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NANOSENSORS
Centre for Energy Research
Institute of Technical Physics and Materials Science

ADVANCED SEMICONDUCTOR DEVICES

03_Metrology

MŰEGYETEM 1782

February 26th, 2020

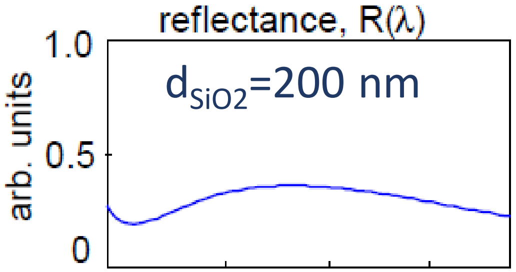
Metrology

- There are **400-600 steps** in the overall manufacturing process of semiconductor wafers, which are undertaken in **1-2 months**. If **any defect** occurs early in the process, all the work undertaken in the **subsequent** time-consuming **steps will be wasted**. One single „killer” defect can ruin a die.
- Throughout the process, a variety of **tests measurements** are carried out to determine both **wafer quality** and **process performance**. After every significant process step, there is an evaluation of the result.
- **Test/monitor wafers** are blank wafers that are included the process step **for postprocess measurements**. Many of these are destructive which cannot be performed on the device wafer.
- Metrology techniques include **electrical** (contact type or contactless), **optical**, **microscopy** (scanning probe, scanning electron etc.) and **combined** techniques. Nondestructive and in-line methods are preferred in the production.

Thickness
and surface morphology measurements

Film thickness evaluation by color

- Thickness of dielectrics (e.g. SiO_2 or Si_3N_4) can be estimated by color
- Interference effect (like oil film on a puddle), depends on the: viewing angle, refractive index of the film and the thickness of the transparent film
- Colors are repeating, so we have to know the order of the color
- The „thickness resolution” of the technique is ~30 nm

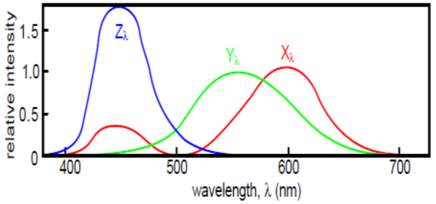


$$X = \int_0^\infty R(\lambda)\, P_o\, P_i(\lambda)\, X_\lambda(\lambda)\, d\lambda\,,$$

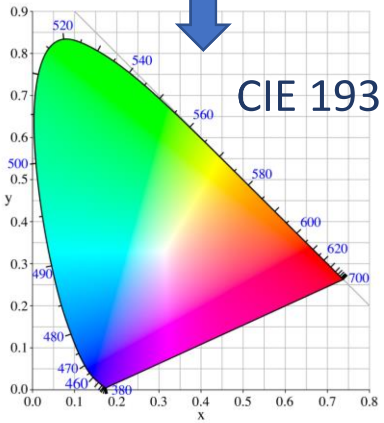
$$Y = \int_0^\infty R(\lambda)\, P_o\, P_i(\lambda)\, Y_\lambda(\lambda)\, d\lambda\,,$$

$$Z = \int_0^\infty R(\lambda)\, P_o\, P_i(\lambda)\, Z_\lambda(\lambda)\, d\lambda\,,$$

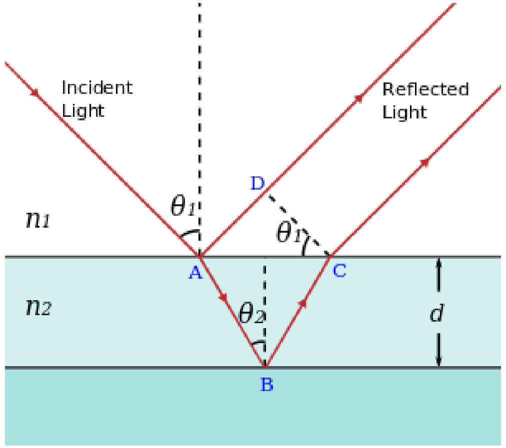
Color matching functions



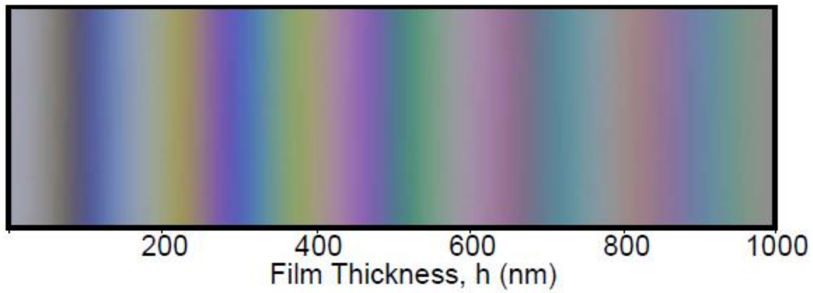
CIE 1931 color space



Optical path length difference between the reflected beams



Apparent color of a SiO_2 film on Si at θ=0° viweing angle



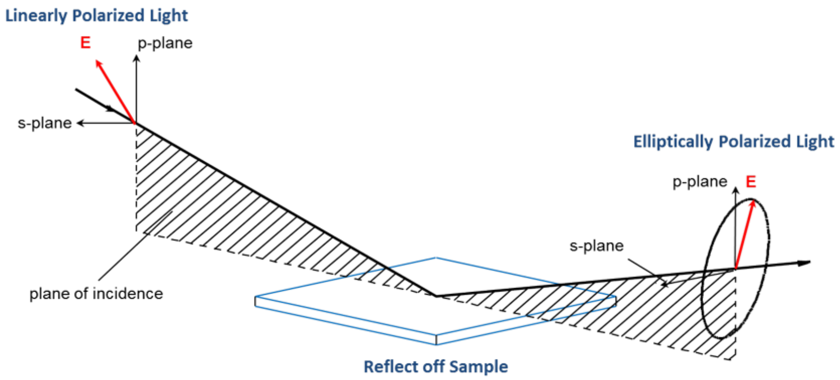
Ellipsometry: more than thickness measurement

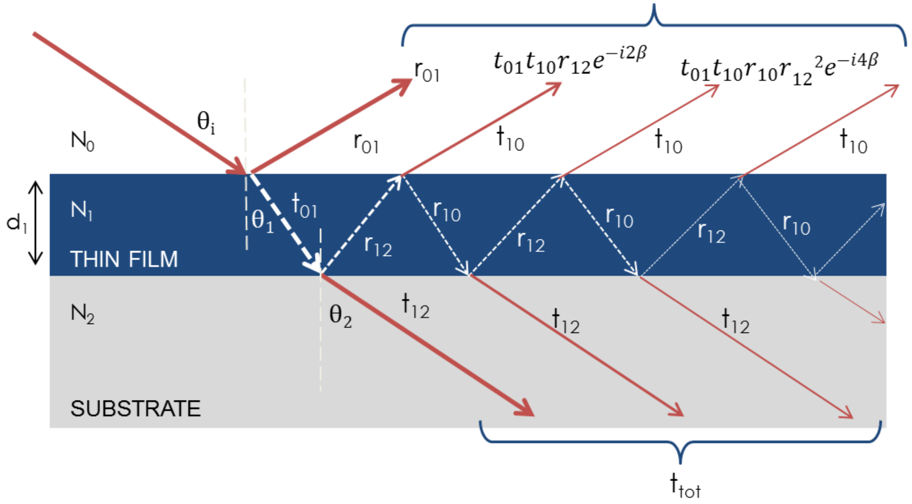
- We measure the change of the polarization of the incident light beam upon reflection on smooth surface
- In case of thin film(s) multiple reflection occur
- Reflectance and transmittance at each interface depend on the complex refractive index of the media and the polarization; can be described by the Fresnel equations:

$$r_p \equiv \frac{E_{rp}}{E_{ip}} = \frac{n_t \cos\theta_i - n_i \cos\theta_t}{n_t \cos\theta_i + n_i \cos\theta_t} \qquad r_s \equiv \frac{E_{rs}}{E_{is}} = \frac{n_i \cos\theta_i - n_t \cos\theta_t}{n_i \cos\theta_i + n_t \cos\theta_t}$$

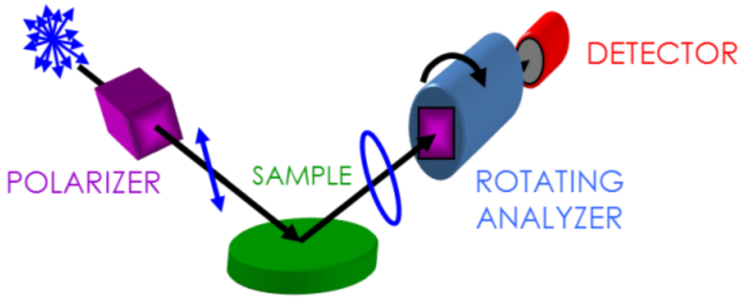
$$t_p \equiv \frac{E_{tp}}{E_{ip}} = \frac{2n_i \cos\theta_i}{n_t \cos\theta_i + n_i \cos\theta_t} \qquad t_s \equiv \frac{E_{ts}}{E_{is}} = \frac{2n_i \cos\theta_i}{n_i \cos\theta_i + n_t \cos\theta_t}$$

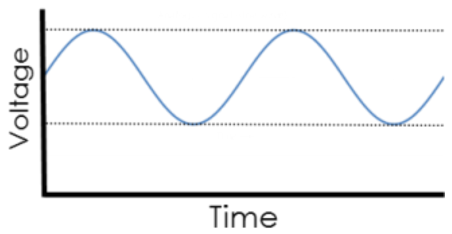
- Each layer and interface can be described by a matrix to calculate the resultant reflection r_p and r_s values → transfer matrix method

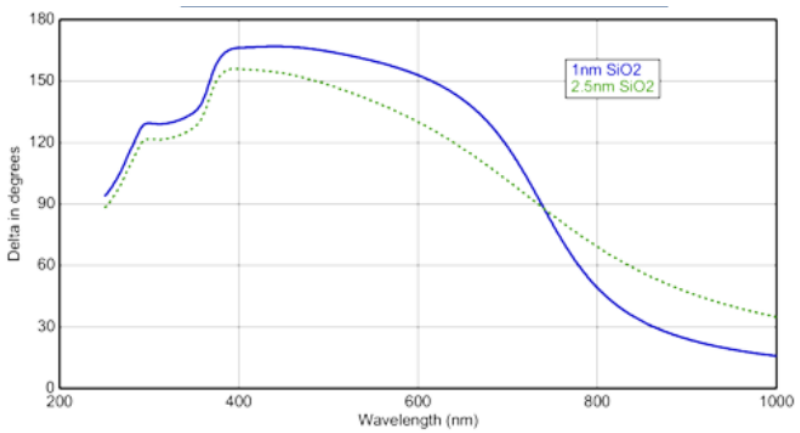




Ellipsometry: more than thickness measurement



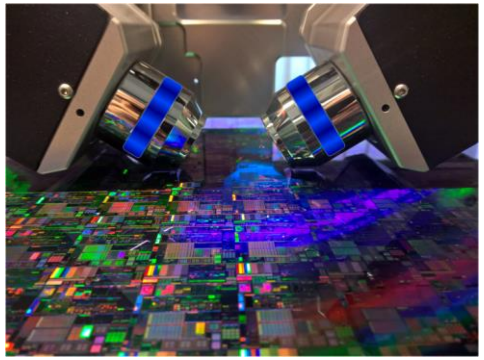


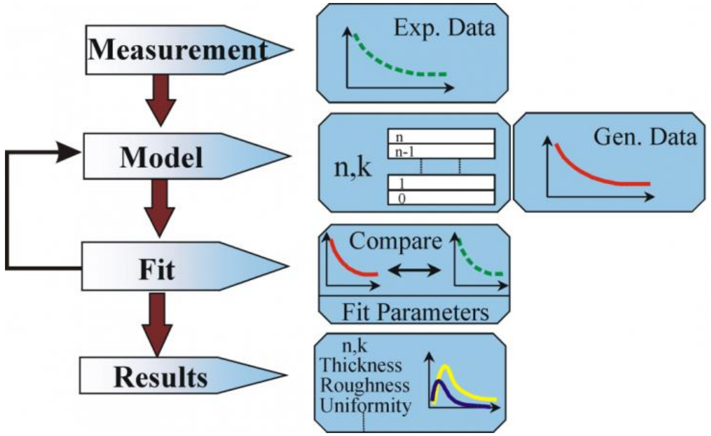


- Complex reflectance ratio:

  Ψ and Δ are the ellipsometric angles $\rho = \dfrac{r_p}{r_s} = tan\Psi e^{i\Delta}$

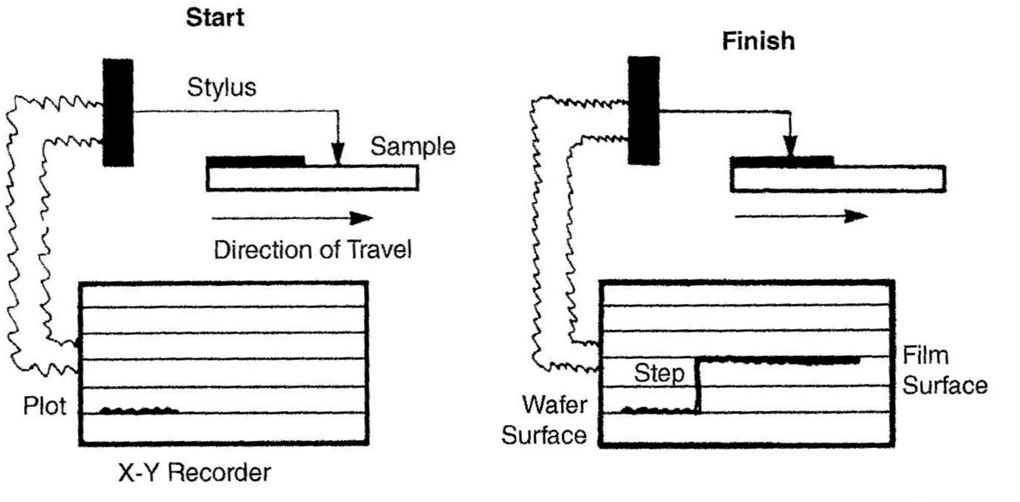
- Broad spectrum provides more information → **spectroscopic ellipsometry**
- **Thickness** and **complex refractive index** can be determined but not directly → **optical fitting**
- **Extremely sensitive** for thickness (**< 1nm** for known dielectrics) and for refractive index
- An important in-line or ex-situ technique in semiconductor manufacturing

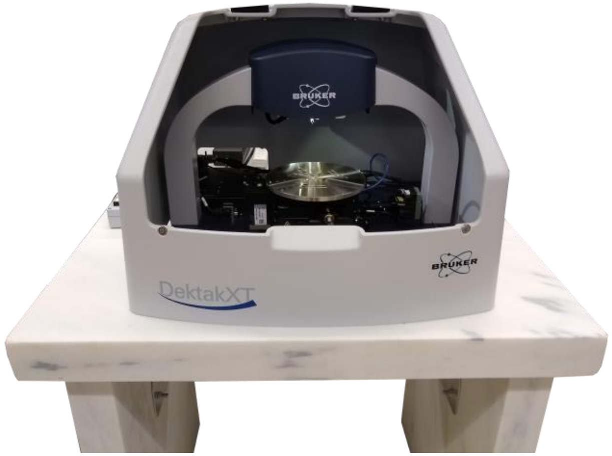




Contact surface profiler (stylus) for surface topography and thickness measurement

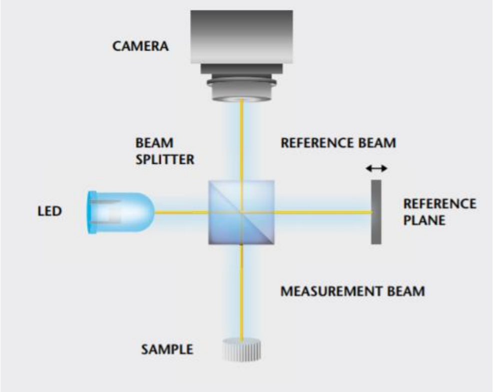
- After leveling the measuring stylus (diamond tip) is landed gently on the surface
- The measurement is made as the stage is slowly moved under the stylus. The stylus is linked to an inductor which generates an electrical signal in response to the vertical position of the stylus.
- The signal is amplified and fed into an x-y recorder.
- For thickness measurement a portion of the film has to be removed on the surface to create a step. Usually it is done with a photolithography + etching steps (or in an alternative way, like marker).
- Accuracy of step-height measurement with fine tip radius is a few nanometer.

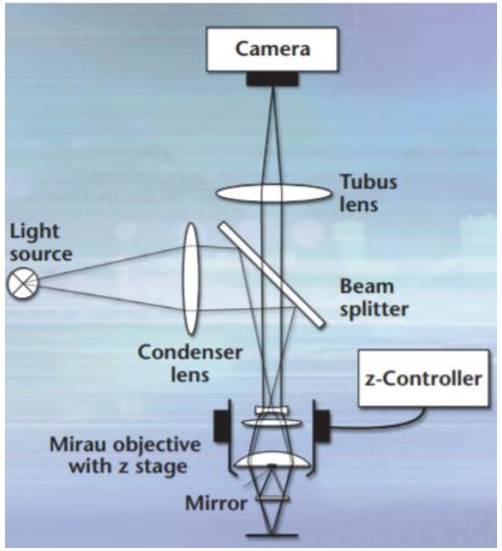




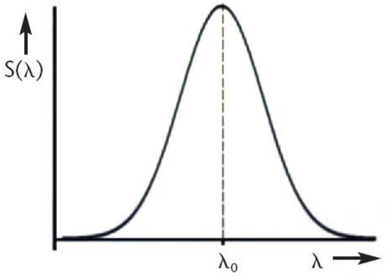
Non-contact surface profiler: white light interferometry

- **White light interferometry** is a non-contact optical method **for surface height measurement** on 3-D structures. Z-resolution can be a few nanometers.
- Interference occurs for white light when the path lengths of the **measurement beam** and the **reference beam** are nearly **matched**.
- **Mirau interferometer** works on the same basic principle as a Michelson interferometer**. On the front lens there is a miniaturized mirror** the same size as the illuminated surface on the object
- The interference signal of a pixel has maximum modulation when the **optical path length of light impinging on the pixel** is exactly **the same for the reference and the object beams.**

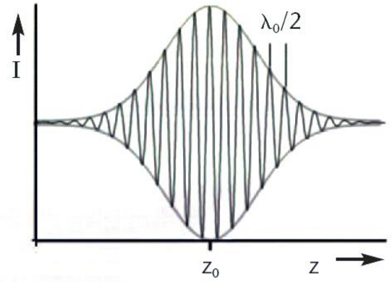




Spectral density function of the light source.



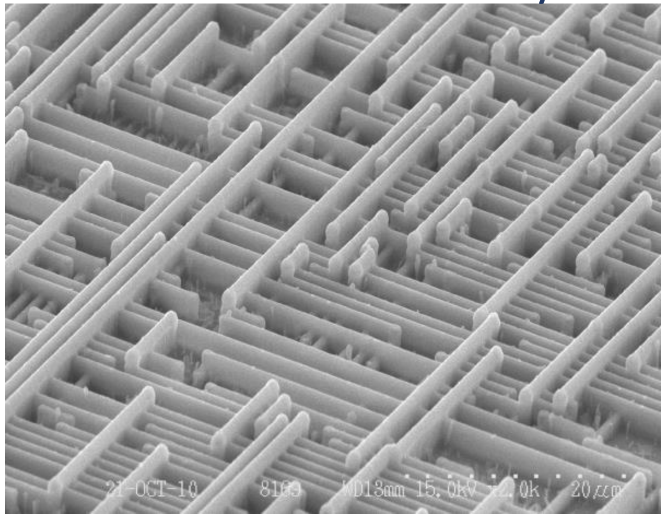
Light intensity as a function of the object mirror position.



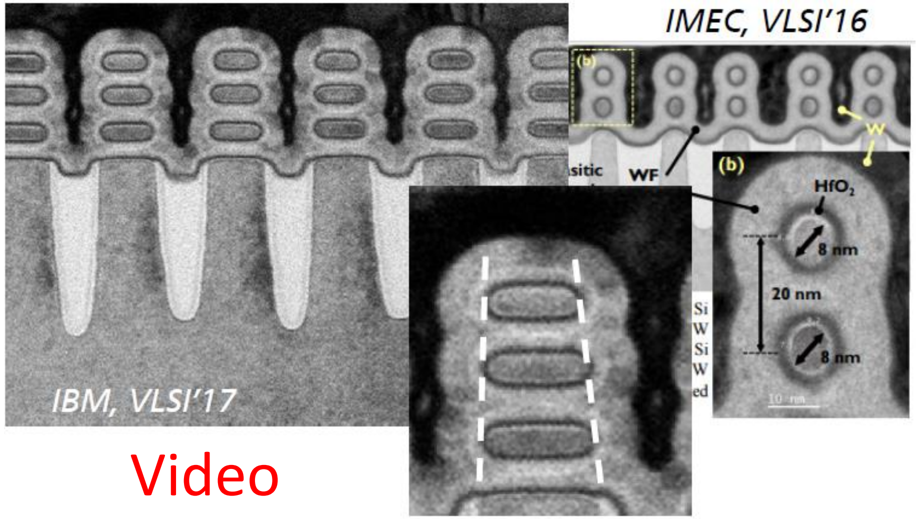
Microscopy techniques

- Optical Microscopy is a standard for 2D visualization to inspect wafers in-line. However, the resolution is limited (~400 nm). Dark-field is more sensitive than bright-field to surface irregularities.
- Inspection and failure analysis by Scanning Electron Microscopy (**SEM**) often combined by Focusses Ion (Ar, Xe, He) Beam (**FIB**) and electron/ion beam assisted deposition (EBAD/IBAD) in cross-beam systems. (The development of FIB was fueled by the IC industry.)
- Transmission Electron Microscopy (TEM) is used for ultra-high-resolution imaging and material characterizations. Here FIB is inevitable for TEM lamella preparation for the site of interest.

BEOL interconnections by SEM



Gate-all-around (GAA) FETs by TEM



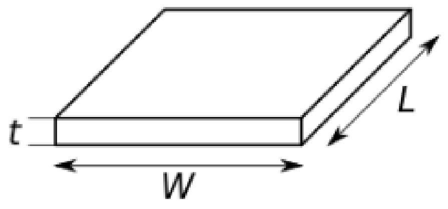
Video

Electrical measurements

Four-point probe method of homogenous thin films and wafers

Ohm's law on thin films: $R = \frac{V}{I} = \rho\frac{L}{A} = \rho\frac{L}{W \cdot t}$

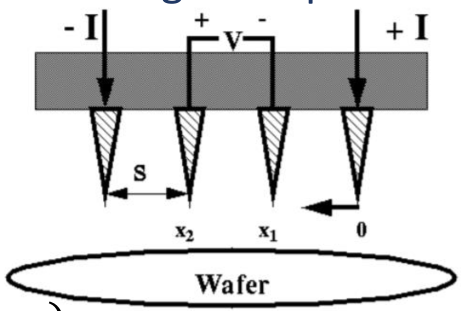
Slab of (semi)conductor



Resistivity: $\rho[\Omega cm] = \frac{1}{nq\mu}$ (n: free carrier conc., q: el. charge, μ [cm^2/Vs]: mobility)

- Four-point probe technique is used to eliminate the serial contact resistance at tips
- The current can be assumed as the superposition of I and –I → R=V/2I
- For very thin layer (**t«s**) homogoneous conductive and large samples (s«D) we get current rings around the outer electrodes (A=2πxt)

Four, equally spaced (s) tungsten tips



$$\mathrm{R} = \int_{x_1}^{x_2} \frac{\rho}{2\pi x t} dx = \frac{\rho}{2\pi t}\ln(x)\Big|_{2}^{2s} = \frac{\rho}{2\pi t}\ln 2 \;\rightarrow\; \frac{\rho}{t} = \frac{\pi}{ln2}\left(\frac{U}{I}\right) = R_s[\Omega/\Box]\ (\text{Sheet resistance})$$

- Measured *U/I* is independent of *s*
- ρ can be calculated if *t* is known → e.g**. to estimate the doping level of Si wafer or an epitaxial layer**
- t can be calculated if ρ is known → e.g. to **estimate the thickness of an Al or Cu thin film**

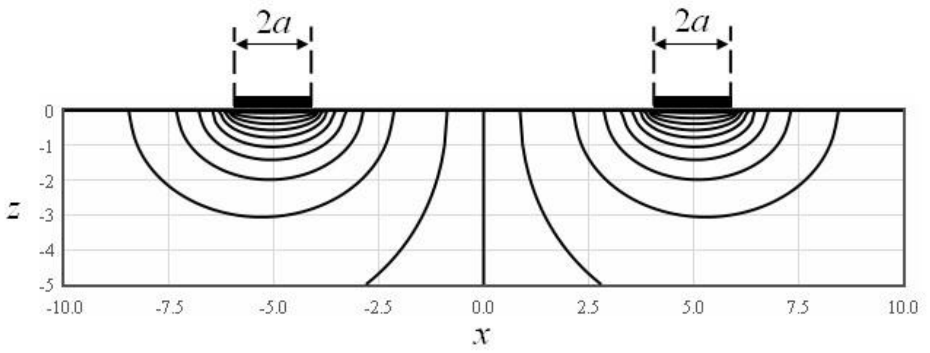
Spreading resistance profiling by two-point probe

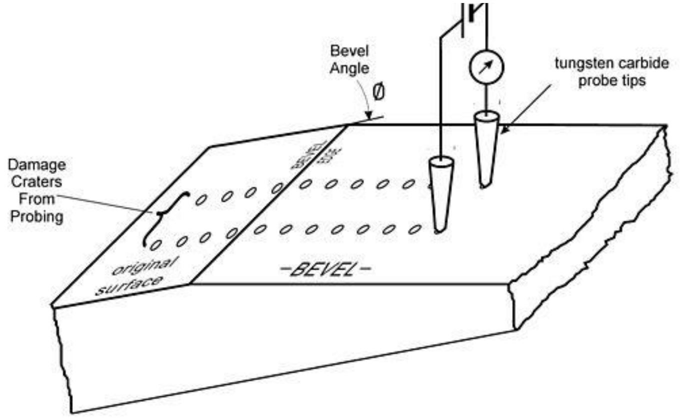
- Two tungsten carbide probe tips placed about ~ 10 um apart
- Low force (~ 1mN) but high pressure (~ 10 GPa) produces localized phase transformation to β-tin → Ohmic contact to Si
- The resistance encountered within the slab (t»2a) is $R \approx \dfrac{\rho}{2a}$

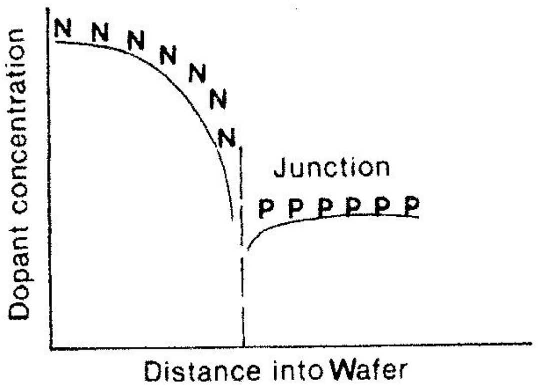
  where r is radius in contact area

  → local ρ information can be obtained

  → doping also by calibration or by table
- Doping profiling can be performed by a bevel (wedge) which is produced by mounting the sample and grinding the bevel on an angle block. Typical bevel angle is ~ 0.001-0.2 rad







Van der Pauw measurement

- Simple technique to determine the sheet resistance, and Hall coefficient of the sample
- Van der Pauw's statement: $e^{-\pi R_{AB,CD}/R_S} + e^{-\pi R_{BC,DA}/R_S} = 1,$

$$R_{AB,CD} = \frac{U_{CD}}{I_{AB}} \qquad R_{BC,DA} = \frac{U_{DA}}{I_{BC}}$$

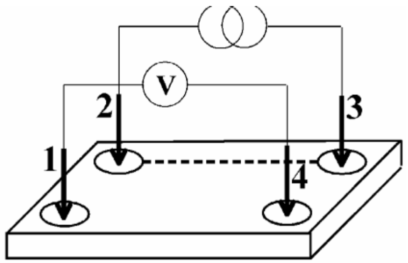
for any shape of homogenous plate

- By applying a more symmetric shape and using the reciprocity theorem and reversed polarity symmetry a more accurate method is obtained for vertical and horizontal contact pairs:

$$e^{-\pi R_V/R_S} + e^{-\pi R_H/R_S} = 1,$$

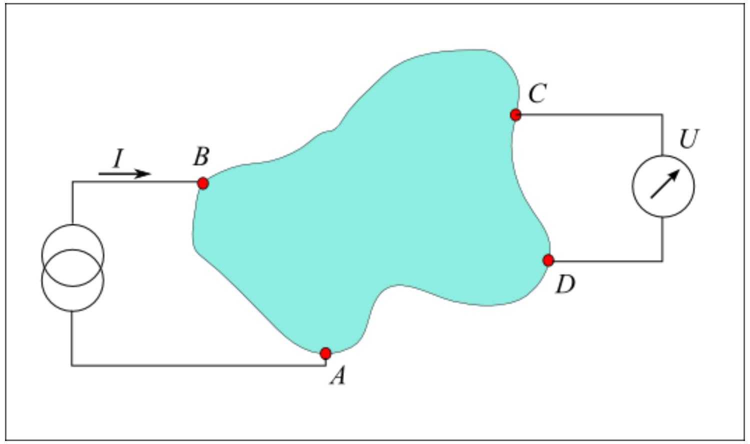
$$R_V = \frac{R_{12,34} + R_{34,12} + R_{21,43} + R_{43,21}}{4}$$

$$R_H = \frac{R_{23,41} + R_{41,23} + R_{32,14} + R_{14,32}}{4}$$

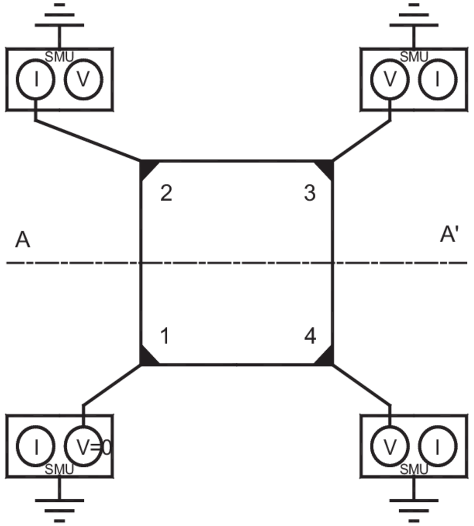


- R_s cannot be calculated directly but using a numerical iterative method

Random shape conductor with edge contacts



Square shaped sample with small Ohmic contacts at the corners

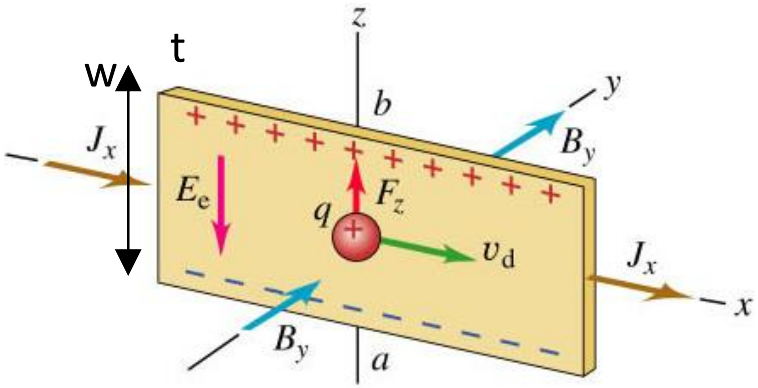


Hall measurement in Van der Pauw configuration

Lorenz force: $F_L = qvB$

Velocity of the free charges: $v = \frac{1}{nAq}$

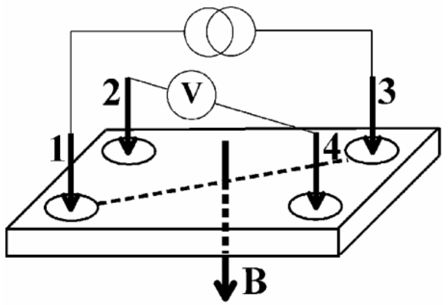
$$F_L = \frac{IB}{nwt}$$



Electric field: $E = \frac{IB}{qnwt}$

Hall voltage: $V_H = wE = \frac{IB}{qnt} = \frac{IB}{qn_s}$

n_s: sheet free carrier density



Measurement of Hall voltage: $V_H = \frac{V_{13} + V_{24} + V_{31} + V_{42}}{8}$

where $V_{ij} = V_{ij}^{+} - V_{ij}^{-}$

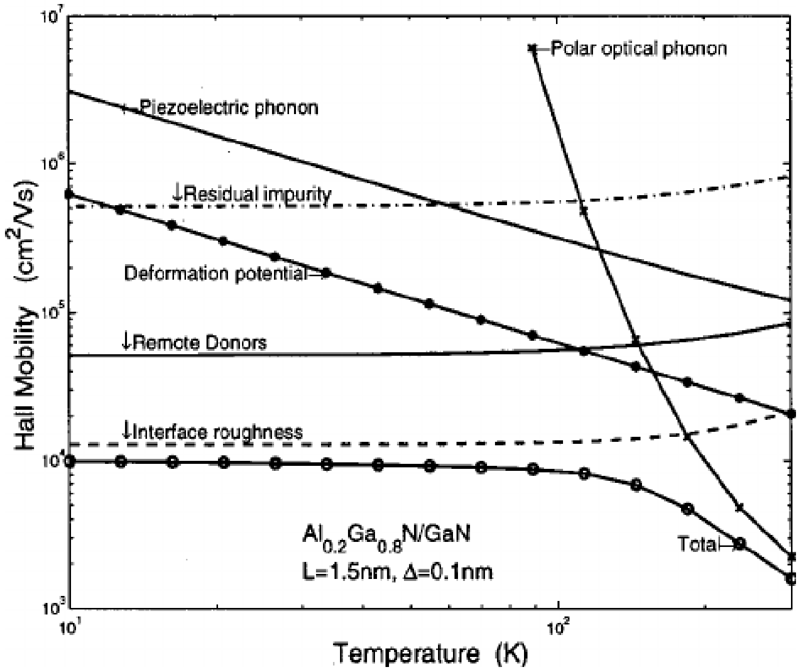
$$n_S = \frac{IB}{q|V_H|} \qquad \rho = tn_s \qquad \mu = \frac{1}{qn_S R_S}$$

Holes (V_H>0) and electrons (V_H<0) can be distinguished.

Mobility and carrier concentration can be separately determined by Hall measurement

Hall measurement in cryostat

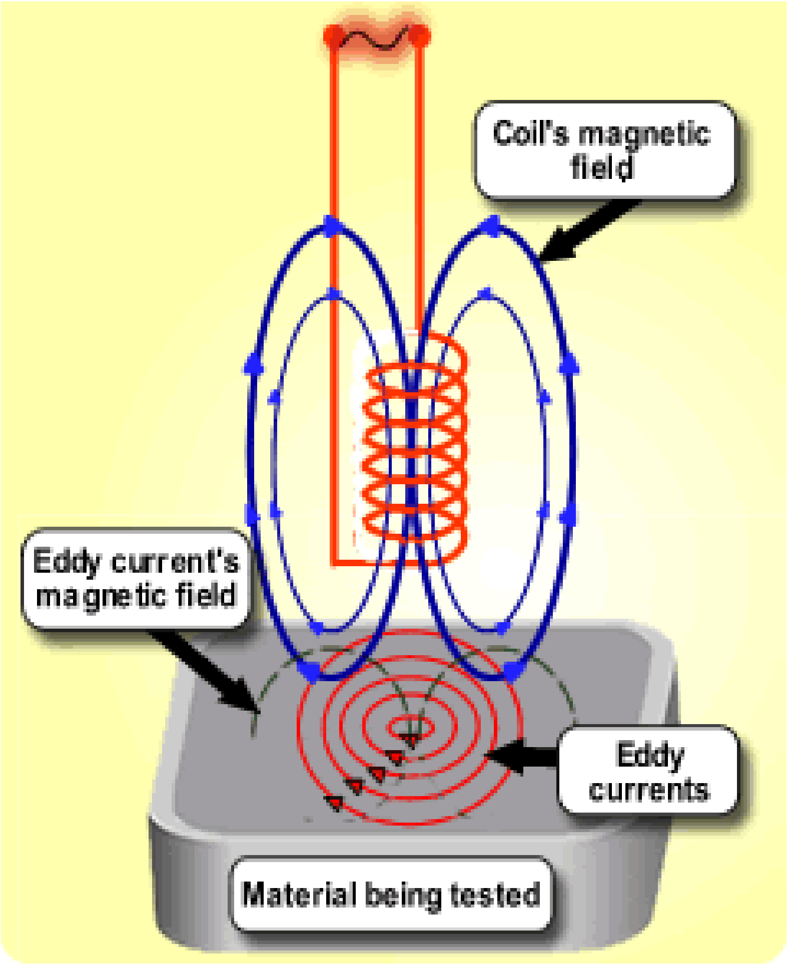
- Variable temperature, high DC magnetic field → accurate measurement in broad range (μ: 1-10^6 cm^2/Vs)
- Temperature dependency of μ can be measured → e.g. to reveal the dominant scattering



Temperature dependence of the electron mobility for each active scattering mechanism in an $Al_{0.2}Ga_{0.8}N/GaN$ HEMT structure

Lake Shore Hall measurement setup

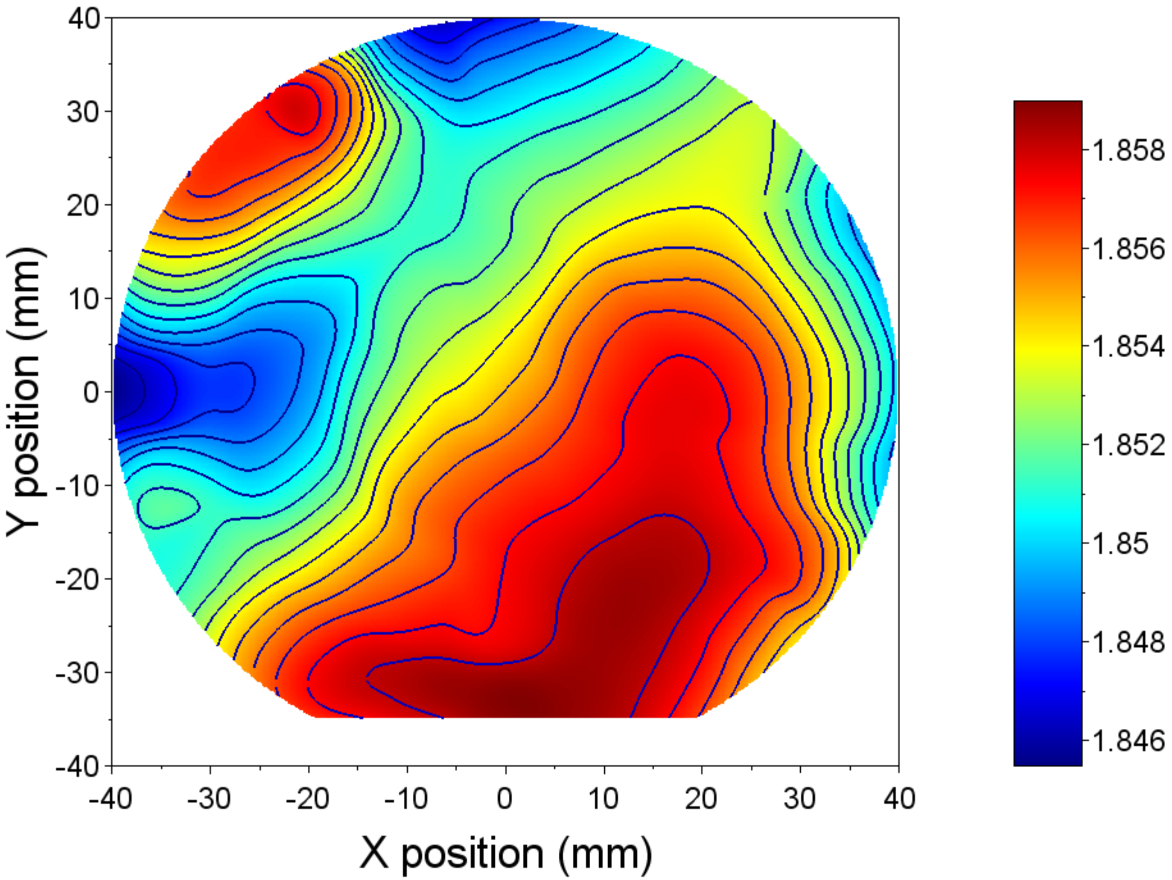
Non-contact Eddy current technique



- Alternating current in a coil induces alternating eddy current in a conducting material.
- The eddy current is higher in good conducting material than in a less conductive material.
- The eddy currents react to the coil used to generate the eddy current.
- It is possible to measure this reaction. The measurement result is the eddy signal: U_{eddy}.
- The measured signal (U_{eddy}) depends on Sheet resistance, in case of thin layers

Example: refractive index map on Ga doped ZnO film

- ALD deposited transparent conductive oxide (TCO) GZO coating on 4” Si wafer for optoelectronic and photovoltaic applications
- Question: the lateral homogeneity (t, Rs, r) of the layer → used characterization methods: Eddy-current and Spectroscopic Ellipsometry (SE) mapping



SE

n at 632.8 nm

Map statistics:

Average = 1.854

Minimum = 1.845

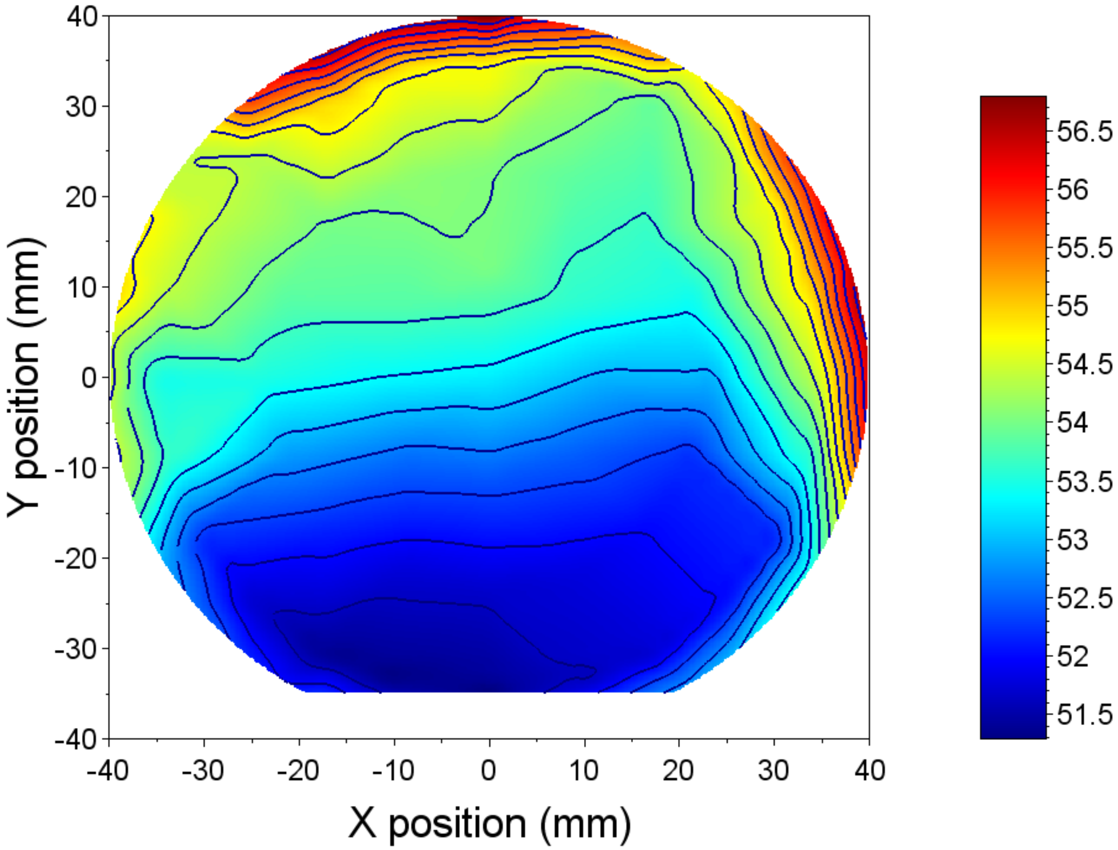
Maximum = 1.859

Range = 0.014

StDev = 0.003

StDev % = 0.165

Example: thickness map on Ga doped ZnO film



SE

Thickness (nm)

Map statistics:

Average = 53.369

Minimum = 51.287

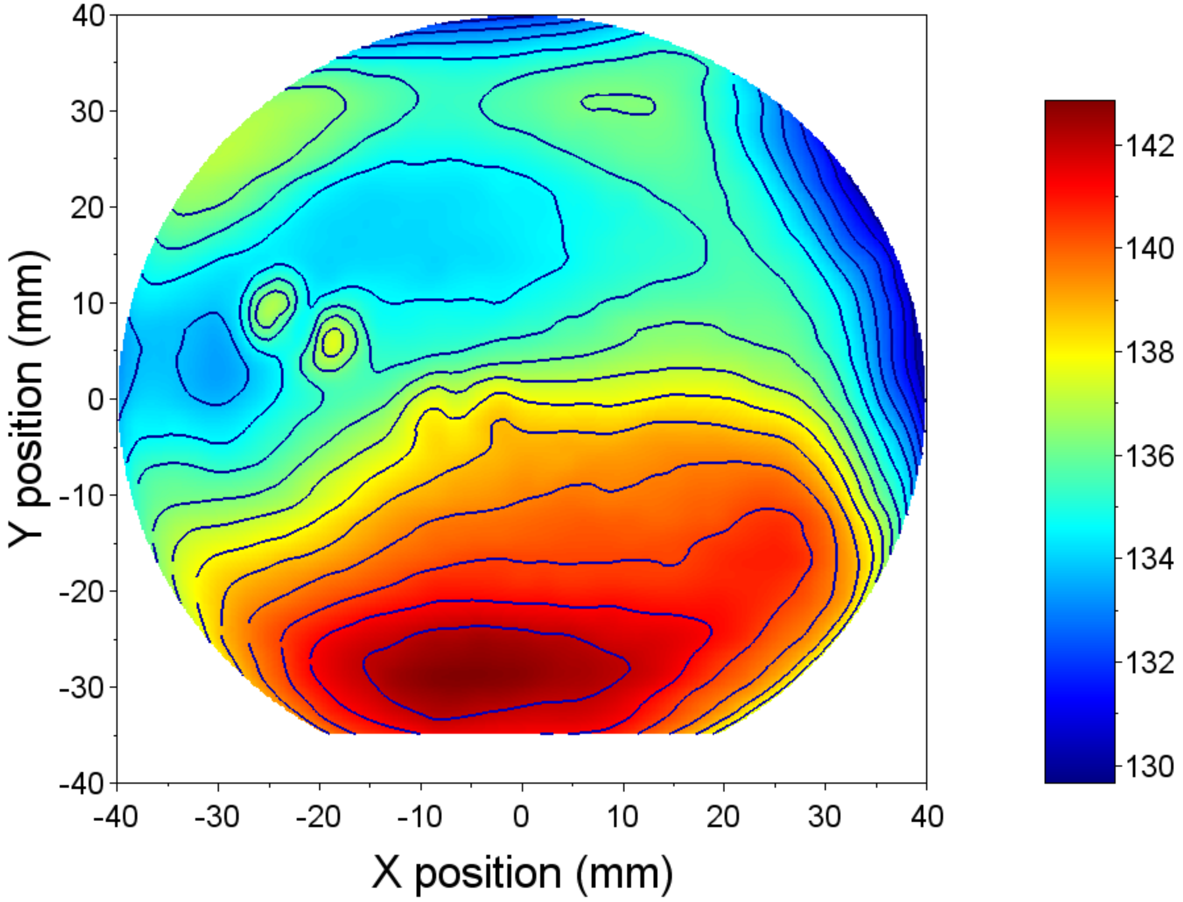
Maximum = 56.795

Range = 5.508

StDev = 1.136

StDev % = 2.129

Example: sheet resistance map on Ga doped ZnO film



Eddy current mapping

Sheet resistance (R_s, Ω/□)

Map statistics:

Average = 137.060

Minimum = 129.654

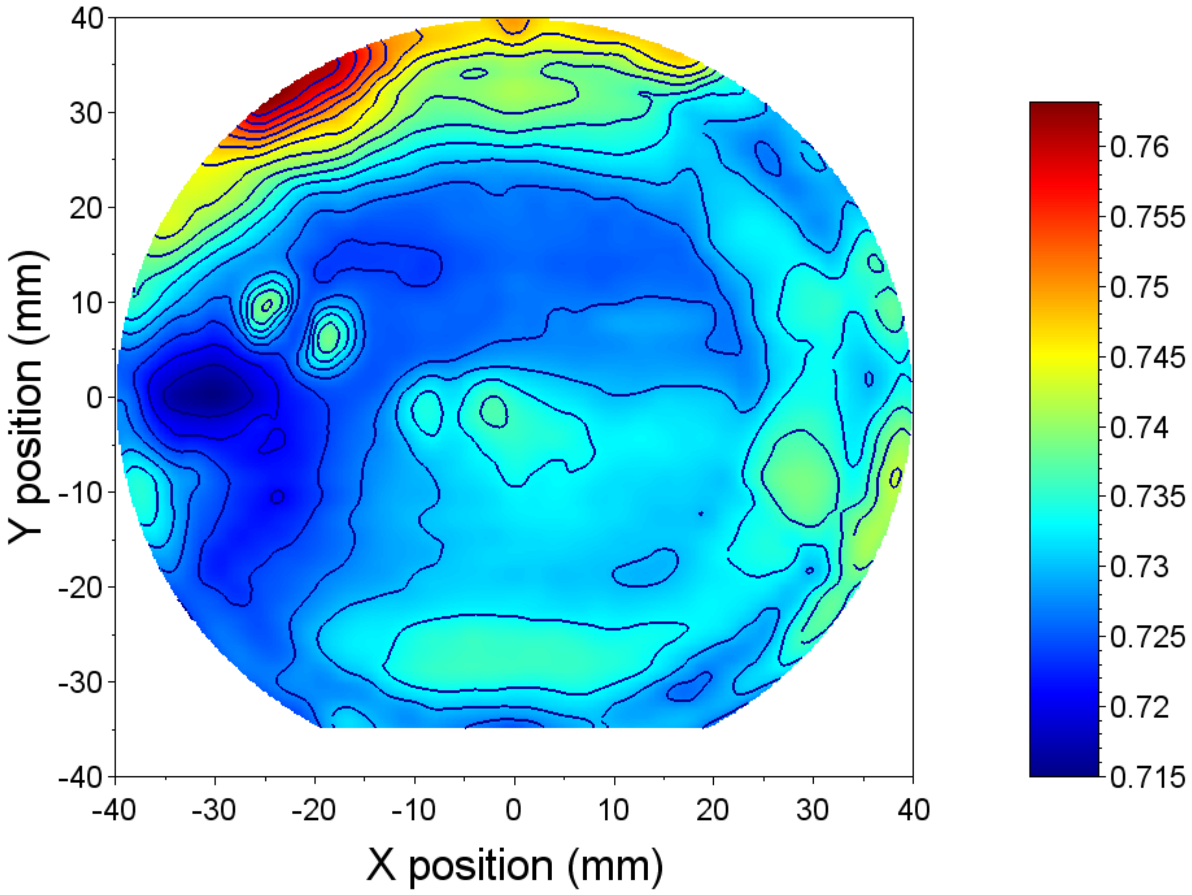
Maximum = 142.860

Range = 13.207

StDev = 2.749

StDev % = 2.005

Example: bulk resistivity map on Ga doped ZnO film



Calculated: $R_S \cdot t$

Resistivity (mΩcm)

Map statistics:

Average = 0.731

Minimum = 0.715

Maximum = 0.763

Range = 0.048

StDev = 0.006

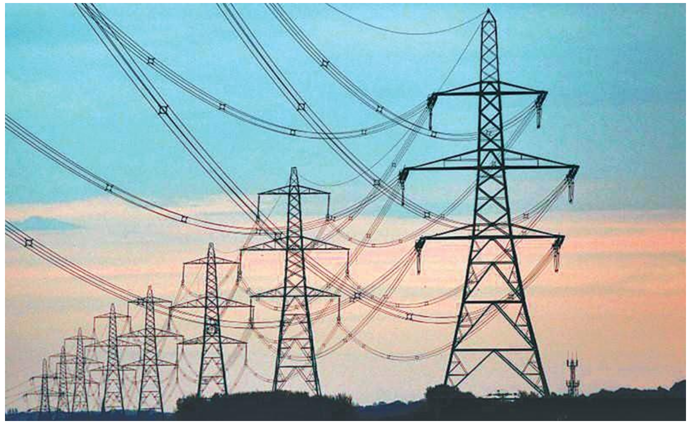
StDev % = 0.850

Conclusions of the study:

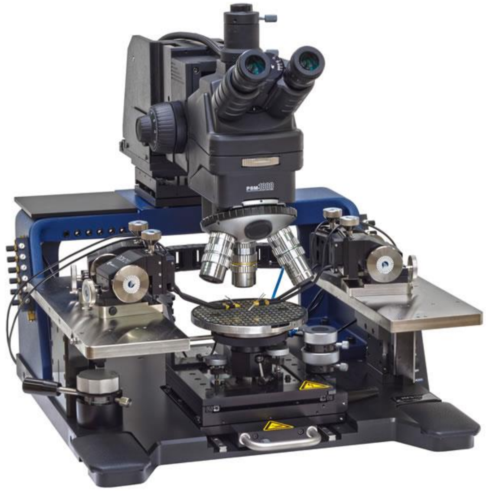
- Material is homogenous, because StDev < 0.2% for the refractive index
- The inhomogeneity in the sheet resistance is due to the thickness non-uniformity

Transmission Line Method (TLM)

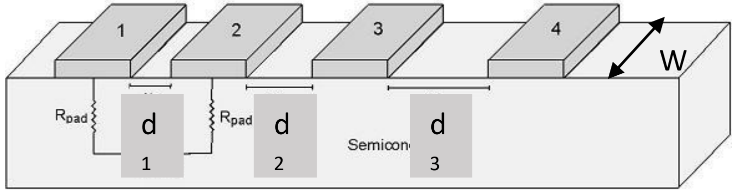
- Low resistance stable Ohmic contact is essential for all electrical IC elements (source, drain, p-n contact etc.) → process optimization is needed (e.g. rapid thermal annealing temperature and time)
- To determine the specific contact resistance ($R_C[\Omega cm^2]$) and sheet resistance of a conductive layer ($R_S[\Omega/sq]$).
- Fabrication of a series of rectangular contacts with increasing spacings (d_i, e.g. following a Fibonacci series)



The „original transmission line"



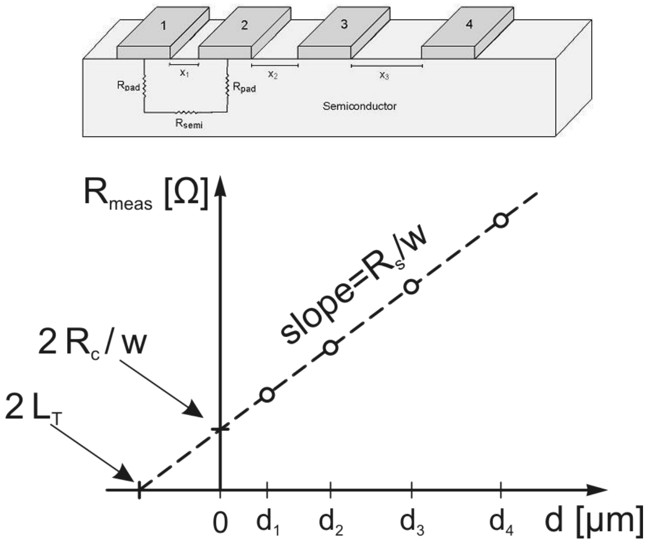
Probe station for positioning the W probes onto the contacts



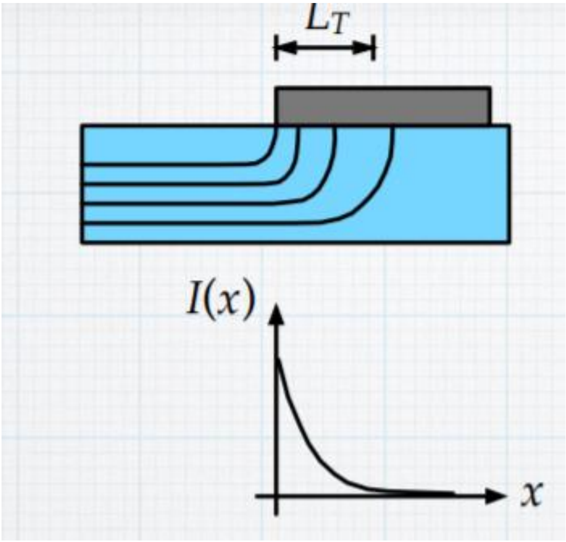
TLM pattern with varying spacings

Transmission Line Method (TLM)

- Measurements of $R_{i,i+1}$ resistances between neighboring contacts
- R_C and R_S can be deduced by the linear fit of $R_{i,i+1}$ vs d_i points; $R_C < 10^{-5}$ -10^{-6} Ωcm is usually acceptable
- L_T transfer length provides information about the current distribution under the contact (current crowding) and hence shows the effective length of the contact .



Linear fit of resistance values between neighboring pads. The slope is determined by the sheet resistance of the layer, while the intercept is by the contacts



Current crowding at the edge of the contact. Moving away from that edge, the current drops off