Inline Metrology
Overview and Challenges

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Metrology Module - STMicroelectronics Crolles

3DAM Workshop - March 2019

ST Crolles Manufacturing and R&D Sites

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Outline

- InLine Metrology Main Quality Criteria
- InLine Metrology Challenges & Trends

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InLine Metrology Main Criteria

Accuracy & Precision

6σ

Sensitivity & Capability

Robustness & Productivity

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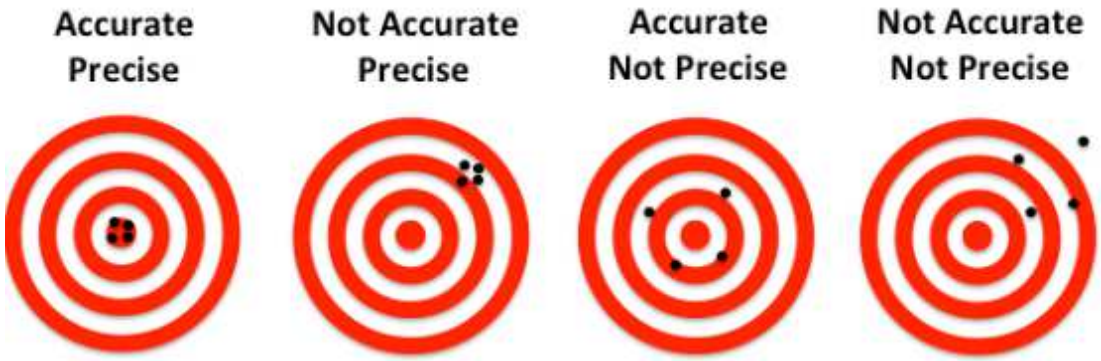
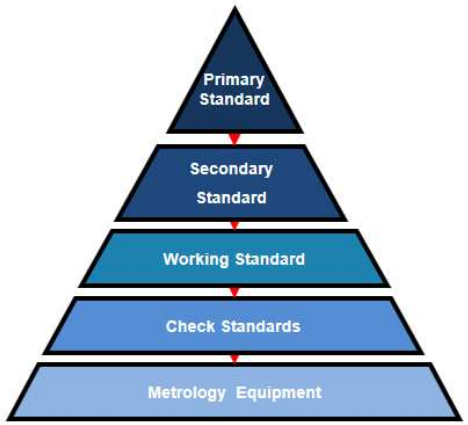
Accuracy & Precision

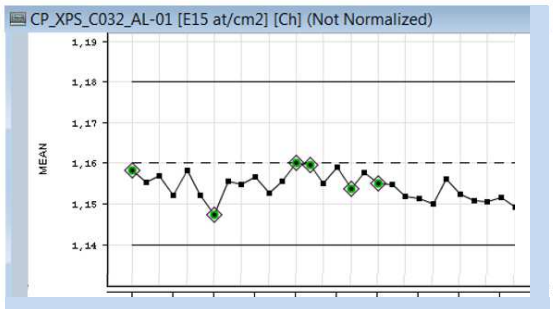
ISO 9001:2015

ISO9001 & IATF
for automotive industries





- **Accuracy** :
  - Inline measurement processes are at the limit of physics
  - Suffering from the lack of available reference standards
  - Alternative is to rely on cross correlation & sponsor academic collaboration



Metrology Monitoring Control Chart

- **Precision** (Repeatability & Reproducibility) :
  - Metrology variability budget requested to be minimum versus process variation to insure proper process control
  - Drastic Control of metrology Equipement precision:
    - Ex: Smallest quantity Al layer in HKMG : 1.2 A +/- 0.4 A

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InLine Metrology Main Criteria

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Sensitivity & Capability

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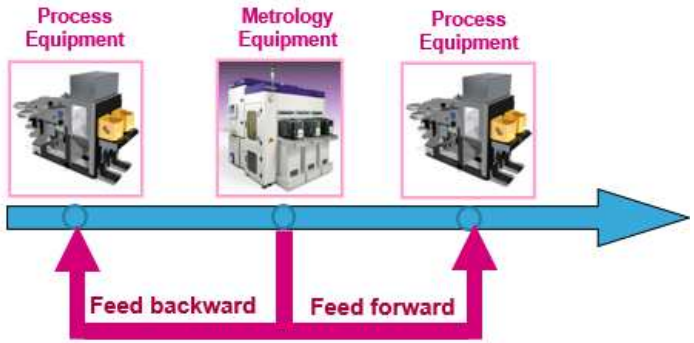
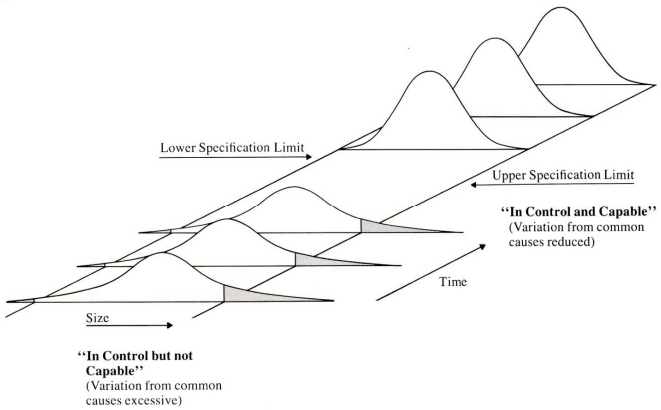
Sensitivity & Capability

Advanced Process Control (APC)



- **Sensitivity** :
  - Metrology provides judgment on lot, DOE, OPC, process window, engineering optimisation, equipment qualification…
  - Small modification in process can have a hugh impact on model or image quality due to its extreme sensistivy
  - Feed forward and backward → direct impact of metrology data quality on process readjustment



- **Capability (Precision/Tolerance Ratio)** :
  - Process capability (Cpk indicator) is a ratio which compares the process spread to the width of the specification tolerance
  - The observed Cpk can be directly impacted by the Metrology individual or fleet variability
  - Individual Stability and Alignment between Metrology systems are direct contributors of the observed Process capability

$$\sigma^2_{Observed} = \sigma^2_{process} + \sigma^2_{Measurement}$$

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InLine Metrology Main Criteria

Accuracy & Precision

6σ

Sensitivity & Capability

Robustness & Productivity

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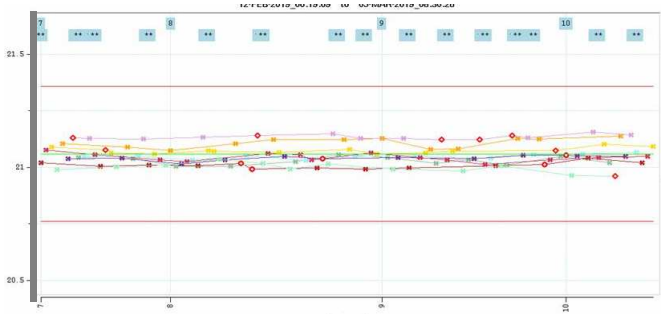
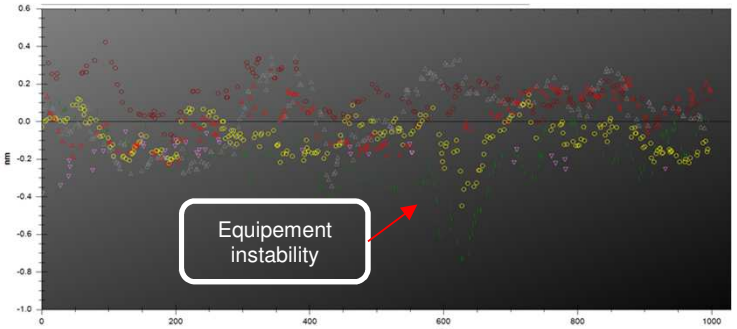
Robustness & Productivity

- **Robustness** :
  - Continuous optimization of hardware & recovery intervention to increase Uptime and Overall Equipment Efficiency (OEE).
  - Suffering from the lack of FDC (Fault Detection Control) compatibility for early detection.
- **Throughput** :
  - Strong difference versus techniques (image, model based…) and environment (air, ultra vacuum…).
  - Fitting sequence being the limited factor for overall measurement process duration.
- **Matching** :
  - Drastic requirement for alignment of readings between multiple metrology equipment.
  - Target for Metrology mismatching < 10% process variation.



Use of monitoring wafer over thickness metrology fleet



Use of production data through multi parameter variance analysis decomposition

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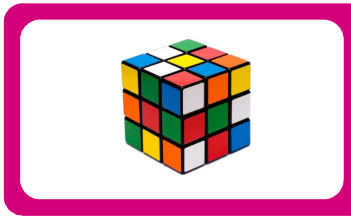
InLine Metrology Challenges & Trends



Advanced Methods

Time to solution

Bridge with domains

Industry 4.0

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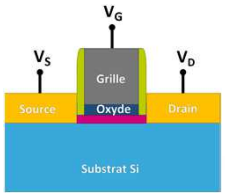

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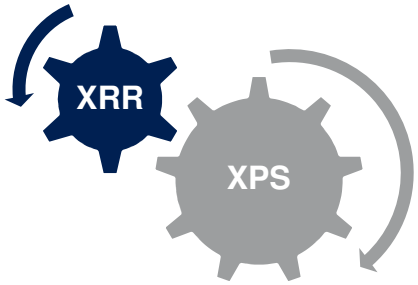
Advanced Methods

Hybrid metrology : getting more than the sum of data

- **Channel SiGe Channel layer :**

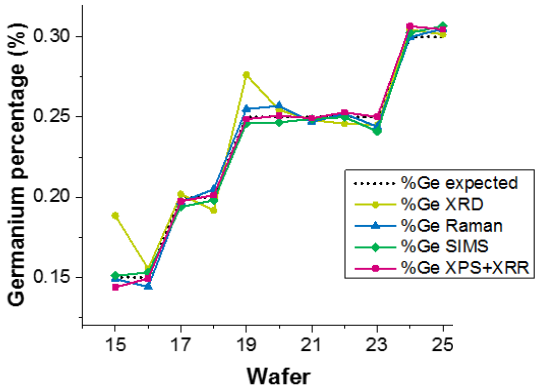


Access to Thickness and %Ge

SiGe < 80A

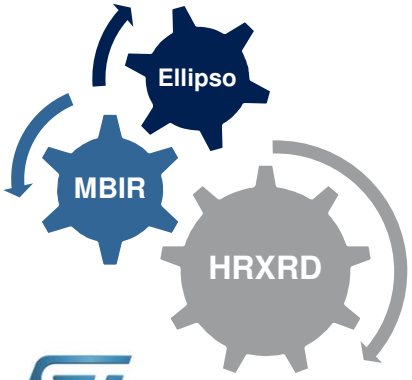
Si substrate

Single SiGe/Si ultra thin layer



Ref: L. Fauquier and al. Proceedings ISTDM/ICSI Conference Japan 2016

- **Raised Source Drain Doped SiGe layer :**

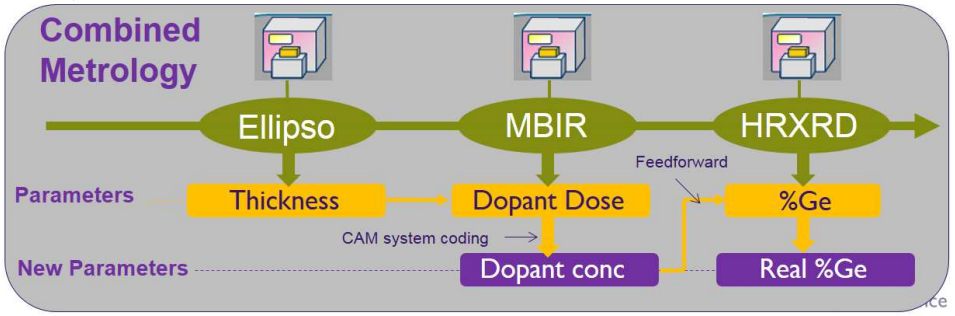


SiGe:B 300A

Si substrate

Highly doped SiGe/Si layer

Access to Thickness, doping and %Ge



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Ref: D. Le Cunff and al. Journal of Micro/Nanolithography, MEMS and MOEMS, Vol 13 (4), 041402, 2014

Hybrid Metrology

- Many publication reported combining SEMCD, AFM, Scatterometry for CD measurement …
- Different level of Hybridization implementation (from feed forward to …offline complex fitting algorithms using combined spectra)
- Hybrid Metrology proven to be beneficial in some cases but conclusion are application dependent
- Measurement error is propagating along the measurement chain
- Hybrid metrology implementation requires standardization and common protocol for exchange of data/spectra between metrology suppliers → Not easy to achieve
- Strong IT development needed but no clear ROI to push further so far

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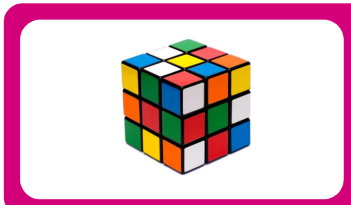
InLine Metrology Challenges & Trends



Advanced Methods

Time to solution

Bridge with domains

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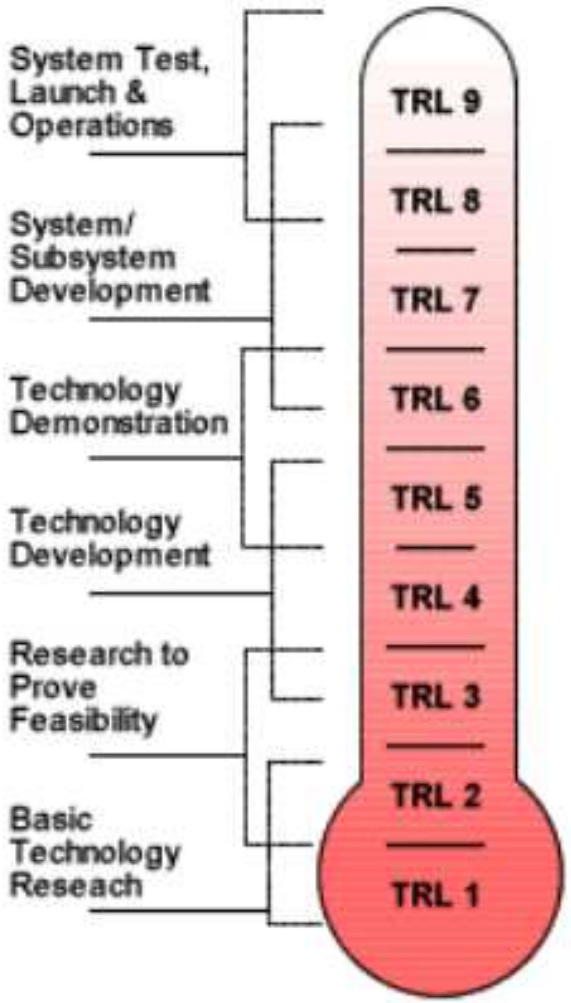
Time to solution

TRL: Technology Readiness Level



- New key characteristics are needed to be controlled inline. In some cases, there is no existing metrology solution in the market.
- Metrology needs to maintien technology watch activities and strong collaboration with key suppliers to be capable to quickly respond to this need with an industrial solution
- European programs and Join Development Program are favorable environment to test innovative techniques in a 2 or 3 years time frame period

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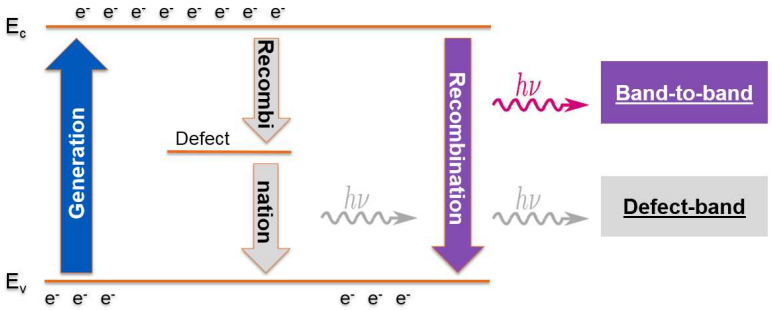
Time to solution

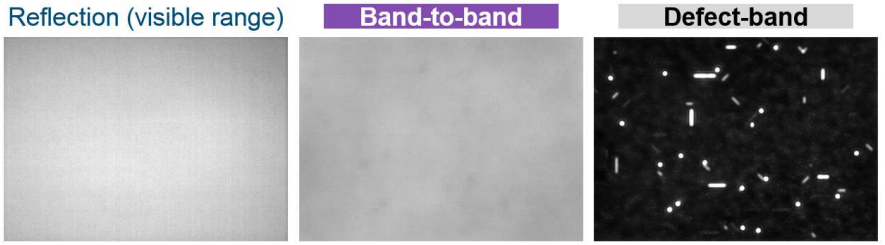
Transfer of specific lab technique to industrial environment

- **Photoluminescence Imaging: buried dislocation detection**



Photoluminescence basic principle

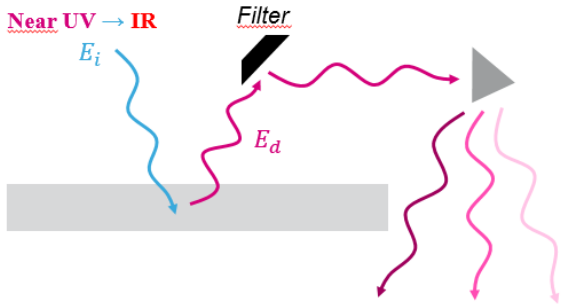
Only non destructive technique able to detect buried dislocations



Si sample with buried dislocations intentionally created using P implant
(6E13 at/cm² @ 1.39MeV) + recovery anneal – PL acquisition time ~3s

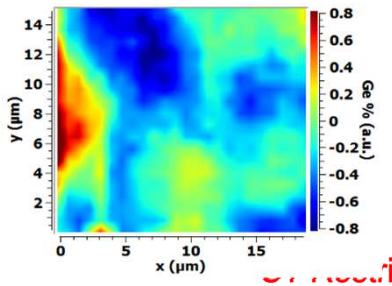
** R. Duru and al. IEEE/SEMI proceedings ASMC Conference 2017*

- **Raman Spectroscopy : Ge composition ultrathin SiGe/Si**



Raman Spectroscopy basic principle

Only non destructive technique to provide Ge% with few µm resolution



** A. Durand and al. E-MRS Spring Meeting (May 26-30, 2014, Lille, France)*

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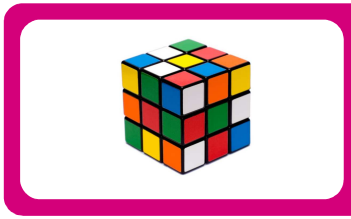
InLine Metrology Challenges & Trends



Advanced Methods

Time to solution

Bridge with domains

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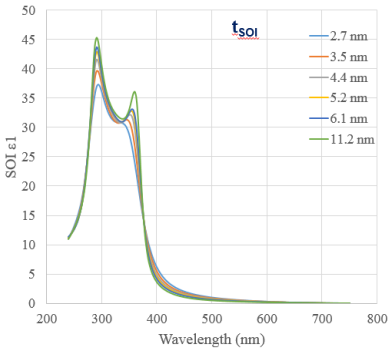
Dielectric constant: Ellipsometry

- Ellipsometry results: Ɛ dielectric function is modified for ultra thin SOI layer



$$\epsilon_r = \epsilon_1 + i\epsilon_2$$

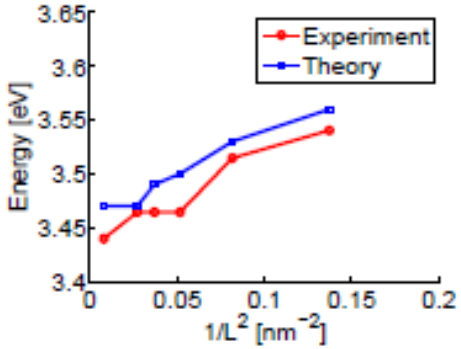
$$\epsilon_1 = n^2 - k^2 \qquad \epsilon_2 = 2nk$$

$$\epsilon = 1 - \frac{e^2\hbar}{\epsilon_0 \Omega} \sum_{c,v,\mathbf{k}} \frac{f_{cv}}{E_{cv}} \left[\frac{1}{\hbar\omega - E_{cv} + i\eta} - \frac{1}{\hbar\omega + E_{cv} + i\eta} \right]$$

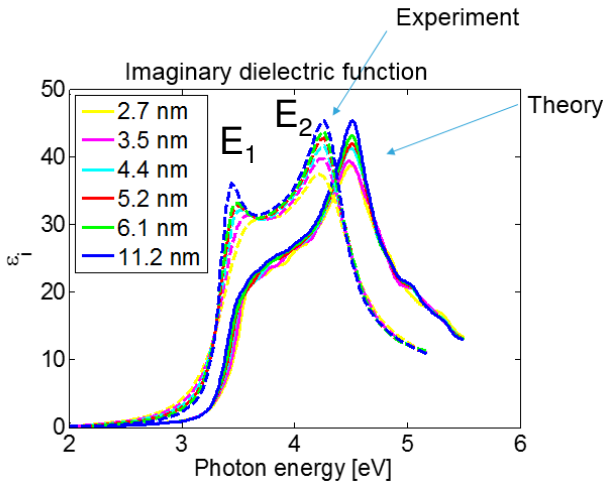
** L. Schneider and al. Proceedings IEEE/SEMI ASMC Conference (May 4-6, 2015, Saratoga Springs, NY, USA)*

- Physical simulation of optical properties through tight binding model

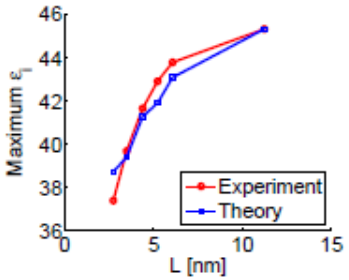
Blue shift in E_1 compatible with Quantum confinement



$$\Delta E = E_{Gap}^{SOI} - E_{Gap}^{bulk} = \frac{(\pi\hbar)^2}{2m^* L^2}$$



Decrease in intensity of E_2 : indiect gap in X in Brillouin Zone



** C. Kriso and al.Solid-State Electroics, Volume 129, March 2017 p 93-96*

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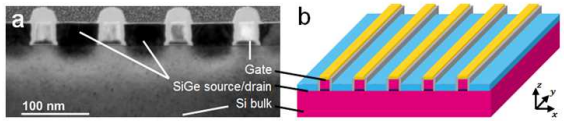
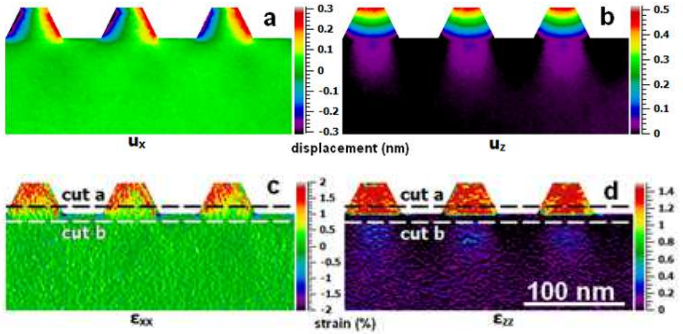


Fig. 1. Bright field TEM image (a) and schematic (b) of the structure

Local Strain: HRXRD

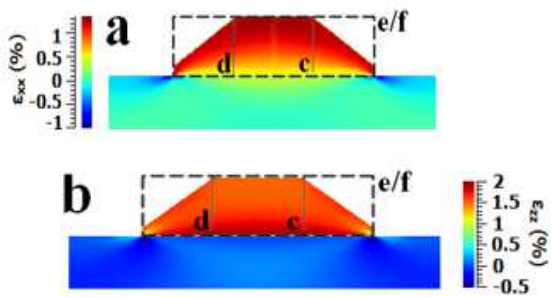
DFEH

Dark Field Electron Holography (DFEH)



Horizontal and vertical displacement field

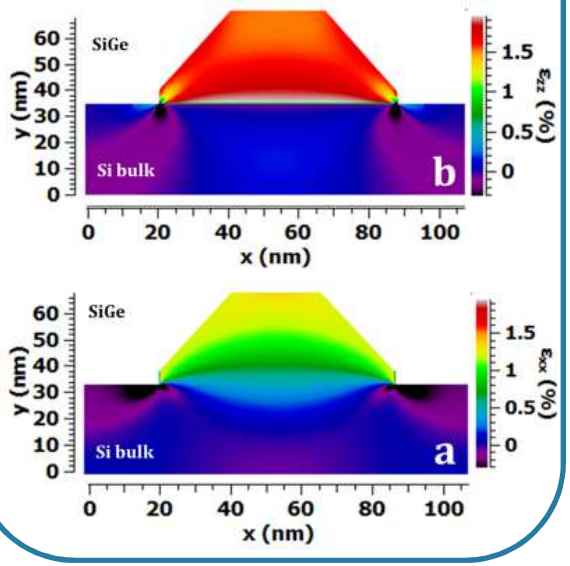
Finite Element Model



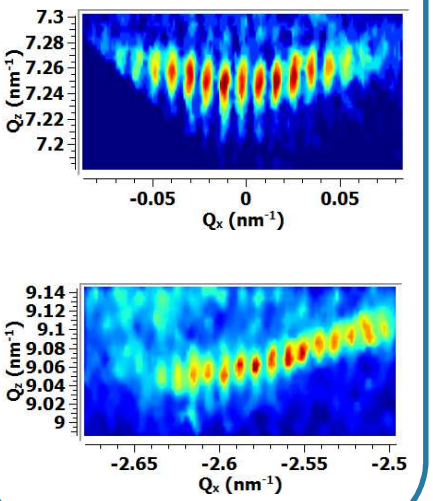
HRXRD

*A. Durand, V. Boureau, et al., *IEEE 15th International Conference on Nanotechnology (IEEE-NANO)*, 2015, pp. 785–788.

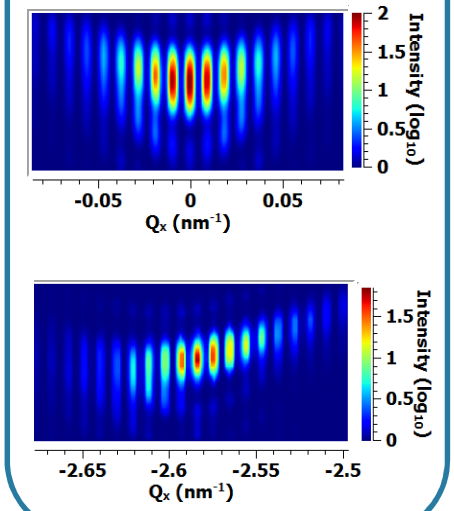
OUTPUT Param → Strain Field



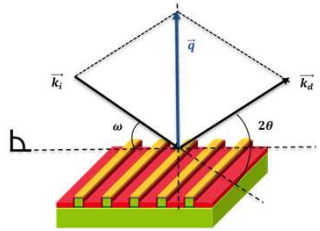
INPUT Param RSM maps



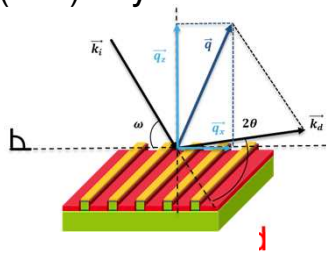
Library Generation



(004) Symetric



($\bar{1}15$) asymetric



InLine Metrology Challenges & Trends

Advanced Methods

Time to solution

Bridge with domains

Industry 4.0

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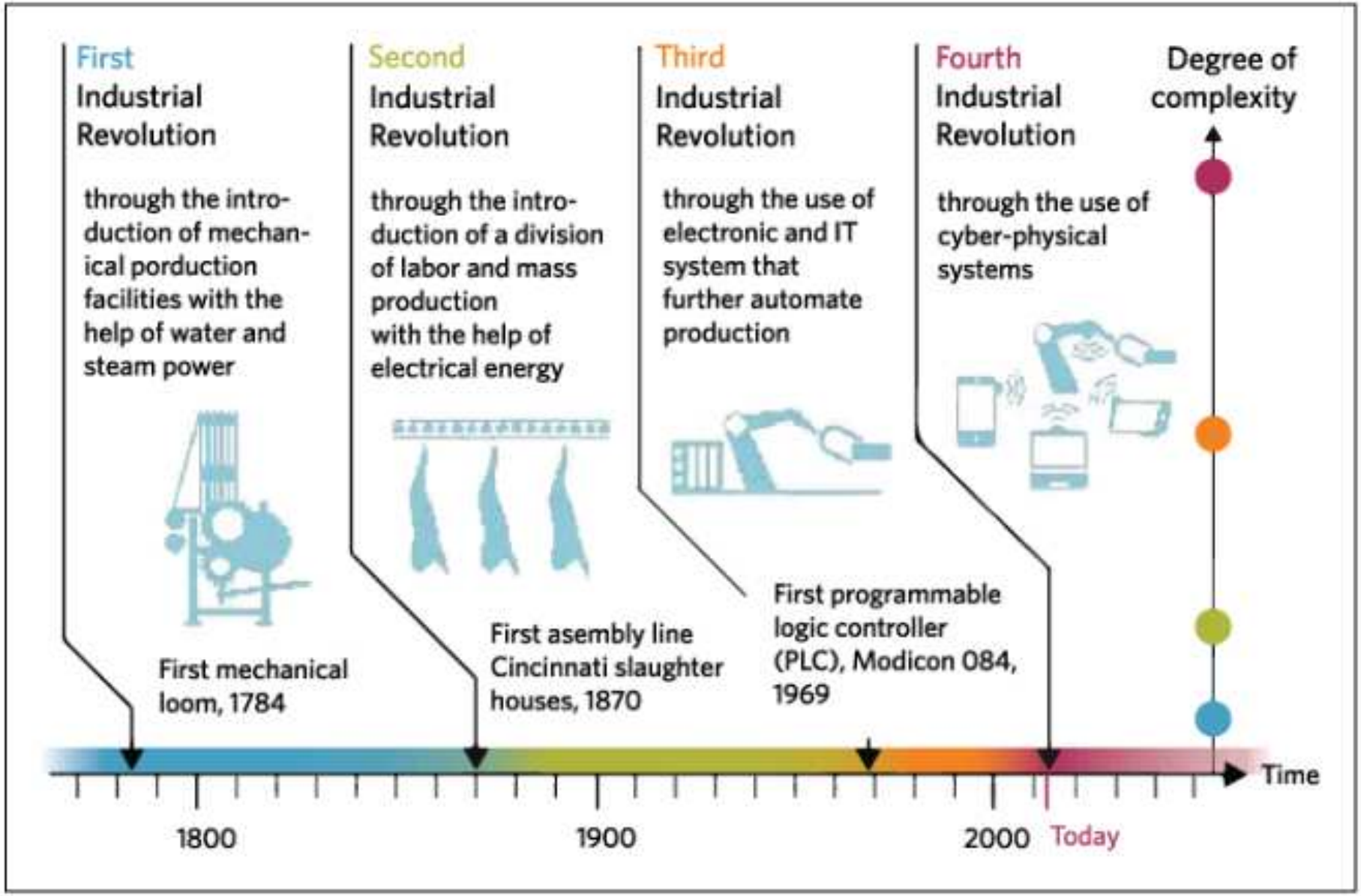
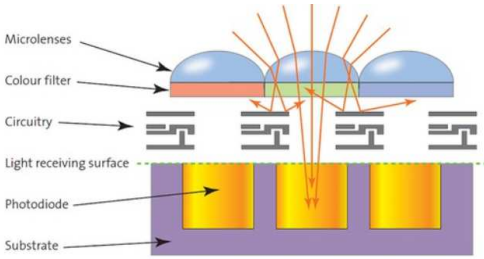
Industry 4.0

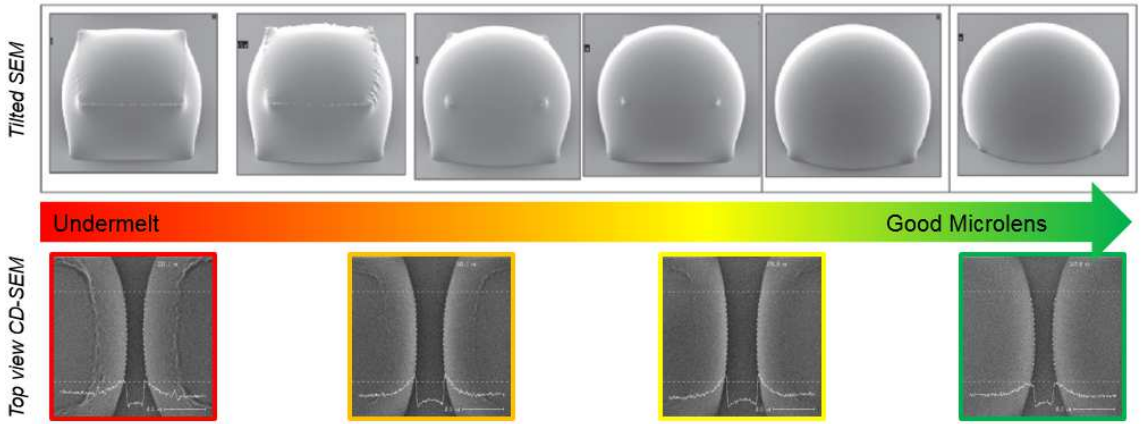


Source EEtimes

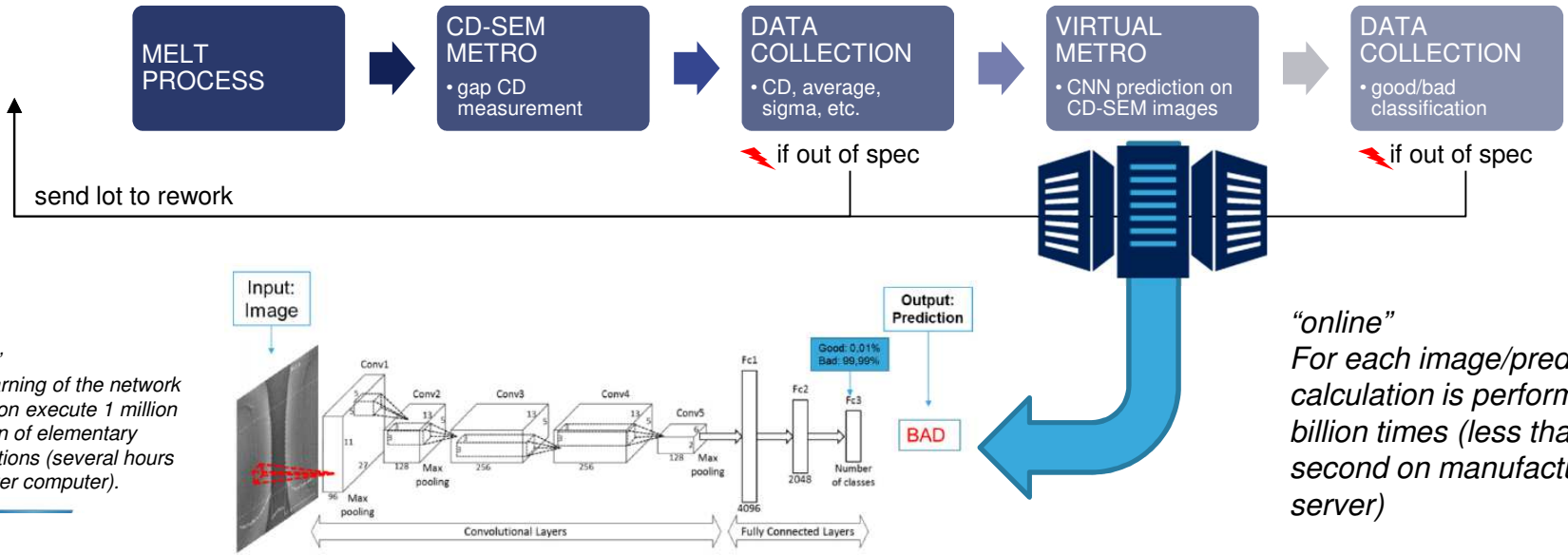
SEMCD image



Get more of what we have already



Synoptic flow of fab automation with active Convolutional neutral Network CNN prediction



"offline"
The learning of the network of neuron execute 1 million of billion of elementary calculations (several hours on power computer).

"online"
For each image/prediction, the calculation is performed 1 billion times (less than one second on manufacturing server)

** J. Ducoté, Proceedings European Mask and lithography Conference (19-20 June 2018, Grenoble, France)*

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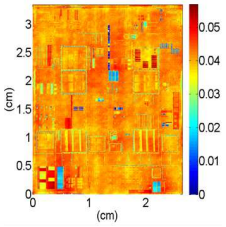
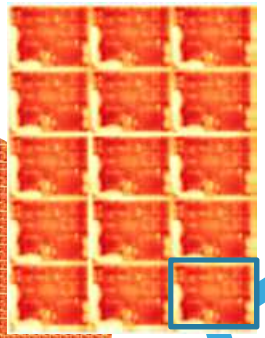
Nanotopography Image

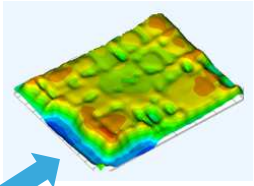


Raw Nanotopography Data
(7M points)

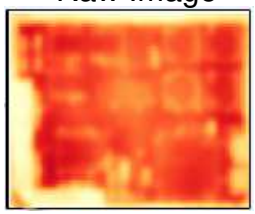
Nanotopography
@ Field level
(2M points)



3D Image representation



Raw Image



Output Parameters:
Average, PV, 3σ

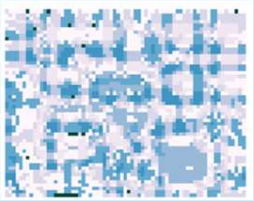
Get more of what we have already

Translate 2D image information in quantitative parameters for enhanced process control

Gradient Map

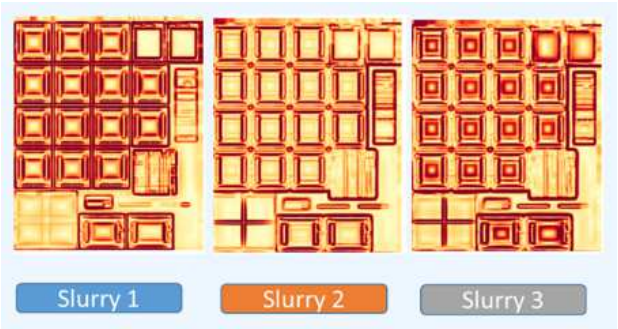
Order 1 Shape

Order 2 Shape

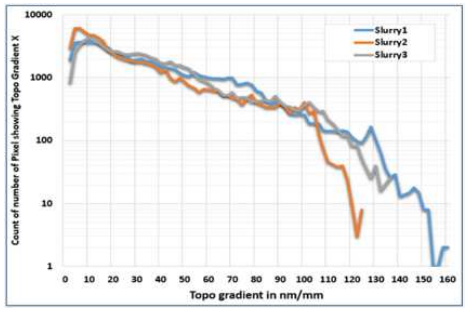


Mathematic treatment of raw data

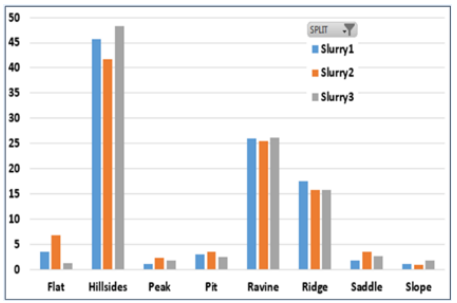
Example: CMP application - slurries selection



Distribution pixel versus gradient



Topography signature versus slurries



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** M. Kessar, Proceedings SPIE Conference (March 2019, USA)*

Conclusion

- Metrology is a pillar of process control and is submitted to key requirements in term of Quality (Accuracy, Capability, Stability…).
- Metrology is a process by its own and therefore submitted to same rules than any other manufacturing process.
- Metrology covers a large variety of technique and requires deep knowledge in Physics, Optics, Material science…→ Synergy with other domains.
- With Big data and HVM, data science analytics will allow future development by treatment of Raw Metrology data or Spectra with low cost of engineering.

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Thank you for attention

Thank you to all ST Crolles contributors

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METROLOGY:

Cost money and Slow you down...

BUT

Allow you to go fast and reach destination safe / in time / everytime

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