EPFL

Course material

Course:

Micro and Nanofabrication (MEMS)

Video:

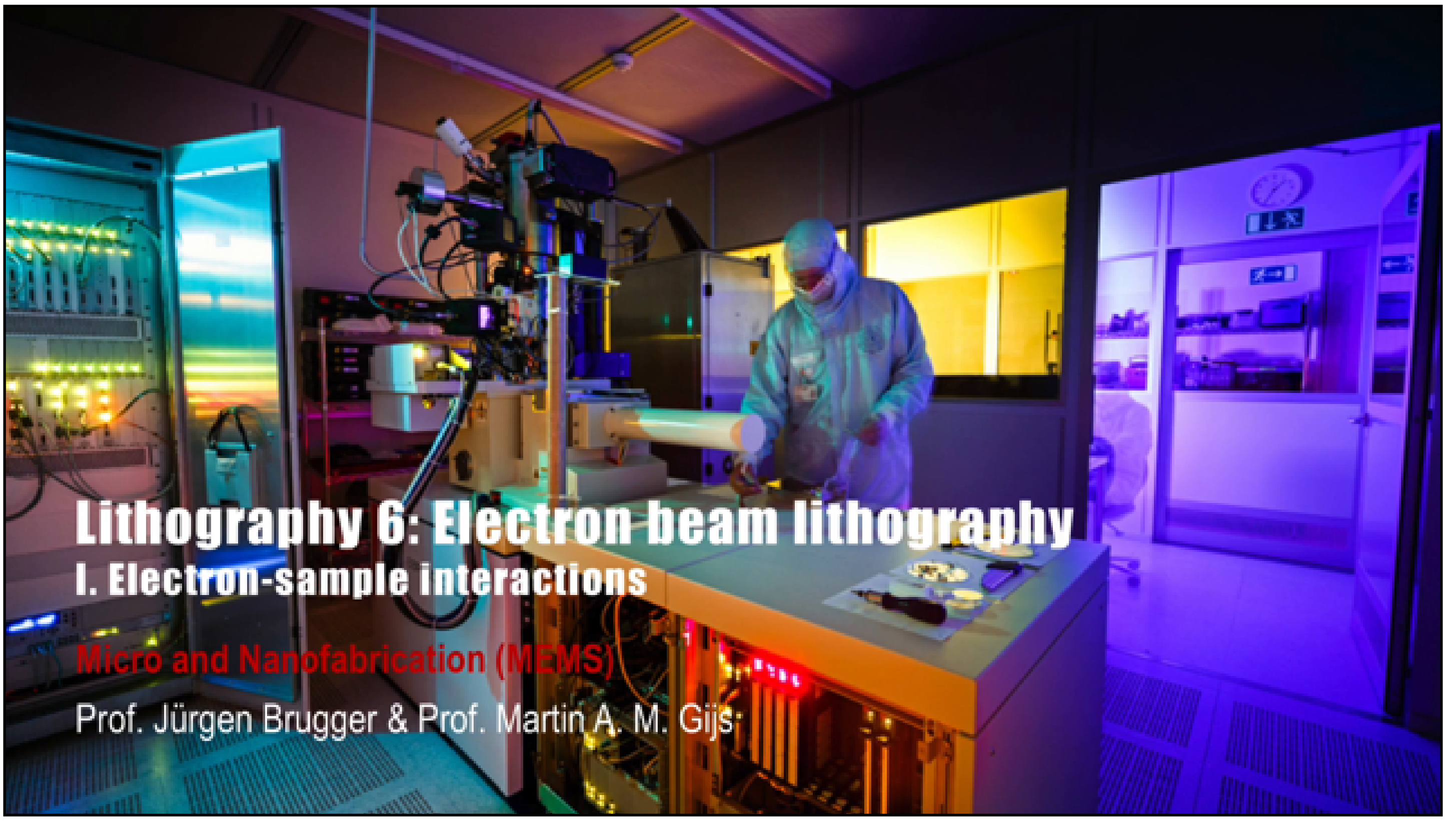
4.12 Lithography 6, Electron beam lithography, I Electron-sample interactions

Concepts (extracted from automatically generated subtitles):

Electron beam lithography. Resist-coated sample. High energy. Resist contrast. Lower voltages. Scatter effects. Various types of e-beam resist. Highest available accelerating voltage. Acceleration voltage. Energy of the primary electrons. Upper right side. Incoming electrons. Similar exposure dose. Proximity effects. High resolution.

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

to video

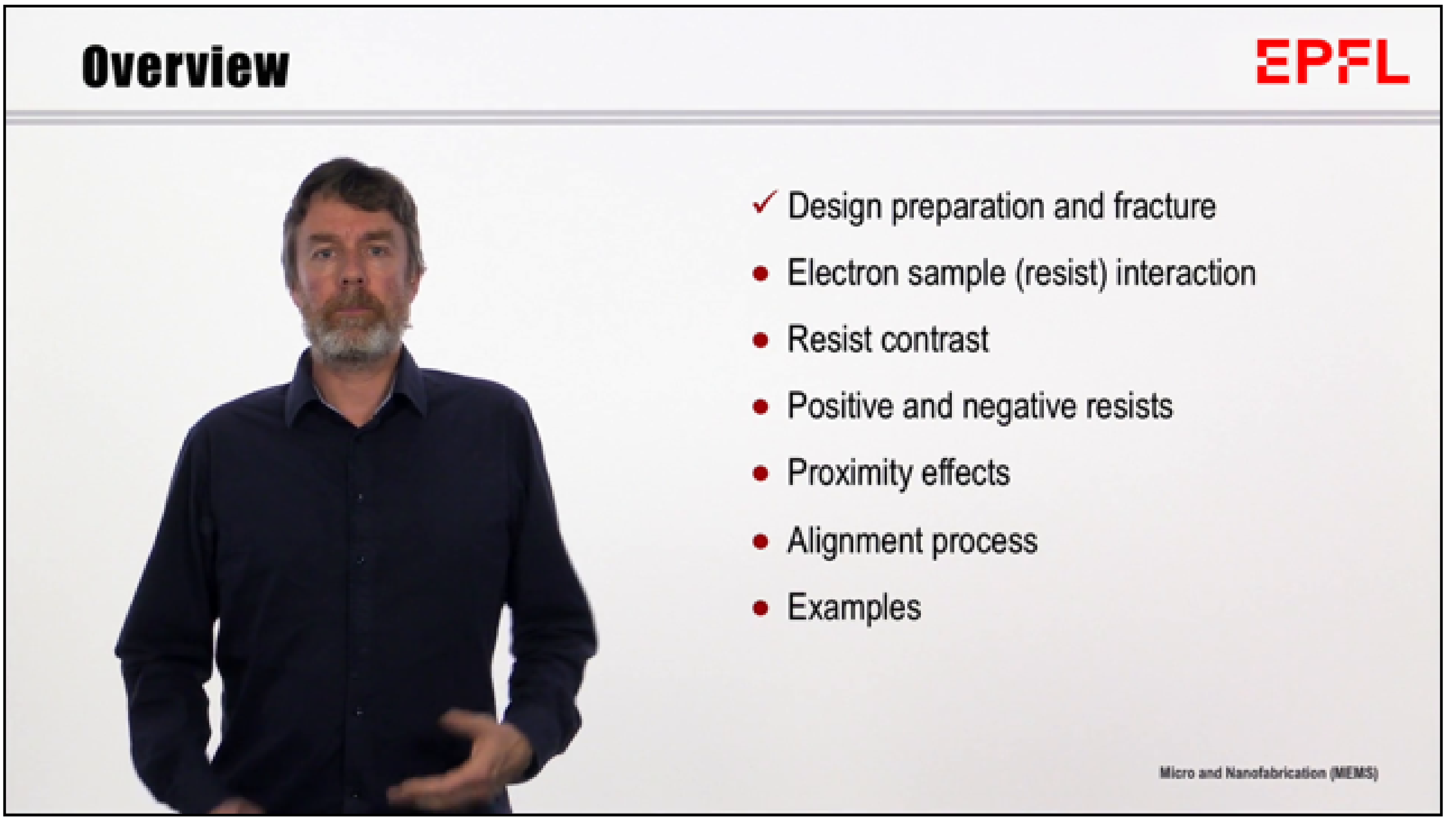


...

notes

summary

0m 0s

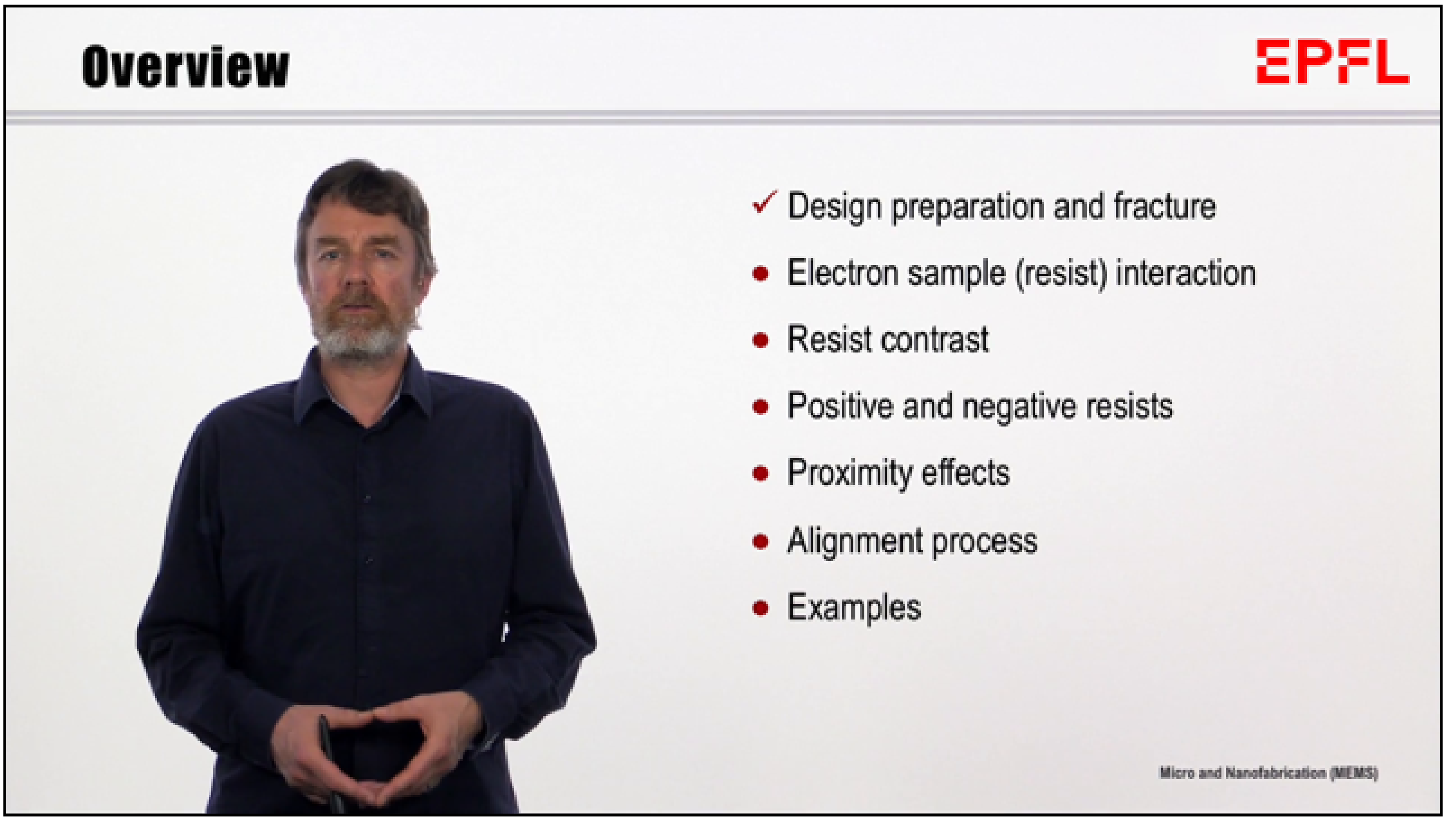


In the previous lessons, we have seen how the design

notes

summary

0m 1s

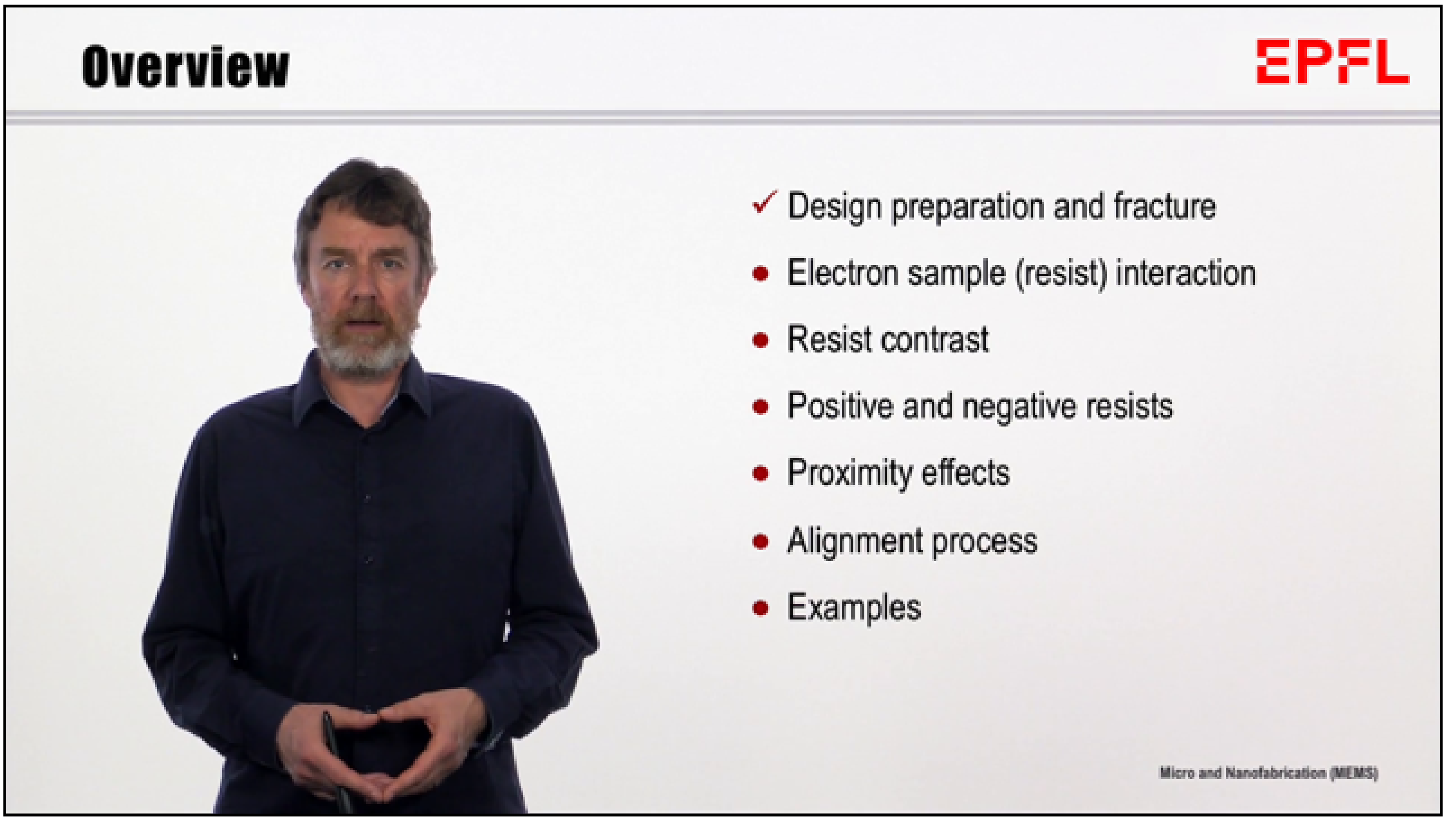


is prepared for electron beam lithography, and in particular about the fracturing of the pattern into convenient units to ensure best beam writing quality such as resolution, but also keeping in mind the writing speed. Here we will now see further details on the e-beam lithography

notes

summary

0m 5s

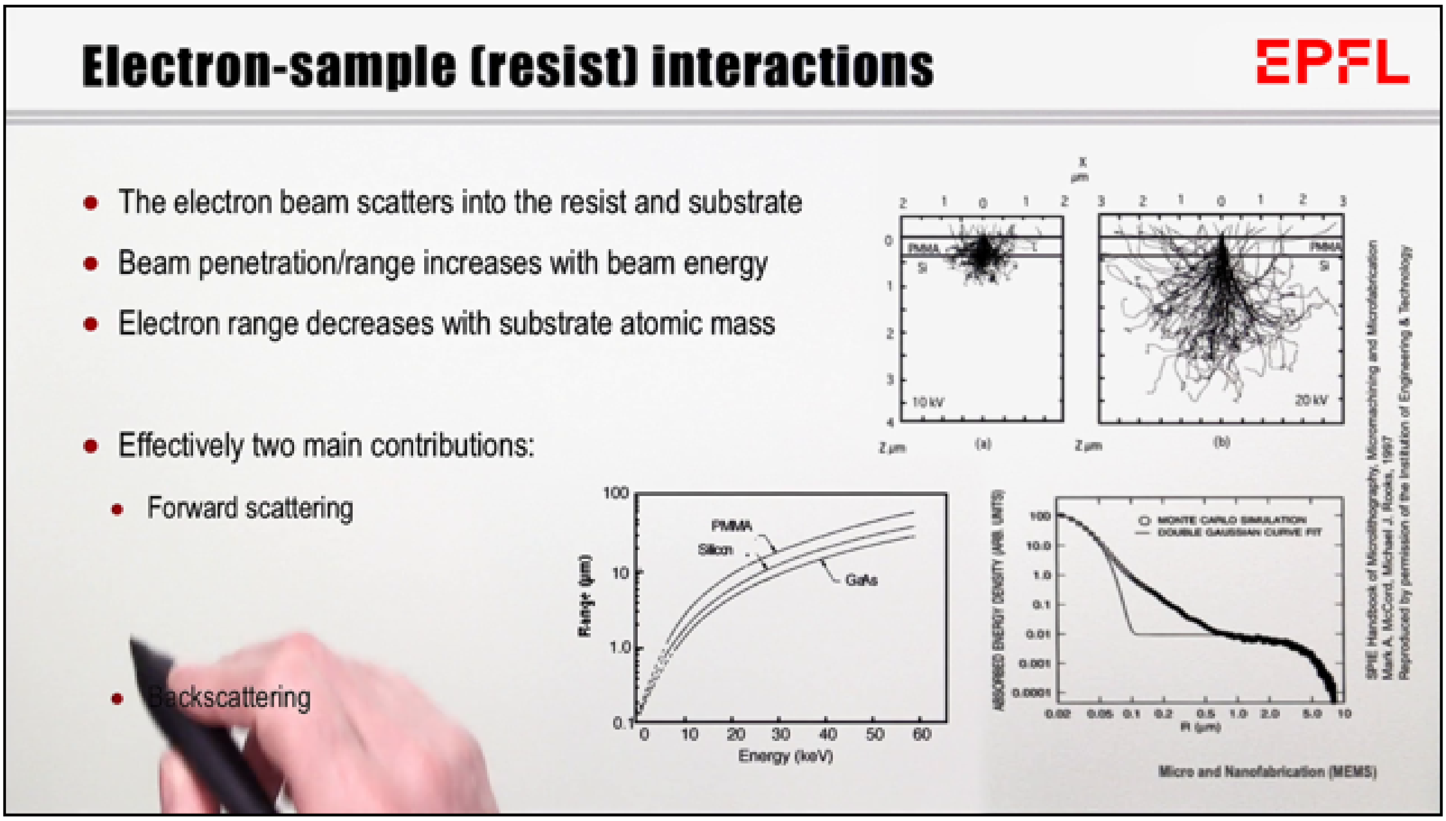


in particular how the electrons interact with the resist-coated

notes

summary

0m 25s

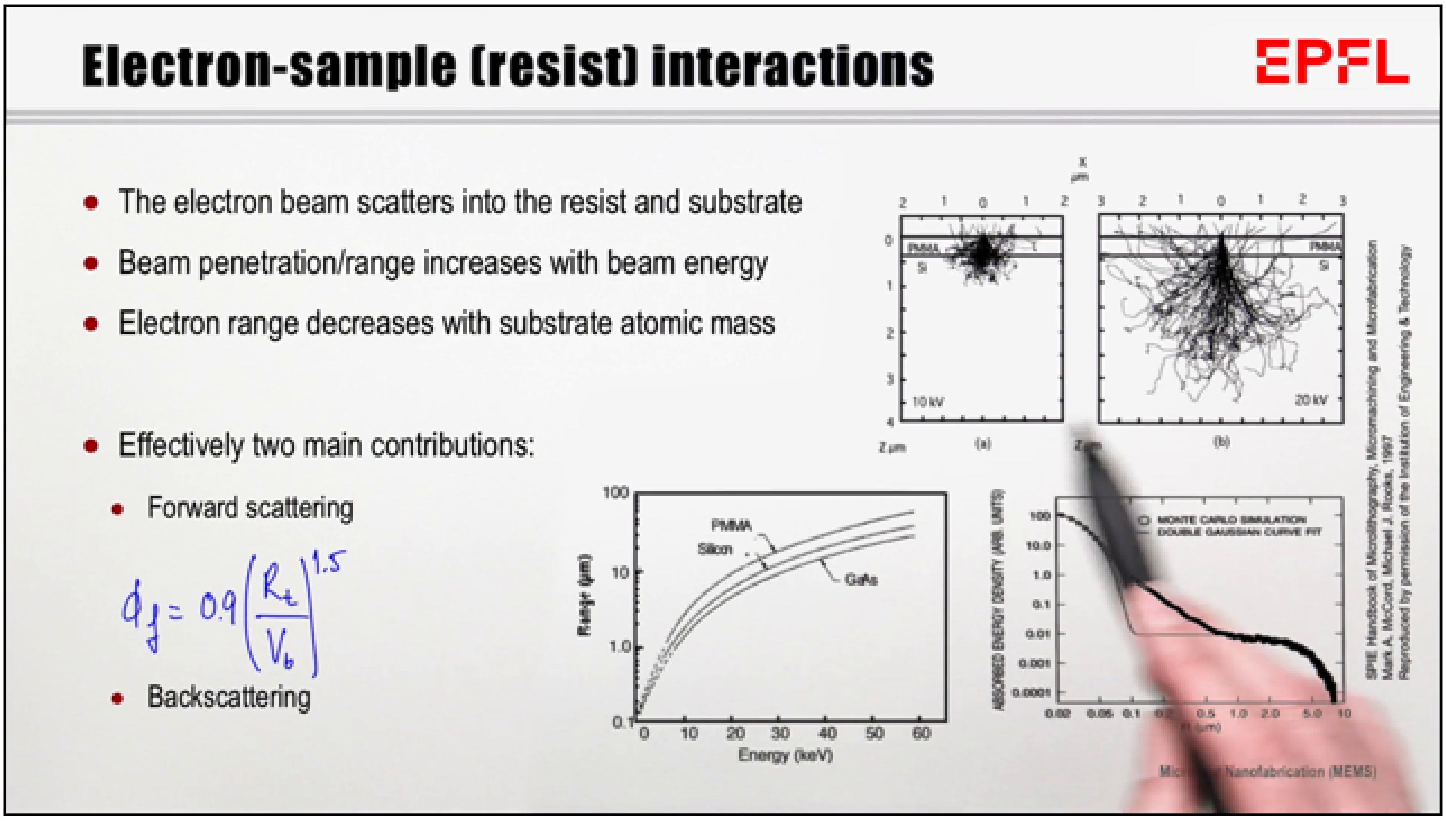


sample, and what parameters are to be understood and optimized. These are the resist contrast, the various types of e-beam resist, proximity effects, as well as alignment processes. The electrons are accelerated to high energy and are focused onto the surface. As the electrons penetrate the resist, they experience so called "scattering". Forward scattering at small angles occurs to the incoming electrons which tend to broaden the initial beam diameter. When the electrons reach the substrate, they undergo large angle scattering, which also leads to back scattering. The increase in effective beam diameter in nano meters, due to forward scattering, can be given apparently by the following formula.

notes

summary

0m 27s



So the forward scattering can be expressed by 0.9 times the resist thickness Rt, over the acceleration voltage, to the power of 1.5. Using the thinnest possible resist and the highest available accelerating voltage can minimize forward scattering. Back scattered electrons may return back to the resist at a significant distance from the incident beam, causing additional resist exposure. This is called the "electron beam proximity effect". The range of the electrons is defined here as the distance a typical electron travels in the bulk material before losing all its energy. The range depends on both the energy of the primary electrons and the type of substrate. So here, on the upper right side, you can see two examples of simulated results showing the distribution of the electrons from the incoming beam, from the top here, that hits the surface, the PMMA photoresist and then the scattering into the resist and the silicone substrate for a voltage of 10 kV	notes

summary

1m 13s

Electron-sample (resist) interactions

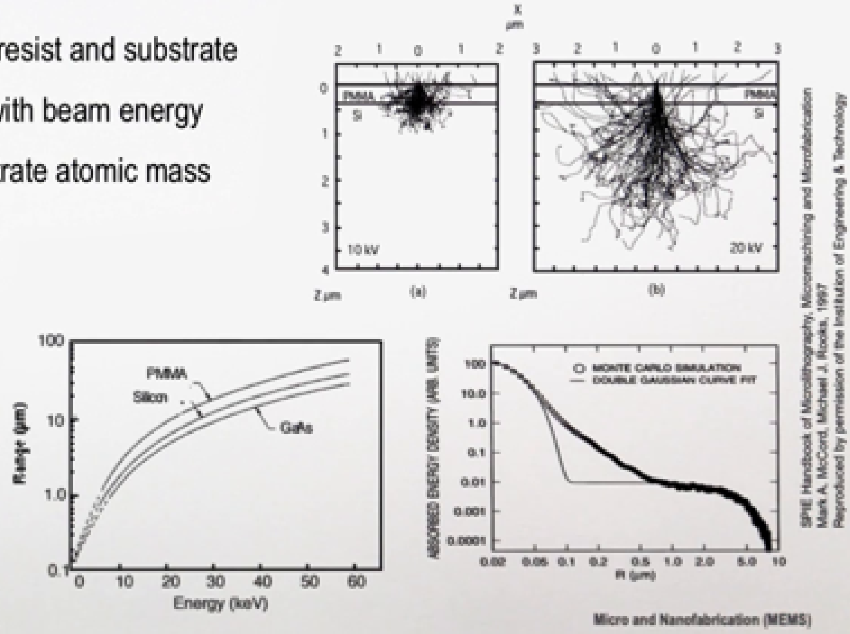
EPFL

- The electron beam scatters into the resist and substrate
- Beam penetration/range increases with beam energy
- Electron range decreases with substrate atomic mass

- Effectively two main contributions:
  - Forward scattering

$$d_f = 0.9\left(\frac{R_t}{V_b}\right)^{1.5}$$

  - Backscattering



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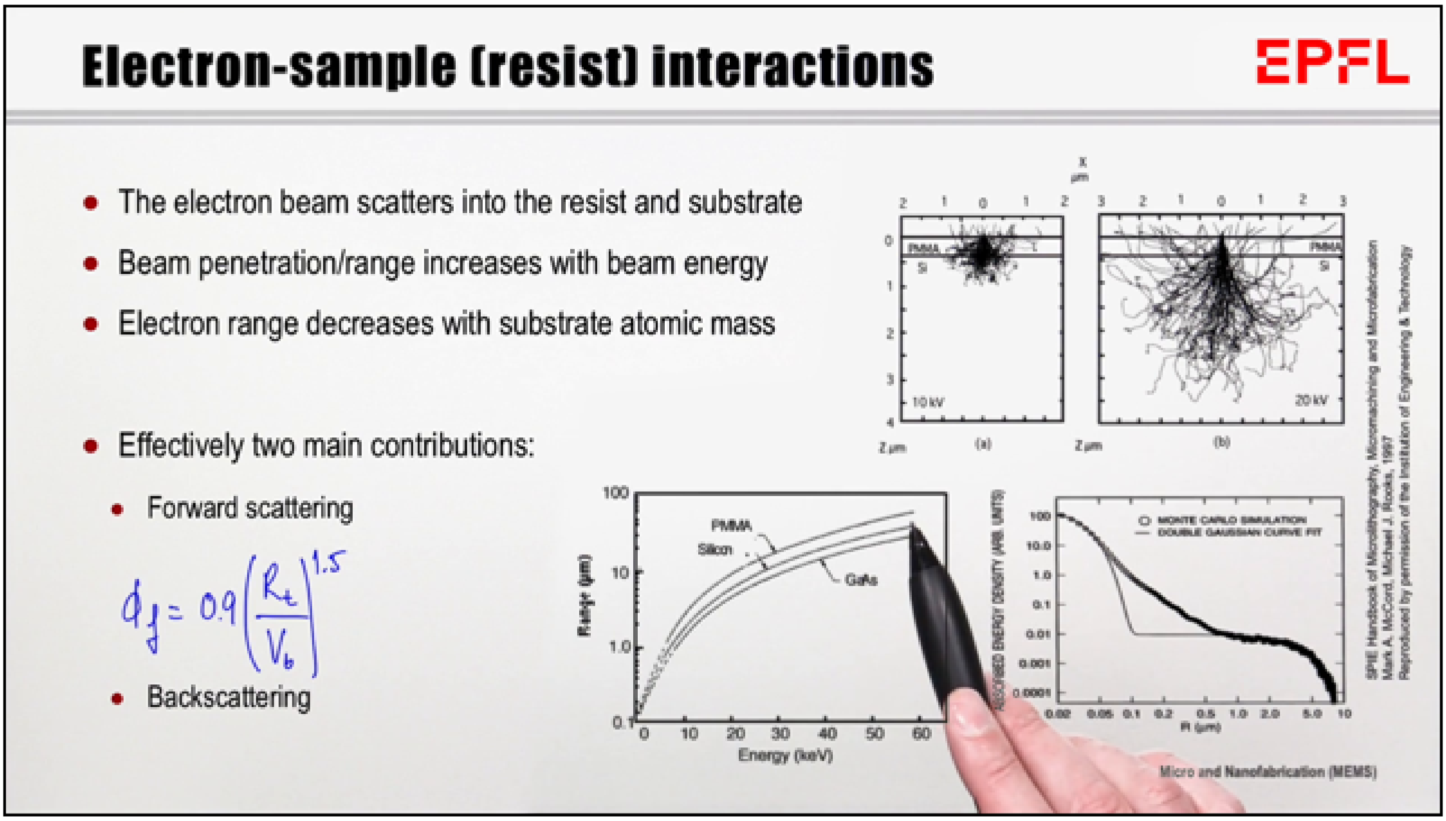
and the same is done here for a voltage of 20kV. We can already see that for example, the forward scattering, which is the widening of the incoming beam during the impact is much more narrow for higher voltages compared to the lower voltages. So, if one aims for high resolution patterning one obviously goes to higher voltages to minimize these scatter effects, forward scatter effect, during the impact. On the other hand, please note also that all these back scattered electrons that come out through the photoresist at some further distance location, also cross-link or alter the photoresist, which then will also be exposed which is then called this proximity effect.

notes

summary

2m 29s



If we now focus on how the atomic mass Z of the substrate material influences the electron range, for a given acceleration voltage, we obtain the following dependents for gallium arsenide, the lower curve, silicone in the middle and PMMA on top. So as expected, high atomic mass materials show a reduced electronic range.

notes

summary

3m 15s

Electron-sample (resist) interactions

EPFL

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  - Forward scattering

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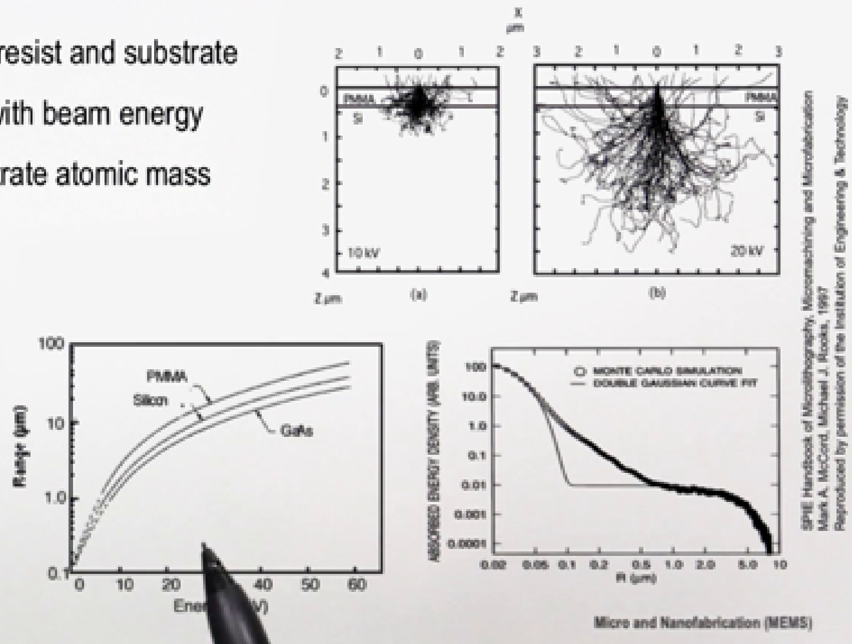


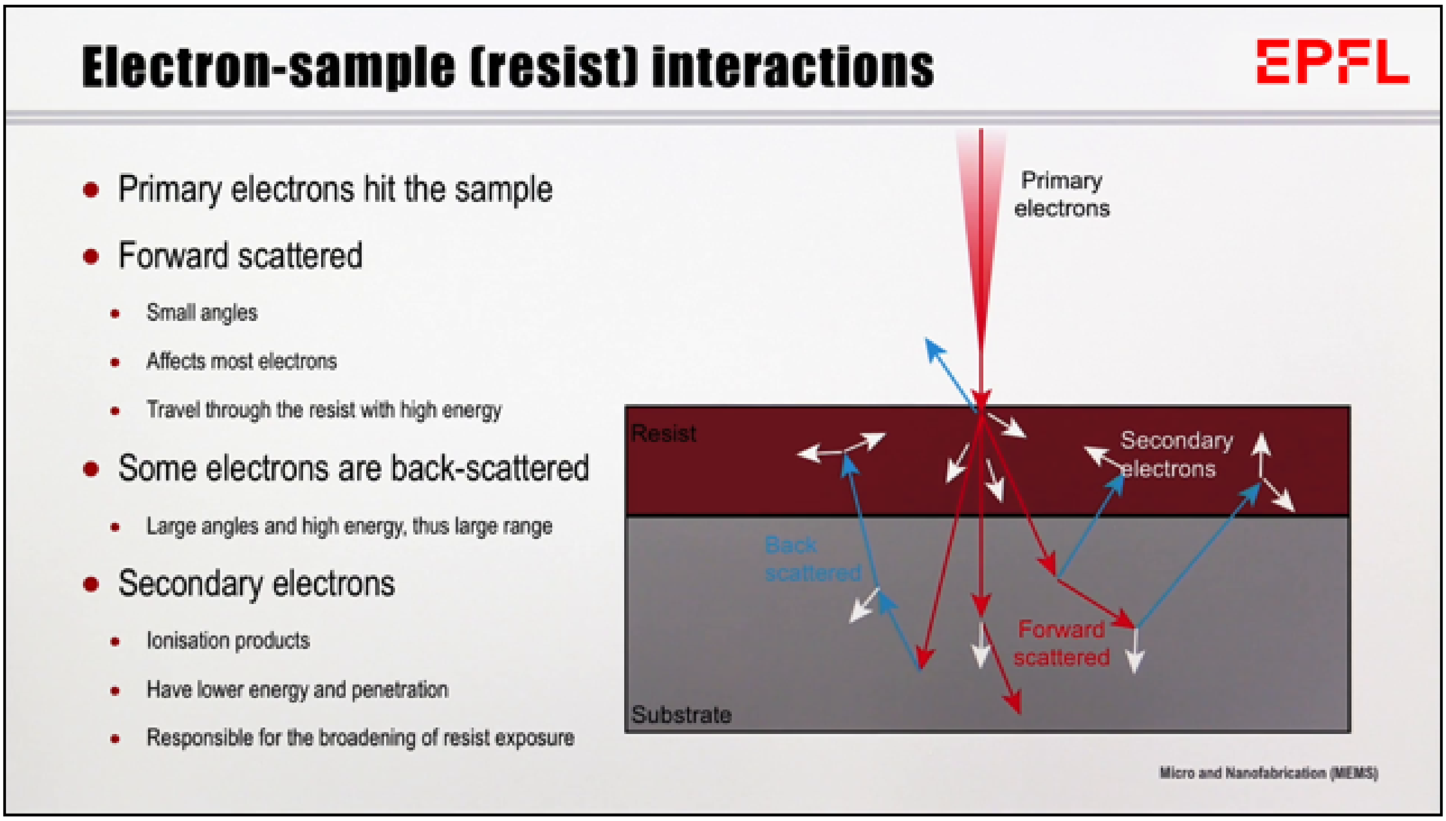
Micro and Nanofabrication (MEMS)

And here on the right side, we see a typical radial energy

notes

summary

3m 37s

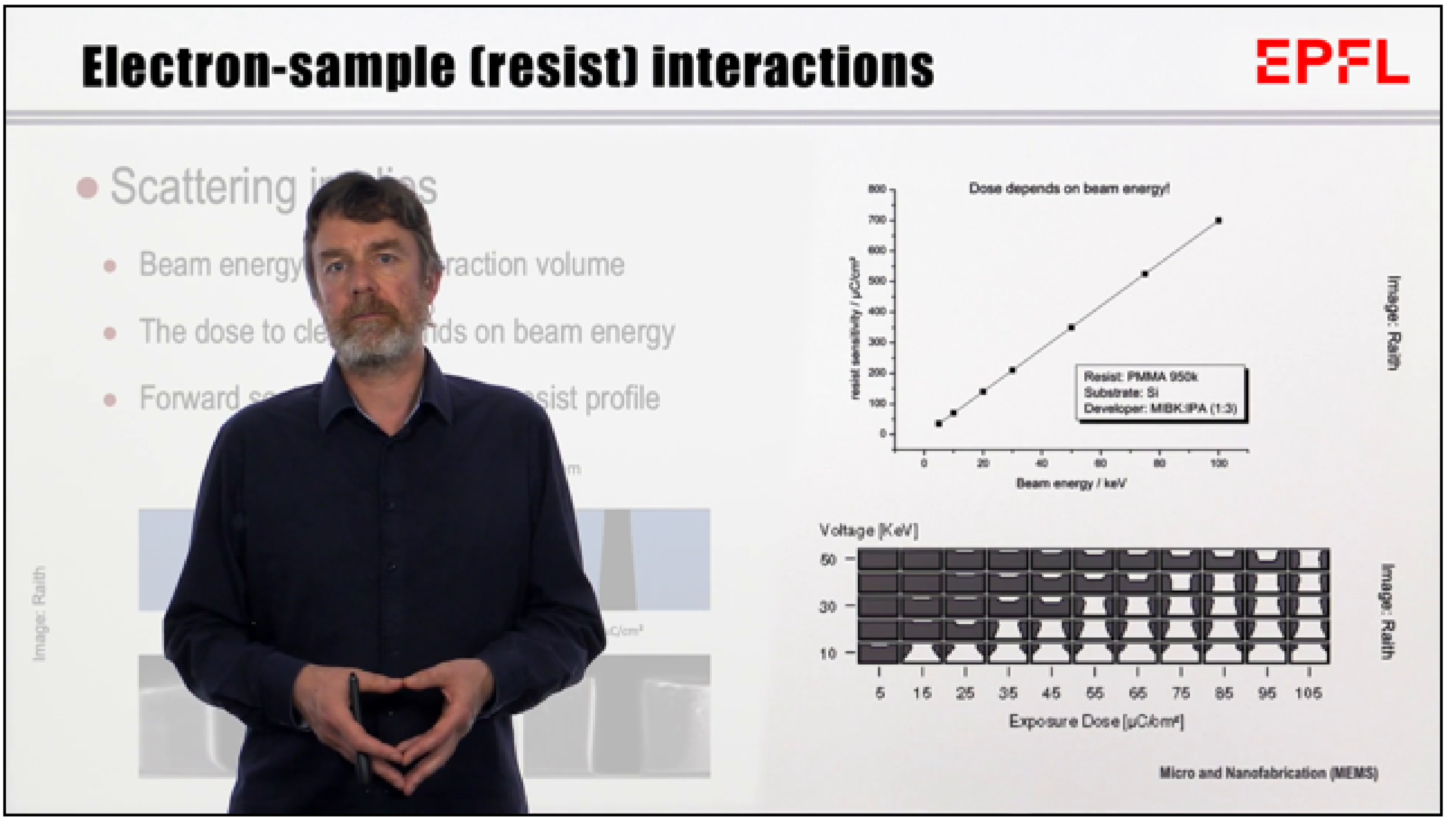


profile away from the beam impact point. The forward and back scattering are approximated by two gaussians. Please, note that this scale is done in a logarithmic scale. Now let's have a more detailed look at how the path of the incoming primary electrons and generated secondary electrons influence the resist exposure, shown here. The photoresist with the substrate and the incoming primary electrons. Forward scattering at small angles of the primary electrons is the first source of beam broadening. As these primary electrons slow down, much of the energy is dissipated in the form of secondary electrons, with energies that are per definition between 2 and 50 eV, so about three orders of magnitude lower than the primary electrons which are at keV. The secondary electrons are responsible for the majority of the actual resist exposure process. The travel range is only a few nanometers, which results in a slight broadening of the exposed area. These two effects largely account for the minimum practical resolution obtainable in the highest resolution electron beam systems, and contribute to the bias that is seen in positive resist where the exposed features

notes

summary

3m 38s



develop larger than the size they were nominally written. Primary electrons may also back scatter at high angles, so in back scattering an electron collides with a much heavier nucleus which results in an elastic scattering event and the electron thereby retains most of its energy but changes direction. These back scattered primary electrons can travel a long distance away from the beam impact point and thereby they create secondary electrons that will expose the resist quite far away from the intended impact location. This results in the well known white background exposure known as proximity effect. Due to the scattering effect, the interaction volume or exposed zone depends on the beam energy. Indeed, a similar exposure dose which is the total charge per surface delivered at different acceleration voltages results in different lithography results. For instance, at high acceleration voltage the electrons mostly penetrate through the resist with little interaction and require a higher dose to clear. As seen in the cross section images, forward scattering is well visible in the tapered resist profiles.

notes

summary

5m 1s

Contrast curve

EPFL

- Sensitivity: dose to clear positive or cross-link negative resist
  - High sensitivity – fast writing
  - Moderate sensitivity – high resolution

$$\gamma = \frac{1}{\log_{10} \frac{D_{100}}{D_0}}$$

γ = positive resist contrast
D_{100} = dose for 100% resist removal
D_0 = threshold dose

- Contrast: slope of thickness to dose variation
  - High contrast – high resolution
  - Low contrast – grayscale lithography

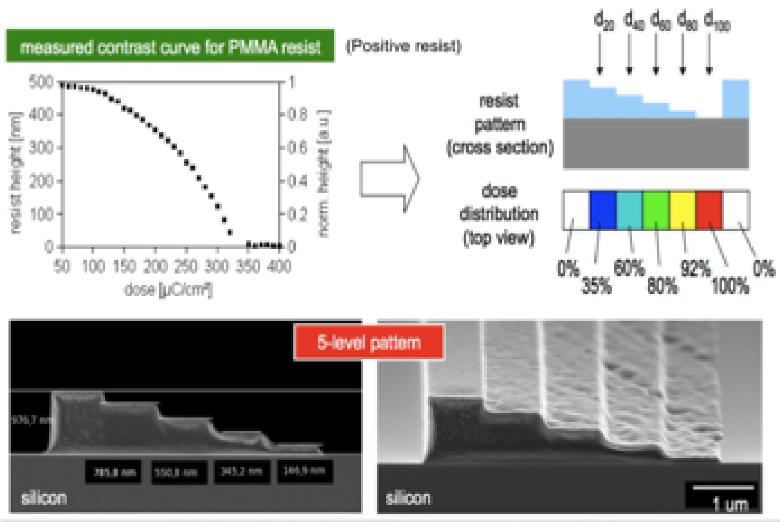


Image: Courtesy PSI, Switzerland

Micro and Nanofabrication (MEMS)

As expected, forward scattering is more pronounced for low acceleration voltages. On the top right, we can see that at higher acceleration voltages a greater dose is needed to obtain full opening of the PMMA after development. High energy electrons penetrate through the resist and scatter in a large volume and thus interact less with the resist than for lower acceleration voltages. At low voltages the interaction volume is limited more within the thin resist layer. In the two figures here below, we can see further illustration of this concept. Additionally from the schematic on the lower right you can see the evolution of dose to clear, as well as the resist profile due to forward scattering. This is shown experimentally from the images on the left. At 640 µC/cm^2 we can see the characteristic tapered angle induced by the forward scattering. For now, let's have a look at the actual resist exposure details which are contrast and sensitivity. Sensitivity is the dose needed to fully clear positive or cross-link negative resist. The high sensitivity resist allows for fast writing. On the other hand, most high resolution resists are of moderate sensitivity for the following reasons. When targeting ultimate resolution, an electron beam of a few nanometer width is used to expose a correspondingly small area. A highly sensitive resist requires only a very limited number of electrons to be exposed. The process is consequently very sensitive to beam shot noise. In order not to be affected by shot noise one typically chooses a lower resist sensitivity so that a relatively large number of electrons are needed for the exposure of very fine patterns. Another important feature of the resist is the contrast, which is defined as the slope of the dose to thickness variation. It is shown here, so D100 is the dose to clear, meaning the lowest dose when the resist is fully opened after development, and D0

notes

summary

6m 13s

Contrast curve

- Sensitivity: dose to clear positive or cross-link negative resist
  - High sensitivity – fast writing
  - Moderate sensitivity – high resolution

$$\gamma = \frac{1}{\log_{10}\frac{D_{100}}{D_0}}$$

γ = positive resist contrast
D_{100} = dose for 100% resist removal
D_0 = threshold dose

- Contrast: slope of thickness to dose variation
  - High contrast – high resolution
  - Low contrast – grayscale lithography

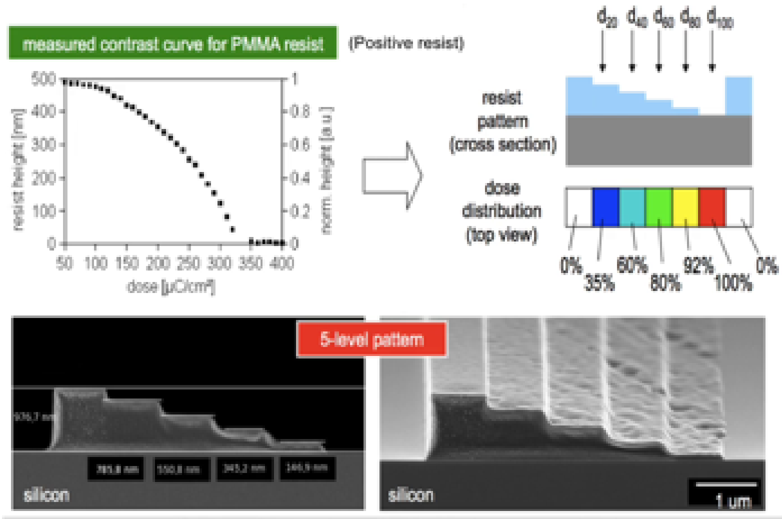


Image: Courtesy PSI, Switzerland

Micro and Nanofabrication (MEMS)

is the largest dose where the resist is still not exposed enough to induce a thickness difference after development. In typical processing conditions, high contrast resists are preferred as it is often correlated with resolution. Essentially, a high resolution resist will result in a binary system. The lower dose threshold resist is unaffected, above the dose threshold it is fully removed in case of positive, or cross-linked in case of negative. Although proximity effects may still distort the pattern, higher contrast results allow reduced blurring of the written pattern. Low contrast resists, on the other hand, find interesting applications in grey-scale lithography. As seen here, the low contrast allows for fine modulation of the final resist thickness in order to create out of plane features. One important point to consider is that resist contrast characterizes the full processing of the resist, which with developing playing an equally important role as exposure. So here in the bottom you see two SEM images that show the result of an exposure and developing of a grey-scale 3D e-beam lithography, and we can see here the entire thickness of the resist, which is roughly 1µm and then it goes down step by step, 785, 550, 345, and 146 nm. With the low contrast resist, one is able to perform such grey-scale lithography which is not possible with the high contrast resist.

notes

summary