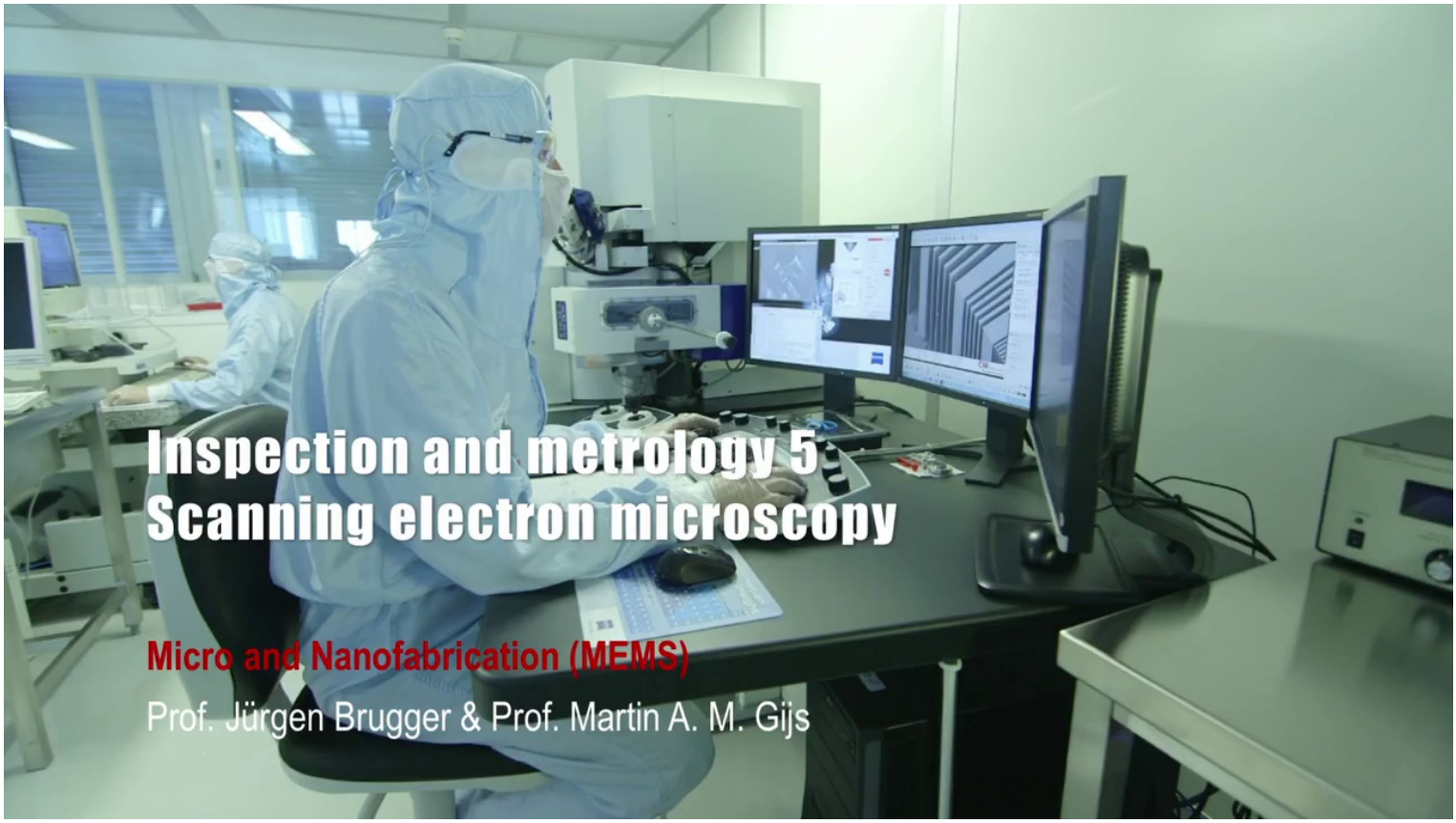

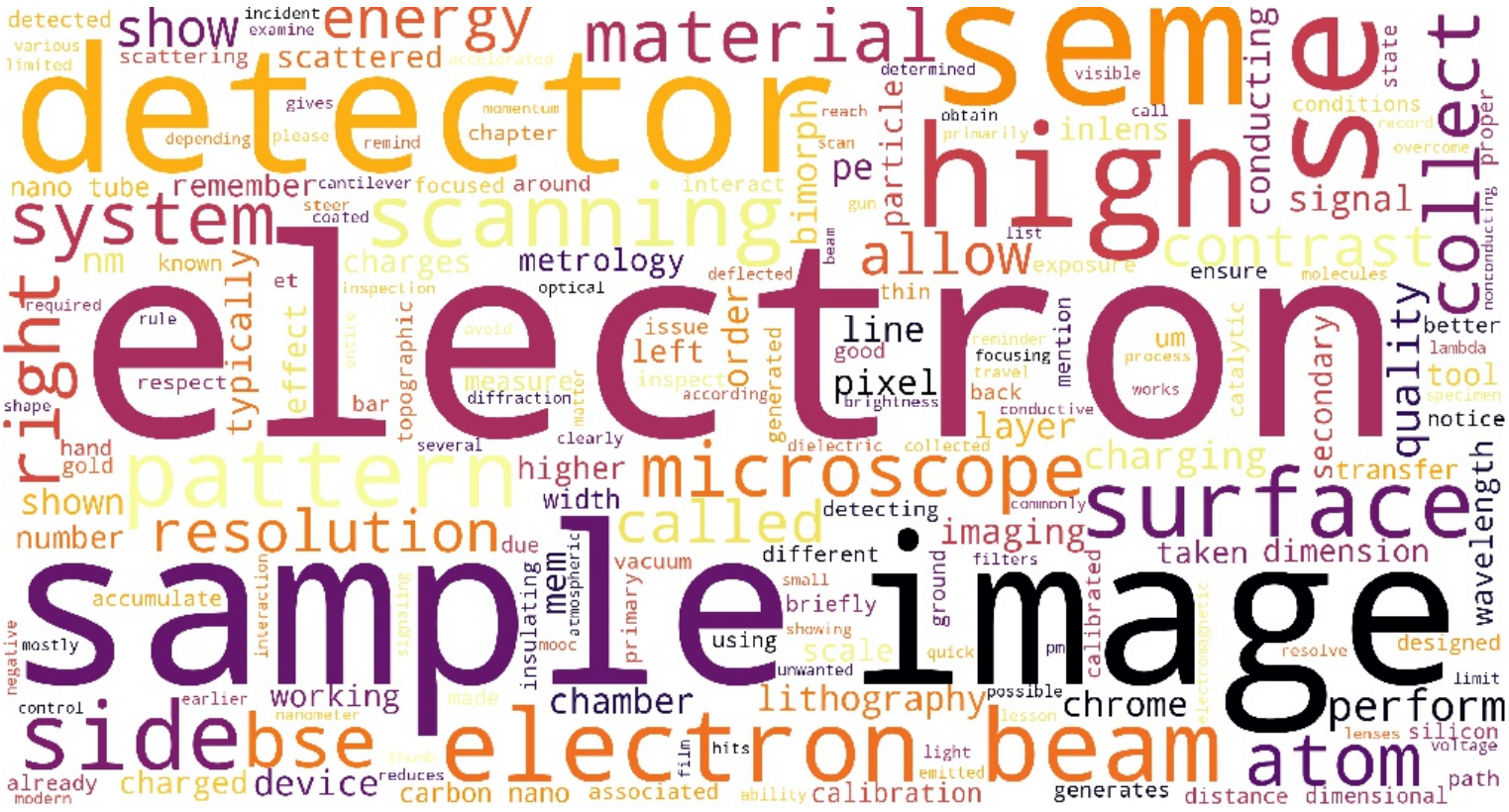

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Scanning electron microscopy

- Physical principle
- Inspection with different electron signals
- Charging issue
- Dimension measurement

Micro and Nanofabrication (MEMS)

Now, I will show you how charged electrons in a scanning microscope can be used to perform inspection, quality control, and metrology. First, I will remind you briefly how an electron microscope works and how electrons interact with matter. Then, I will list the various electron signals that I used to examine the sample. I will briefly mention the issue of electrons charging, and show how the SEM can be used to perform dimensional metrology at a nanometer scale.

Scanning electron microscopy

Why use electrons instead of photons?

- Overcome the optical diffraction limit:

$$\sim \lambda/2$$

- Electron wavelength, De Broglie equation

kV	1	10	100
nm	0.038	0.012	0.0038

$$\lambda_e = \frac{h}{p}$$

λ: wavelength
h: Planck's constant
p: momentum

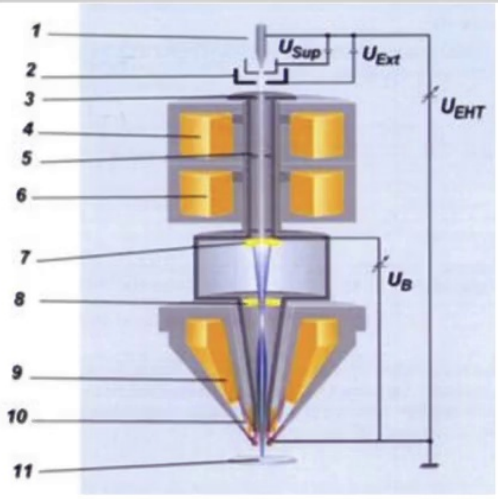
Using electron results in higher resolution compared to visible light

Micro and Nanofabrication (MEMS)

As a quick reminder to what we have already seen earlier in this mooc, in the chapter of electron beam lithography. We use a focused electron beam primarily to overcome the diffraction limit of optical systems that are typically in the order of lambda over 2, or around 300 nm for visible light. Remember that electrons can be associated to a wavelength, depending on the electron energy, the associated wavelength can be as small as a few pm. Please notice however that the resolution of a scanning electron tool is not limited by the electron wavelength, but by the focusing ability of the system and the electrons scattering, as we have already seen in the lithography lesson. As a thumb rule, remember that a SEM can resolve images of conducting samples down to a few nm, as we can clearly see on this electron microscope here, showing the bi-morph cantilever in very high resolution.

Schematics of SEM system

- System similar to EBL:
  - E-gun: 0.02 – 30 kV
  - Electromagnetic lenses
  - Vacuum system
- Electrons ➔ detectors ➔ image
- Morphology & compositional analysis
- Resolution: ~1nm
- Accuracy: +/-3%
- Conductive samples required for high quality imaging



Zeiss The GEMINI II column

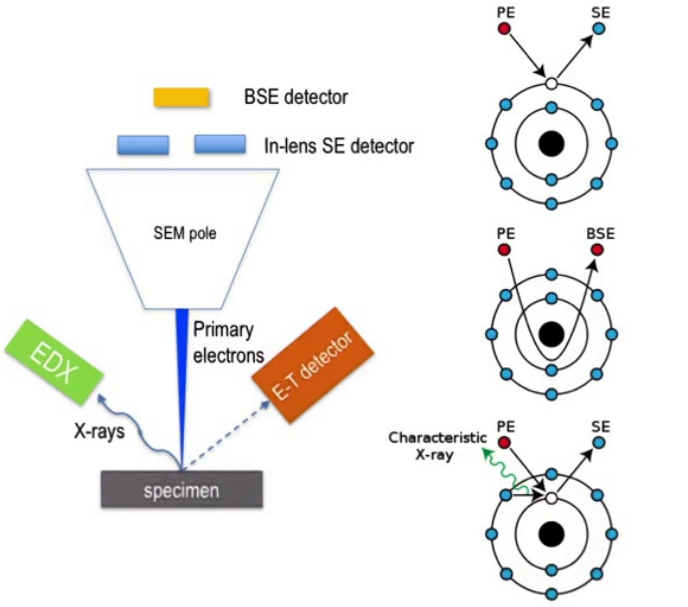
1.	Gun	7.	BSE detector
2.	Extractor	8.	In-lens SE detector
3.	Anode aperture	9.	Objective lens
4.	Upper condenser	10.	Scanning coils
5.	Single hole aperture	11.	Specimen
6.	Lower condenser		

Micro and Nanofabrication (MEMS)

In a scanning electron microscope, electrons are emitted from an electron gun here, and accelerated under high voltage to obtain momentum and travel through the chamber. Several electromagnetic lenses shape and steer the electron beam. In order to avoid unwanted scattering between electrons and atmospheric molecules, the entire system is working in a vacuum chamber. The electron beam is focused on the specimen surface down here and interacts with its atoms. Detectors and filters, here, number 7 and 8 collect the back scattered electrons. The brightness of each pixel is determined according to the number of collected electrons. The electron beam is deflected to scan the sample surface pixel by pixel and line by line to record an image. During the electron scanning process, negative charges will accumulate on the surface of dielectric material which reduces the image quality. Therefore, for high quality images, a conductive sample is required, or a non-conducting material has to be coated with a thin conducting film. Typically, in good conditions, a modern SEM system can reach resolutions down to about 1 nm and below.

Inspection with different electron signal

- Secondary electron (SE) imaging
  - Surface structure
- Backscattered electron (BSE) imaging
  - Atomic number ↑, BSE ↑ ➔ material contrast
- High efficiency SE (HE-SE2) imaging
  - Topography and edge enhancement
- Energy-dispersive X-ray (EDX)
  - X-ray detection
  - Spectroscopic compositional analysis

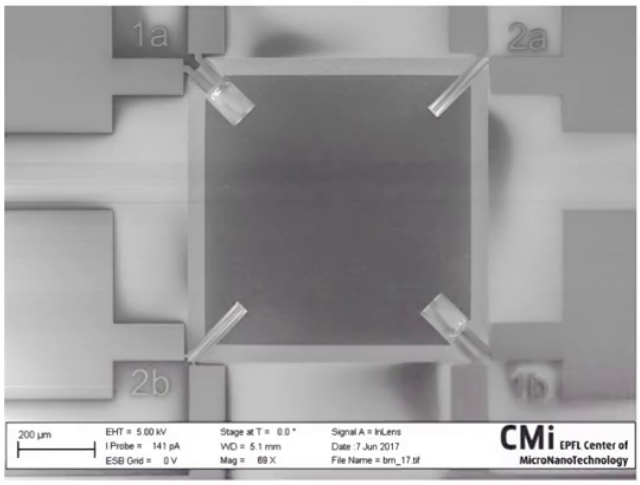


https://commons.wikimedia.org/wiki/File:Electron_emission_mechanisms.svg

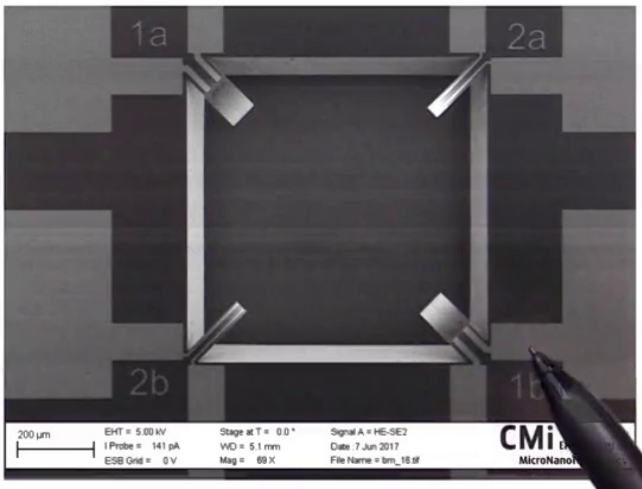
Micro and Nanofabrication (MEMS)

Different electron signals can be detected in a scanning electron microscope system. On the right side, you see possible electron atoms interaction. We call the incident electron as primary electron (PE). Mostly, when a PE hits an atom, it generates a secondary electron (SE). Which we can collect to have the secondary electron image or so called SE image. This is the most commonly used signaling in SEM which gives us a good contrast caused by the sample surface topographic structures. The SE detector is situated in the electron beam path as shown here in blue. And is called in lens SE detector which collects most of SE efficiently. Best scattered electrons (BSE) are primary electrons that are reflected or back scattered by elastic collisions with atoms. Atoms with higher atomic number generates higher BSE signals, which allows detecting material contrast. Another special detector is called Everhart- Thornley detector (ET detector). It is designed to collect both SE's and BSE's. Unlike the In-lens SE detector, the E-T detector is placed on the side in the SEM chamber as shown here in orange. To be able to collect SE and BSE with large angles with respect to the PE. This enhances the image contrast for topographic and etch features. The signal generated from these detectors is called high efficiency SE imaging (HE-SE2) for the specific SEM model that we used during the demonstrations in this chapter. PE with high enough energy can also knock out inner shell electrons from the sample atoms. This causes an electron from a higher energy state to fill the empty state whereby a photon is released. This is the so called characteristic X-ray. By detecting the energy dispersive x ray, we can therefore, perform spectroscopic compositional analysis of the sample in other words, we can determine what material we are looking at, and this at a very high spatial resolution.

Inspection with different electron signal



InLens-SE
SEM image of Bi-morph

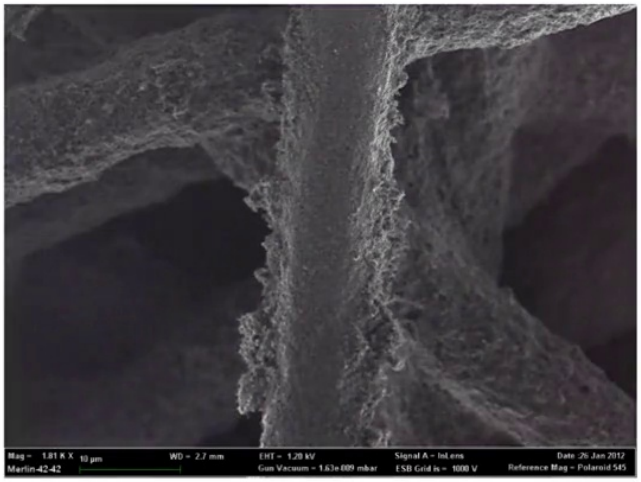


HE-SE2
SEM image of Bi-morph

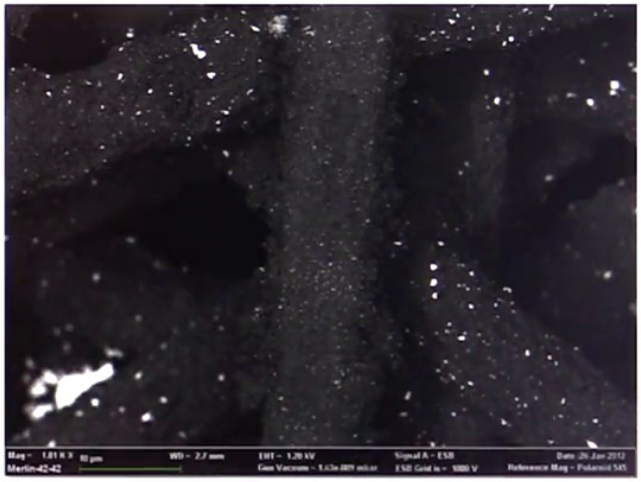
Micro and Nanofabrication (MEMS)

Here, we can see 2 SEM image taken with different detectors. Both images are taken under same conditions such as electron energy and working distance. On the left side, we see the image taken by in-lens secondary electron detector. It is very bright because it collects most of SE. On the down side, the charging effect of the sio2 layer on the bi-morph is also obvious. On the other hand HE-SE2 detector shown here on the right hand side provides better contrast and clearer edge definition in the case of the bi-morph device. For our purpose, the choice of this detector is thus preferred.

Inspection with different electron signal



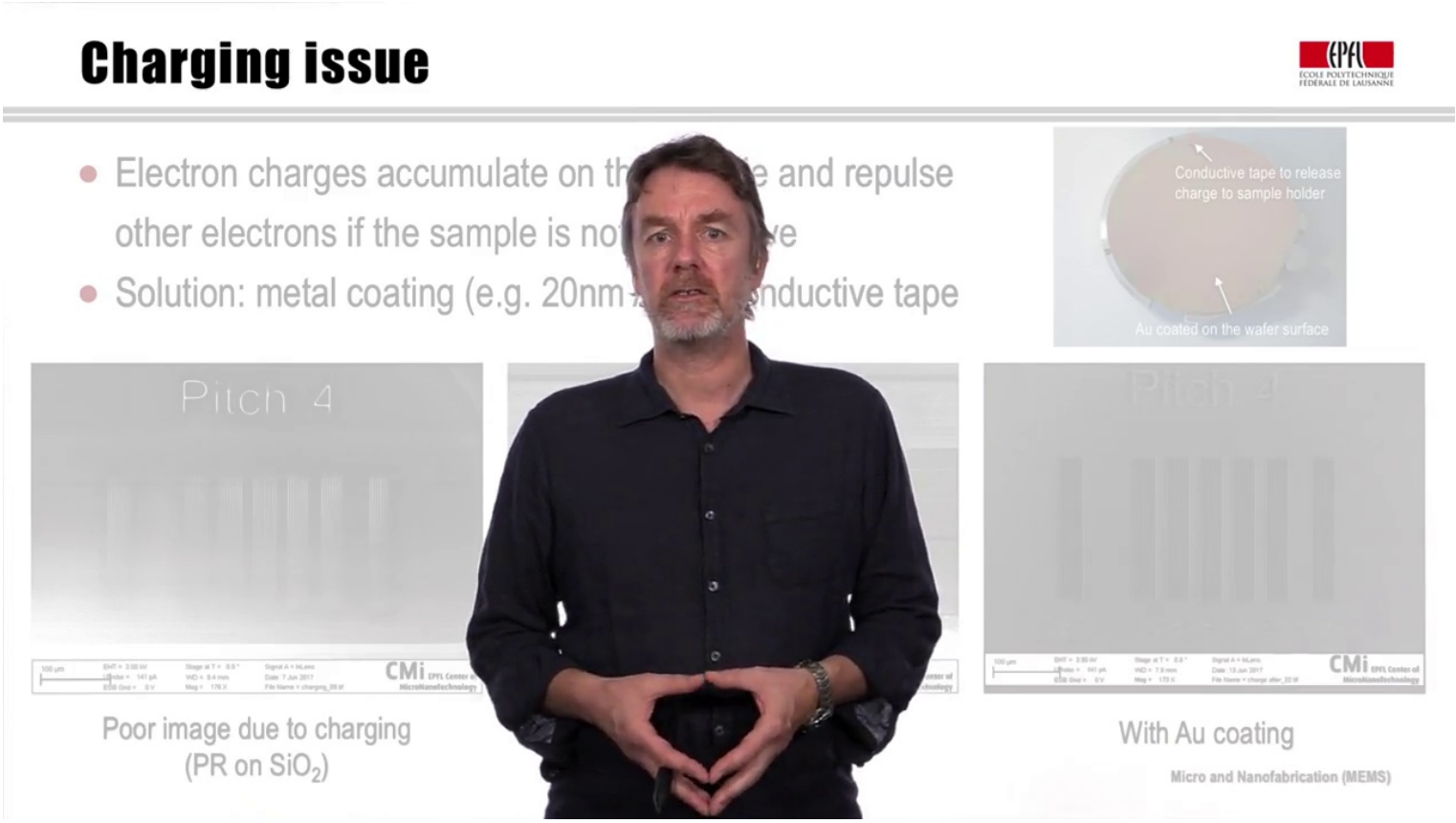
InLens-SE
SEM image of carbon nano tube bundle



BSE
SEM image of carbon nano tube bundle

Micro and Nanofabrication (MEMS)

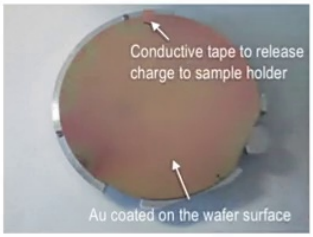
In order to better demonstrate the material contrast of BSE image, here, we use a carbon Nano tube sample as an example. Such a sample is used to adjust and calibrate the SEM tool. Here are bundles of carbon Nano tubes. The scale bar is 10um. The InLens SE image on the left side, here we cannot distinguish the metal and cobalt catalytic nanoparticles that are used during the synthesis of carbon nano tubes. While in the BSE image on the right side, each catalytic particle are highlighted and can be easily detected.

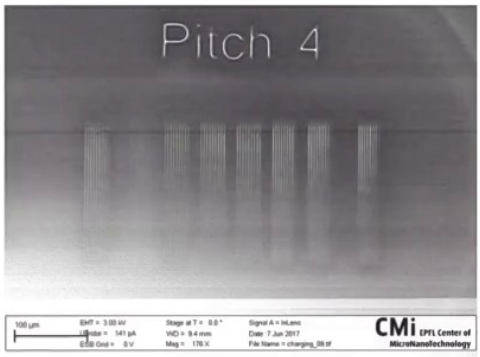


If there is one downside of charged particle imaging to mention, it is the problem of charging. If the electrons used to image the sample cannot be removed to ground, then, they will accumulate in the sample, which will deviate the trajectory of the next

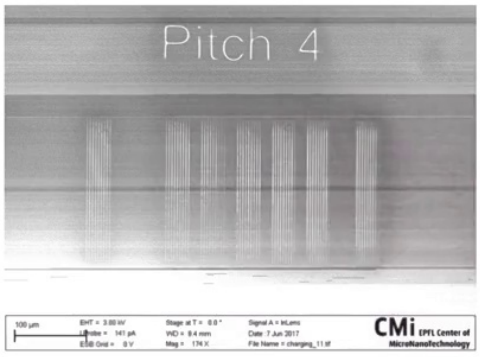
Charging issue

- Electron charges accumulate on the sample and repulse other electrons if the sample is not conductive
- Solution: metal coating (e.g. 20nm Au) + conductive tape

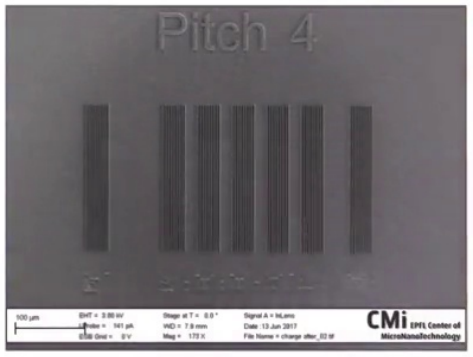




Poor image due to charging (PR on SiO_2)



Even worse over time (PR on SiO_2)



With Au coating

Micro and Nanofabrication (MEMS)

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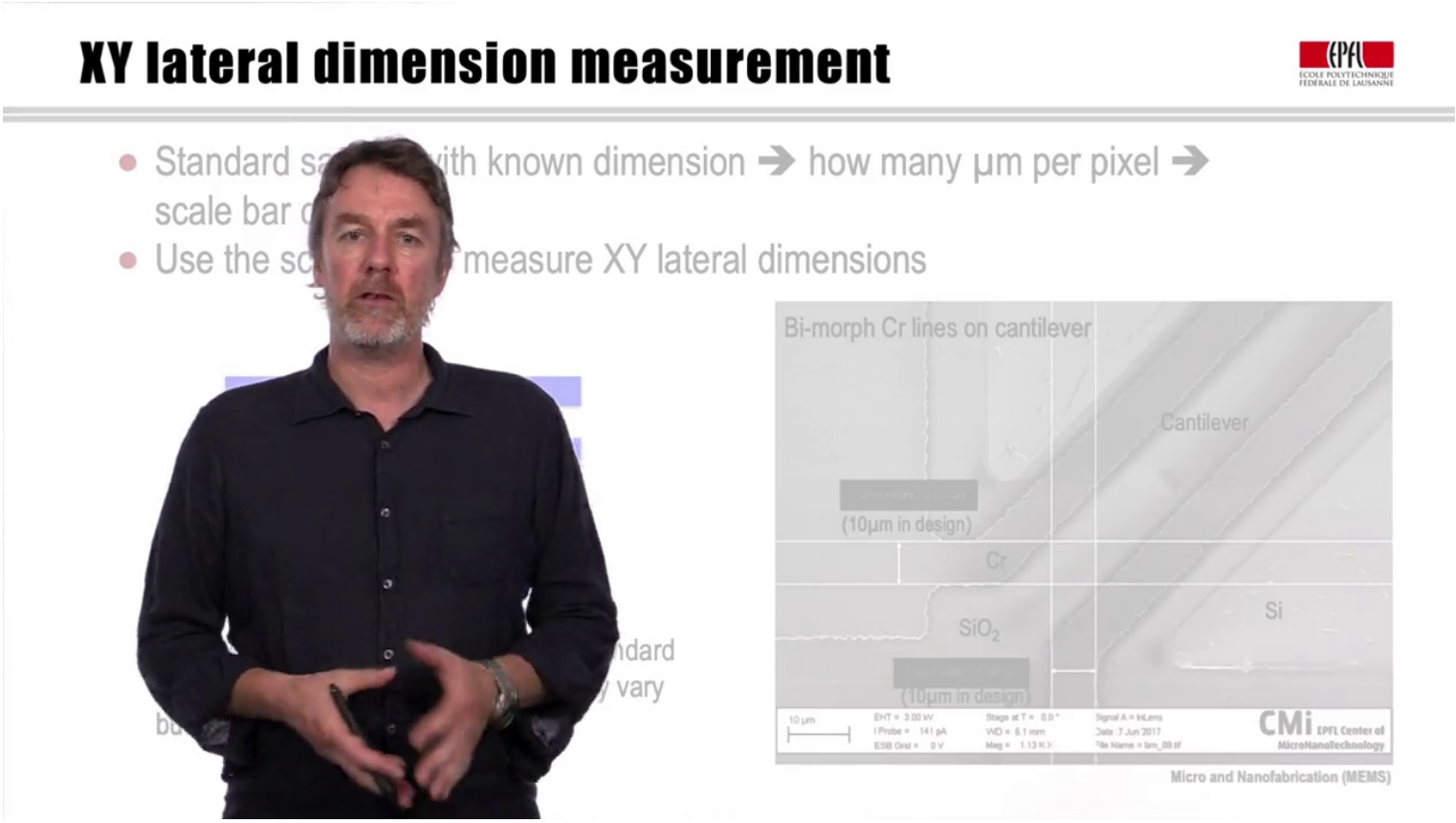
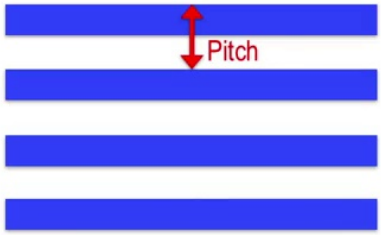
electrons. A direct consequence is a blurred image. The 3 SEM images here show photoresist which is insulating on sio2 which is also insulating. One can see the charging effect in the left image that increases over time, in the middle. One remedy is to coat the sample with a very thin conducting layer, either gold or chrome layer. The result can be seen here on the right. Notice that, of course, we are now imaging the gold layer on top of the sample. But for many investigations in MEMS, this is not an issue, and allow seeing the surface quality of the device. To conduct the electron charges to ground, it is important to ensure a proper conduction path. For instance by means of a conducting tape as shown here.



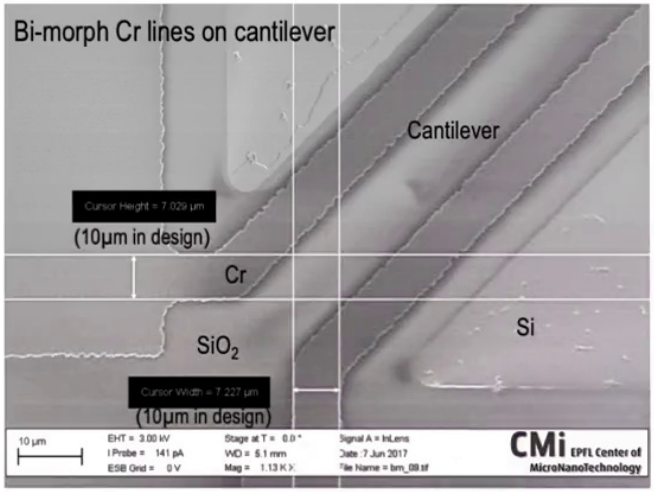
In order to perform a calibrated dimension measurement in an SEM, one needs to first ensure that the instrument is calibrated. This is done typically using a calibration with known dimensions. This will translate then, the conversion ratio between each pixel in the digital data acquisition and the sample dimensions in nm or um.

XY lateral dimension measurement

- Standard sample with known dimension ➔ how many µm per pixel ➔ scale bar calibration
- Use the scale bar to measure XY lateral dimensions



Periodic pattern fabricated by EBL as standard sample for calibration, the line width may vary but **the pitch** is highly accurate



This allows defining a scale bar which then can be used to measure the size of unknown samples with high accuracy. The calibration sample are typically made by electrons beam lithography. It is however also well known that, due to over exposure or under exposure, or over or under development, the exact pattern whidth is not perfectly predictable. That is why instead of using the pattern line width as calibration reference, one favors a periodic pattern where the pitch is highly accurate even if the individual pattern widths are not very precisely defined. The SEM image on the right shows the surface of the bi-morph device where the SEM is now used to measure the width of the chrome pattern. The white lines are positioned on the SEM tool to accurately measure the chrome pattern. Here we confirm now that the value obtained before, that the chrome pattern is about 7.2 um wide, which is much less than the designed 10 um, and which is due to some lithography effects.

Summary

- Magnification up to 500,000X
- Accurate dimensional measurement
- Nano scale inspection (tilting possible)
- Soft samples could be slightly damaged by high energy electrons

Micro and Nanofabrication (MEMS)

Here you see how to inspect a MEM sample in a scanning electron microscope, we mount the sample holder with the silicon MEM sample on the transfer stage. A load lock maintains the high vacuum inside the SEM chamber during the sample transfer. After the sample transfer, we setup the right configuration of the system. The first step is to position the sample to a proper working distance with respect to the electron column and detector. Then, we use the controller to tune the electron beam and the image. Here on the screen, you see the electron beam image made on a silicon sample with deep reactive ion etched grooves. You see how one can navigate around and zoom in and out. Here, we have seen how electrons, as charged particles in a SEM, can be used to inspect a MEM device surface. It allows for very high resolution in imaging, and allows for dimensional metrology. Remember that some materials might be damaged by the electron charges or heat generated.
