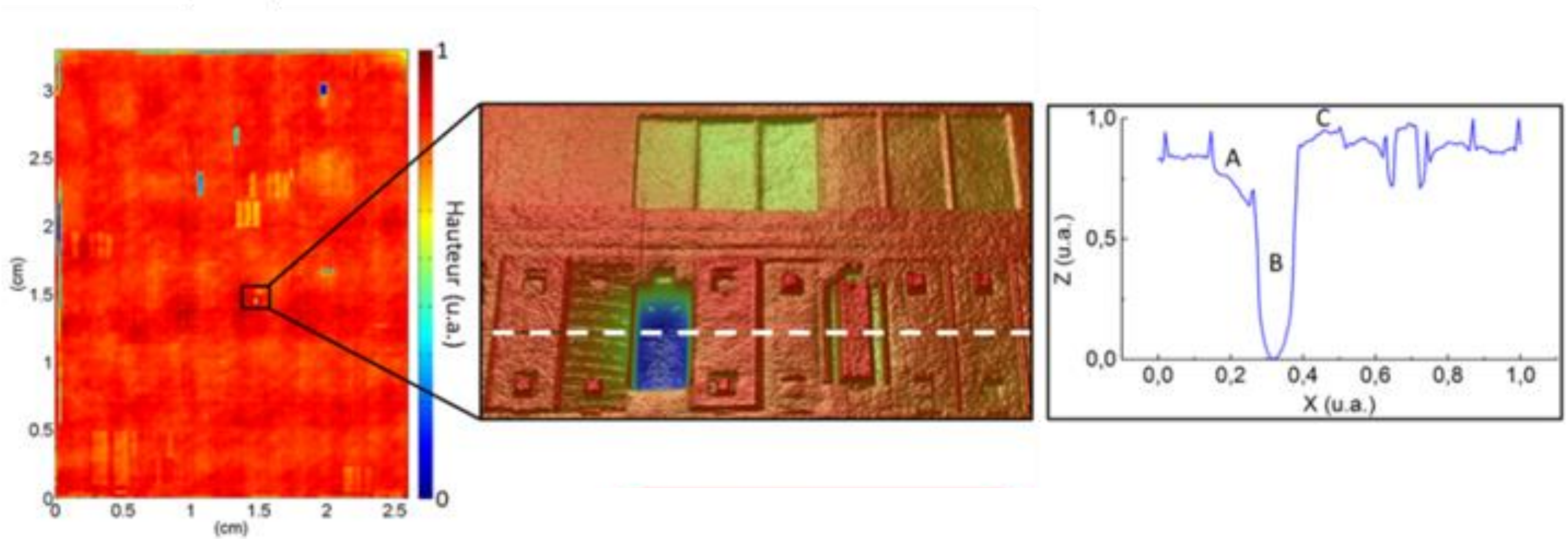
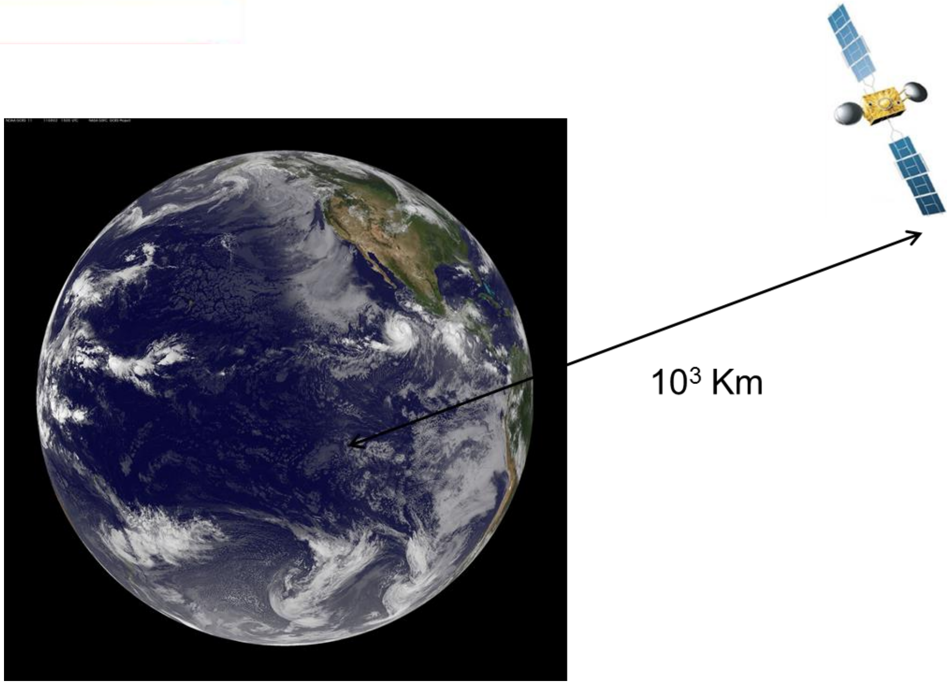


IC nanotopograpby



CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

FCMN, Monterrey, California, USA | C.Beitia | 21-23/03/2017

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

- **Nanotopography needs**
  - 3D system integration
    - Hybrid Bonding
    - Monolithic Ics
  - CMP and Bonding

- **State of the art**
  - Mechanical profiler
  - AFM
  - Optical profiler

- **The challenges**
  - Data acquisition
  - Data Analysis/Data storage
  - Traceability and uncertainty

- **Conclusion**

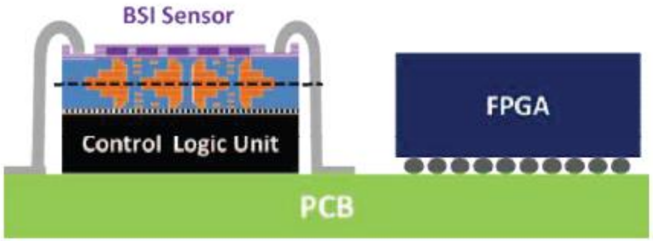
CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

Today trends in semiconductor arena:

- It will continue with development of advanced technological nodes (Moore law)
- BUT in parallel develop new alternative technologies (3D monolithic) and advanced packaging (More than Moore)

- Different applications: 3D Heterogeneous integrations; 3D monolithic for 3DIC, 3DMemory

Example: Back side CMOS Imagers:

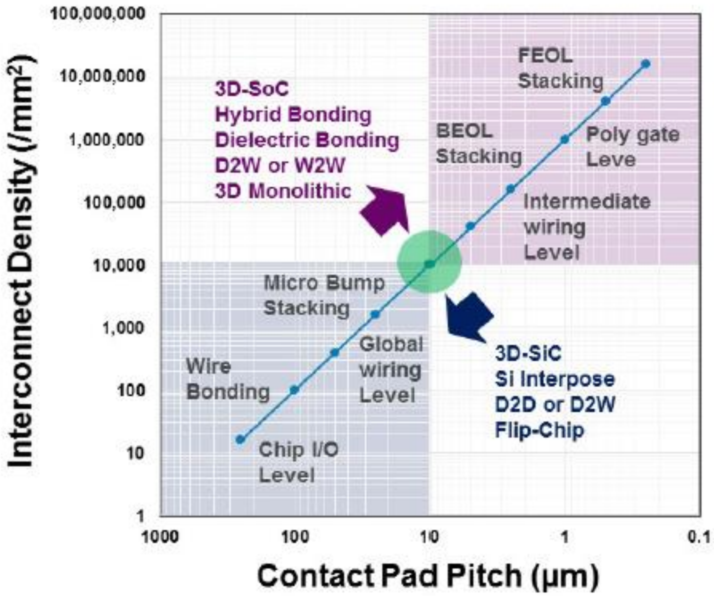


BSI Sensor [Back Side Imager]
- Photodiodes for rolling shutter image capture
- Primary reading circuit

Control logic unit [Memory + Individual Pixel Processing]
- Analog-to-digital converter
- Massively parallel processing
- SIMD components

FPGA [Field-Programmable Gate Array]
Baseband and large scale parallel signal processing

High density connection needs:



L.Benaissa et al, Proceeding 17th Electronics Packaging Technologies Conference, 2015.
K.Soon-Wook et al, 66th Electronics Components and Technology Conference, 2016.

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

Key technology enabling 3D schema :

- TSV
- Thinning
- CMP
- Bonding

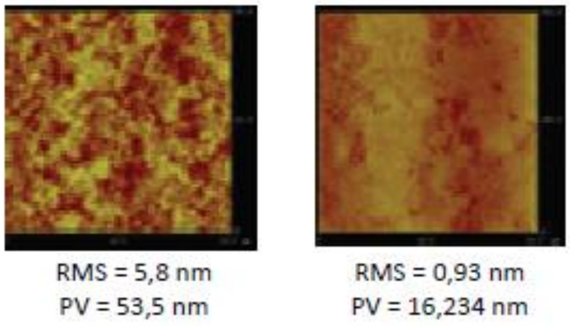
- **Bonding requirements:**
  - Global wafer shape
    - Flatness, Total thickness variation (TTV)
    - Bow warpage
  - Substrate surface quality
    - Smoothness
    - Micro-roughness
  - Cleanliness
    - Particle
    - Organic residuals
    - Metal ions

What is flatness?
What is roughness?

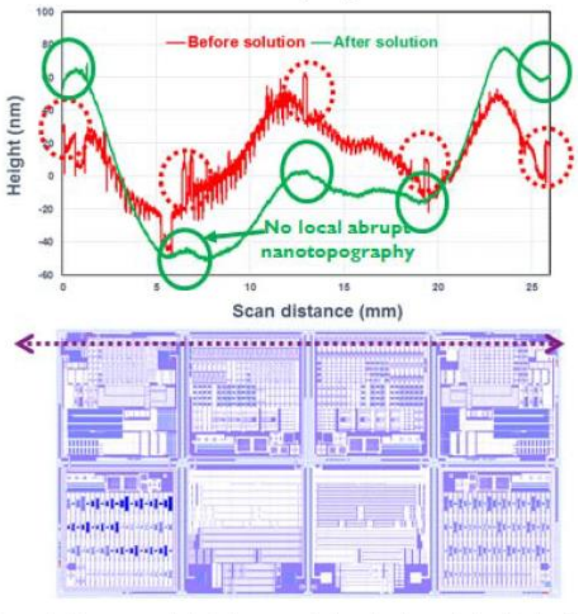
CMP becomes critical!

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

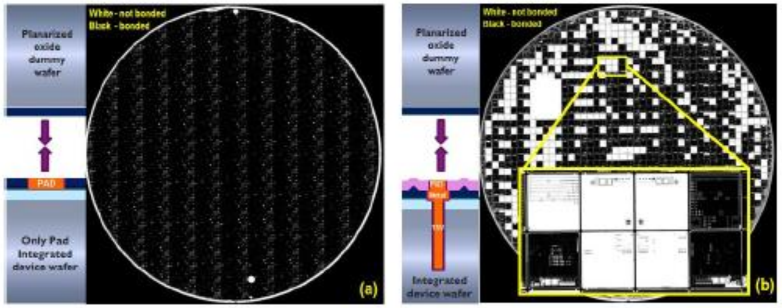
- **Roughness and flatness requirements for bonding:**



Roughness AFM measurements (20µmx20µm) evolution with CMP.



Topography evolution with process.



SAM images between one process without topography and another wafer with topography.

Nanotopography and roughness are KEYS.
CMP control is key.

A paradigm change in CMP control, move from TBOX like to in-die (2D vs 3D)

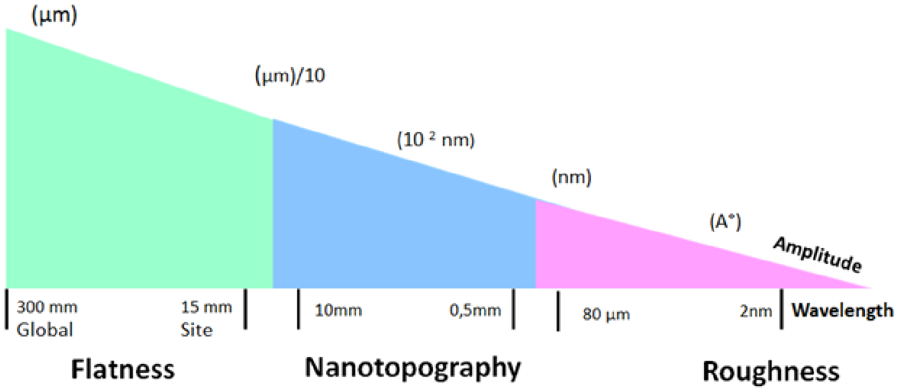
L.Benaissa et al, Proceeding 17th Electronics Packaging Technologies Conference, 2015.
K.Soon-Wook et al, 66th Electronics Components and Technology Conference, 2016.

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

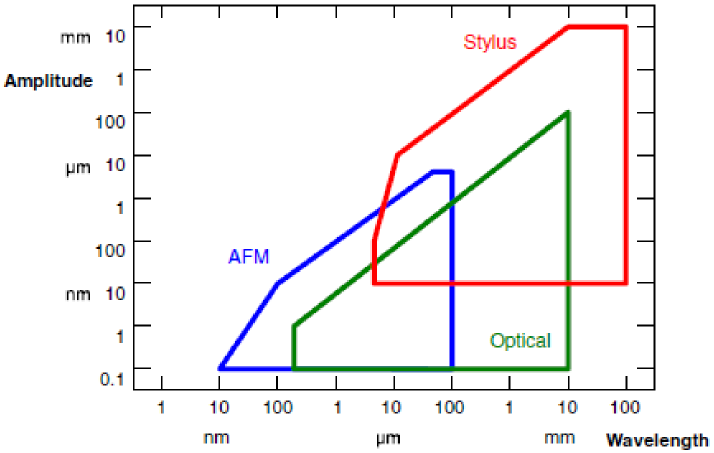
- Bonding flatness and roughness requirements:

Flatness and roughness are multiscale in nature. Actually wafer level flatness is well covered, roughness at µm level as well. However in between there is a gap spite some solutions are available.

Input requirement for successful bonding



Tool for development and control

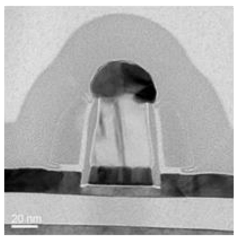


In a substrate level without considering the process there is a large scale Range to look at flatness and roughness in xy and z (Flatness at 10^2 nm range in z over the wafer and for roughness over nm in a µm level area)

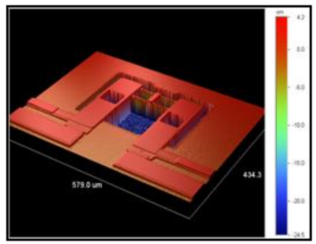
CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

On top of the substrate input requirement as the wafers are processed with devices on them They will add topography at different wavelength (transistors, mems, die and wafer).

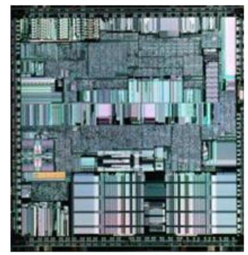
Device process to control



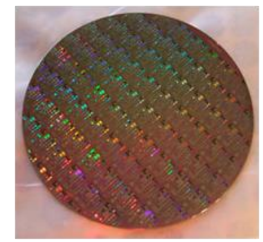
Transistor/NEMS
≈ 10^1 -10^2 nm



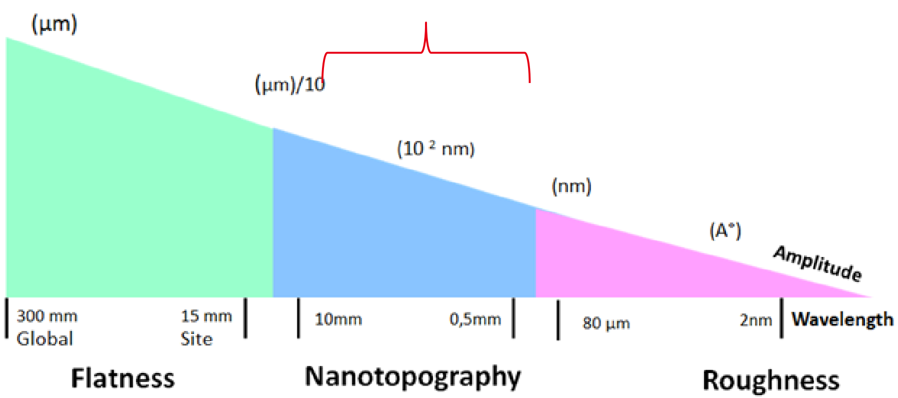
MEMS
≈ 10^1 - 10^2 µm



Die
≈ 10^0 mm - 10^0 cm



Wafer ≈ 10^1 cm

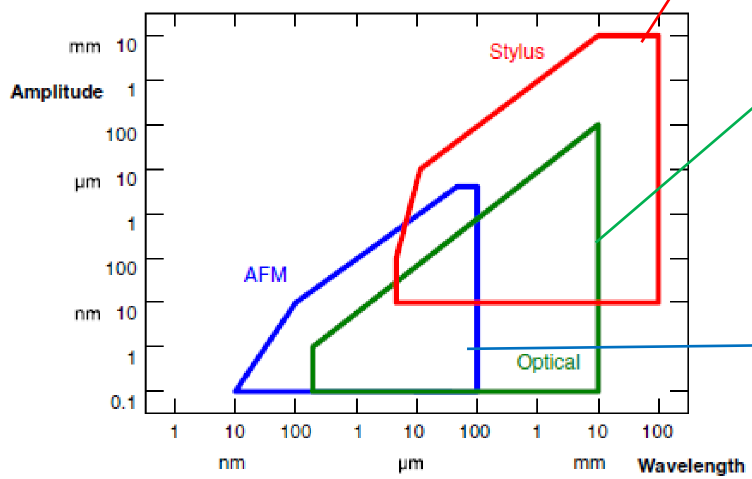


CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL: DATA ACQUISITION

Scales for process parameter:

- Area on interest from μm^2 to cm^2 over the wafer
- Lateral resolution needed from 10^2 µm up to 10^2 nm
- Vertical 10^2 nm up to nm

Tool for development and control



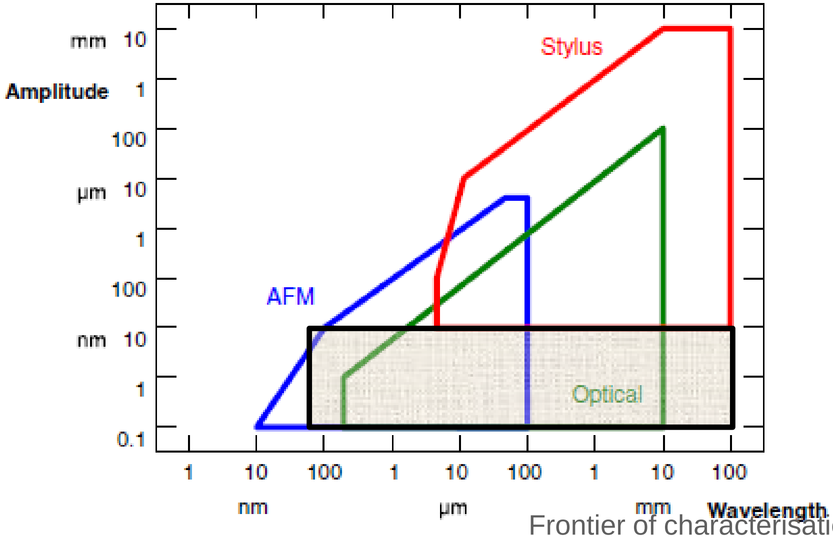
- **Available metrology solutions:**
  - Mechanical profilometry
    Pro : Historical reference
    No need of sample preparation
    Cons
    Slow
    Contact
    Probe sample convolution
  - Optical profilometry
    Pro: larger range (wafer, Die)
    Non contact
    Fast
    Cons: Artifact due to heterogeneity of materials on the wafer
    Require à metal layer
  - AFM
    Pro: Highest resolution x,y,z
    Non mechanical contact
    May have artifact linked to sample heterogeneity
    Cons; Slow
    Complex material interaction

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL:DATA ACQUISITION

Scales for process parameter:

- Area on interest from µm² to cm² over the wafer
- Lateral resolution needed from 10^2 µm up to 10^2 nm
- Vertical 10^2 nm up to 10^{-1}nm

Tool for development and control



- Industry requirements
  - High throughput
  - Larger dynamic range
  - AOI/resolution compromise

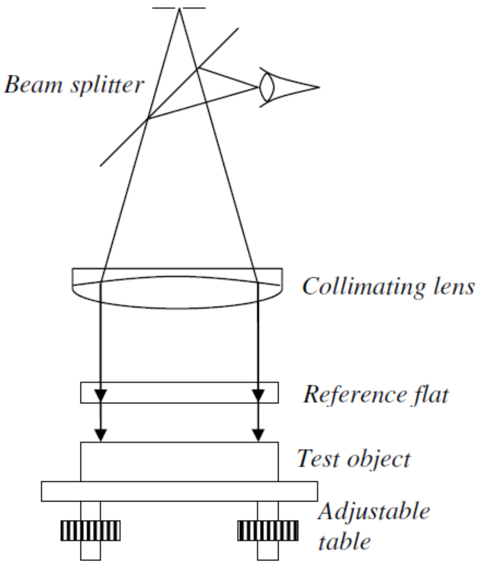
Two complementary approaches give the more flexible solution

- Optical profilometry
  - Interferometers
    - High T-put
    - Wafer level
    - Die level (low resolution)
  - Microscope interferometer
    - Medium T-put
    - Die level (high resolution)

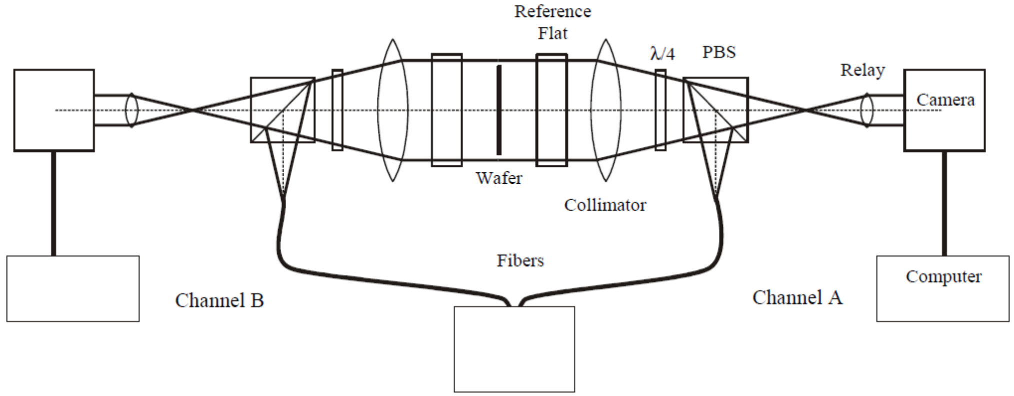
CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

- **Interferometers**
  - Large AOI wafer level
  - High t-put
  - Z resolution < 1nm
  - X-Y resolution 100-200 µm

Fizeau



Dual Fizeau



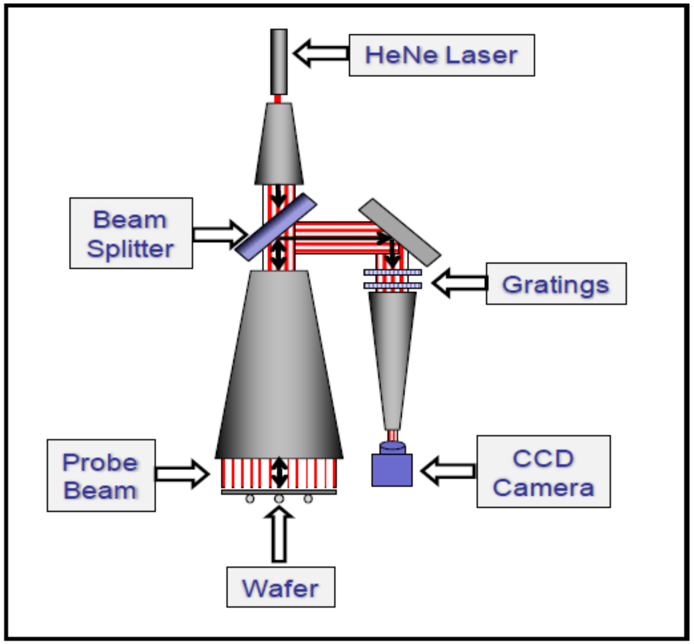
Dual Fizeau, source: Klaus Frischlad et al, SPIE 6672, Advanced Characterization Techniques for Optics, Semiconductors, and Nanotechnologies III, 667202 (10 September 2007)

Szwedowicz, K.K. (2006), 3D-deflectometry: Fast nanotopography measurment for the semiconductor industry, Eidhoven University.

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

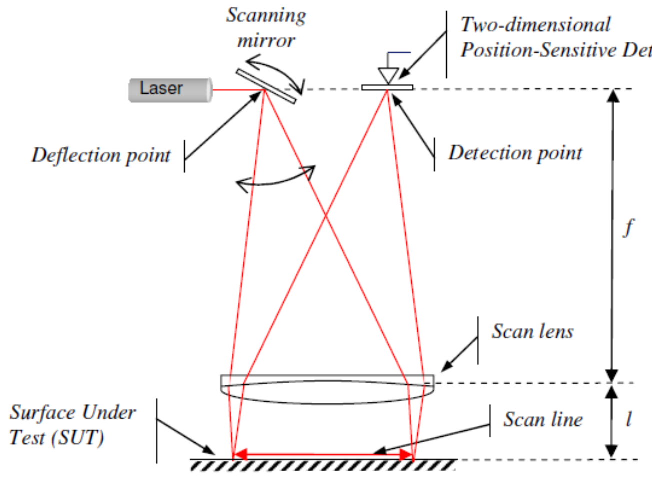
- **Interferometers**
  - Large AOI wafer level
  - High t-put
  - Z resolution < 1nm
  - X-Y resolution 100-200 µm

Shearing



Owen David et al, Proceeding of 11th Wafer level packaging Conference, 2014

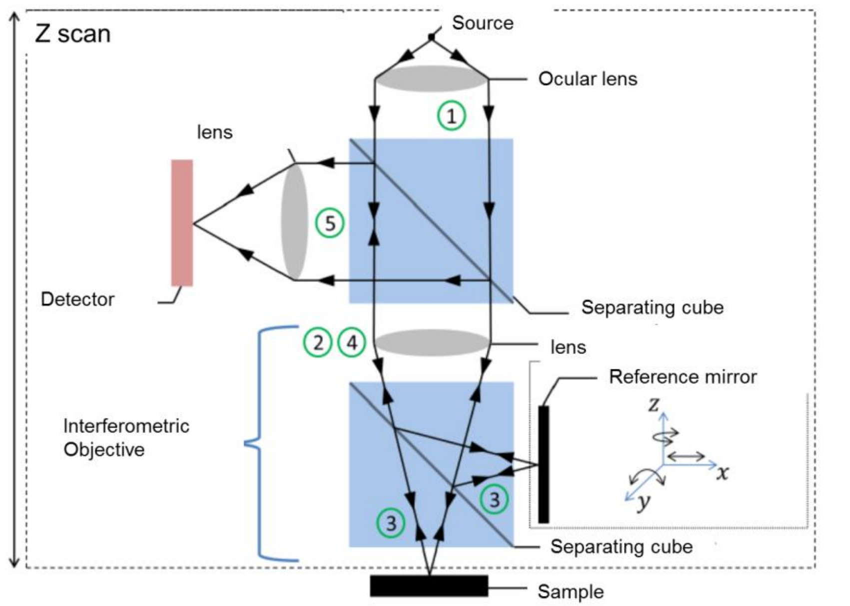
Deflectomety

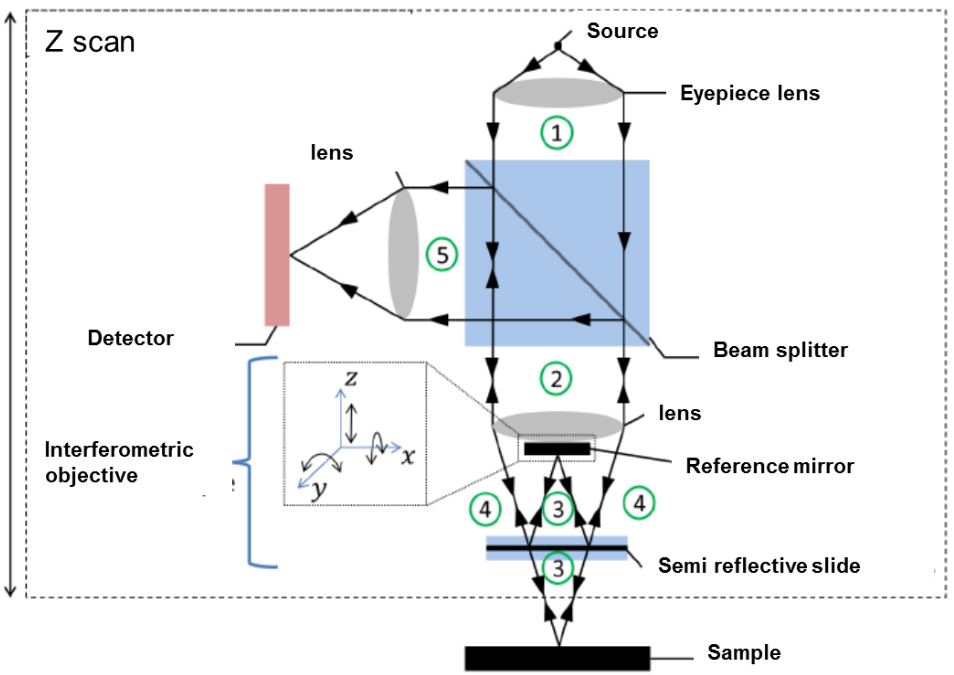


Szwedowicz, K.K. (2006), 3D-deflectometry: Fast nanotopography measurment for the semiconductor industry, Eidhoven University.

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

- **Microscope Interferometer (Michelson, Mirau)**
  - Large AOI Die level with stitching
  - Medium T-put
  - Z resolution < 1nm
  - X-Y resolution 0,3 - 10 µm (depending in objectives)



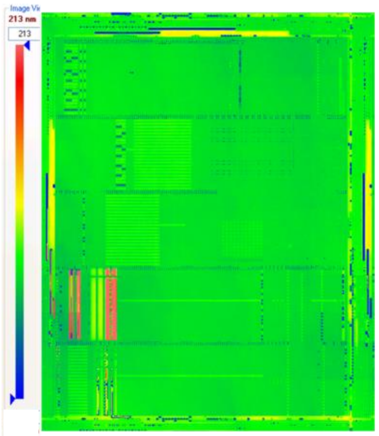


Material Heterogeneity challenges

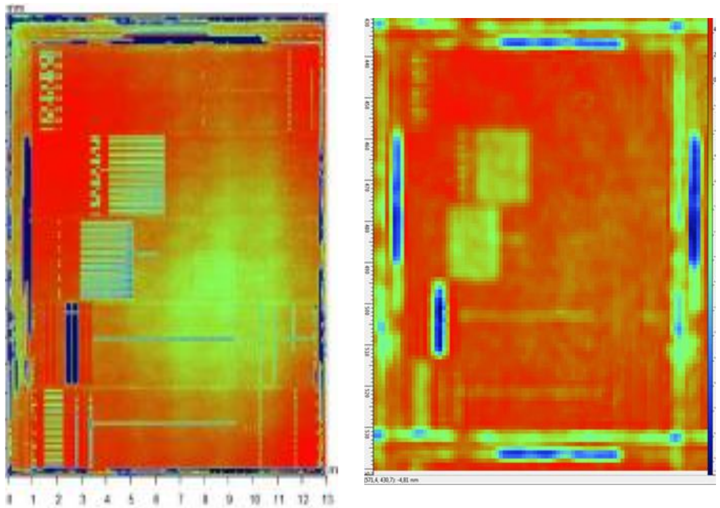
CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

Material heterogeneity: The practical but destructive solution, an ultrathin conformal metallic layer. Example FEOL CMP process.

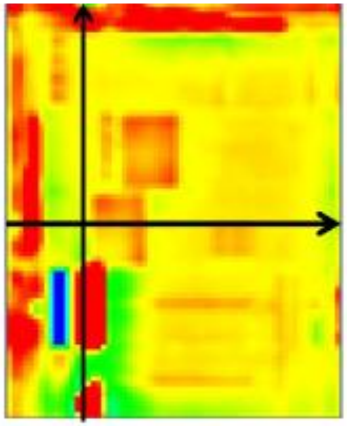
Wo Metal



W Metal



W/oMetal



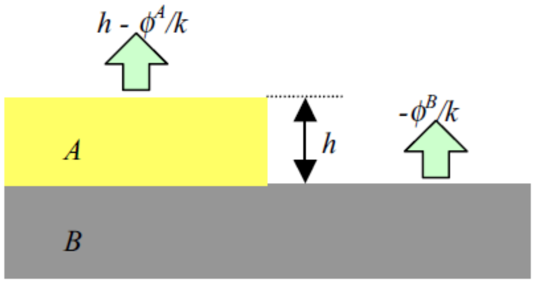
High Resolution

Low Resolution

Need: New approaches to avoid metallic layer deposition !
Otherwise will be used just for R&D

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

Material heterogeneity



Under reflection on a surface depending on surface properties a phase shift can occurs, creating a bias in the height measurements.

PSI

$$I(x,y,z) = I_s + I_m + \gamma\,(x,y,k)\cos[\varphi_{topo}(x,y,k,\theta) + \phi_{ref}(x,y,k,\theta)]$$

WLI

$$I(x,y,z) = I_o \int_{k_o-\Delta k/2}^{k_o+\Delta k/2} \{I_m + \gamma\,(x,y,k)\cos[\varphi_{topo}(x,y,k,\theta) + \phi_{ref}(x,y,k,\theta)]\mathrm{F(k)}\}\,\mathrm{dk}$$

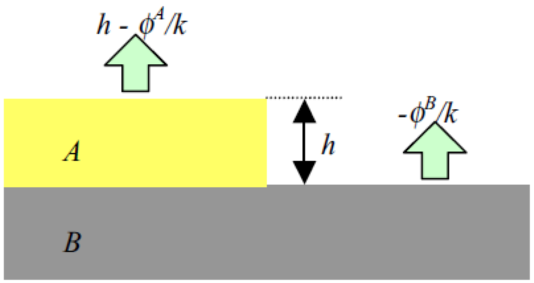
$$\phi(x,y,k) = \frac{2\,n_1 k_2}{n_1^2 - (n_2^2 + k_2^2)}$$

(assuming that there is not theta variation respect to normal incidence)

M.C. Park, S.W. Kin, Optics Letters27(7), 420 (2001)
A. Harasaki, J. Schmit, J.C. Wyant, Applied Optics 40(13), 2102 (2001)

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

Material heterogeneity



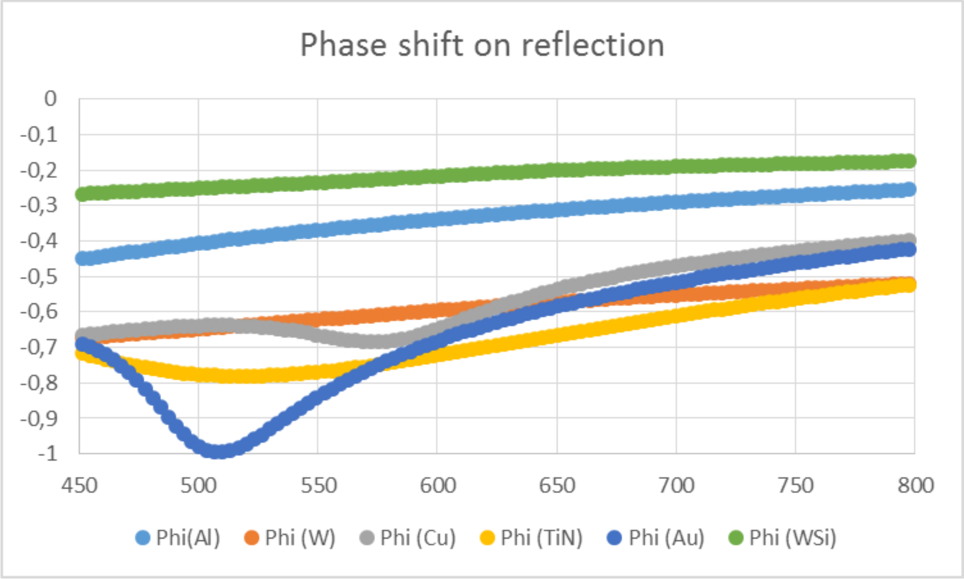
M.C. Park, S.W. Kin, Optics Letters27(7), 420 (2001)
A. Harasaki, J. Schmit, J.C. Wyant, Applied Optics 40(13), 2102 (2001)

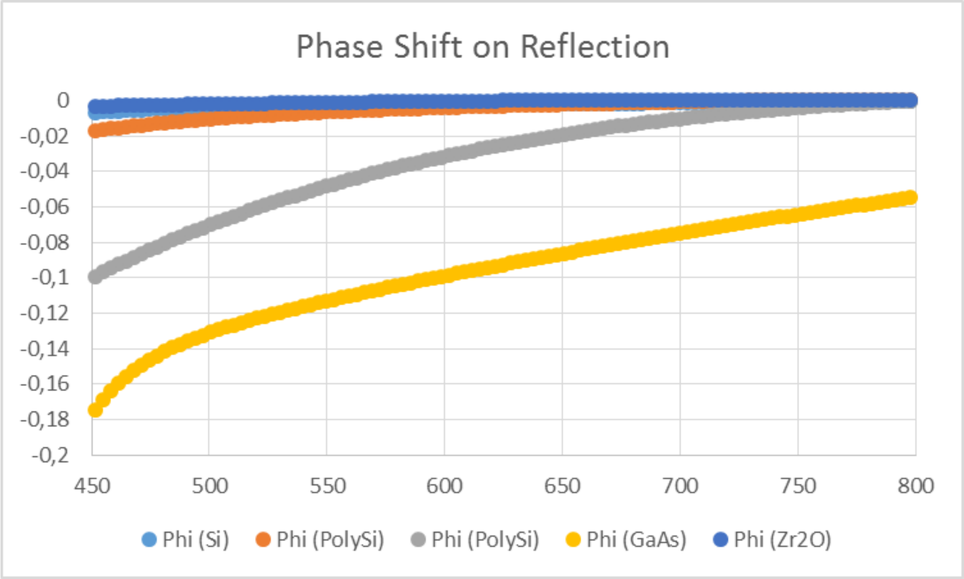
Table 1. Height Offsets Comparison of VSI and PSI Techniques

Metal	VSI Offset (nm)	PSI Offset[a] (nm)
Silver	36.0 ± 1.0	25.1 ± 0.2
Aluminum	13.0 ± 0.8	12.7 ± 0.1
Gold	0 ± 0.2	33.4 ± 0.5
Molybdenum	5.9 ± 0.9	13.4 ± 2.0
Nickel	15.4 ± 0.9	20.8 ± 1.8
Platinum	13.3 ± 1.0	18.1 ± 1.4

[a]Calculated at the wavelength of 600 nm.

In principle we can fix it (with a priori knowledge)or measured
Work in progress…

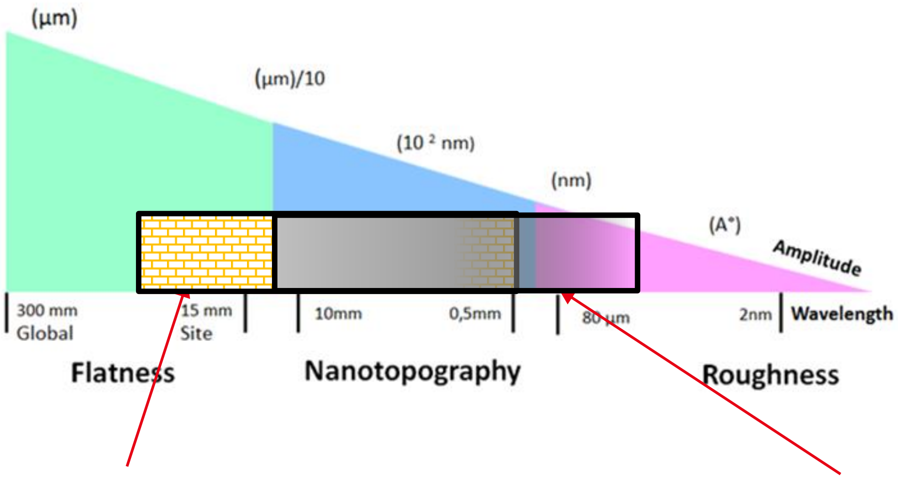




Scale acquisition challenges

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

CMP scale needs for Bonding on IC stacked → Extended « nanotopography » range



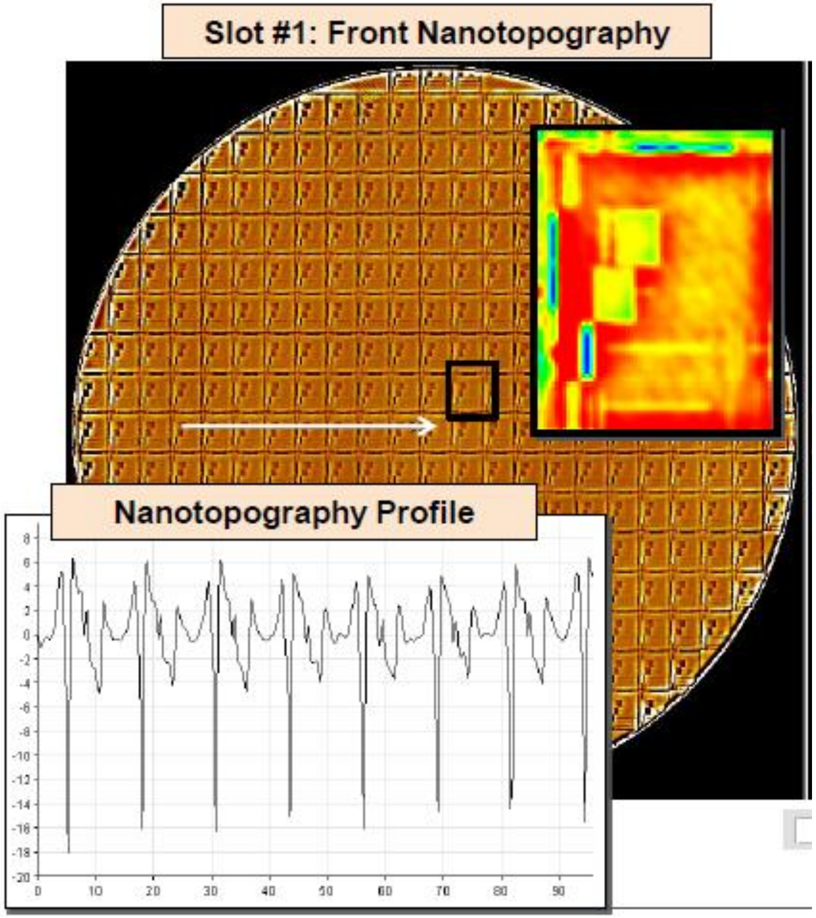
Low Resolution
Die size can be up to 30 mm square size
Interferometer-Deflectometrie

High Resolution
CMP dummies and structure can be down up to 1 µm size with nm amplitudes
Interferometric Microscopes

Need both technologies to acquire the whole process information!

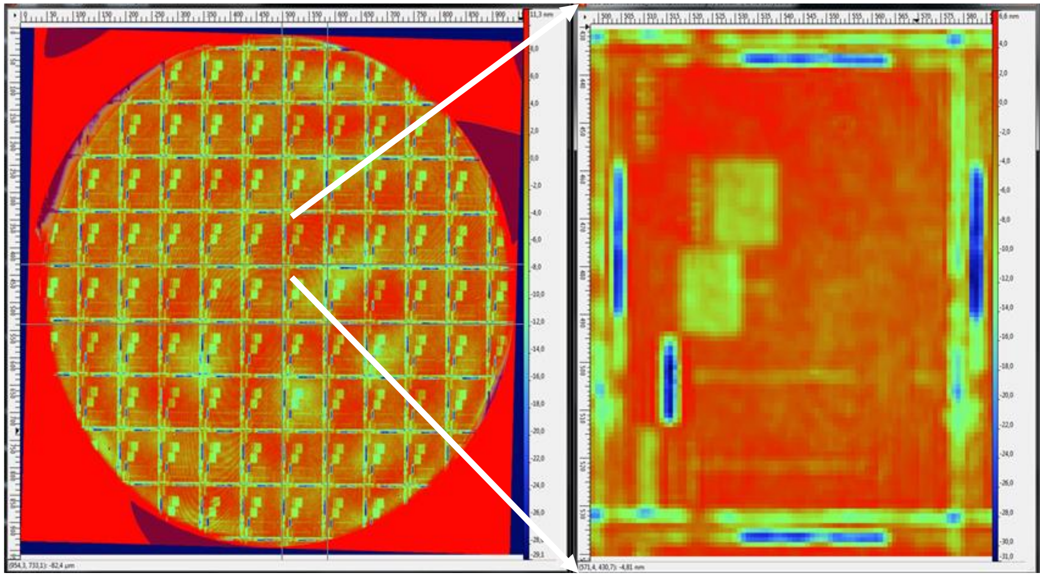
CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

300 mm FOV Fizeau interferometer



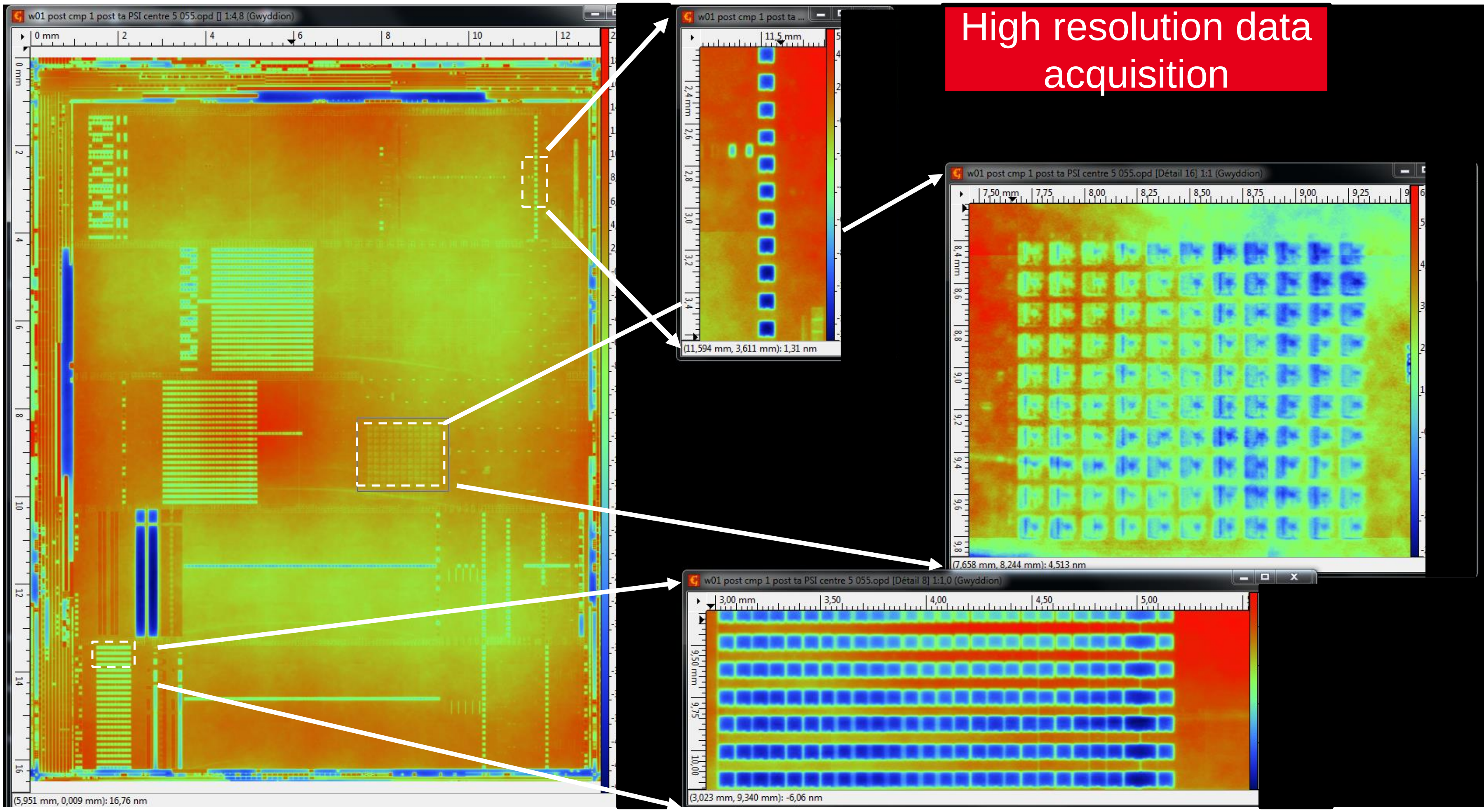
Low resolution data acquisition

100 mm FOV Fizeau interferometer



Low resolution interferometer acquisition gives global die level information over all the wafer, but it does not allow access to information in-die details below 10^2 µm.

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

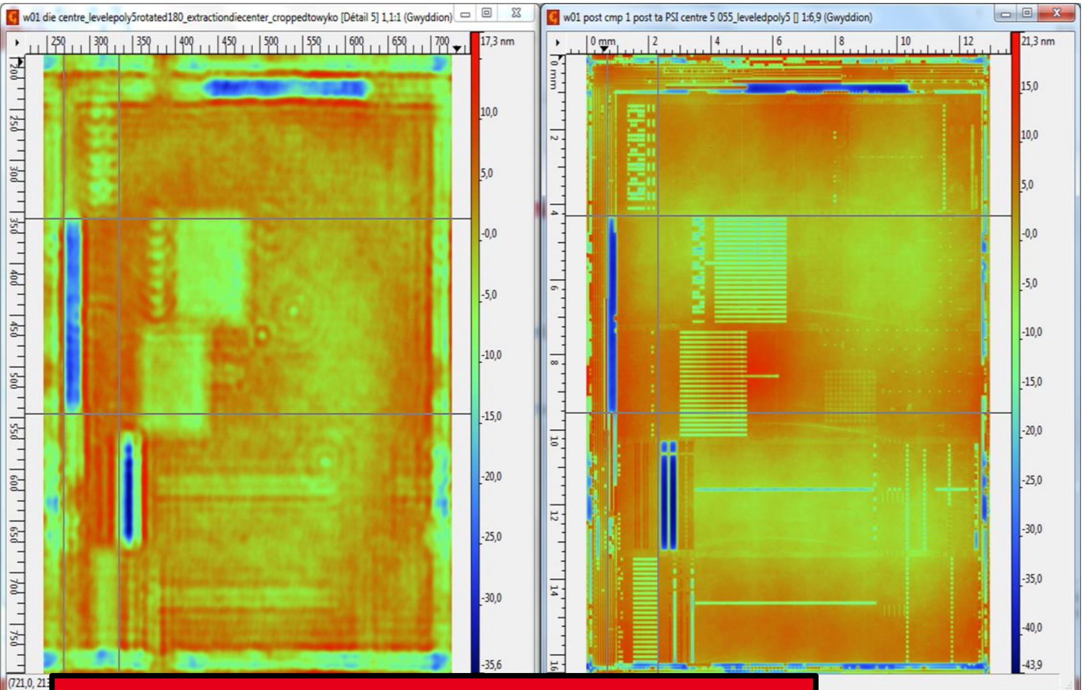


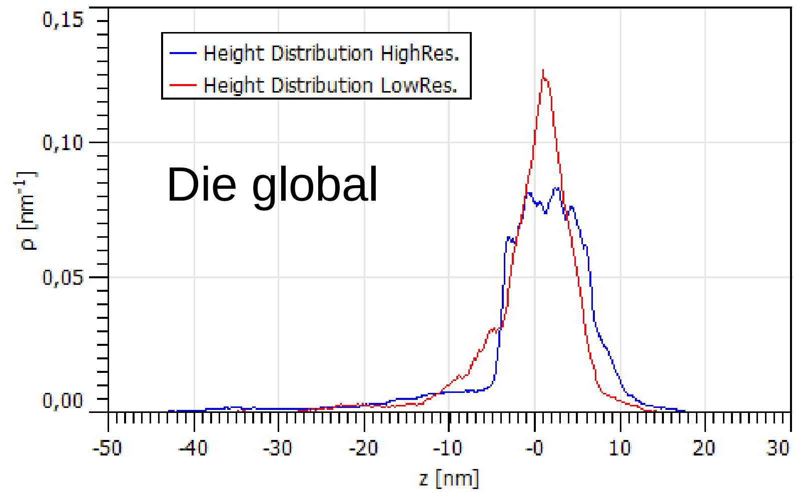
High resolution interferometer acquisition give detailed die level information on some dies, up to 3 µm resolution and allowing further analysis on detailed specific area up to 300 nm resolution level
Need stitching 100-300 images for 2 cm^2 to 9 cm^2 die size.

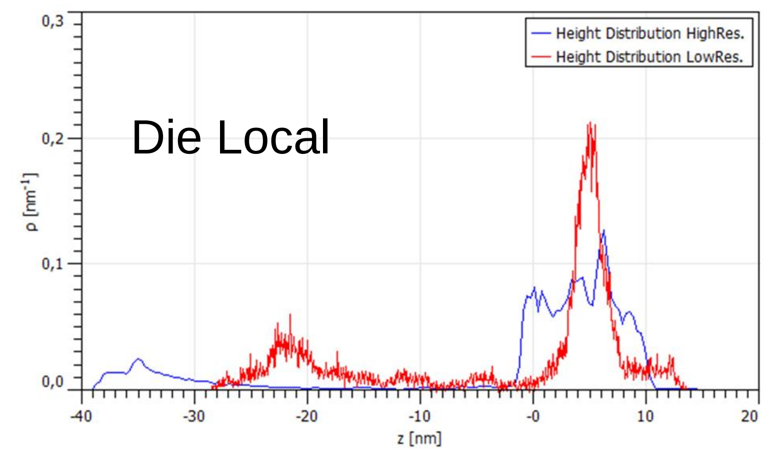
CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

- **Data fusion:**
  - Stitching algorithms reliable and fastest (specially when dummies from cmp are present)
  - Multiscale data fusion algorithms to combine low resolution with high resolution data

This to cover the extended nanotopography range needed by process.







Need to put in place alogorithms to keep information and meausresument consistency at all scales …

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

- **The ideal data acquisition « virtual tool »**

Without metallic layer

Interferometer
Detailed Wafer level
Global Die info.
(60 wafer/hour)

Microscope
Detailed Diel Level
Global Device
High Resolution
(5-10 wafer hours/3Dies)

AFM
Device level
(couples of points /3 dies -wafer)

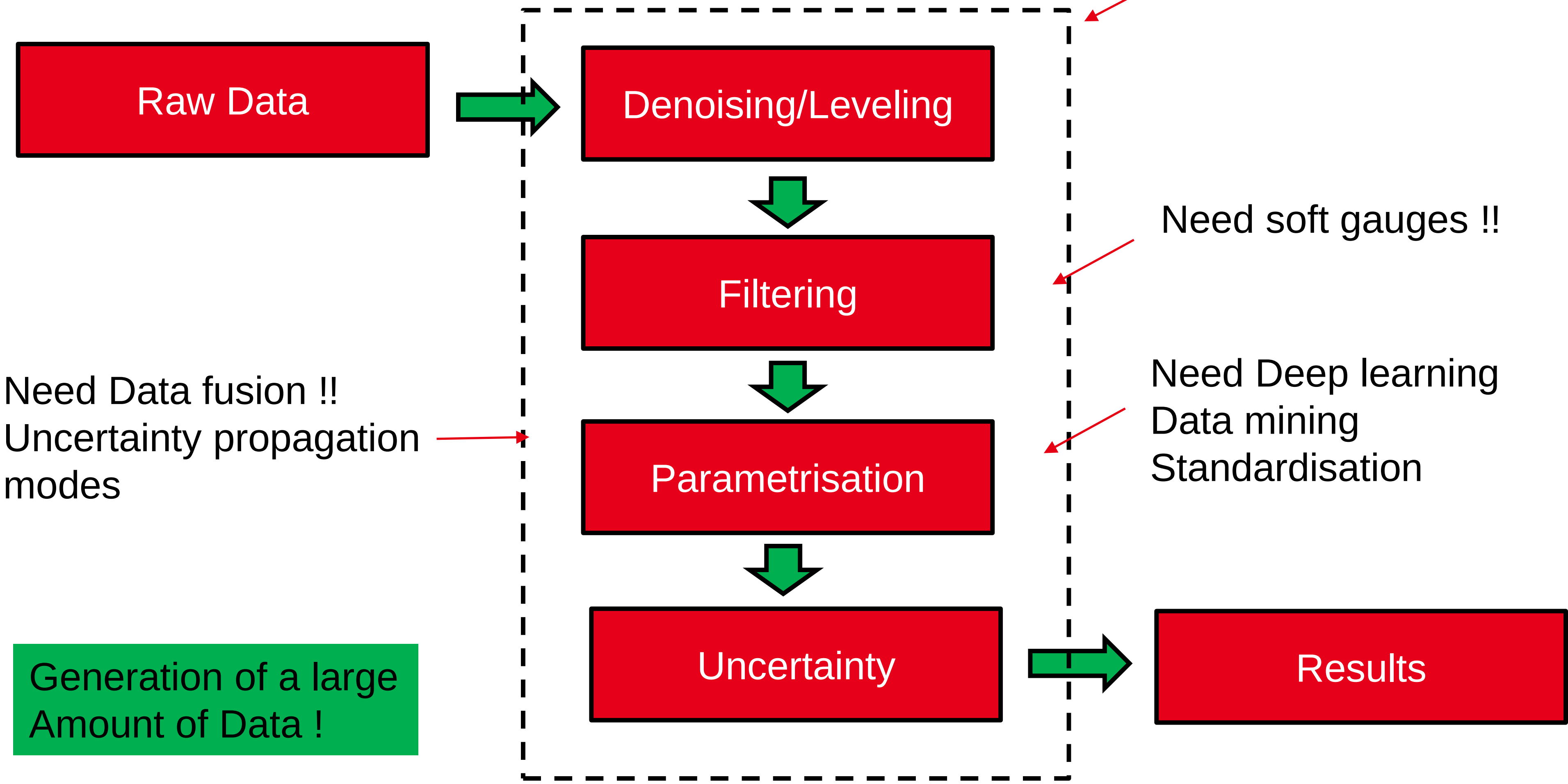
Multiscale-Multi sensor Datafusion

Data analysis / Data storage challenges

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

- **Areal surface analysis flowchart**

The black tool-boxe for Analysis.



CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

- **Areal surface parameters which one to choose?**
  - Global?
  - Local?

Height parameters	
Sa	Arithmetical mean height
Sq	Root mean square height
Sp	Maximum peak height
Sv	Maximum pit height
Sz	Maximum height
Ssk	Skewness
Sku	Kurtosis

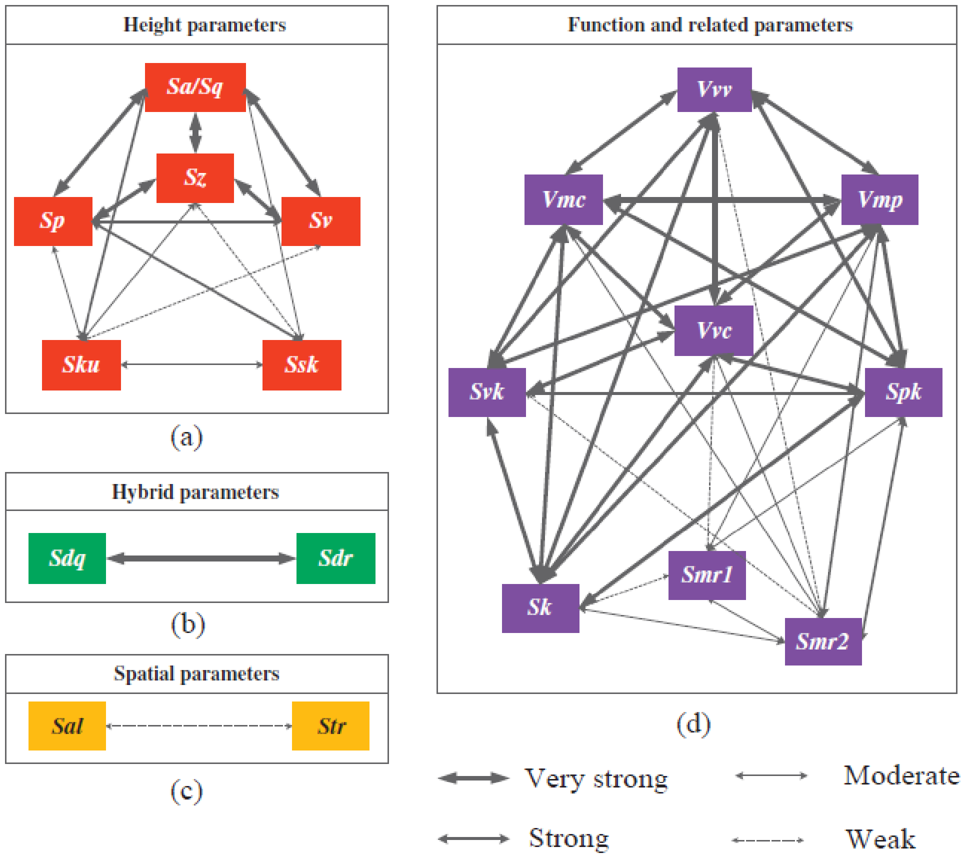
Hybrid parameters	
Sdq	Root mean square gradient
Sdr	Developed interfacial area ratio

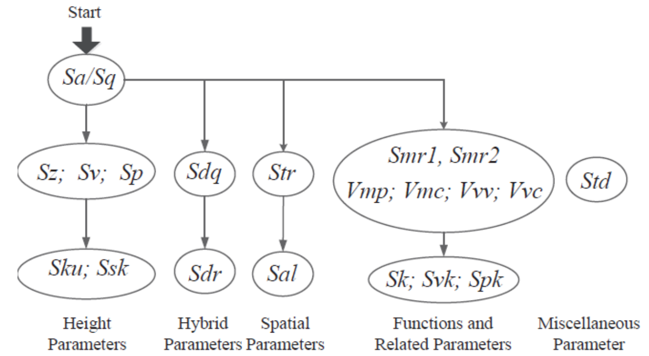
Miscellaneous parameter	
Std	Texture direction

Function and related parameters	
Vmp	Peak material volume
Vmc	Core material volume
Vvv	Dale void volume
Vvc	Core void volume
Sk	Core height
Spk	Reduced peak heigh
Svk	Reduced dale height
Smr1	Material ratio
Smr2	Material ratio

Spatial parameters	
Str	Texture aspect ratio
Sal	Autocorrelation length

Fig. 1. List of areal parameters used in the assessment





Q.Qi et al, Procedia CIRP 27 (2015) 149 – 154

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

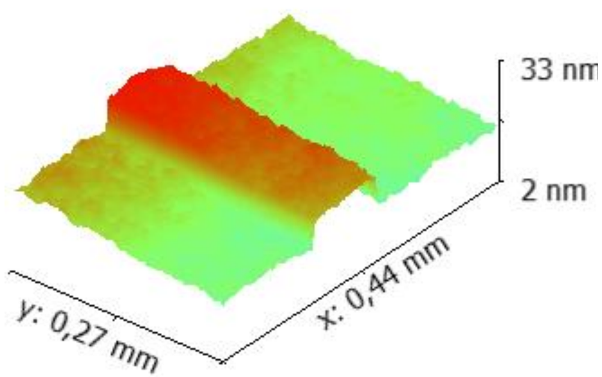
- **Data produced**
  - Low resolution images wafer level
    - 200 MB/Wafer x 2 if front side and backside
  - High resolution
    - 64 MB/Die x 5 Dies/wafer
  - Sampling/Lot
    - 2 wafers
  - About 1GB/lot

- **Need an optimized strategy for:**
  - Data Analysis
    - Parameter selection
    - Data mining/Deep learning
  - Data storage
    - Only raw data
    - Raw data and treated data
    - Raw data and treated Data+ analysis results

Uncertainty/ Traceability

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

- The context:
- Areal surface metrology is getting more and more demanding for process CMP, Bonding and different technologies.



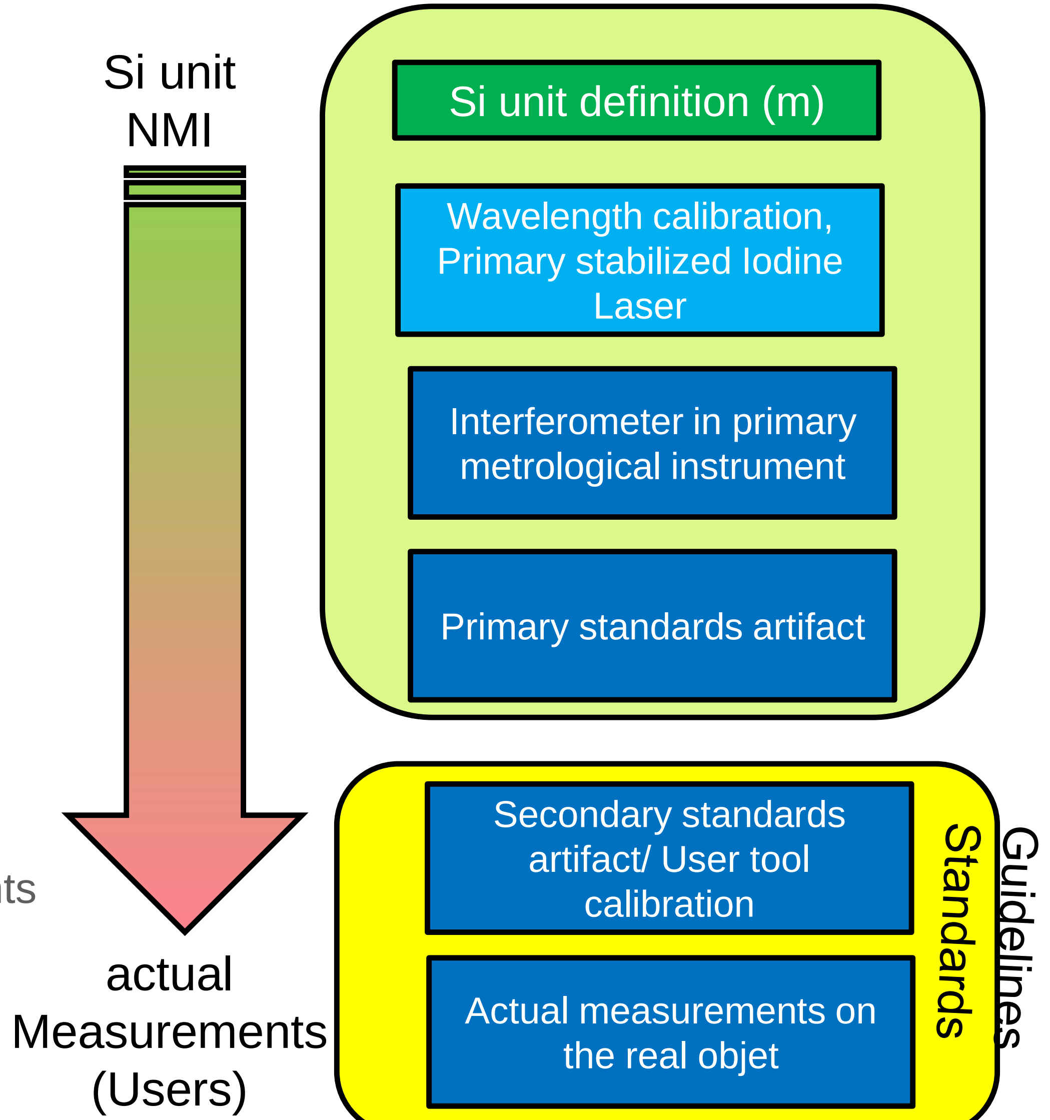
- What is the status on traceability and uncertainty for Areal Surface?

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

- **Traceability:**

  « Property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons <u>all having stated uncertainties</u> »

- **Traceability realization, needs:**
  - Physical Standards artifacts
  - Reference Metrological instruments
  - Guidelines standards
  - Software standards



CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

Where are we at the ISO level and semi-level ?

ISO 25178: Geometric Product Specifications – Surface texture: areal

Part 1: surface texture indications

Part 2: terms, definitions and surface texture parameters

Part 3: specification operators

Part 6: classification of methods for measuring surface texture

Part 70: material measures for the calibration of instruments

Part 71: softgauges - SDF file format

Part 72: softgauges - X3P file format

Part 600: nominal characteristics of surface texture measuring instruments

Part 601: nominal characteristics of contact (stylus) instruments

Part 602: nominal characteristics of non-contact (confocal chromatic probe) instruments

Part 603: nominal characteristics of non-contact (wavefront interferometric microscope) instruments

Part 604: nominal characteristics of non-contact (coherence scanning interferometry) instruments

Part 605: nominal characteristics of non-contact (point autofocus profiling) instruments

Part 606: nominal characteristics of non-contact (focus variation) instruments

Part 607: nominal characteristics of non-contact (confocal) instruments

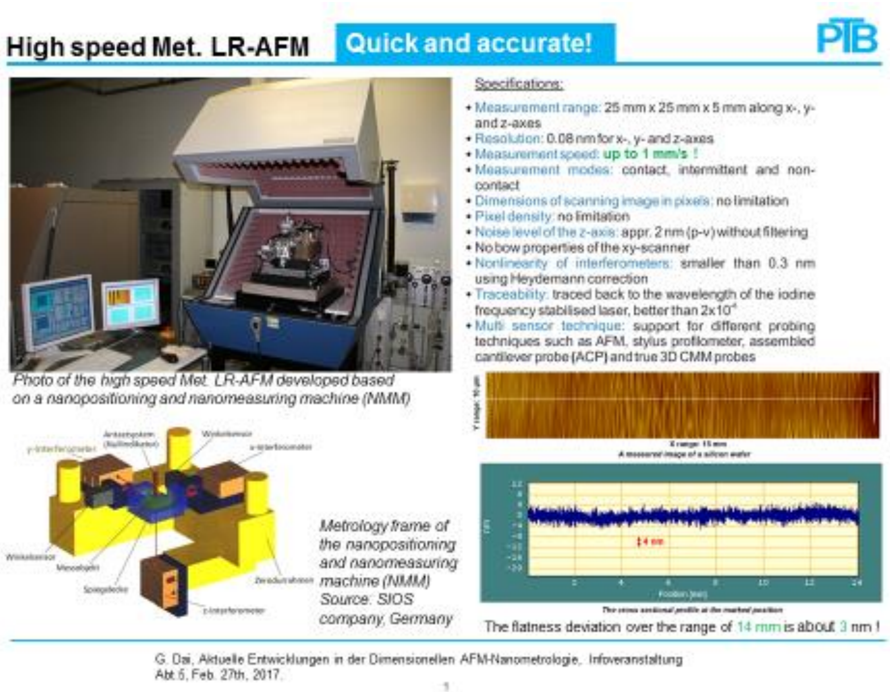
Part 700: calibration of surface texture measuring instruments

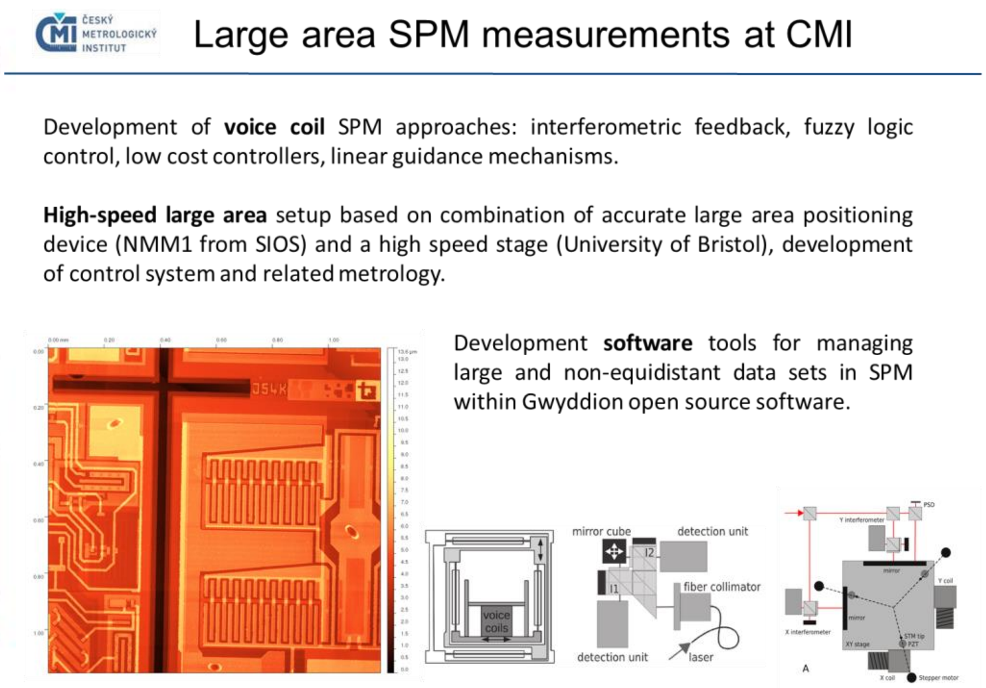
Part 701: calibration and measurement standards for contact (stylus) instruments

SEMI M43: **Guide for Reporting Wafer Nanotopography** :

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

- **Traceability realization, needs:**
  - Metrological reference instruments large area AFM or profilometer (Europe has CMI, NPL, PTB)
  - Protocols need to work on parametrization, data fusion and uncertainty propagation





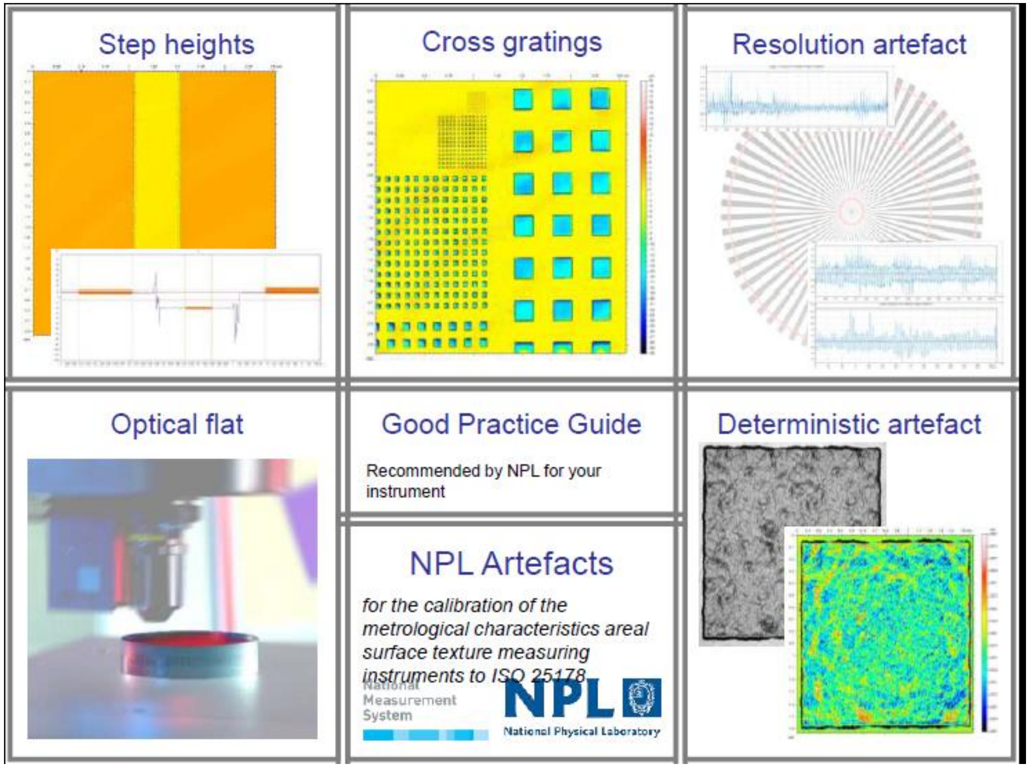
Courtesy of Dr. Gaoliang Dai and Dr. Petr Klapetek

Work on going on the frame of 3D stack EU EMPIR program

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

- **Traceability realization, needs:**
  - Standards artifacts are available (NIST, NPL, VLSI…)
  - Missing secondary artifact at wafer level to check tool level (e.g. WWU)

- **User instrument metrological characteristic**
  - Noise
  - Linearity and squareness
  - Residual flatness
  - Resolution



CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

- **Traceability realization, needs:**
  - Guidelines standards
  - Definitions
- **Metrological characteristics are expected to be common to all instruments**
  - Noise
  - Linearity and squareness
  - Residual flatness and amplication coefficient
  - Resolution
- **Example: Resolution in ISO 25178**
  - Common optical lateral resolution giving by the Rayleigh or Sparrow limits, is not enough.
  - The term “lateral period limit” is proposed and join both the ability to resolve fwo features and the availability to measure the correct height.
  - Lateral period limit is defined as the 50 % cut off point from the instrument transfer function and can be determined by measuring star pattern, grating step of spheres.
  - The ideal is to determine the optical transfer function as this not has height restriction.

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

- **And Uncertainty.**
- **Today at the best measurements are given with statistic type A contribution only.**

- **Metrological characteristics are expected to be common to all instruments and it should help to stablish the input uncertainties to propagate to the final measurements.**

- **ISO 25178 proposed at set of characteristics and associated instrument specifications from which a good estimation of the input uncertainty of type B for a given instrument can be stablished.**

Metrological characteristic	Instrument specifications	Notes
Amplification coefficient (z)	- Step height repeatability - Step height accuracy	Expressed in height units and/or as a percentage of the measured height
Linearity deviation (z)	- Height response linearity	Expressed as a maximum permissible error (MPE)
Measurement noise	- Surface topography repeatability - Repeatability of the RMS	Expressed as a standard deviation for each specifications
Topographic lateral resolution	- Optical lateral resolution - Lateral sampling	The specifications are for influence factors that *relate* to lateral resolution
Residual flatness	(not specified)	Calibrated and adjusted in situ using a *system error subtract* procedure
Field amplification and linearity (xy)	(not specified)	Calibrated and adjusted *in situ*

P. De Groot, Proc. of SPIE Vol. 9110 "Dimensional Optical Metrology and Inspection for Practical Applications III" (Baltimore, MD 2014),

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

- **Uncertainty chain contributors**

$$I(x,y,z) = I_s + I_m + \gamma\,(x,y,k)\cos[\varphi(x,y,k,\theta) + \phi(x,y,k,\theta)]$$

$$I(x,y,z) = I_o \int_{k_o-\Delta k/2}^{k_o+\Delta k/2} \{I_m + \gamma\,(x,y,k)\cos[\varphi(x,y,k,\theta) + \phi(x,y,k,\theta)]\mathrm{F(k)}\}\,\mathrm{dk}$$

Uncertainty Propagation

Instrumentation

- Wavelength calibration
- Lateral Axis calibration
- Linearity
- Flatness
- noise
- Piezo and/or Z scan calibration

$$tan[\varphi] = f\big(I_{step},(x,y)\big)\ or\ \gamma\big(\delta(z)\big)$$

Signal Treatment

- Phase Unwrapping
- Envelop maxima finding
- Stitching Data fusion
- Multiple scale and multiple sensor Data fusion

$$h = f(x,y)$$

Data Analysis

- Parametrization (Sq, Sz, Std, Sk…)
- Physical modeling (Zcmp, Bonding Energie,…)

CHALLENGES IN NANOTOPOGRAPHY MEASUREMENTS AT DIE LEVEL

- **Conclusion**
  - Nanotopography measurements is key for enabling CMP and Bonding process for different technological applications.
  - The classical limits of nanotopography need to be extended in both size in this use case.
  - Today this is possible with available technology BUT need additional work.
  - Need to be non-destructive
  - No a single instrument can cover all range so an acquisition of the whole information will require multiple sensor with data fusion strategies integrated
  - Data analysis and Data storage will need to be addressed to avoid loosing information and optimizing data storage
  - Traceability and uncertainty will need additional work specially on the final uncertainty and measurement capability quantification

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Leti, technology research institute
Commissariat à l'énergie atomique et aux énergies alternatives
Minatec Campus | 17 rue des Martyrs | 38054 Grenoble Cedex | France
www.leti.fr