate monitor

Micro and nanofabrication (MEMS)

Here you see photos of our clean room equipment from thermal evaporation. On the left side is shown the front panel with a loading port and the control panel. On the right photo you see how the equipment looks from the back side with all the connections for pumps, heat sources, monitors, et cetera. A sophisticated equipment like this has many features as you can see here, an e-beam source with the pockets for various materials, resistive heating, then here is a list of possible materials that can be evaporated in such an equipment, it can hold four and six inches wafers. It has a very large distance between the source and the substrate, more than one meter and you remember this is important for the directionality and shadow, and which is therefore very good for lift-off, it can deposit from room temperatures to 200 degrees, and it has a very strong pump to reach a vacuum in the order 10^{-6} to 10^{-7} Torr. And it has the before mentioned quartz, crystal deposition rate monitor.

PVD summary



Simple, fast and affordable technique
No surface damage
Electrically conducting and insulating materials
High purity films

Shadowing
Poor step coverage of non-planar structures
Non-uniformity over large areas
Difficult to evaporate compounds

Micro and nanofabrication (MEMS)

This concludes this part of the PVD lesson on thermal evaporation. You have seen that it is a fast and simple technique to coat a wafer with a thin material film. There is no surface damage, it is done in a high vacuum which yields high purity films. No atoms from the atmosphere are incorporated into the film. Limitations come from the shadowing poor step coverage of high aspect ratio structures, non uniformity over large areas and the difficulty to evaporate compounds because of their decomposition or phase change at high temperature. So let's now have a look in the clean room how such an equipment is operated in details. In the next lesson, I will explain to you how sputtering can be used to form a thin-material film.
