Course material

Course:

Micro and Nanofabrication (MEMS)

Video:

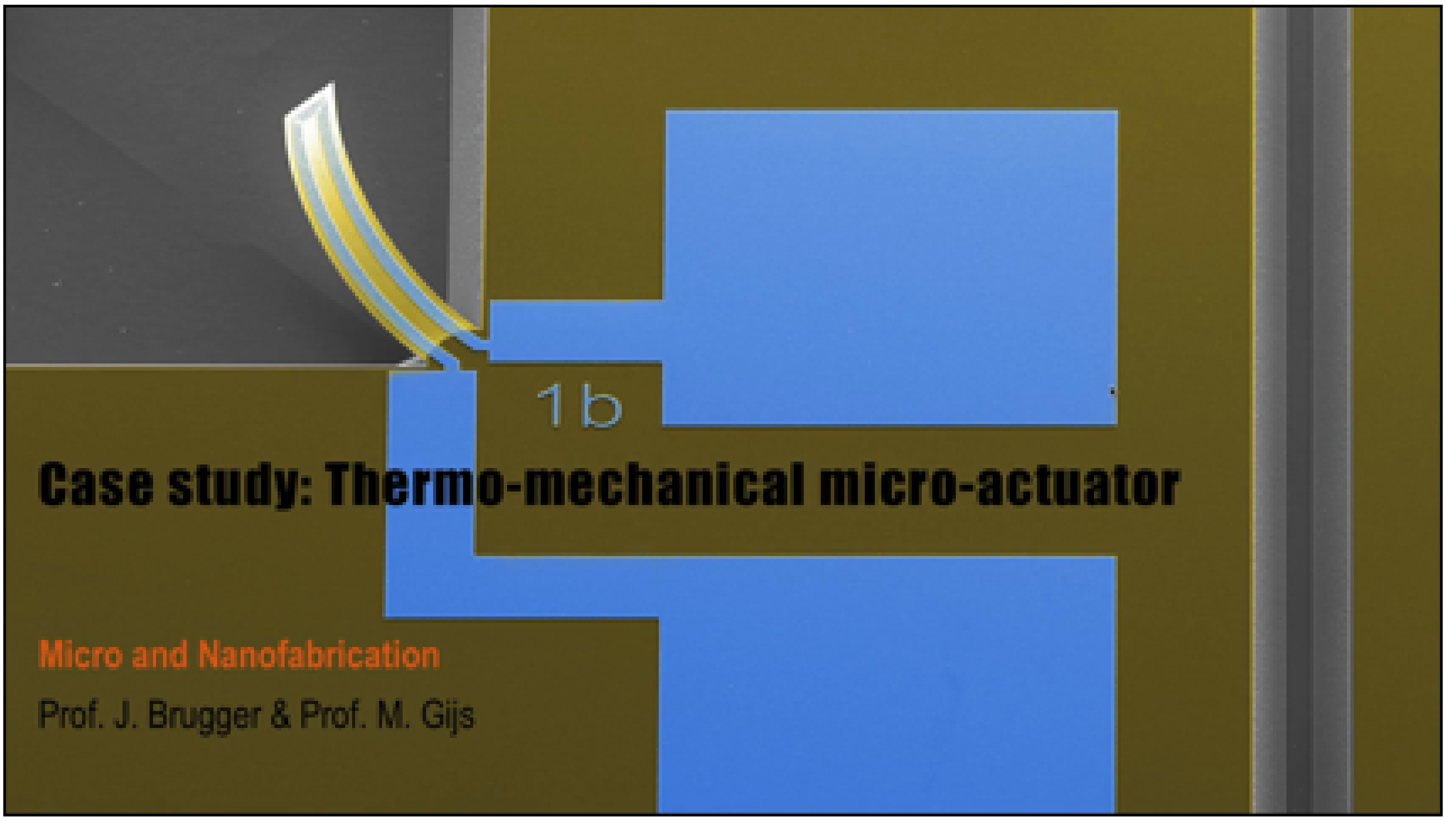
1.4 Case study, Thermo-mechanical micro-actuator

Concepts (extracted from automatically generated subtitles):

Silicon wafer. Curvature radius of the bending. Right hand. Left hand. Right side. Etch selectivity. Radius of curvature. Right photo. Possible fabrication steps. Exposed resist. Silicon dioxide layer. Chrome layer. Well defined sequence of lithography. Exposure mask. Advanced mems processes.

to video sequence search
(within Micro and Nanofabrication (MEMS).)

to video

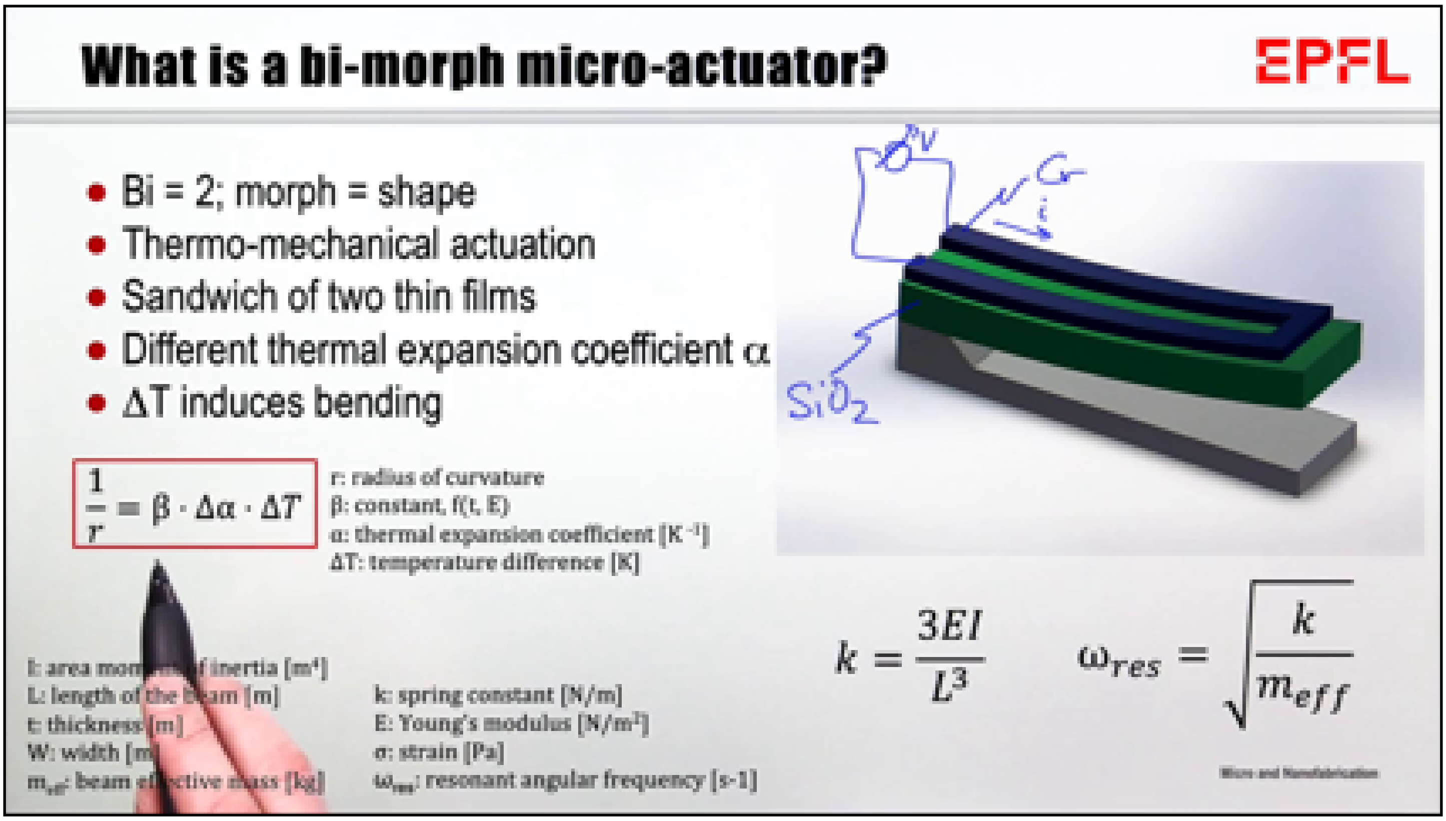


...

notes

summary

0m 0s

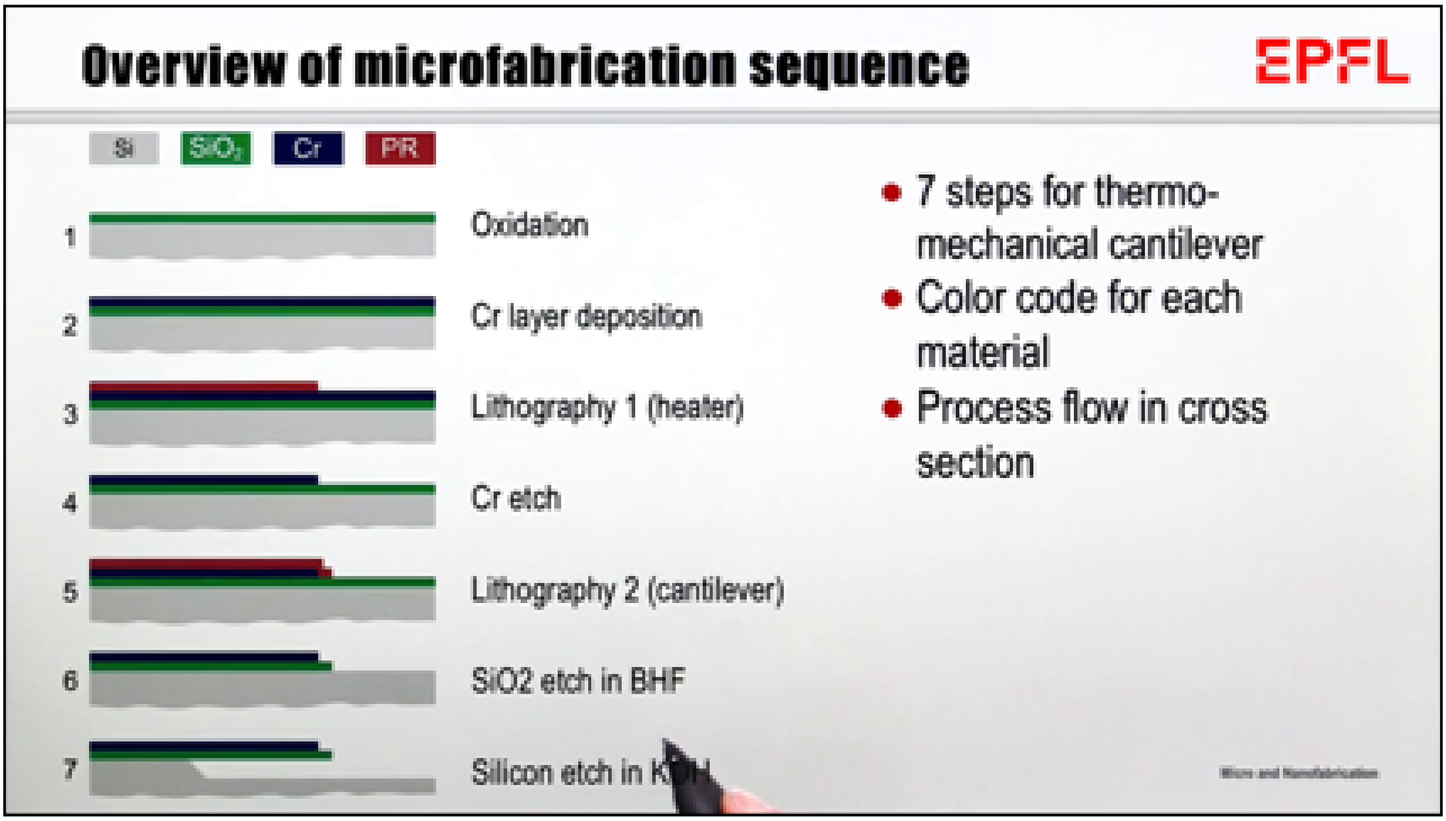


Welcome to this lesson in micro and nano fabrication. The picture behind me shows a colorful SEM image of a bi-morph MEMS actuator. And in the next few minutes, I will show how it was fabricated in our clean room at EPFL. Although it does not involve all possible fabrication steps that are nowadays available in advanced MEMS processes, It initiates you the students to the basics of a process flow. As you will see, the fabrication is a well defined sequence of lithography, thin film deposition, as well as wet and dry etching. In my left hand, I'm holding a silicon wafer before the fabrication. And in my right hand, you see a similar wafer containing hundreds, if not thousands, of MEMS devices like in the background. But before diving into microfab aspects, let's briefly recall how a thermal mechanical device, or bi-morph, actually works. A bi-morph is a device that can take two or more shapes. 'Bi' means 2 in Latin, and 'morph' means shape in Greek. On the right side you see a typical example of a bi-morph made by 2 thin films. In our case, *SiO2* in green, and Chromium in blue. Since both materials have very different thermal expansion coefficients α, they induce a bending when the temperature changes. When you apply a voltage to the Chrome layer... you induce a current that will heat up, this... cantilever, and by the temperature change will induce bending. The curvature radius of the bending can be expressed by a formula shown here. Where the radius of curvature

notes

summary

0m 1s

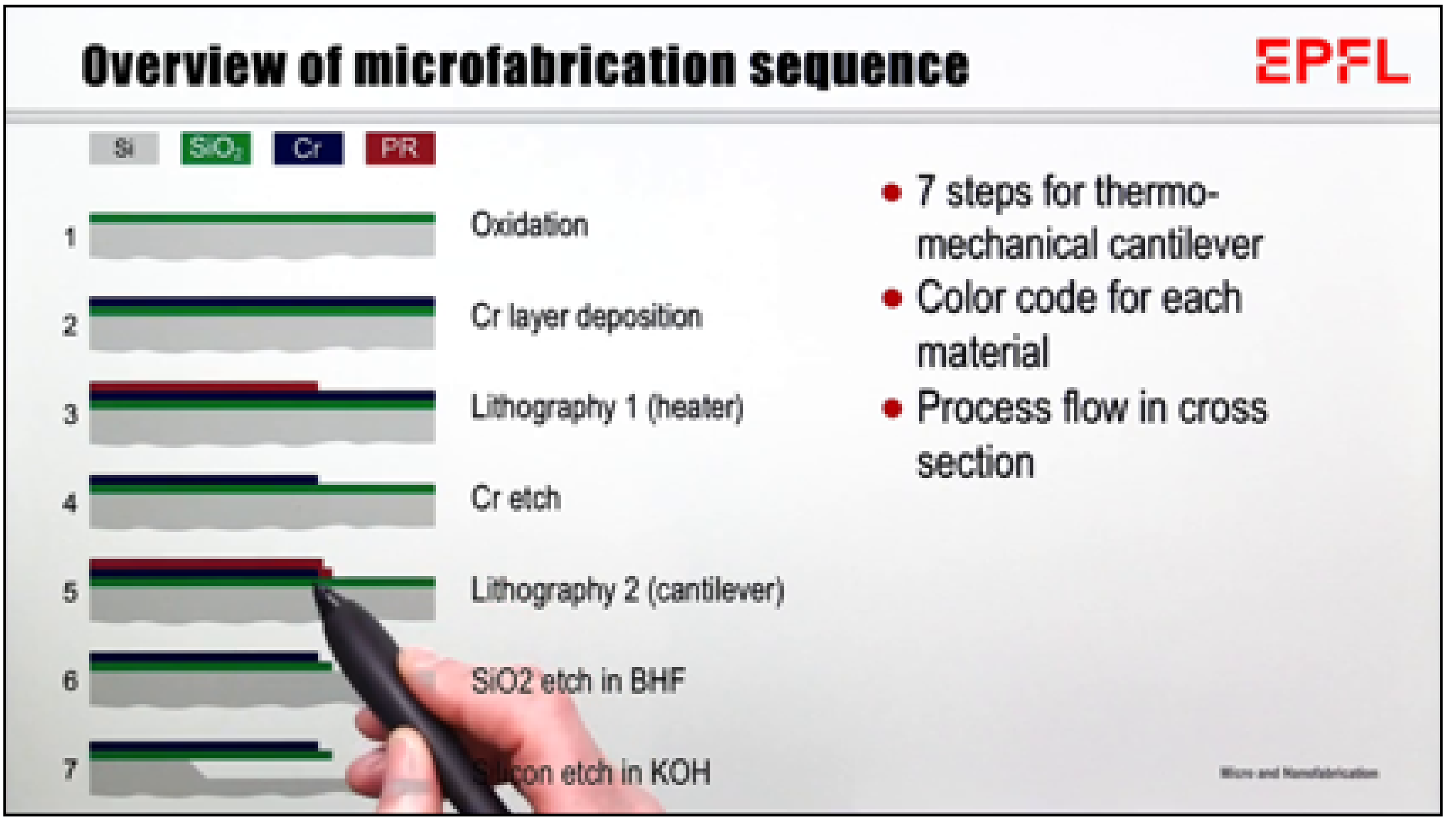


is described by β times the difference in thermal expansion coefficients of the 2 materials, Chrome and Silicon dioxide and the temperature change. β is a constant, as a function of the thickness of the device and its Young's modulus. Other formula to describe the system are the spring constant of the cantilever, and the resonance frequency. And here's a list of all important parameters that can be used to describe the system. In the accompanying documents you can see how this formula can be derived from basic physics. The process flow is typically shown schematically by a sequence of cross section figures. In the case of the bi-morph cantilevers, there are 7 major process steps.

notes

summary

1m 49s

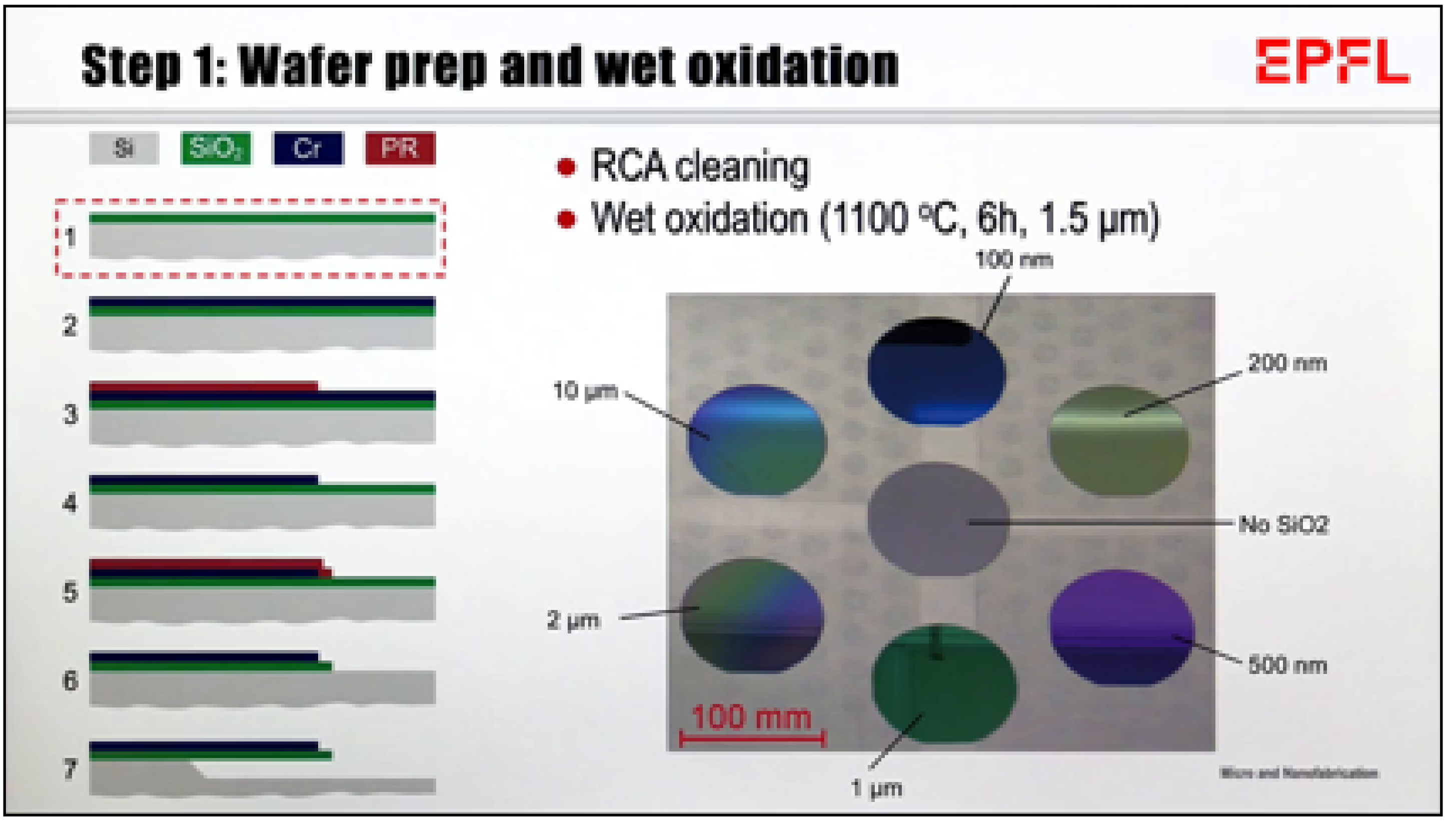


The representation is in principle sufficient to show the effect of added thin films,

notes

summary

2m 37s

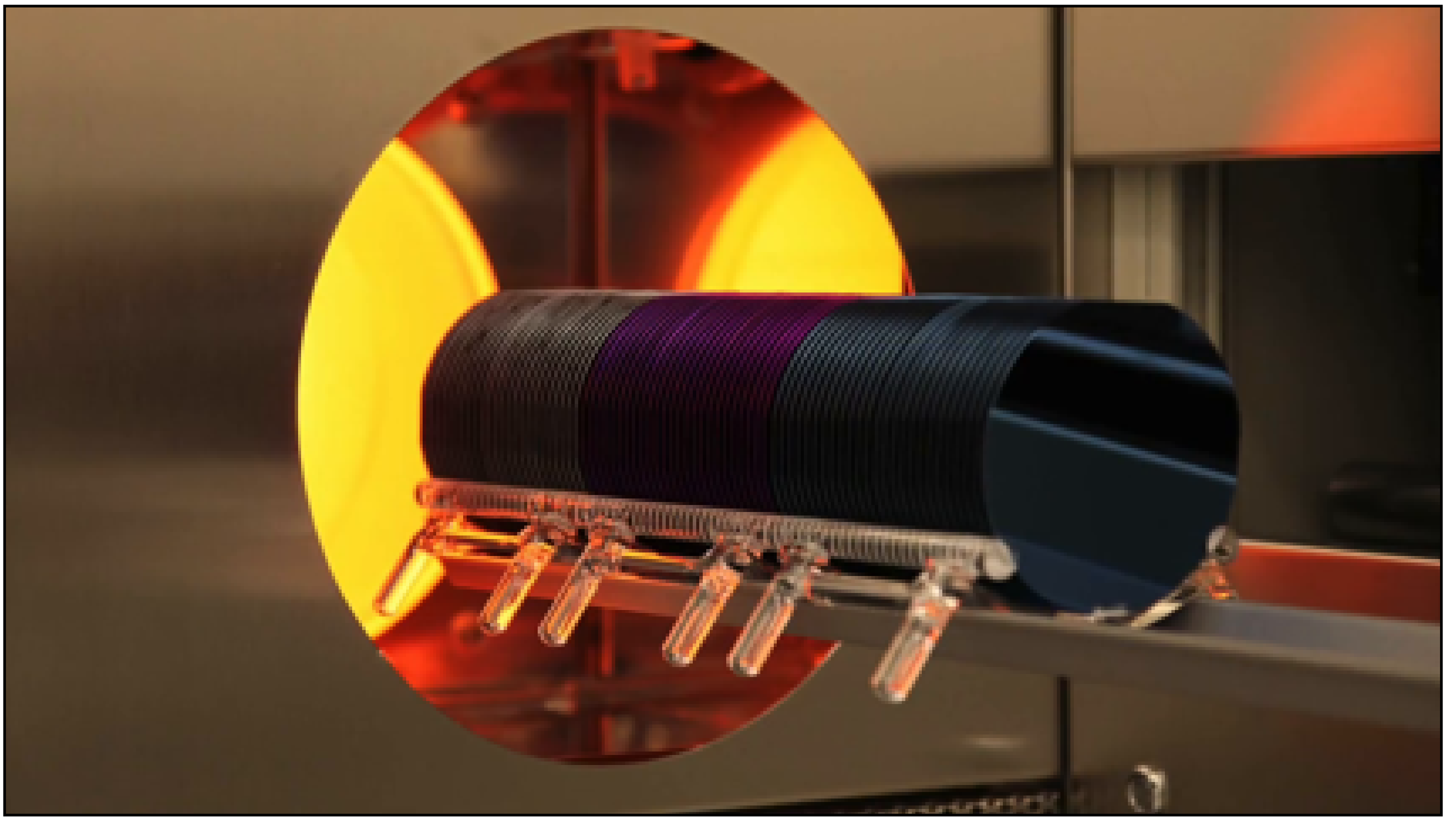


and the effect of wet and dry etching on each layer. Such a document will accompany the wafer during the process To know always exactly at which step of the process the wafer is. And what process parameters have been applied to each wafer. Now let's have a look at each of the 7 steps in detail, 1 by 1.

notes

summary

2m 43s

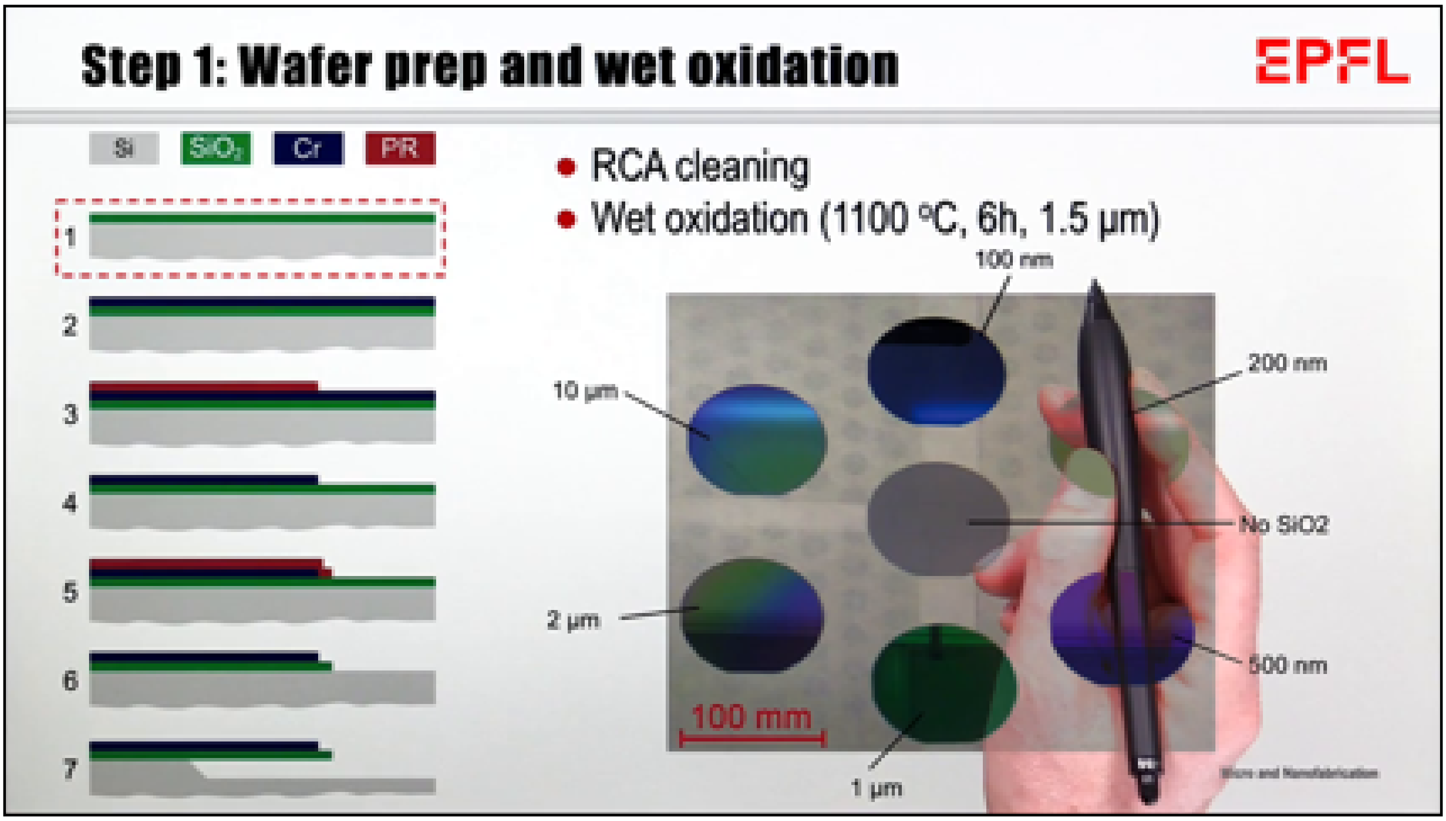


The first step is to grow a Silicon dioxide layer, which will be one of the 2 bi-morph materials. Before the actual oxidation, the wafer is thoroughly cleaned. This process is called RCA cleaning, which is an industry standard since the 1960s, and consists of a couple of steps. Wet oxidation is then carried out in the furnace

notes

summary

3m 3s

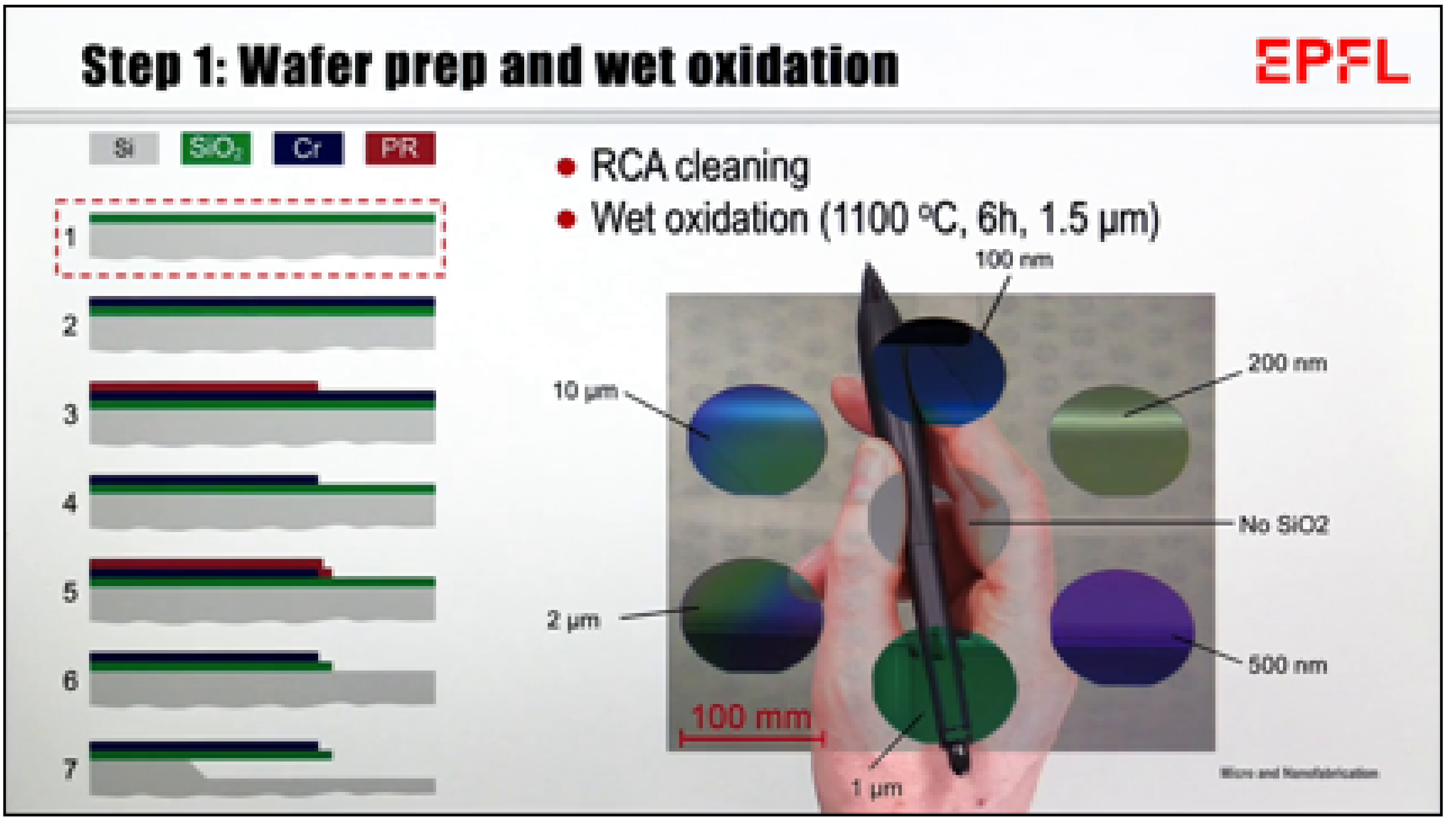


with oxygen rich atmosphere. Silicon on the surface is thereby transformed into a Silicon dioxide layer that grows with time, while consuming the underlying silicon. To form a 1.5 micrometer thick SiO2 layer,

notes

summary

3m 23s

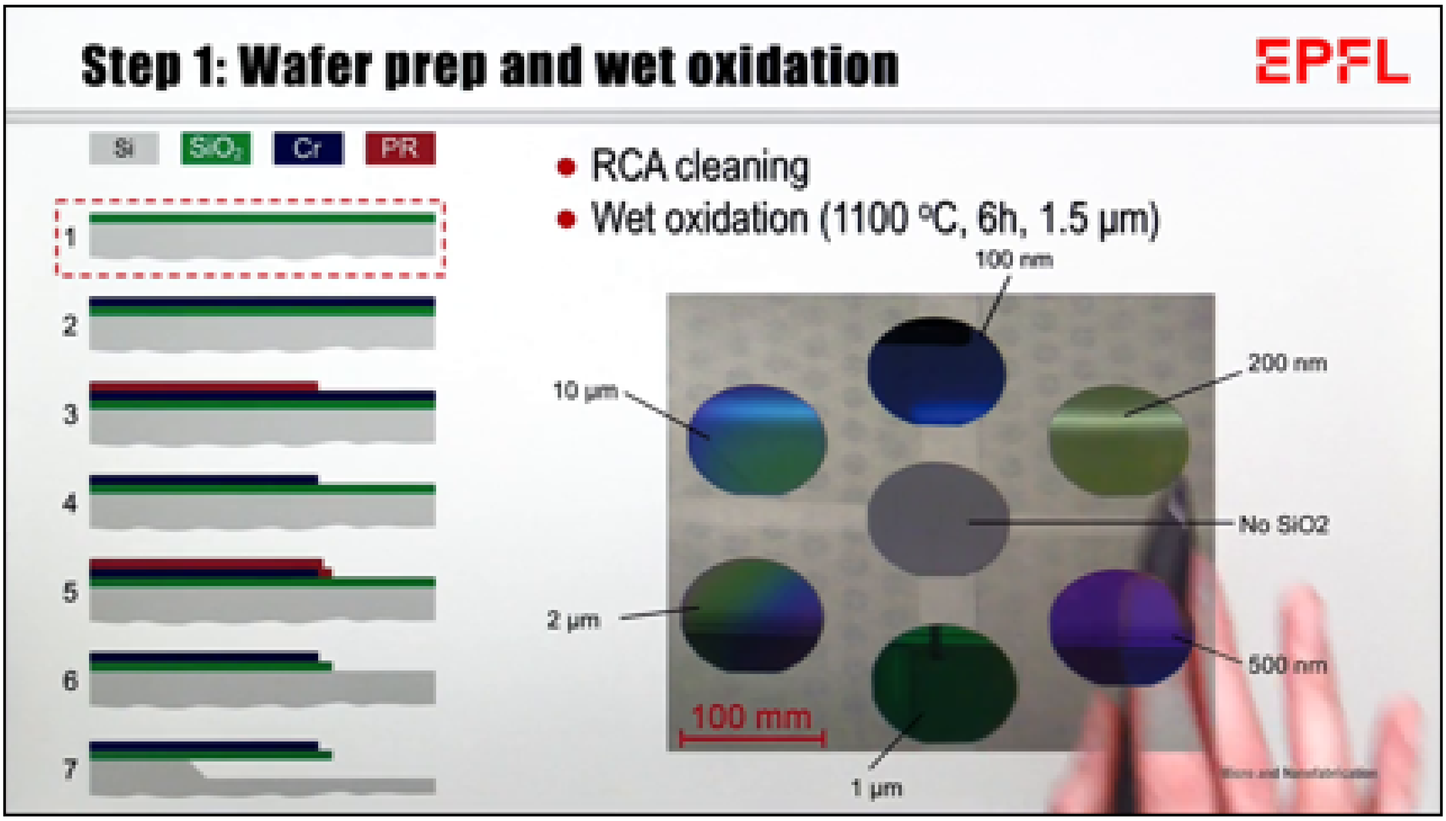


we typically oxidise the silicon wafer during 6 hours at 1100 degrees C.

notes

summary

3m 37s

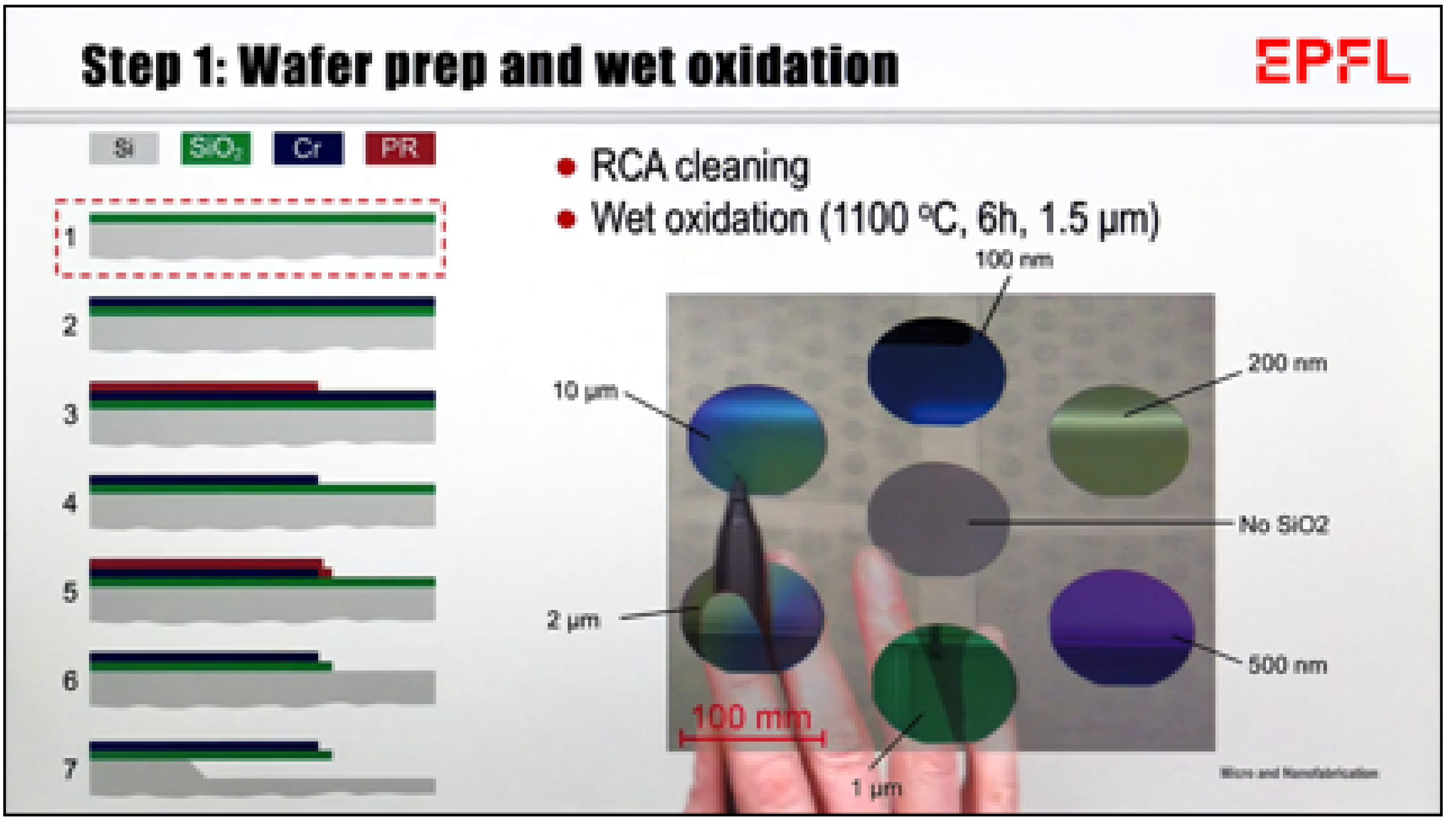


Here you see a couple of silicon wafers, 100 millimeters in diameter or 4 inch. The centre is a silicon wafer without any silicon dioxide, looks grey, and here is a couple of silicon wafers with different silicon dioxide thicknesses

notes

summary

3m 41s

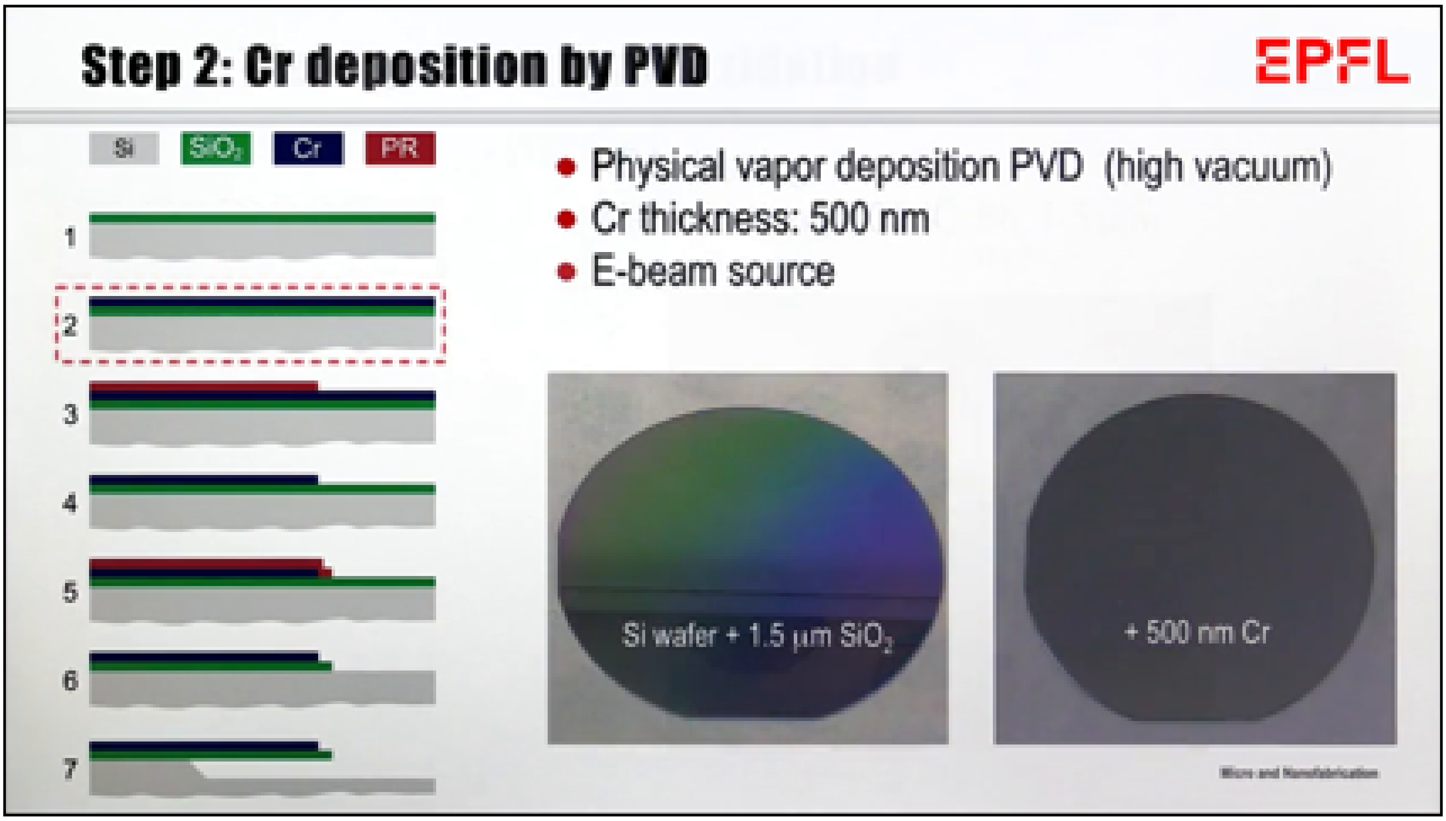


ranging from 100 nanometre, up to 10 micrometre.

notes

summary

4m 1s



We can see clearly the difference in colour, which is due to the interference of the dielectric thin film on the silicon wafer. With experience, one can actually indicate already what thickness the wafer is. However, to measure precisely, one will then rely on an ellipsometer.

notes

summary

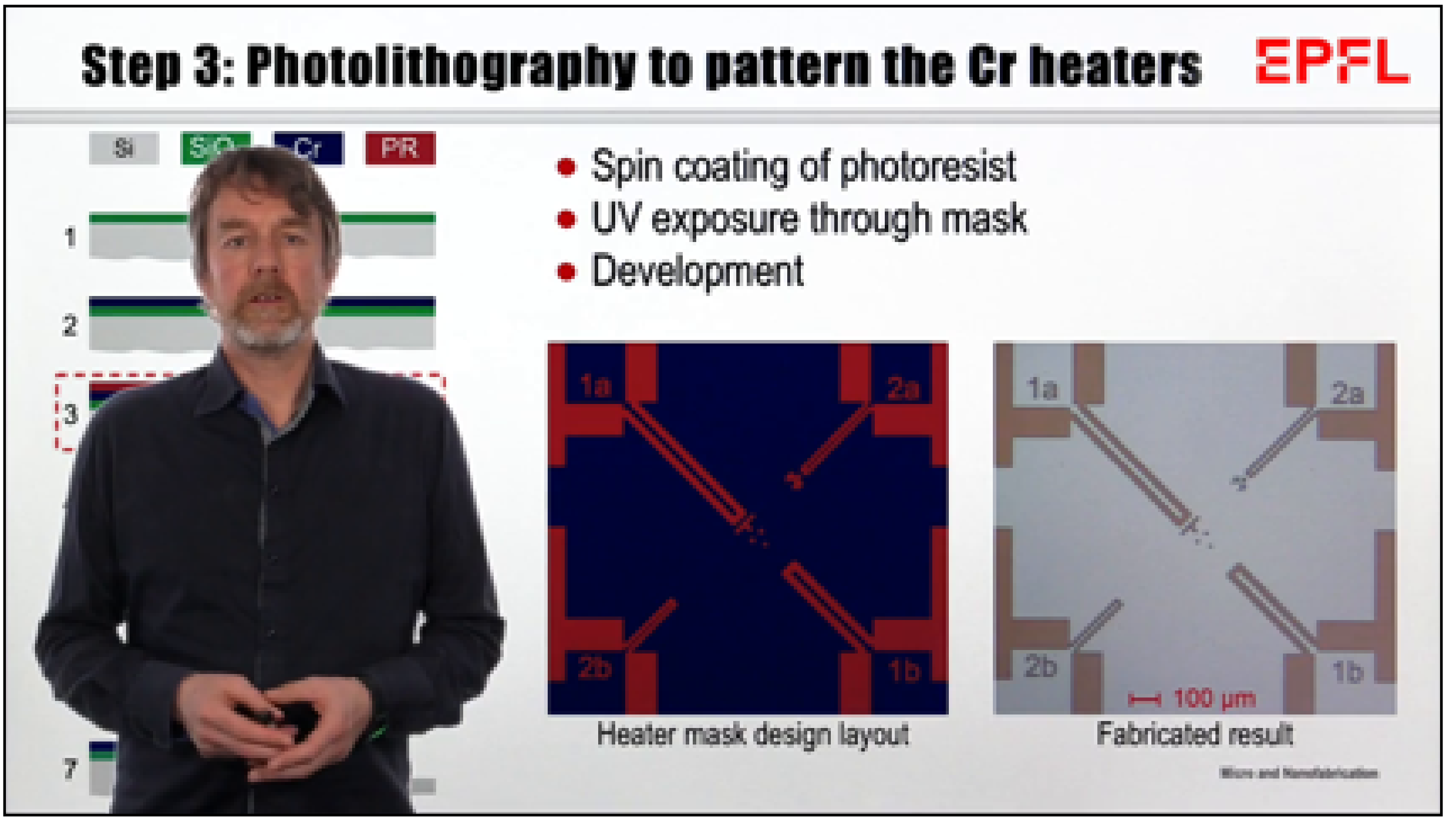
4m 3s

Step 2 is the physical vapor deposition of the chromium layer. Which is the second material in the bi-morph cantilever. This layer serves 2 purposes. First, as a thin conductor, it will allow driving a current to heat up the surface that will result in the bi-morph activation. Second, chromium is chosen before other metals because it has very different thermal expansion coefficient than silicon dioxide. This mismatch will induce a very pronounced bi-morph effect when heated. In this particular case, we deposit a 500 nanometre thick chromium layer using an electron beam evaporator equipment. And here on the right side, you see 2 photos. The left one shows a silicon wafer with the 1.5 micrometer silicon dioxide appearing again, colorful. And the right photo shows the same wafer, after having been coated with 500 nanometer chromium. Now the wafer looks again like a reflecting mirror. This photo shows the PVD thermal evaporator equipment in our clean room. With the scientist loading evaporant material at the lower part. The substrate wafers will be mounted on the upper part, which gives a long source substrate distance for optimal film uniformity.

notes

summary

4m 22s

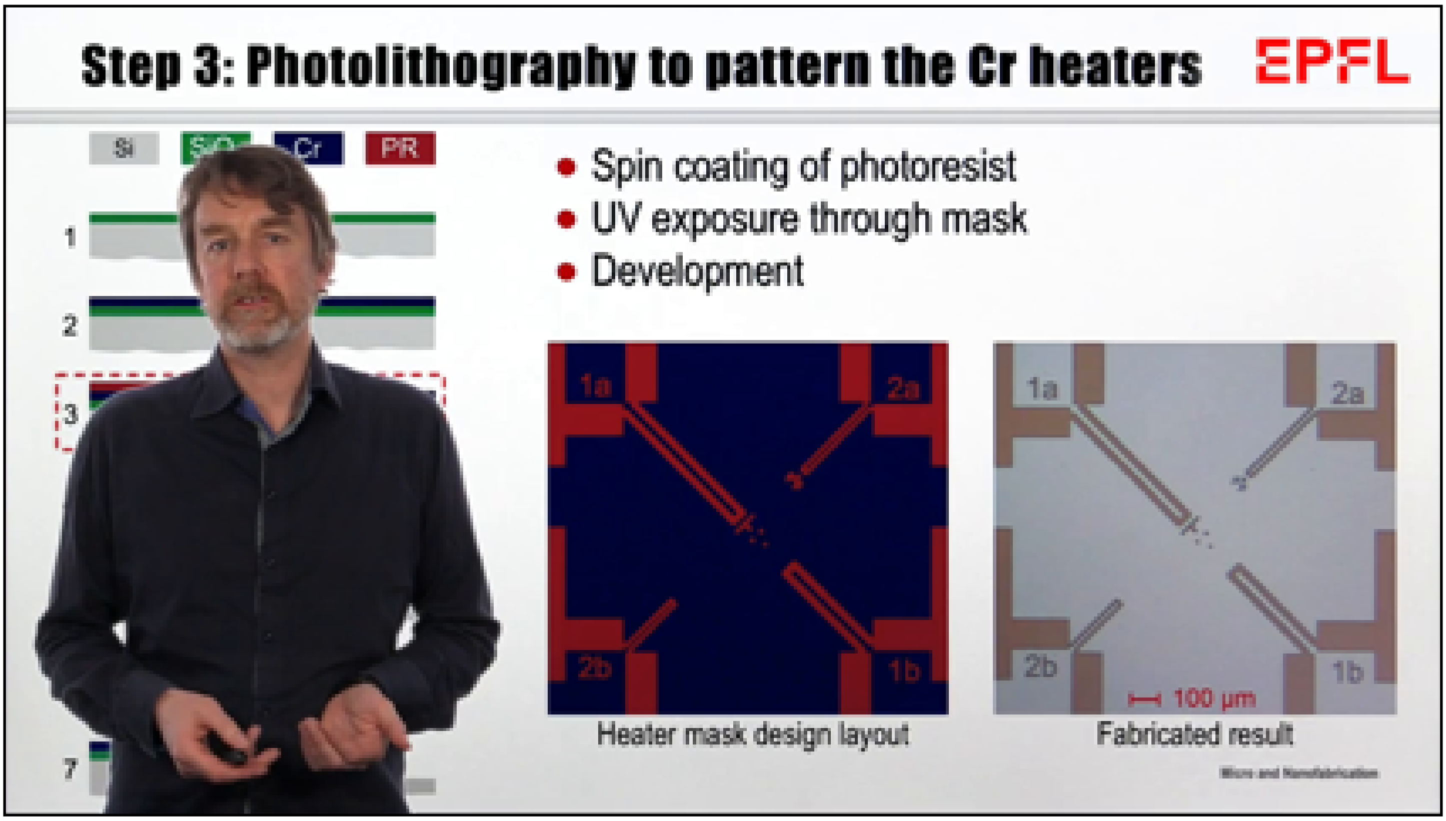


Once the substrates are loaded, the door will be closed, and the air will be pumped out to install the high vacuum.

notes

summary

5m 37s

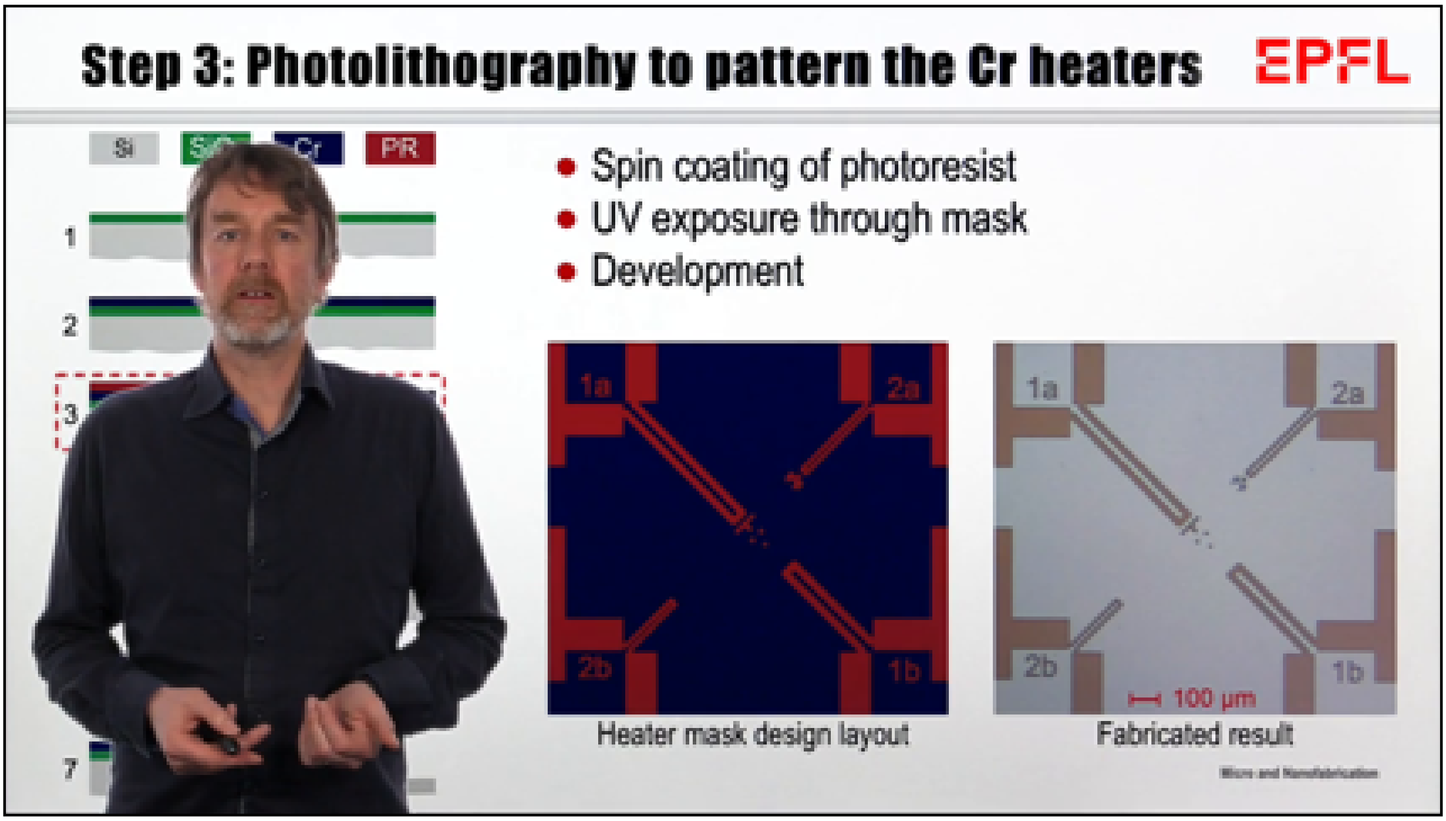


Step 3 shows the first photo-lithography step that has to go to pattern the chrome layer into micro heaters that are subsequently used to heat up the cantilever and to induce its bending. Photo-lithography is the process step that creates the pattern in the photoresist

notes

summary

5m 47s

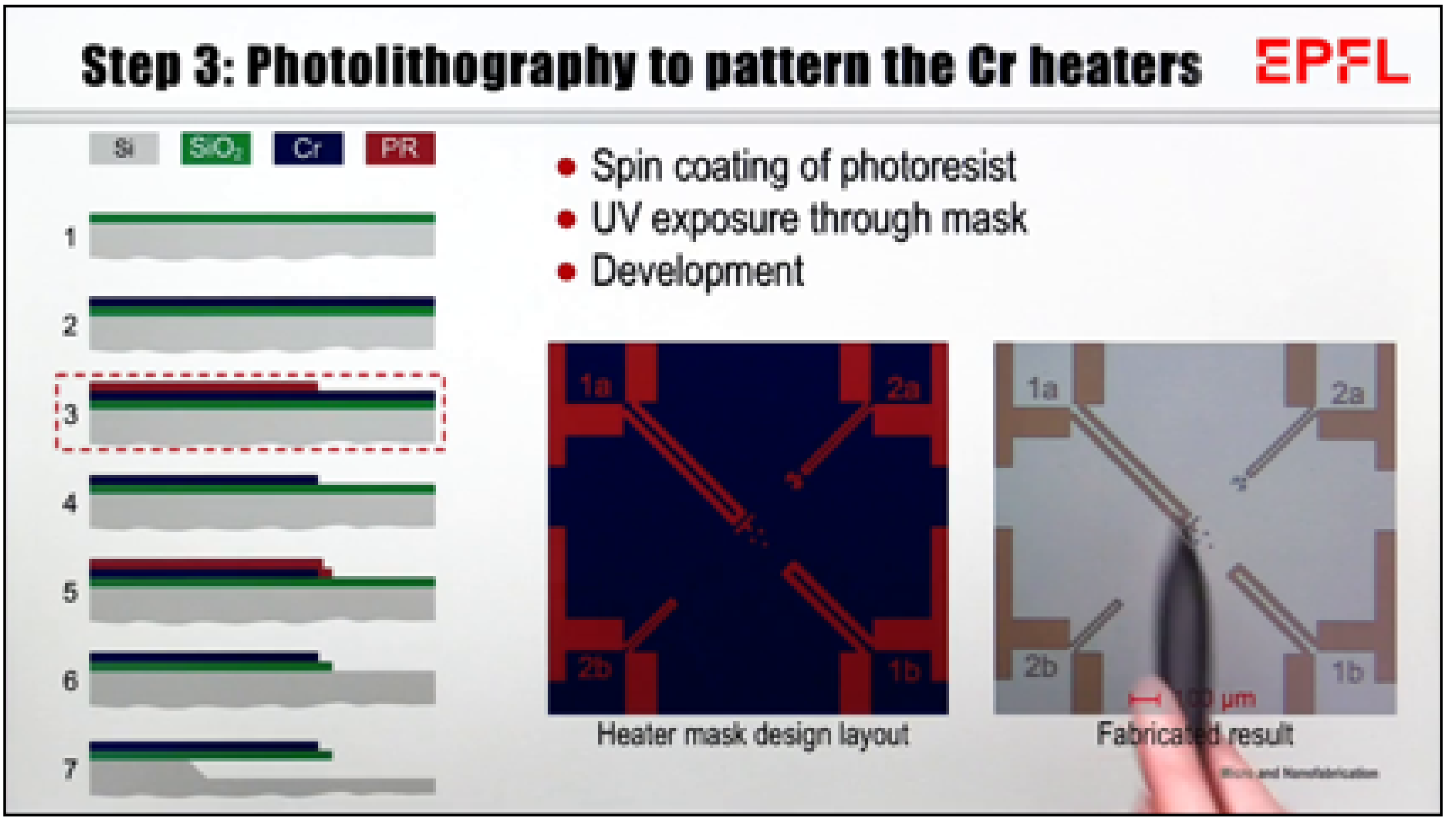


by local elimination through an exposure mask.

notes

summary

6m 1s

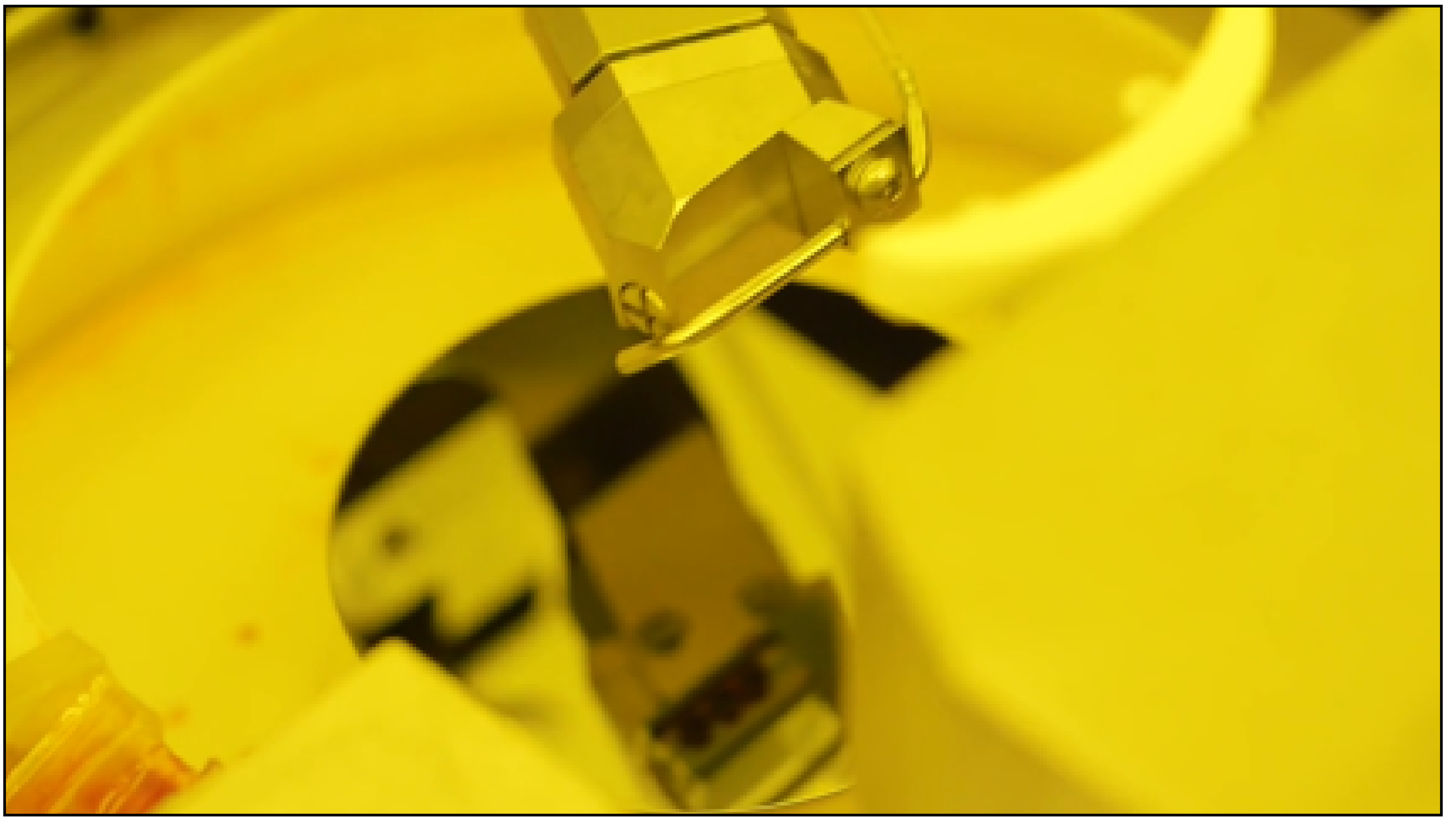


The exposed resist is developed and remaining resist pattern protects the underlying material from being etched. So on these 2 photos, you see on the left side, a computer drawing of the design layout, where we see 4 heater loops in chrome. On the mask, and on the right side, we see the fabricated results. So what you see here in brownish,

notes

summary

6m 4s

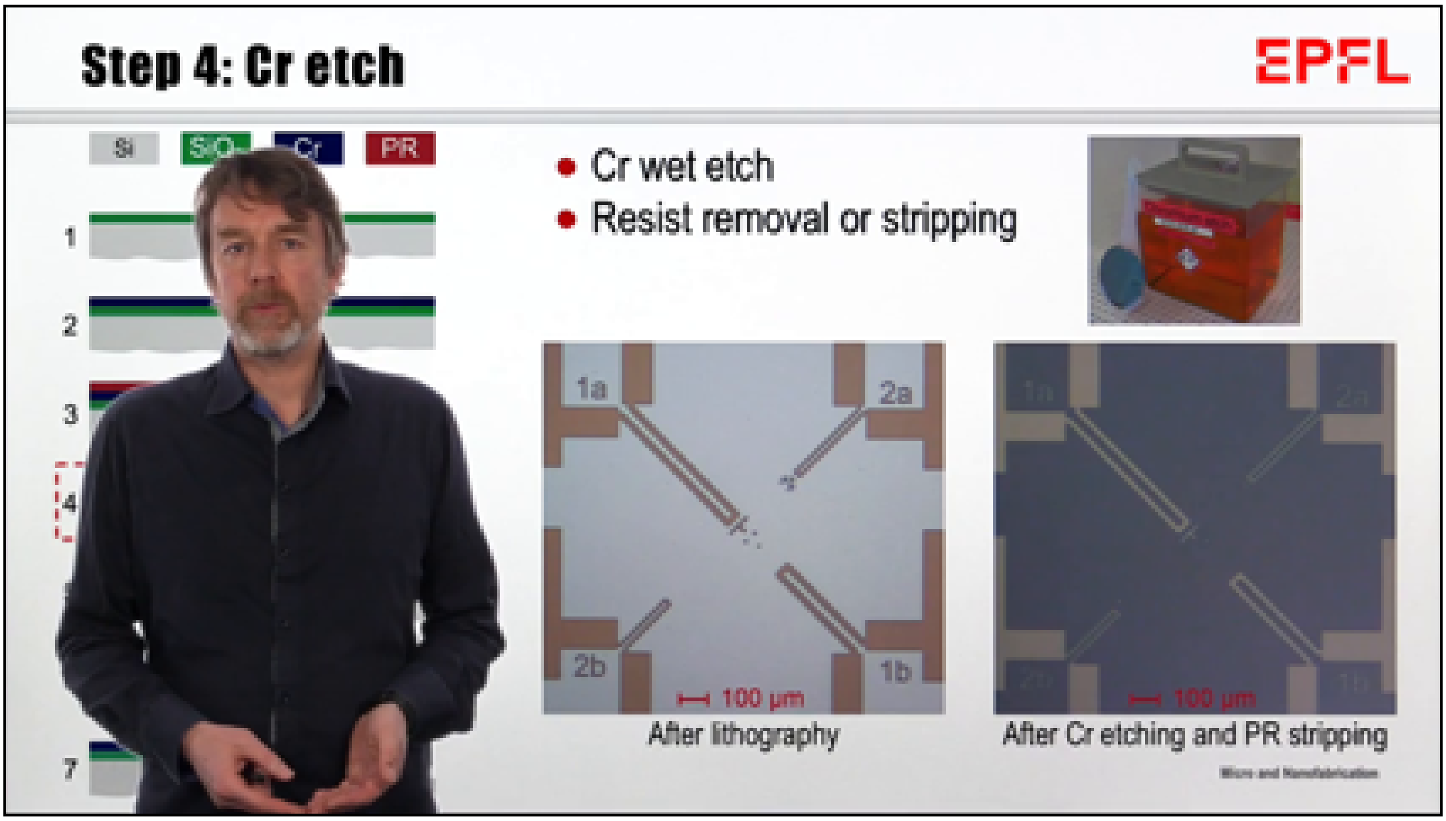


is the pattern photo-resist on top of the chrome layer. This is the step after the lithography before actually the chrome etching.

notes

summary

6m 31s

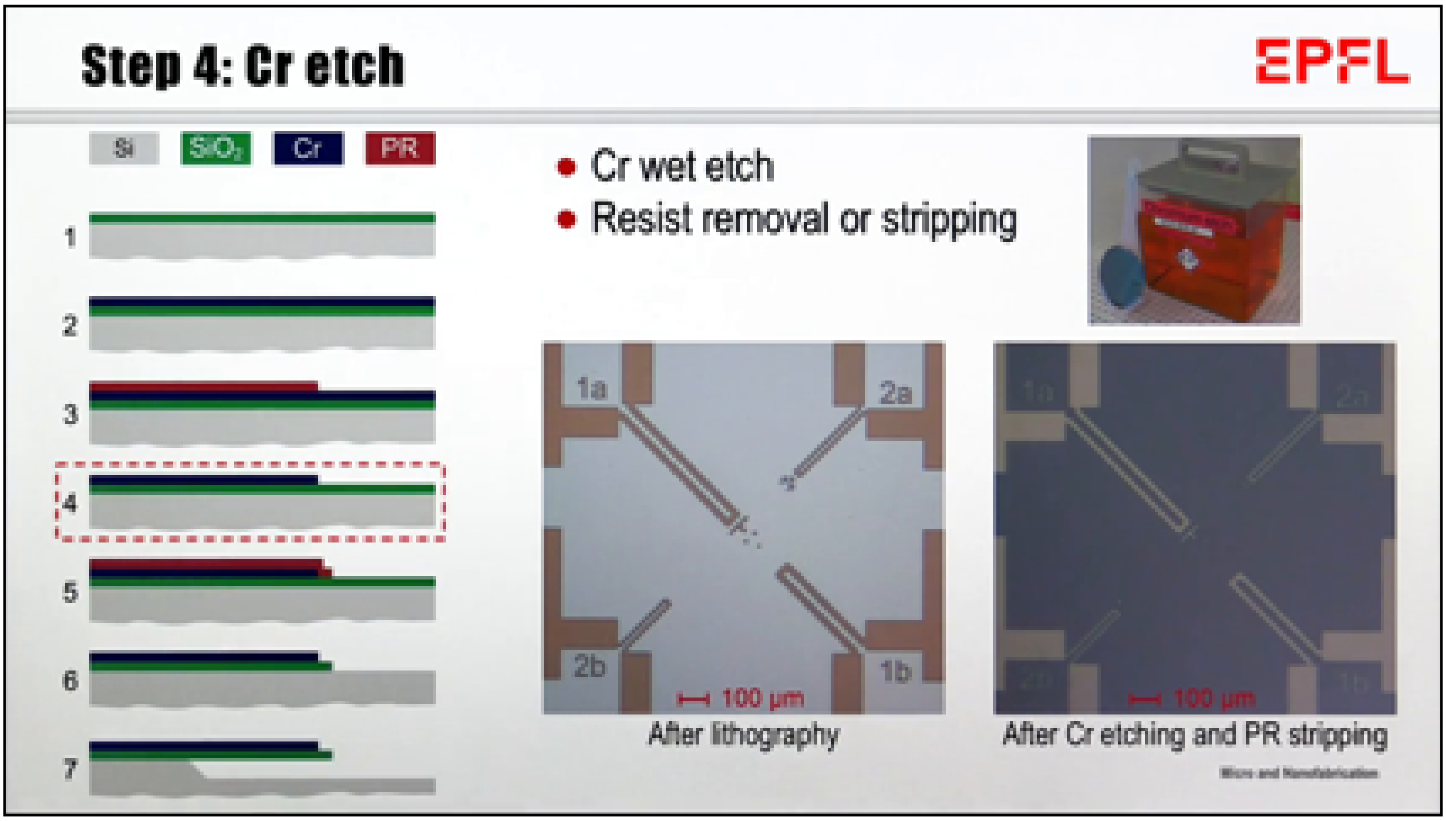


In this video sequence, you see how the photo-resist is spin coated on the wafer substrate. To this end, the wafer is spun at high speed and the resist is dispensed in the center. This forms a uniformed resist layer over the entire wafer surface. We will see details, how thick? And how uniformed the resist film is? In the dedicated lesson on lithography. Once the photo-resist is patterned, we can now proceed to etch the chrome. To this end, we use a dedicated chromate solution as shown on the upper right corner. The wafer with the photo-resist pattern is placed into the chromate solution after the chrome has completely etched through, a strong color contrast appears on the wafer.

notes

summary

6m 40s

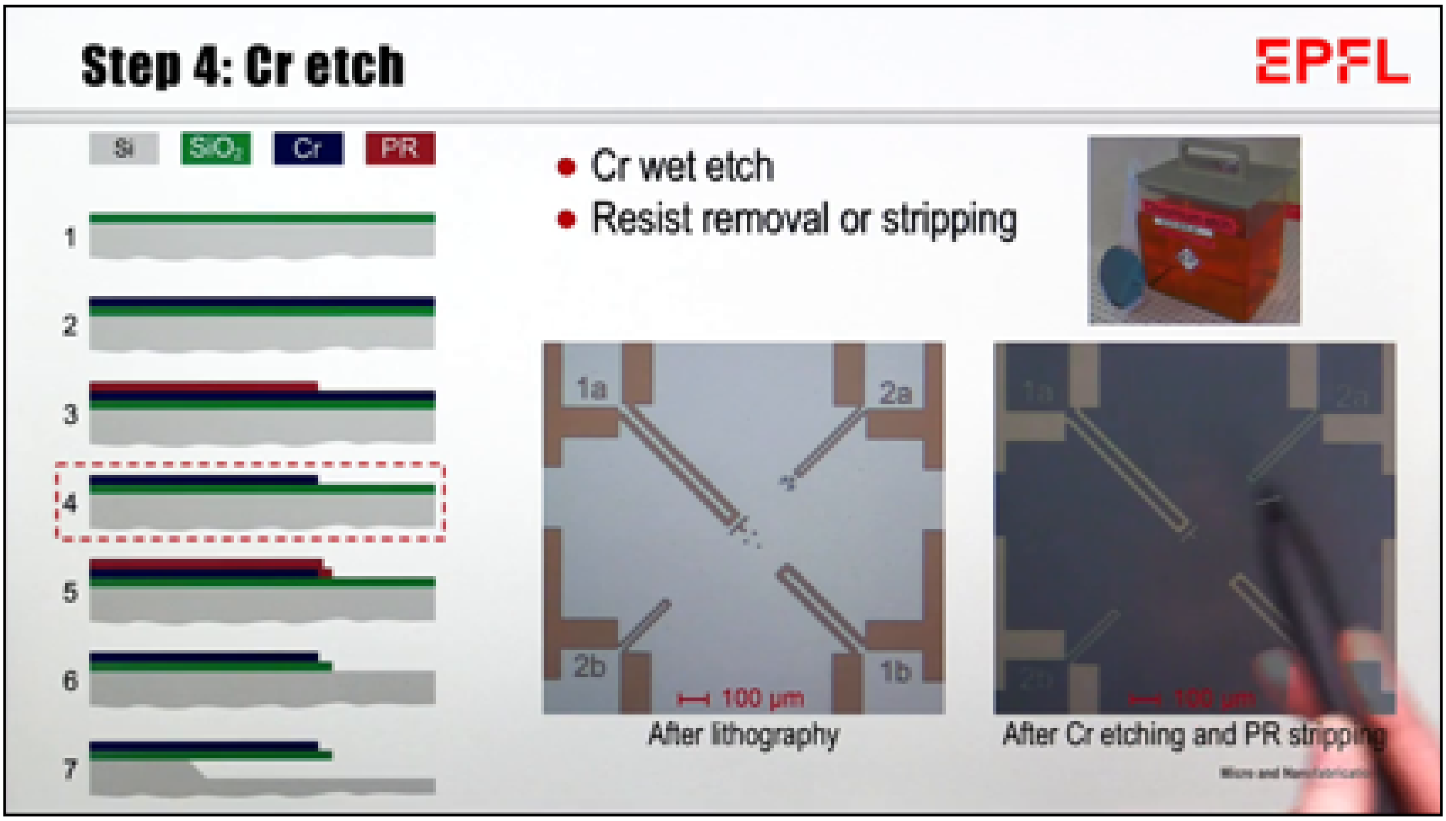


At this point, the photo-resist can be removed by a so called stripping process followed by thorough rinsing and cleaning.

notes

summary

7m 25s

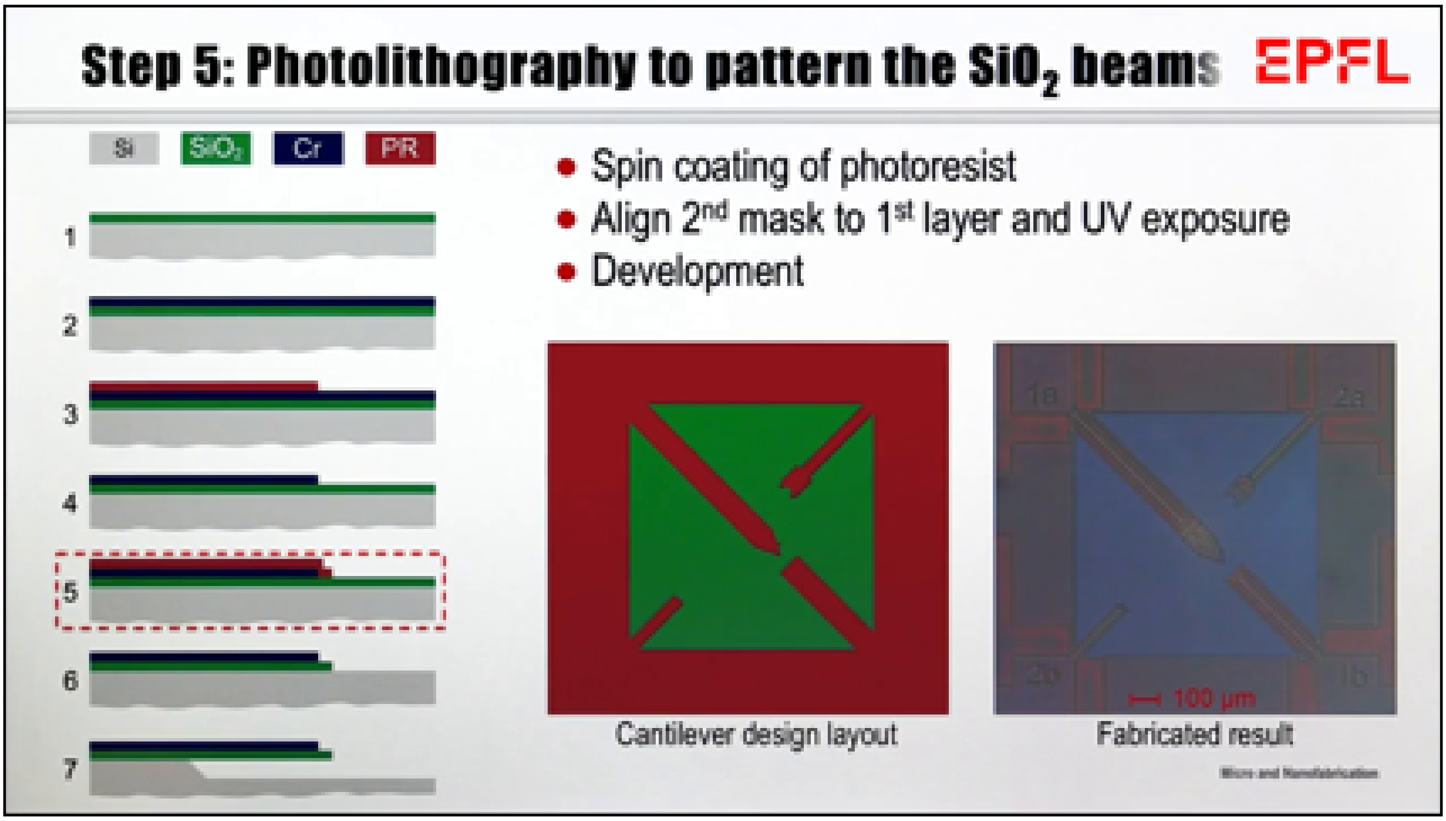


Here you can see 2 photographs. On the left side you see the situation, after the lithography, with the photo-resist on the chrome. And on the right side, you see the situation after the chrome etching, and the photo-resist stripping. We can see nicely,

notes

summary

7m 32s

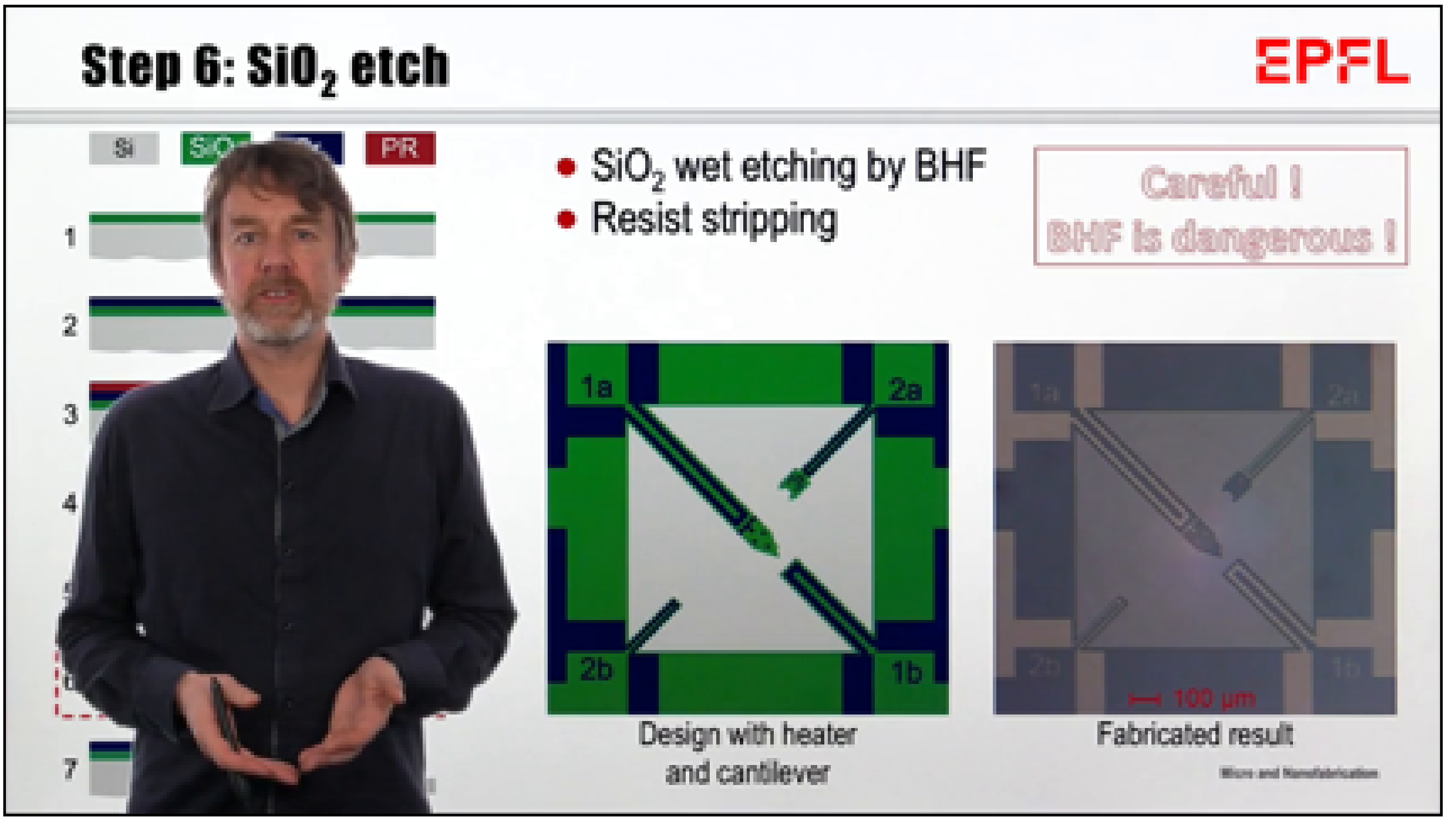


the well defined chrome pattern that will define the micro heaters on top of the *SiO2* layer. Now that the chrome is patterned, we can structure the underlying

notes

summary

7m 47s

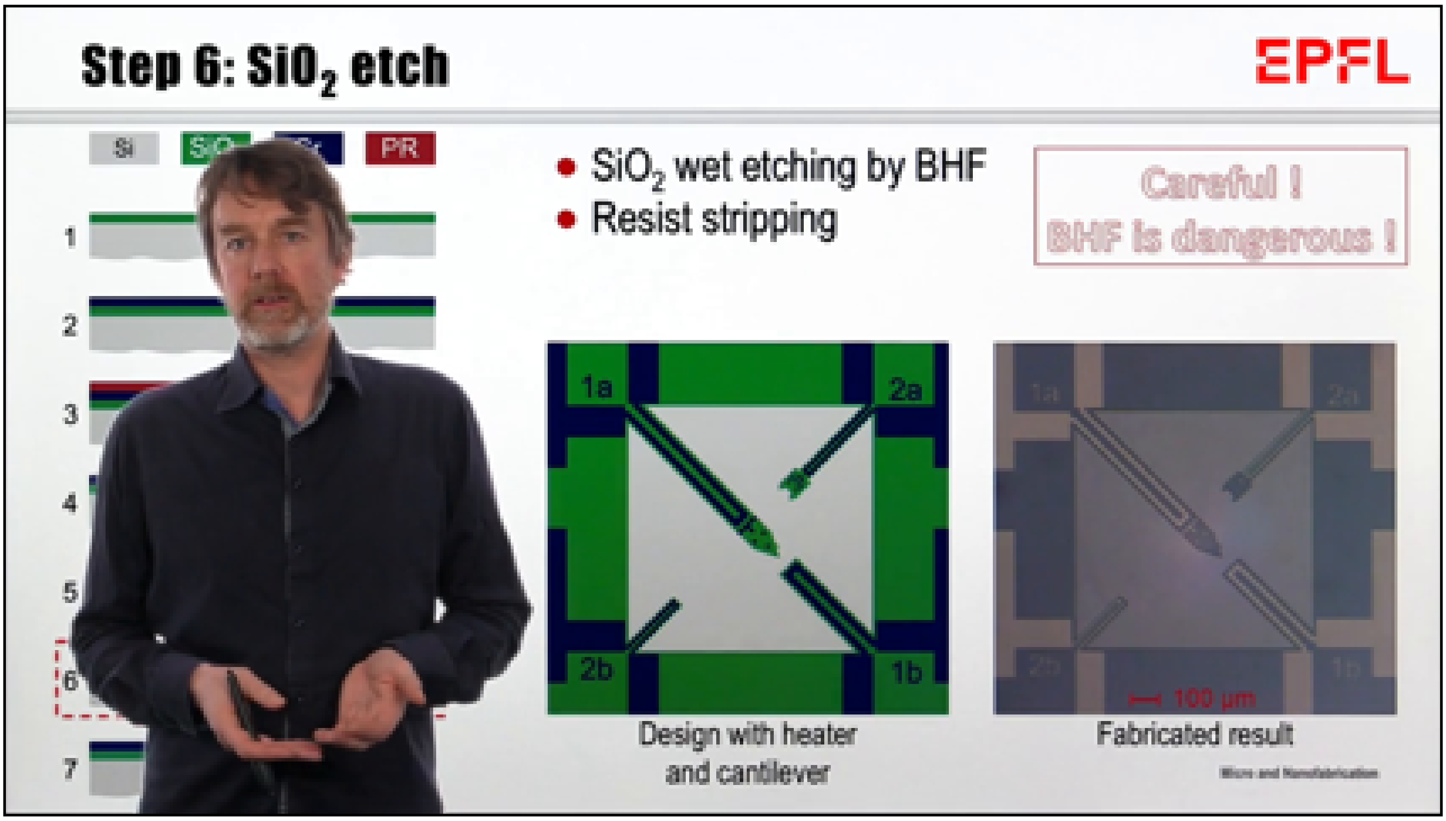


SiO2 layer to carve out the cantilever shape. This step also defines the shape of the anisotropic silicon etch to release the beam from the substrate. Before UV exposure, the photo mask is aligned to the first one by means of a so called mask aligner. The left image shows the cut mask lay out, where as the right image, shows the optical photo of the 4 cantilevers. One can actually see clearly the 2 layers now. The shape, of the cantilever in transparent photo-resist defined in the second lithography. And the chromium, that was defined in the first lithography step. This allows checking that the alignment of the mask is within the tolerance specifications.

notes

summary

7m 55s

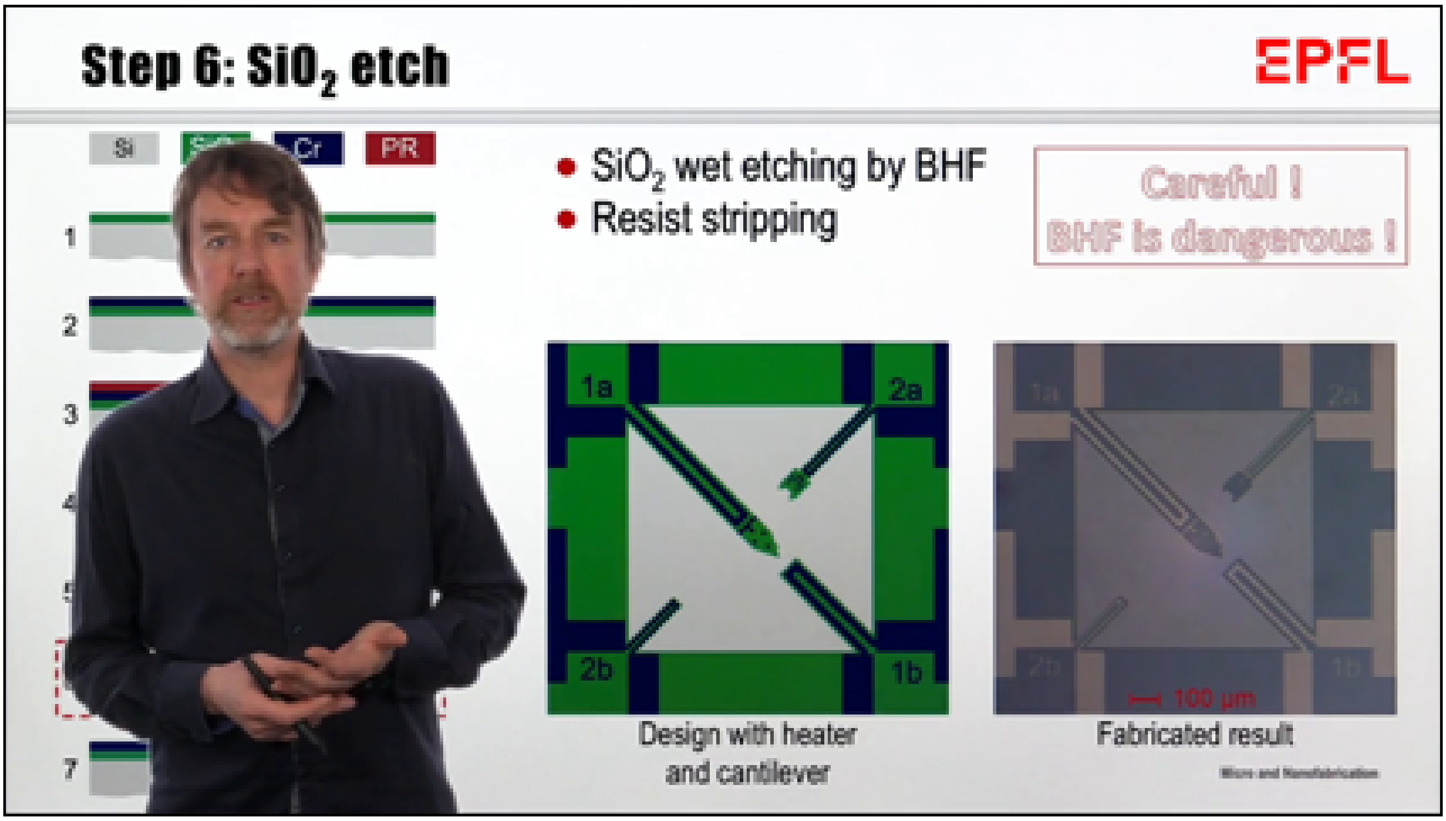


The photo-resist that we patterned in the previous steps serves now to protect the silicon dioxide during the etching in buffered hydrochloric acid, *BHF.* This etchant has *SiO2* etch rate of about 80 nanometer per minute. And the etch selectivity to silicon is almost infinite.

notes

summary

8m 41s

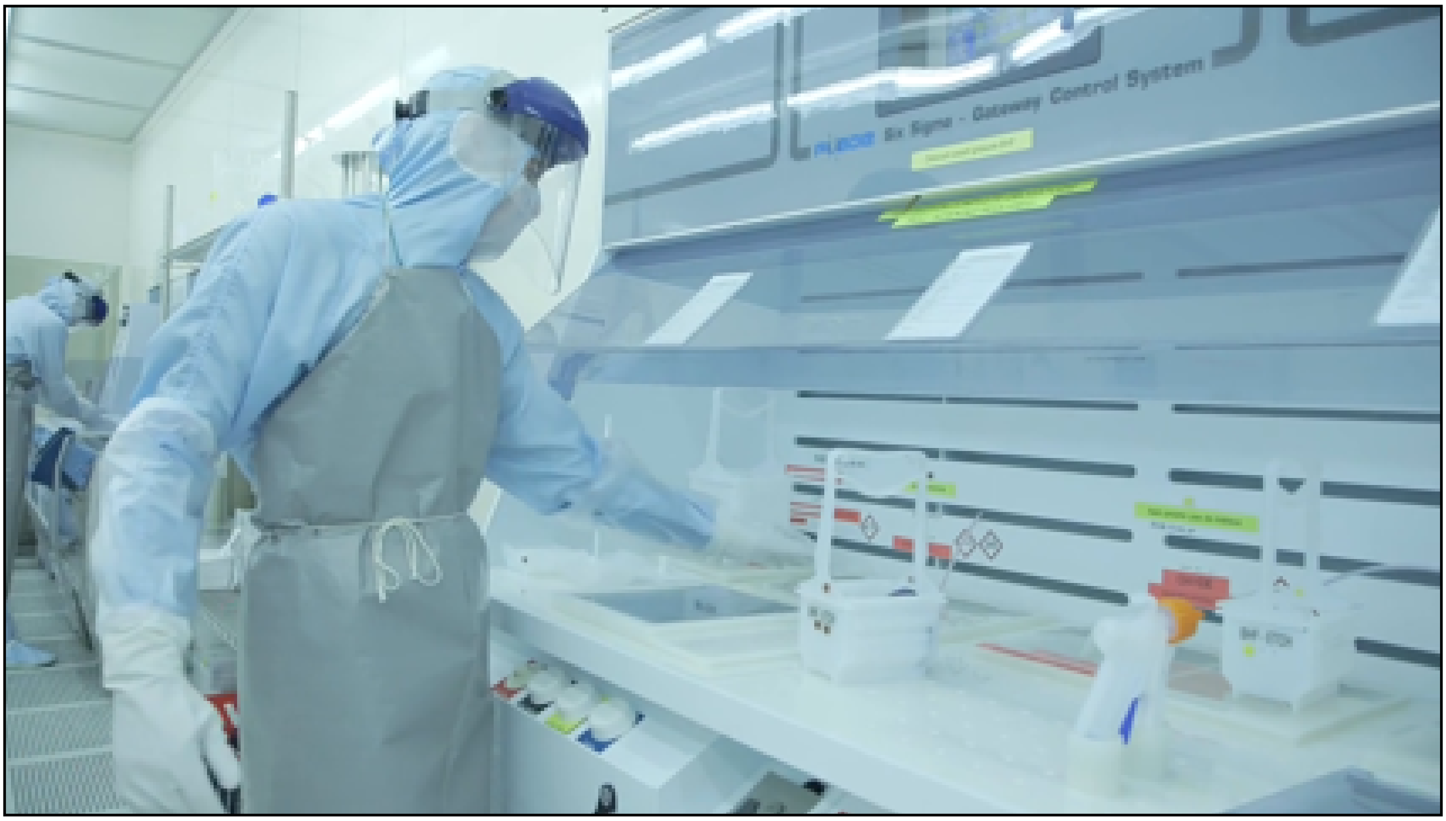


Thus for etching the 1.5 micrometer thick silicon dioxide, we typically need about 20 minutes etch time which stops naturally at the silicon surface. Be very cautious. *BHF* is dangerous and strict safety measures have to be applied. After the *SiO2* etch, the photo-resist can be stripped, exposing again the chrome layer.

notes

summary

8m 56s

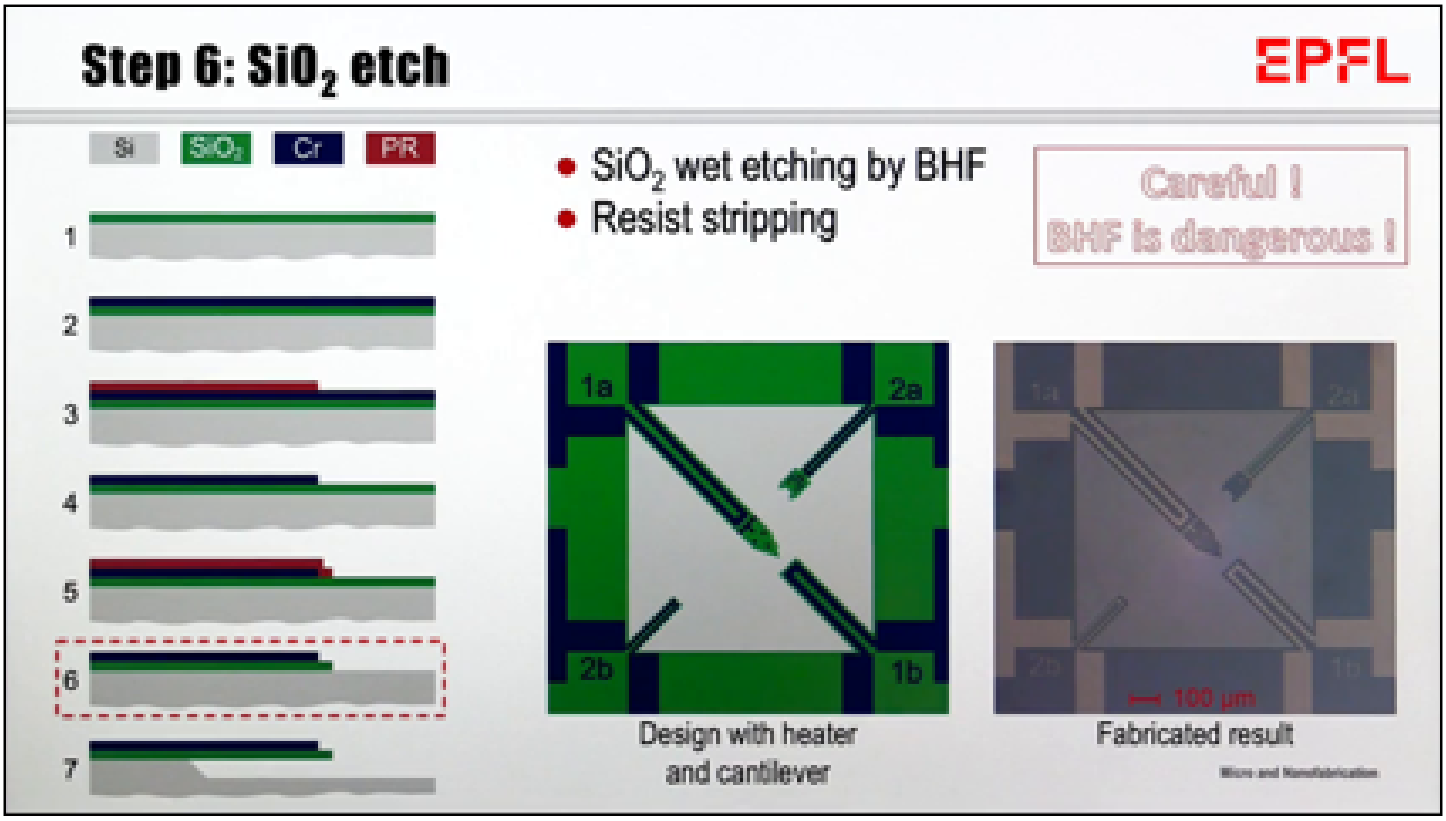


This video sequence shows a clean room scientist,

notes

summary

9m 13s

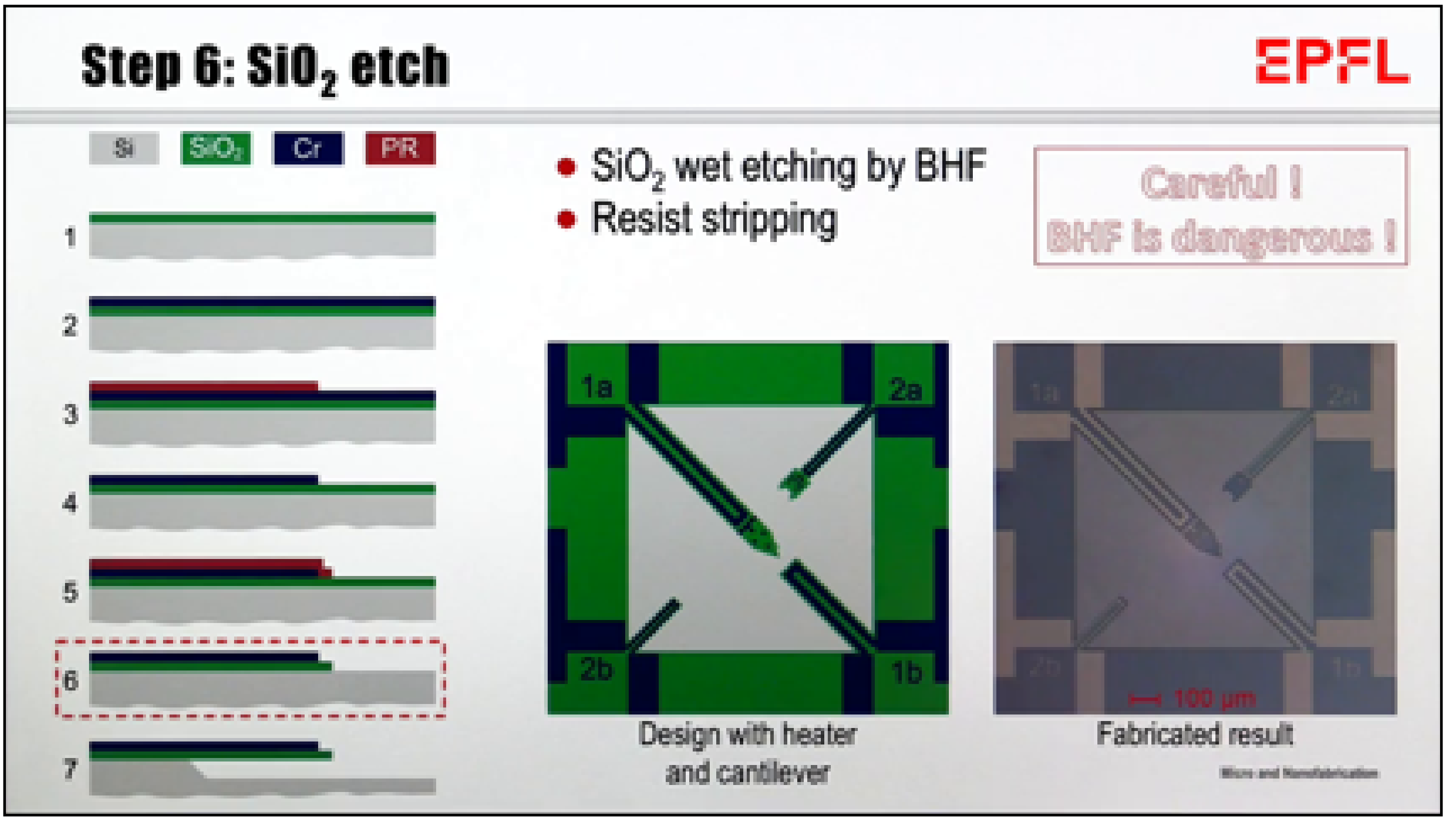


who puts a batch of wafers into the *BHF* etch bath, to etch the silicon dioxide. Please notice the serious protection that is needed.

notes

summary

9m 16s

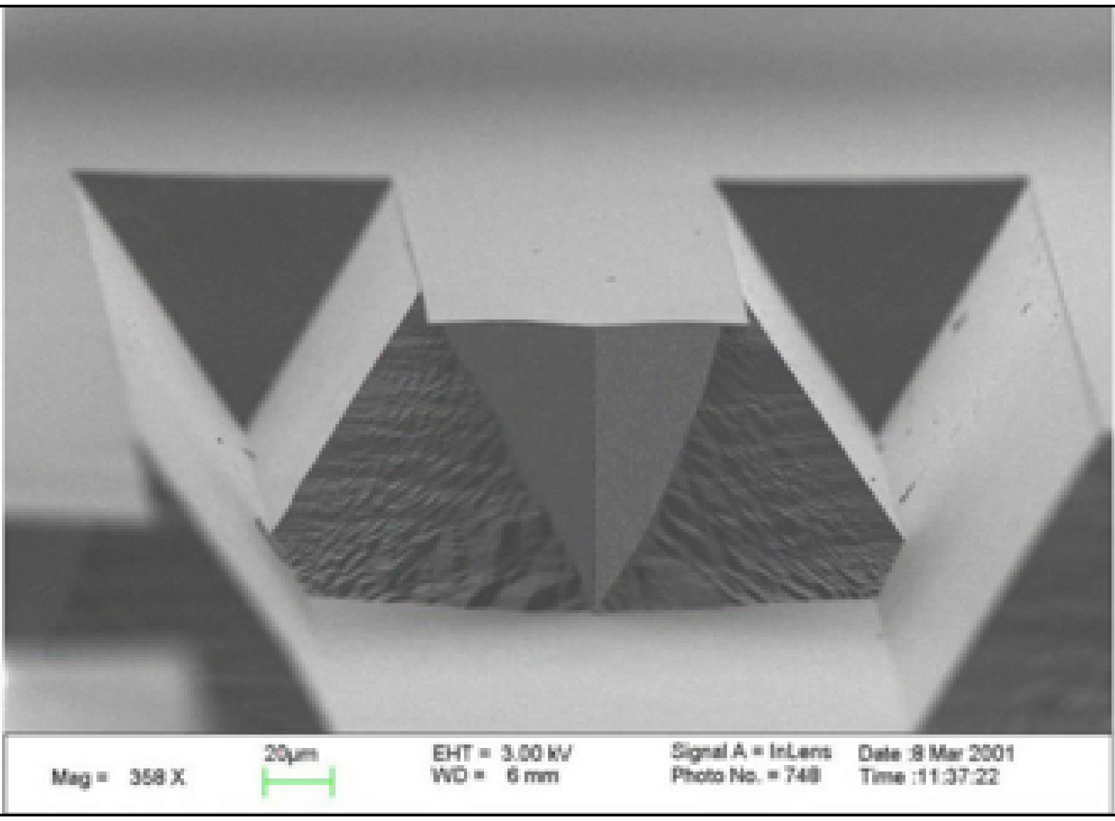


On this right photo, you can see now the result after the fabrication, where we can see in dark grey the contours of the silicon dioxide cantilevers still on the silicon. And in light grey, the chromium heater pattern that runs on top of the 4 cantilever shapes.

notes

summary

9m 29s

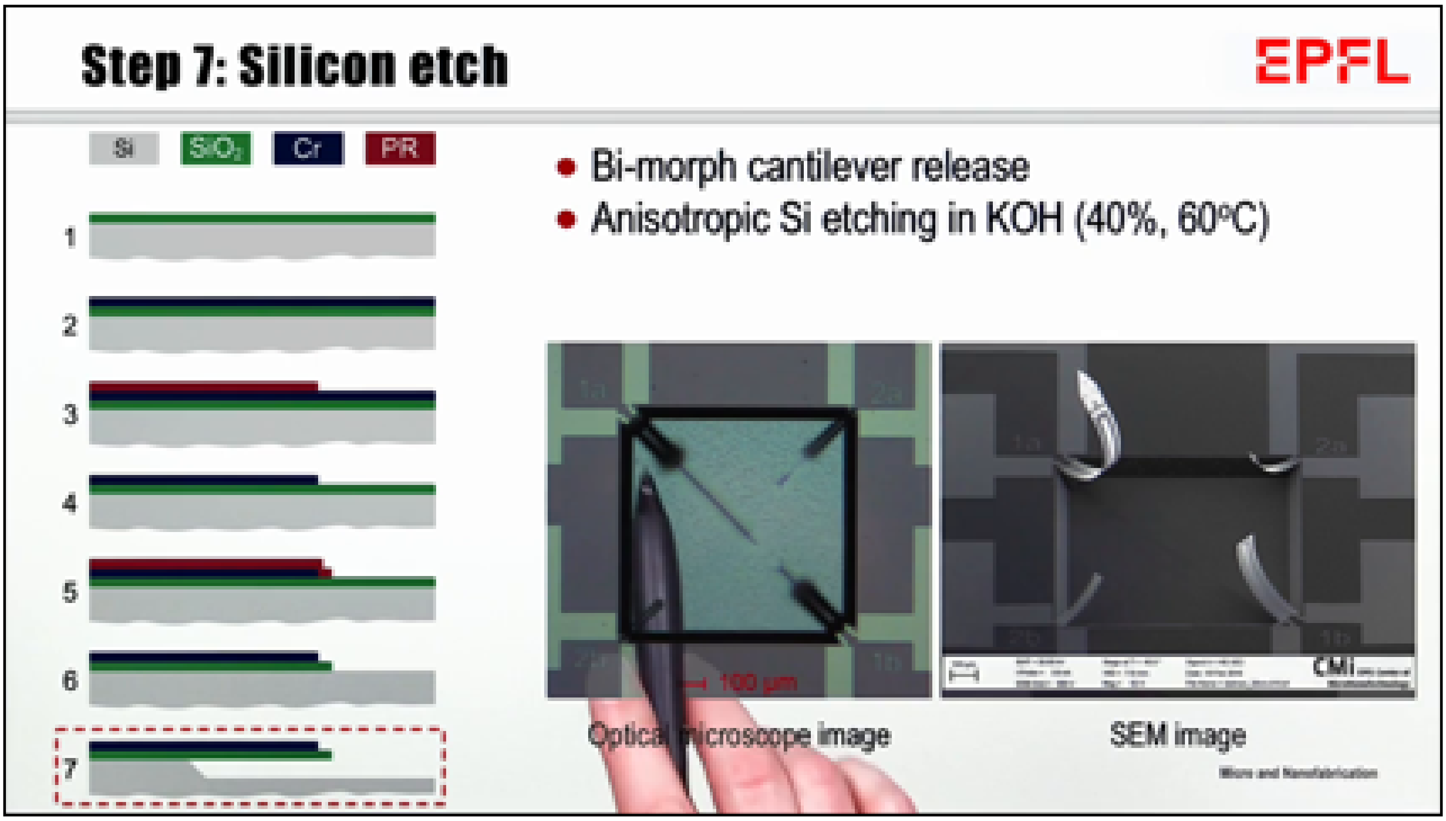


The final step releases the cantilever beam from the underlying silicon by anisotropic under etching. While there are several options that can be used to etch silicon, such as dry plasma silicon etching. We use here the anisotropic wet etching of silicon done in Potassium hydroxide, also called *KOH*. This method is very versatile, and widely used for these type of structures. The silicon 1,0,0 plane has an etch rate of about 20 micrometers per hour

notes

summary

9m 47s



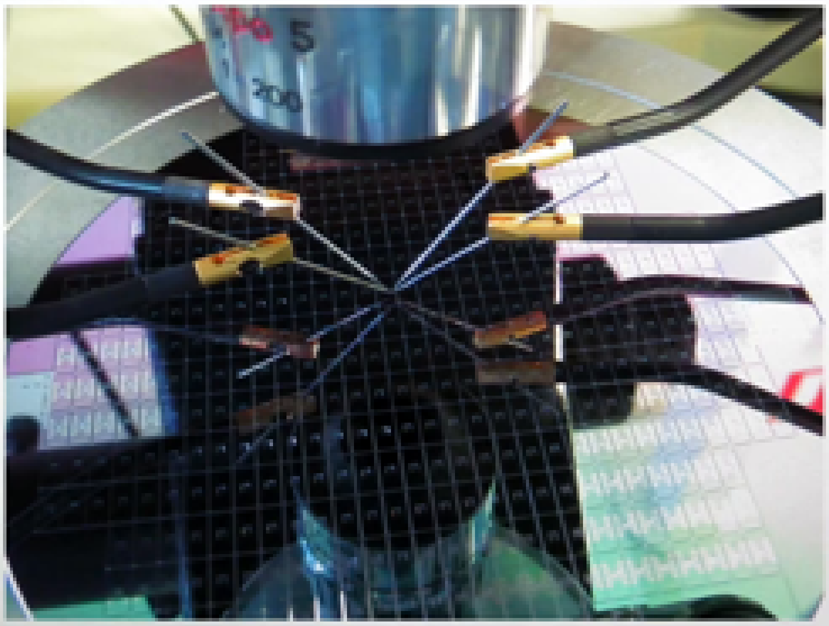
in *KOH*. Whereas the 1,1,1 silicon planes are hardly etched at all which allows creating the well defined 3D etch structure in the shape of a truncated inverted pyramid. The *SiO2* thereby serves as an etch mask to define the borders of the etch structure. With the largest cantilever beam 80 micrometers wide, we need about 2 hours to under etch 40 micrometers from each side. When the under etching is completed, and the cantilever released from the silicon, the intrinsic stress in the *SiO2* chromium sandwich layer induces an out of plane bending of the cantilever. On the right side, we see 2 photographs. showing the fabricated bi-morph cantilevers. On the left, an optical microscope image taken from above. Where we see nicely the square that has been etched by the KOH into the silicon. And the 4 cantilevers in the corner that have been under etched. Cantilevers themselves are not easily visible because they are pre-stressed,

notes

summary

10m 12s

Thermo-mechanical characterization



~ 50 Ohm resistance

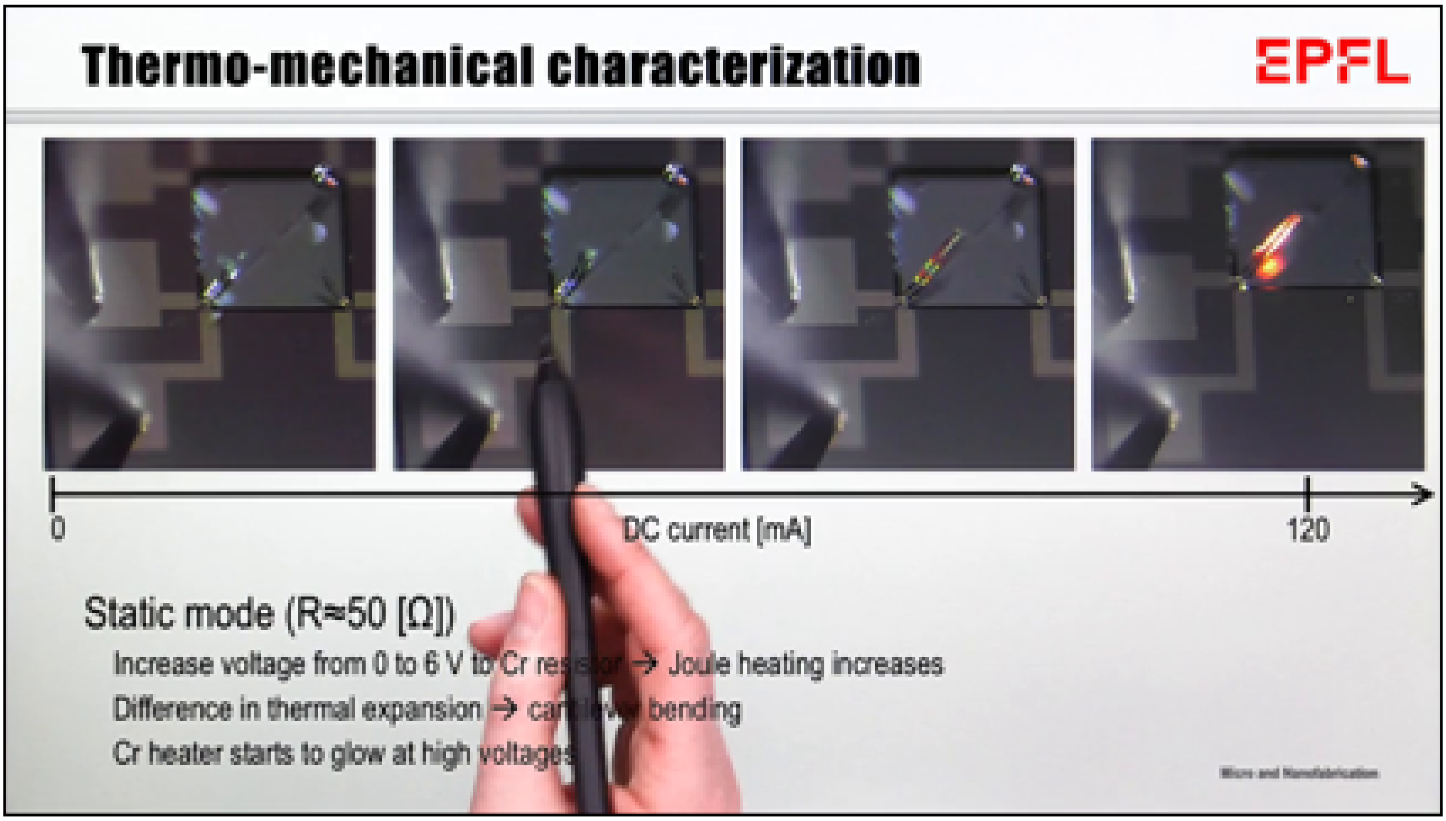
Micro and Nanofabrication

and pre-bent largely, so they're out of focus of the microscope. To see them better, we're going to the scanning electron microscope. Where we see now nicely the cantilevers in all details. We also see nicely, the square that has been etched by the *KOH* into the silicon. The cantilevers are largely bent due to the stress between the *SiO2*, and the chromium. Please note that at this point of time, there's no heating applied. So this stress, is the intrinsic stress due to fabrication, and not an actuated bending.

notes

summary

11m 13s



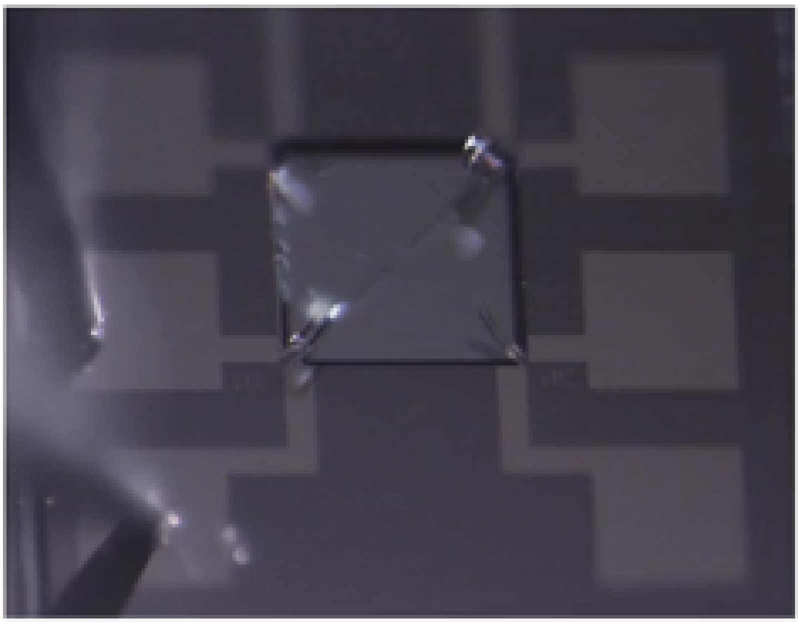
The bi-morph thermo-mechanical micro actuators are now ready for characterization. For this, we use a probe station that can align micro needles to the contact pads to apply electrical signals to various devices on the chip or wafer, and to measure *IV* curves. In our case, we have measured the resistance These 4 optical images, show bi-morph device under various *DC* currents. Please remember, that the initial bending of the cantilever is due to the intrinsic stress and occurs already at room temperature. It is not due to heating. Heating in fact will bend the lever downwards. From left to right, the voltage is increased from 0 to about 6 volts, which gives us an increasing current as shown here. The current heats up the chrome layer by Joule heating. Already in photo 2, We can see that the bi-morph

notes

summary

11m 54s

Thermomechanical characterization



Movie showing the bi-morph cantilever driven by DC with the same voltage range as before (0 – 6 V)

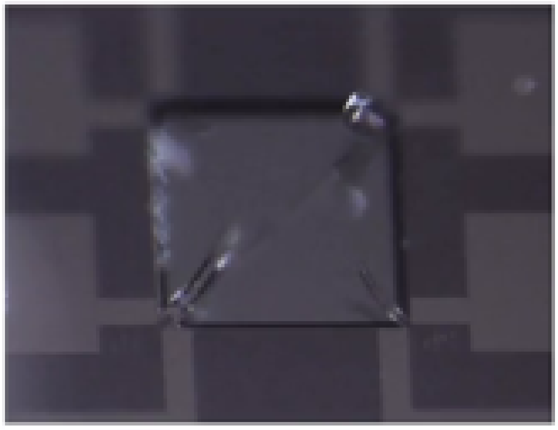
has moved downwards a bit. This actuation effect is more pronounced in this photo, where we also start seeing a color change. This color change is due to the heat generated in the chrome resistor, which emits radiation. Increasing the current further, we can see that the bi-morph starts to glow. Running this experiment for a very long time will damage the device like a fuse.

notes

summary

13m 1s

Thermomechanical characterization



Movie showing the bi-morph cantilever driven by AC by applying a peak to peak voltage of 4-5 Vpp.
Currents are between 0-100 mA
Frequency between 1 – 10 Hz

Micro and Nanofabrication

Here you can see a movie that shows the actuation of the bi-morph cantilever driven by *DC* voltage. Using the same voltage range as shown in the slide before, from 0 to 6 volt. You can see in real time when ramping up the voltage and current, that the cantilever starts bending down. And at very high current levels, the cantilever starts to glow, and ultimately might burn like a fuse if the experiment is run too long.

notes

summary

13m 33s

And here you can see, the actuation of the bi-morph when the voltage is changed manually. Details of the frequency response is provided by the accompanying documents. Please have a look, as they provide useful information on the bandwidth in which such a device can operate. As you can guess, this is not only a function of the mechanical resonance frequency of the cantilever, but also of the heat dissipation away from the cantilever. This concludes this chapter on the fabrication of the bi-morph cantilever. I hope you learned how one can get from a blank silicon wafer, hundreds and thousands of micro devices, by series of micro fabrication steps. In the next chapters, my colleague and I will present more technical details on the different fabrication steps.

notes

summary

14m 6s