

Optical surface profile measurement

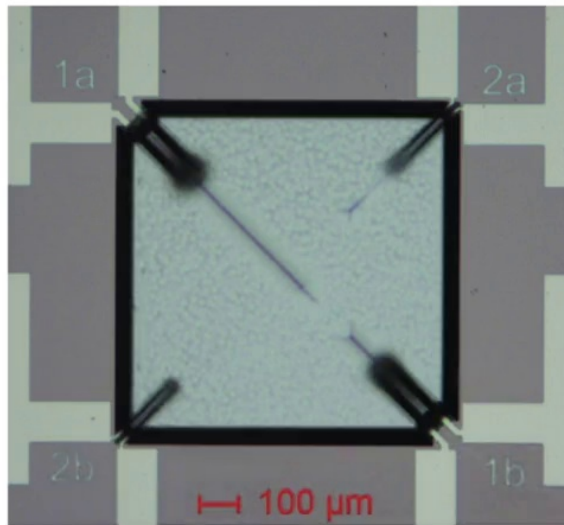


- White light interferometric (WLI) surface profiler
- Bi-morph measurement with WLI
- Laser beam surface profiler
- Thin film stress measurement

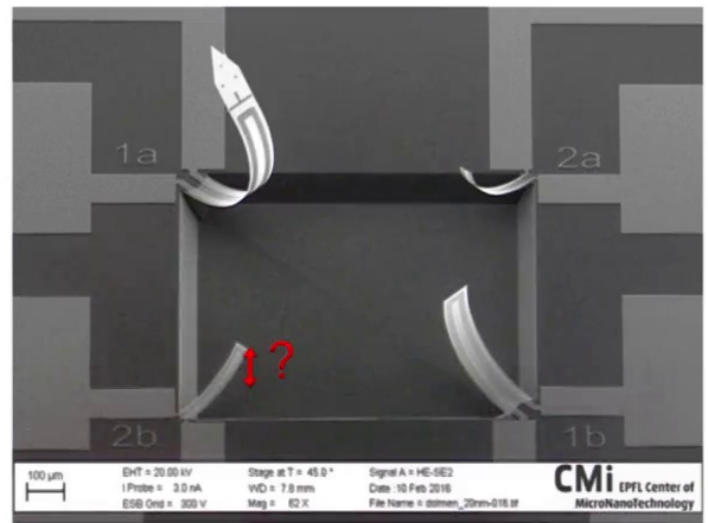
Micro and Nanofabrication (MEMS)

Two additional examples of optical inspection and metrology are a white light interferometer and the laser beam surface profiler. They are particularly useful to determine the 3D aspect of MEMS surfaces as well as film stresses. We will use again our bi-morph example and will use both methods to determine the bending of substrate and the bending of cantilever devices.

Bi-morph surface profile measurement



Optical microscope



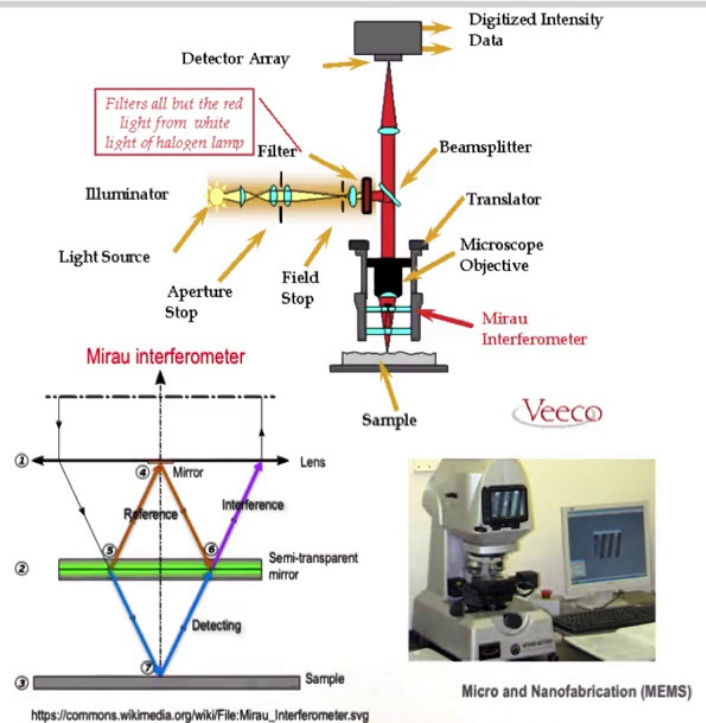
How high is the cantilever bending upwards?

Micro and Nanofabrication (MEMS)

Here you see again our well known bi-morph actuated devices, let us now quantify precisely how much actually a cantilever is bent upwards. Remember we could estimate this value by the focus control of an optical microscope like shown here. But, let's have a much more precise approach now.

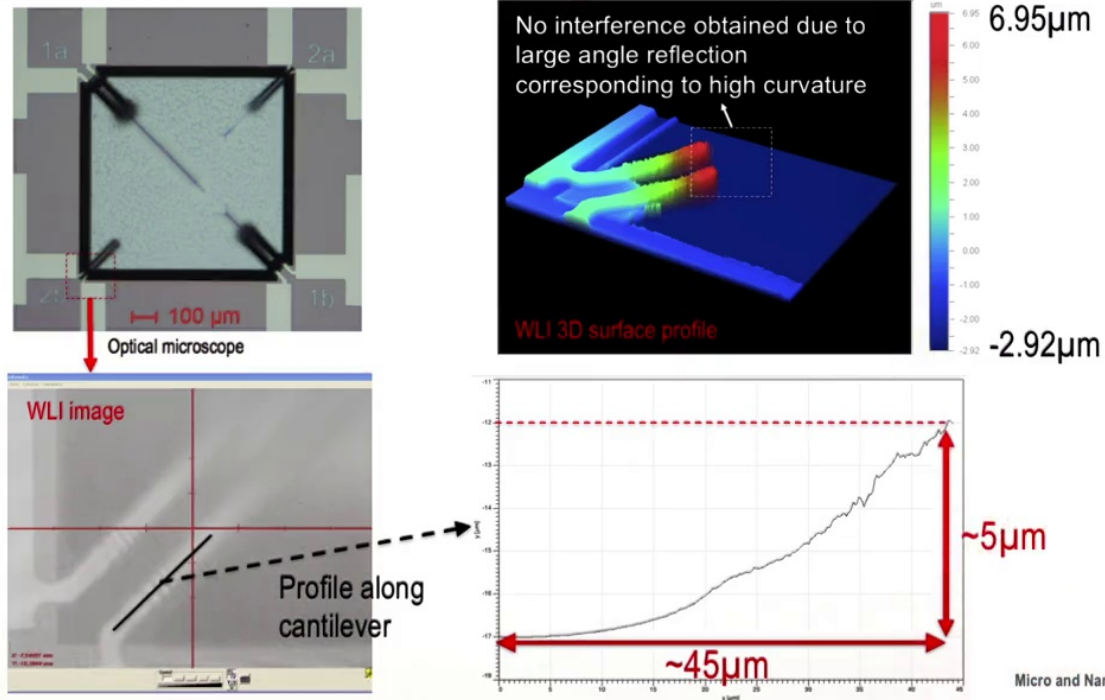
White light interferometric surface profiler

- Mirau interferometer embedded objective lenses
- Surface topography → optical path change → interference change
- Scan in vertical direction to obtain 3D surface profile
- Field of view: up to 2.5mm x 1.9mm
- Vertical resolution: < 1nm
- Vertical scan range: 1mm
- Non-contact, non-destructive



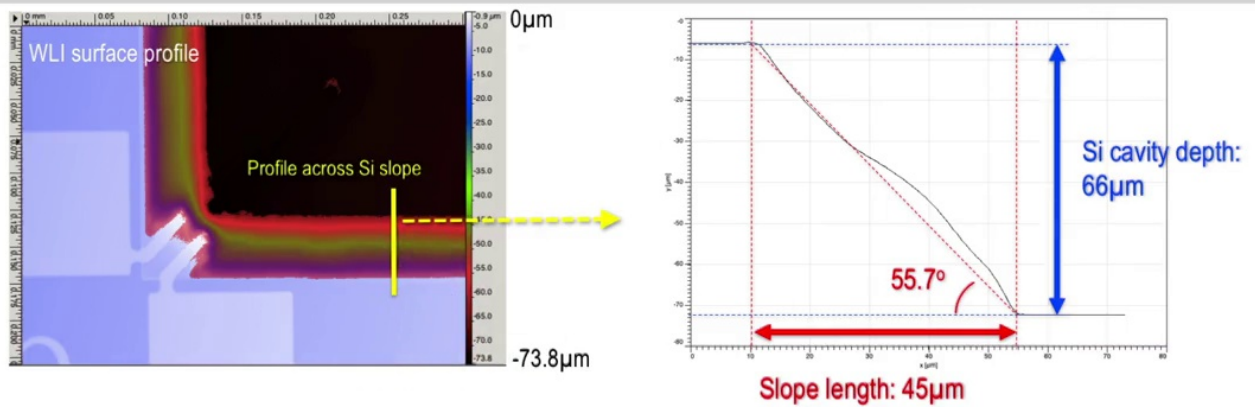
The principle of the white light interferometer is shown here on the right side with a general overview of the setup, a zoom into the detail of interference part, and the photography of the system in our clean room. The white light interferometer system works as follows. The light coming into the mirau interferometer, is focused by the lens, and further split into 2 beams using a semi-transparent mirror. The reference beam is shown in orange, whilst the object beam is shown in blue. On a flat sample surface, the light path of the reference and the object beams are totally identical, which means the light path difference is 0 and hence constructive interference occurs. On the other hand, if the sample surface is not flat, the light path difference between the reference and the object beam is no longer 0. Instead, interference intensity as shown in purple here, will change accordingly and is detected by a light intensity detector. This way, the topographic information of the sample surfaces is obtained, typical values for field of view resolution and "z" scan range are listed here.

Bi-morph measurement with WLI



On the left side, you see the bi-morph cantilever device imaged with the normal optical microscope. Inspecting the bi-morph under the white light interference gives us additional information. White light interference image delivers interference fringes that allow quantifying very precisely the out of plane bending of the cantilever. We can see these fringes here on the bent part of the cantilever. By creating a profile along the cantilever, you obtain the bending curve with quantitative values as shown here. Please notice that for high bending angles above 45 degrees, the system cannot detect any more interference fringes. This can be seen in the curve, by the noisy curve and bumps. The white light interference allows creating a 3D colored map on the high profile. Here, red means high, and blue means low. From a certain point the value and height cannot be extracted, because the bending curvature of the cantilever is too high. In this case, tilting the sample could be a solution.

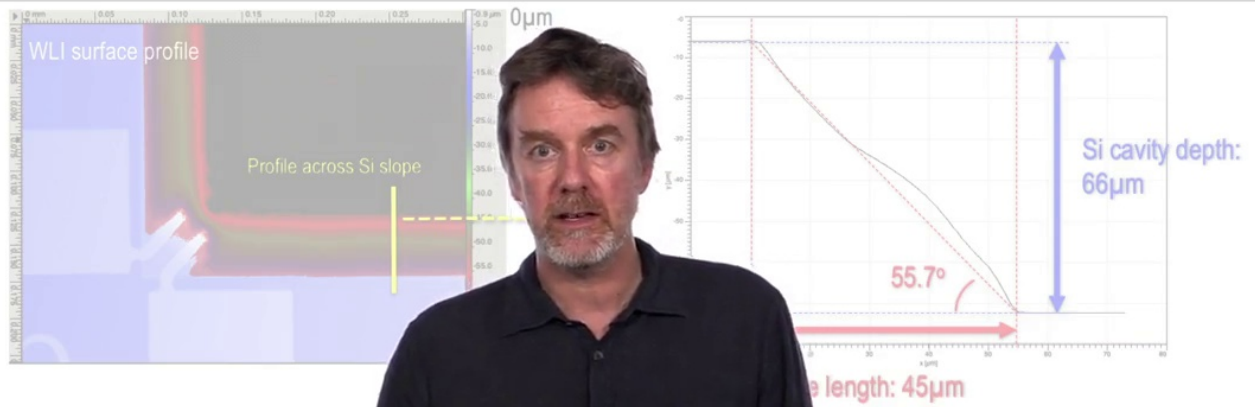
Bi-morph measurement with WLI



Micro and Nanofabrication (MEMS)

The white light interferometer also allows measuring the width of surface patterns and depth of edge grooves as shown here. In this example, let us assess the silicon slope that results from the anisotropic silicon etching in KOH.

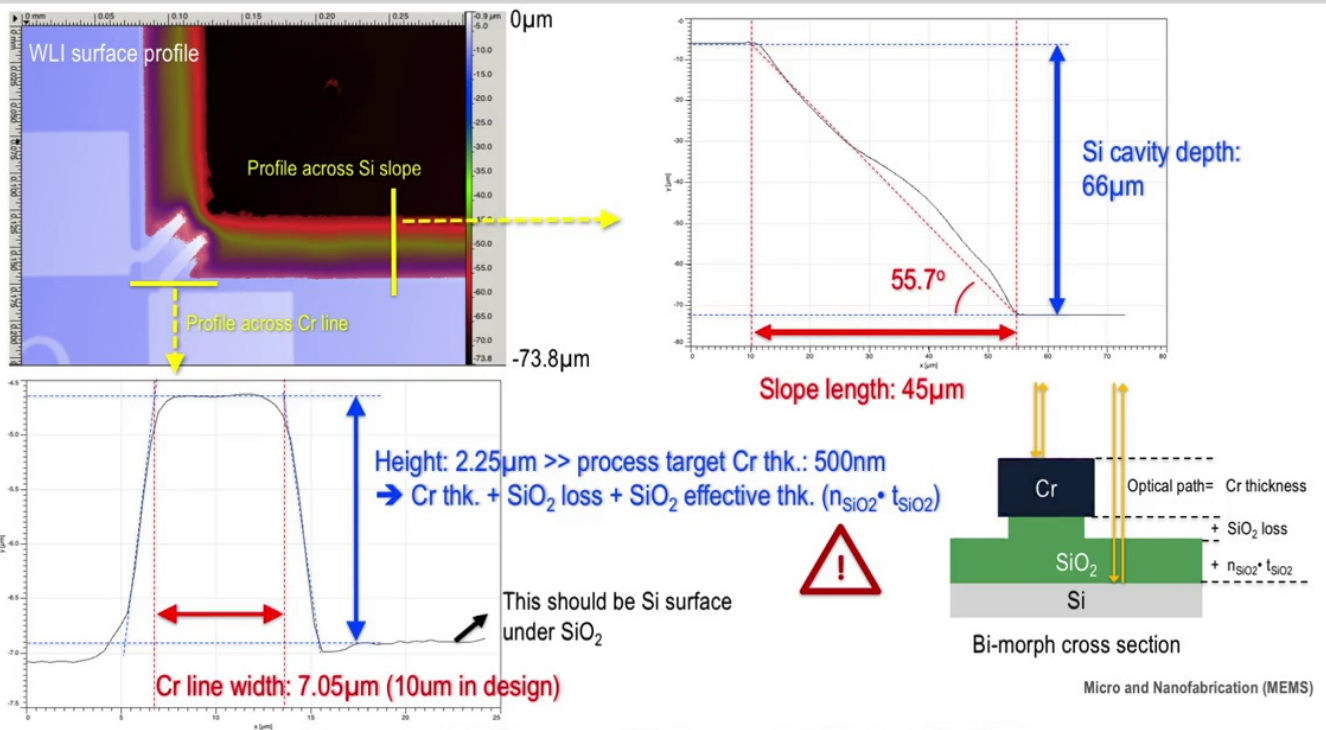
Bi-morph measurement with WLI



Micro and Nanofabrication (MEMS)

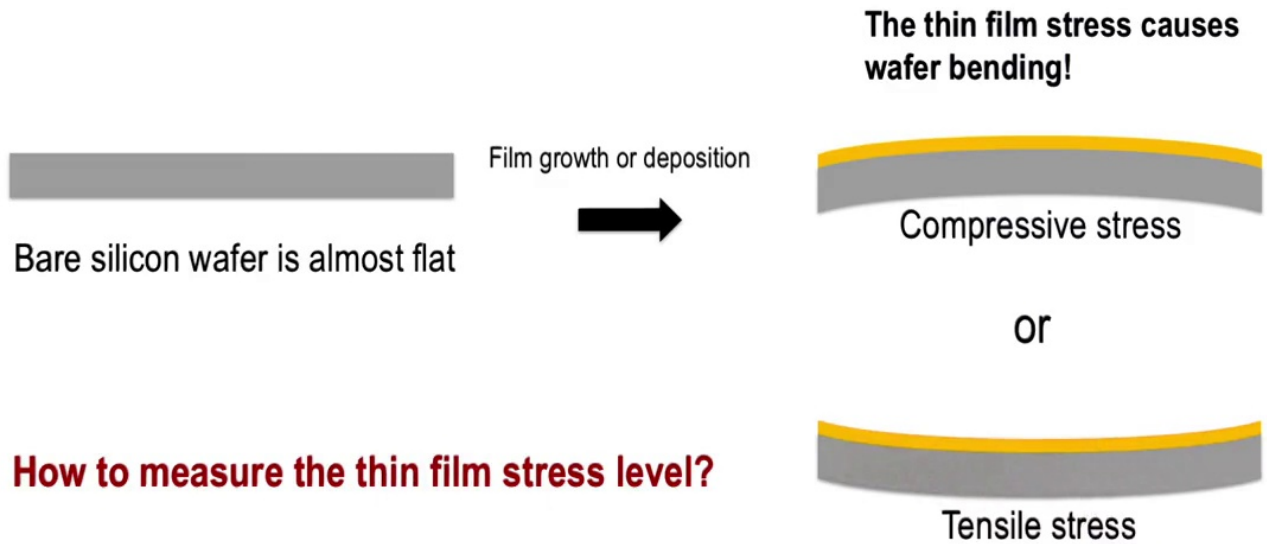
We know it should be about 54.7 degree, which is the angle between the 100 and 111 crystal planes of the silicon. But let us measure it now. The data from the white light interferometer tells us that the silicon cavity is 66 um deep.

Bi-morph measurement with WLI



And the silicon slope is $45\mu\text{m}$ long. With these two values, we calculate the angle to be 55.7° , which agrees very well with the theoretical value. We can also measure the width and the thickness of the chrome line here. But doing so, I also would like to draw your attention that each measurement should be accompanied with a thorough consideration of the sample condition, to be able to correctly interpret the measurement results. Here, the measured line width of the chrome pattern is $7.05\mu\text{m}$. This is quite in contrast to the design width of $10\mu\text{m}$. This difference in values is most likely a result from a non-optimized lithography and chrome wet etch process, and should be improved for more critical devices. The thickness measurement indicates $2.25\mu\text{m}$ as thickness. Remember that chrome thickness was designed to be 500nm . So, how come that we measure $2.25\mu\text{m}$ now? Let us have a look here at this drawing which shows the cross section at the point of interest. The white light interferometer actually detects the surface of silicon underneath the transparent silicon dioxide film. Here. Therefore, the optical path difference is the sum of both: the thickness of the chrome and the thickness of the silicon dioxide. In addition, we need to take into account that the SiO_2 has a refractive index of about 1.5 . Which also changes the light propagation inside this medium. Therefore, since the height difference is detected by the light path difference between the reference and object beams, we have to consider the silicon dioxide thickness as effective thickness, which equals the refractive index of silicon dioxide multiplied by the thickness of silicon dioxide. Therefore, the measured total height difference is obviously larger than the true summation of 500nm for the chrome thickness, and the true silicon dioxide thickness of about $1.3\mu\text{m}$. If we take into account the thickness loss due to the KOH etching and which was already confirmed by the measurement result in the previous lesson. The situation here reminds us always not to trust a measurement result without reasonable evaluation.

Stresses in thin films



Micro and Nanofabrication (MEMS)

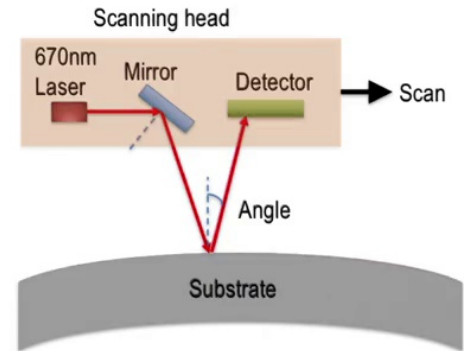
Remember in the mooc lesson on physical vapor deposition, we mentioned that the stress from the deposited thin film could lead to wafer and device bending. The origin for this upward or downward pending can be either compressive or tensile stress. Here, I would like to introduce a methodology to determine a thin film stress level by measuring the wafer bending before and after thin film coating.

Laser beam surface profiler

- Laser beam to detect the entire wafer surface profile → curvature
- Too large wafer curvature will affect fabrication process
- Wafer curvature → thin film stress level
- Stoney equation:

$$\sigma_f = \frac{E_s}{6(1-\nu_s)} \cdot \frac{t_s^2}{t_f} \left(\frac{1}{r_{sf}} - \frac{1}{r_s} \right)$$

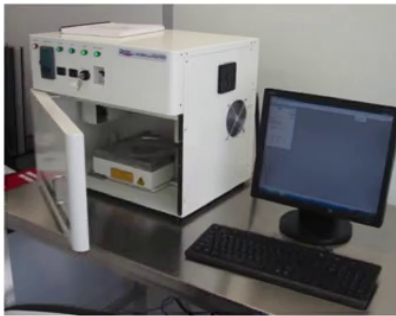
σ_f = stress in film in [Pa], by convention negative stresses are compressive
 E_s = substrate Young's modulus in [Pa]
 ν_s = Poisson ratio of the substrate
 t_f and t_s = film and substrate thickness in [m]
 r_{sf} = radius of curvature of the substrate with the thin film in [m]
 r_s = radius of curvature of the substrate before deposition in [m]



Micro and Nanofabrication (MEMS)

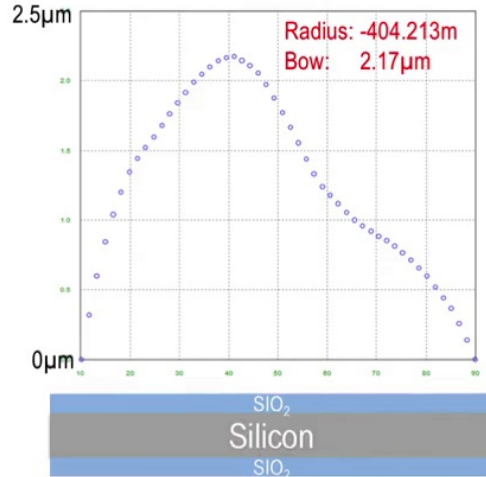
To this end, we use a laser beam surface profiler. It creates a line scan over the entire wafer surface and thereby determines the surface profile and radius of curvature. The drawing here on the right side shows the principle. A laser beam is aligned to the wafer surface and then the reflected beam is detected. The scanning head incorporated both the laser source and the detector. The head is scanning across the entire wafer at a fixed height, and any bending of the wafer will induce changes in the angle of reflection. Therefore, the curvature profile of the entire wafer surface can be obtained. To determine any stress built up during fabrication, we measure the wafer curvature before and after the film deposition. Then we calculate the thin film stress values according to the Stoney equation shown here. You already know it from a previous lesson.

Thin film stress measurement

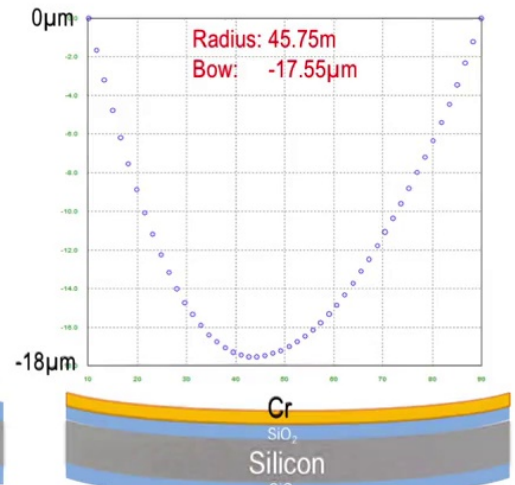


Laser beam surface profiler

Bi-morph wafer:



Before Cr deposition



After Cr deposition

$$Cr \text{ film stress} = \frac{185 \text{ GPa}}{6(1-0.06)} \cdot \frac{(525 \cdot 10^{-6} \text{ m})^2}{0.5 \cdot 10^{-6} \text{ m}} \left(\frac{1}{45.75 \text{ m}} - \frac{1}{-404.213 \text{ m}} \right) = 0.44 \text{ GPa} = 440 \text{ MPa (tensile)}$$

Micro and Nanofabrication (MEMS)

Taking the wafer with bi-morph cantilever device as an example, let us now see how by adding the chrome film, the shape of the wafer changes. The left curve shows the profile of the silicon wafer coated on both side with SiO₂. shown here... before chrome, the bow is 2.17 μm which comes slightly from the wafer cutting and polishing. The right curve shows the same wafer after 500 nm thick chrome layer on one side. Now the bow is about -17.55 μm. From these values, we calculate the chrome film stress to be 440 Mpa(Mega Pascal) in the tensile direction, based on this formula. Such values are typical and induce the resulting bending as a common artifact during thin film processing. The bow here in the measurement result, indicates the height difference between the peak and the valley of the surface profile.



- WLI surface profiler
 - XYZ dimension measurement
 - Released structure measurement
- Laser beam surface profiler
 - Wafer curvature
 - Thin film mechanical stress
- Non-contact, non-invasive
- No sample preparation needed

Micro and Nanofabrication (MEMS)

This concludes this lesson on optical surface analysis method for MEMS inspection and metrology. I have shown the white light interferometer and the laser beam surface profilometer. Both are non-contact and thus do not contaminate or damage the sample. They are simple to use, and allow for important in-process characterization of thin film and stress parameters.