The Future

Prof Liam Blunt

In process surface metrology for roll to roll manufacture of printed electronic devices

EPSRC Future Metrology Hub
University of Huddersfield, UK

MetMap

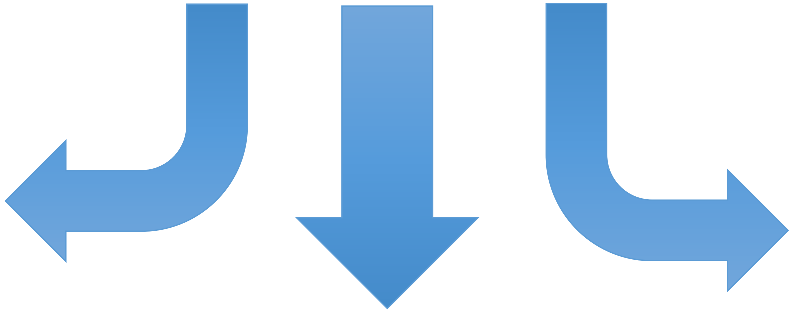
Integrated Metrology for Precision Manufacturing Conference
22 - 23 January 2019, Knowledge Transfer Centre
Advanced Manufacturing Research Centre, Sheffield, UK

High Added Value Manufacture

Manufacturing contributes over $11tr to the global economy[1]

High value manufacturing is the application of leading-edge technical knowledge and expertise to the creation of products, production processes, and associated services which have strong potential to bring sustainable growth and high economic value to developed economies

Specific Technology Drivers

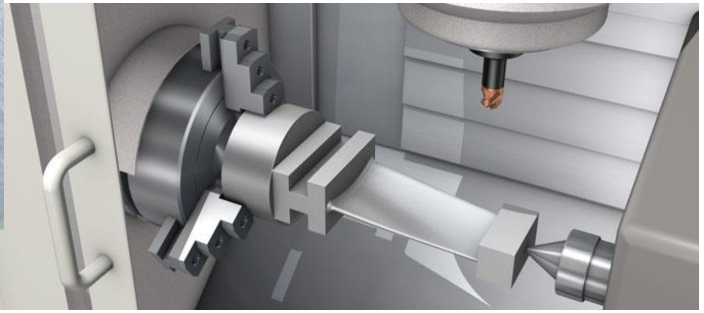


Products are usually high precision

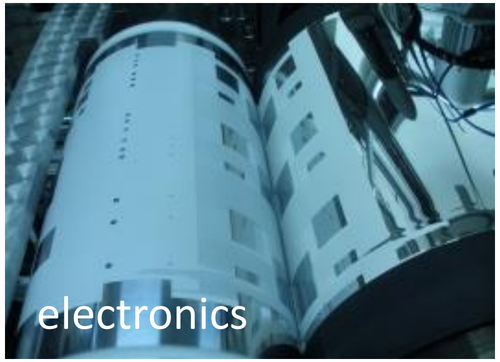
Expensive production facilities

In process metrology *desirable for maintaining quality with fast throughput*

optics



aerospace



electronics

bio tech

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[1] United Nations Statistics Division, United Nations National Accounts Main Aggregates Database, Value added by Country, 2010

Sensor/Instruments for future Manufacturing

- Contained within a machine tool/production line
- Robust in the manufacturing environment
- Achieve the same level of accuracy as lab-based measurement systems

Ideal Measurement systems

- ***Speed**: More than KHz*
- ***Robustness**: Operate in dynamic manufacturing systems*
- ***Sensor/instrument size**: Miniaturisation*
- ***Measurement ratio**: Coverage; high dynamic range*
- ***Accuracy & traceability**: Same level as a standard lab instrument*
- ***Cost**: Relatively inexpensive*

In Process Surface Metrology Challenges

Measurement Speeds matched to process < 500m/min or even kHz,

Ultra fast camera technology and powerful light source power (LUX)

Calibration/verification in situ

Challenging but feasible with clever design

Environmental effects

Reduce effects, use enclosures, cleverer design, fast acquisition, compensation

Too much data to handle!

Try to use only what is really important!

Exemplar case study; Manufacture of printed electronic devices

- Printed Flexible photovoltaic cells
- In-process measurement of – protective *barrier coatings*
- Functional Specificatiom for Barrier Properties
  - Water Vapour Transmission Rate WVTR
- Defect classification and correlation with function
  - Advanced Surface Metrology
- In-process measurement solution………

Nanomend

The Future

Fraunhofer
IVV

NPL
National Physical Laboratory

University of
HUDDERSFIELD

Flisom
Flexible Solar Modules

IBS
Precision Engineering

cpi ...the future inspired

TNO innovation for life

rethink.
storaenso

KITE
INNOVATION EUROPE

TAMPERE UNIVERSITY OF TECHNOLOGY

ISOVOLTAIC

ISRA
VISION

Open your mind. LUT.
Lappeenranta University of Technology

iscent

EU project: To develop technologies that are able to detect and correct micro and nano-scale defects in Roll to Roll produced Photo Voltaic films and polymer coated fibre products, without slowing production speed.

Roll to Roll Manufacture?

Roll-to-roll processing (R2R), is the process of creating electronic devices on a roll of flexible polymer sheet or metal foil. It refers to any process of applying coatings, printing and joining foils.

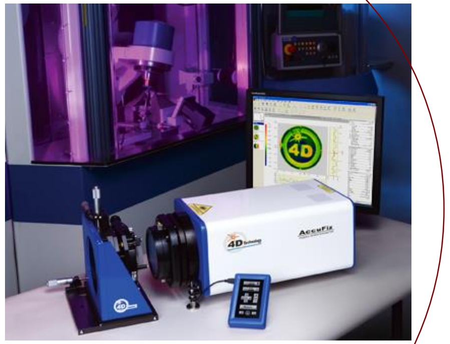
The process starts with a rolls of flexible material and involves re reeling after processing to create an output roll. **Metrology and Cleaning/Repair** needs to integrate with film processing e.g. post ALD atomic layer deposition of Al_2O_3(40nm)

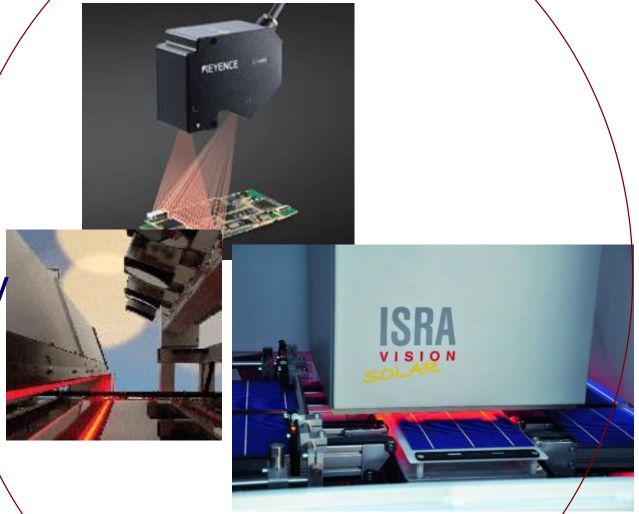
Conventional Measurement Solutions

A number solutions have derived from lab based instrument manufacturers or are camera based looking for specific targeted features

Robust conventional instrumentation (expensive, slow!)

Fast acquisition!~30µsec (very expensive)



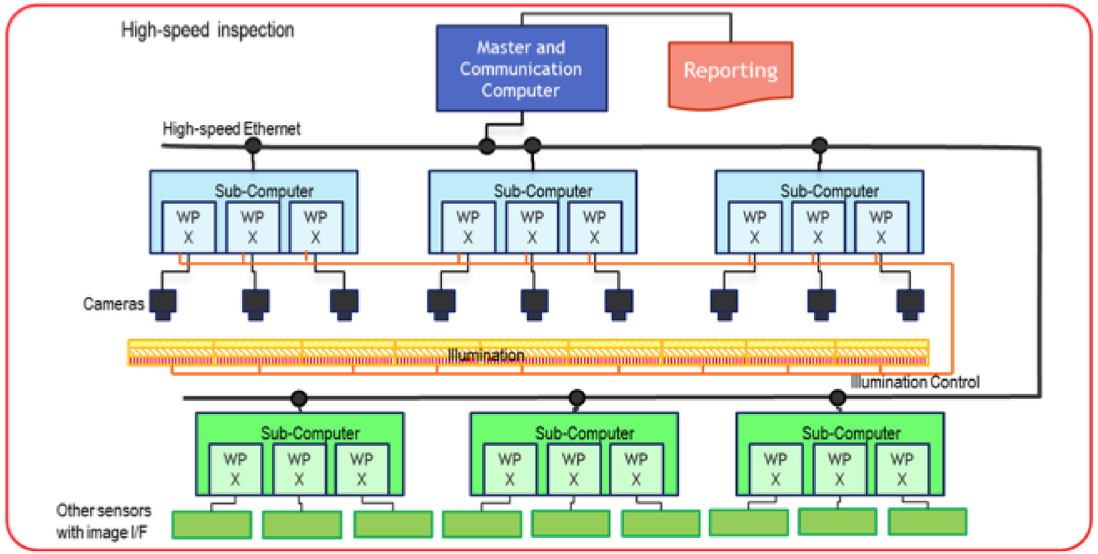


High res, high speed cameras (less expensive low resolution)

Roll2 Roll Surface Measurement

Need multiple or moving sensors to give roll coverage **BUT** :-

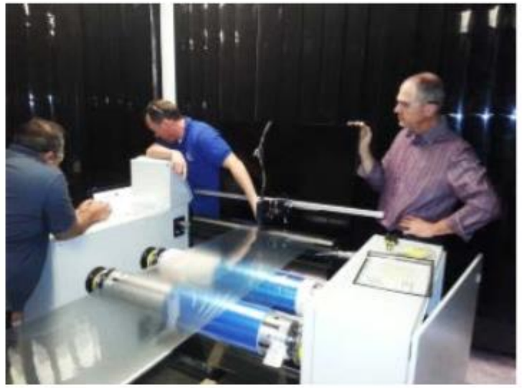
- Sensors need registering in a single coordinate system.
- Sensors need overall control
- Targeted on specific surface defects/characteristics
- Individual sensors relatively inexpensive
- Generate **masses** of redundant data multiple TB/min



Courtesy of ISRA Vision

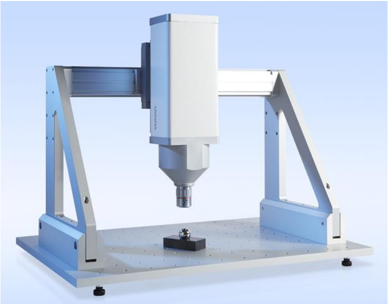
New Generation Solutions Arising

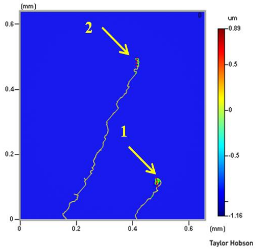
FlexCam 4D Technologies, USA

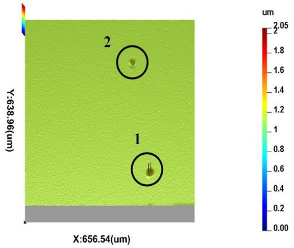


Vitriflex presentation from AIMCAL conference 2014.

WSI (IBSPE,Huddersfield NL/UK)







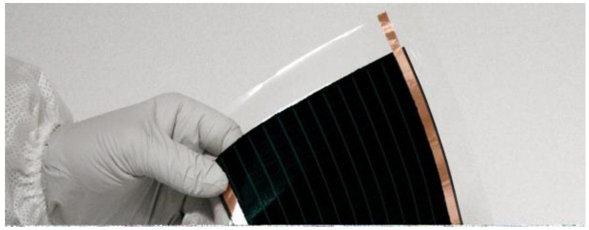
NanoMend

Photovoltaics, Rigid and Flexible

Flexible

Photovoltics

(CIGS)inexpensive/m^2

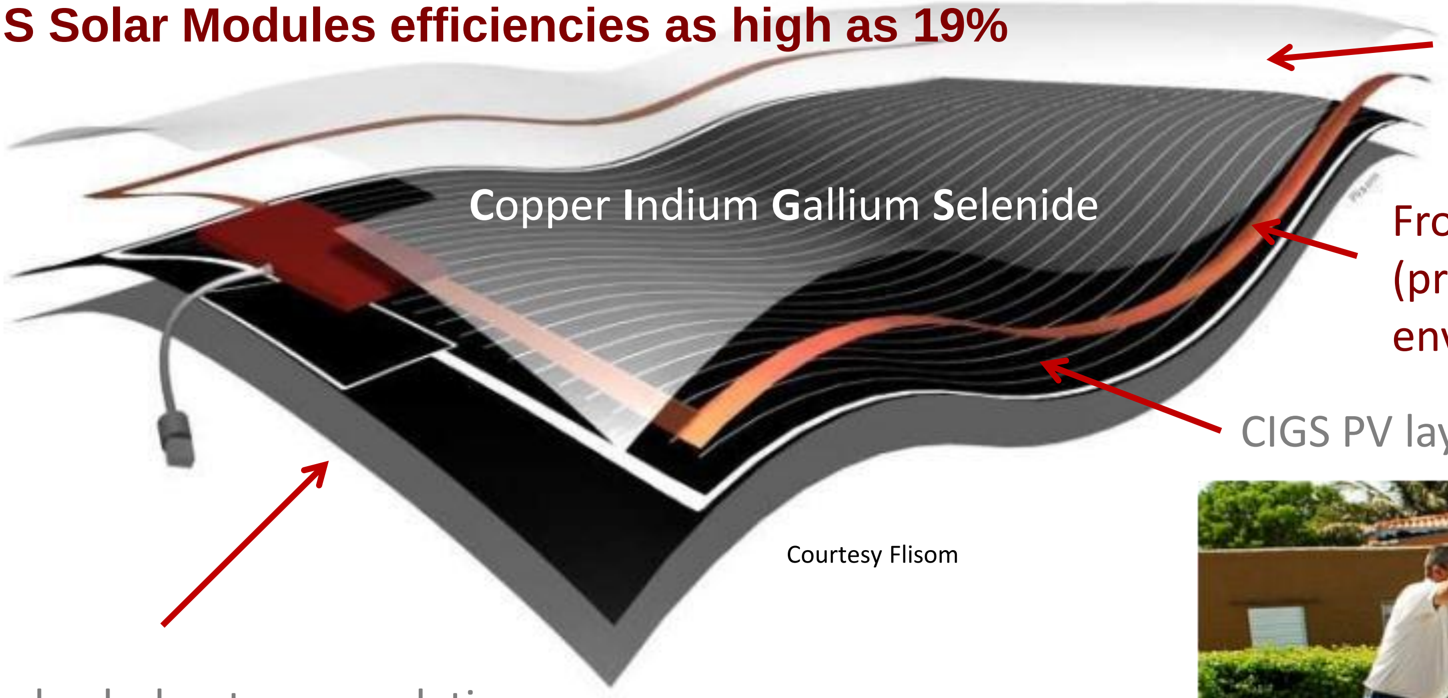


Rigid Si based Photo Voltaics (expensive/m^2)

(crystalline or amorphous Si)

Flexible Solar Modules, CIGS; basic layer groupings

- **Highly suitable for Building Integration**
- **Latest CIGS Solar Modules efficiencies as high as 19%**



light management

Copper Indium Gallium Selenide

Front encapsulation/barrier layers (protects cells from water vapour in environment)

CIGS PV layers

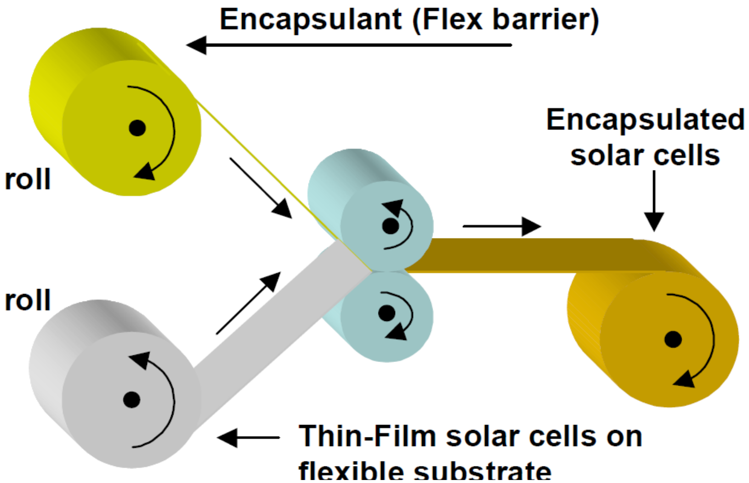
back sheet encapsulation

Courtesy Flisom

Front sheer barrier/encapsulation layer is the most expensive element per m^2.

Flexible PV Modules

- Flexible PV modules are manufactured using roll to roll (R2R) technology.
- BUT these modules require a flexible barrier material to prevent water vapour ingress.



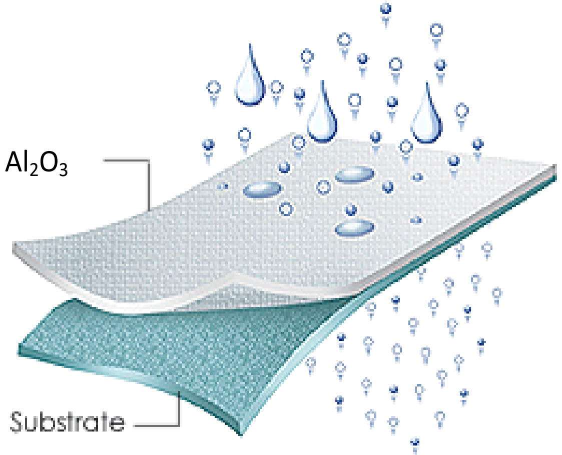
Encapsulant (Flex barrier)

roll

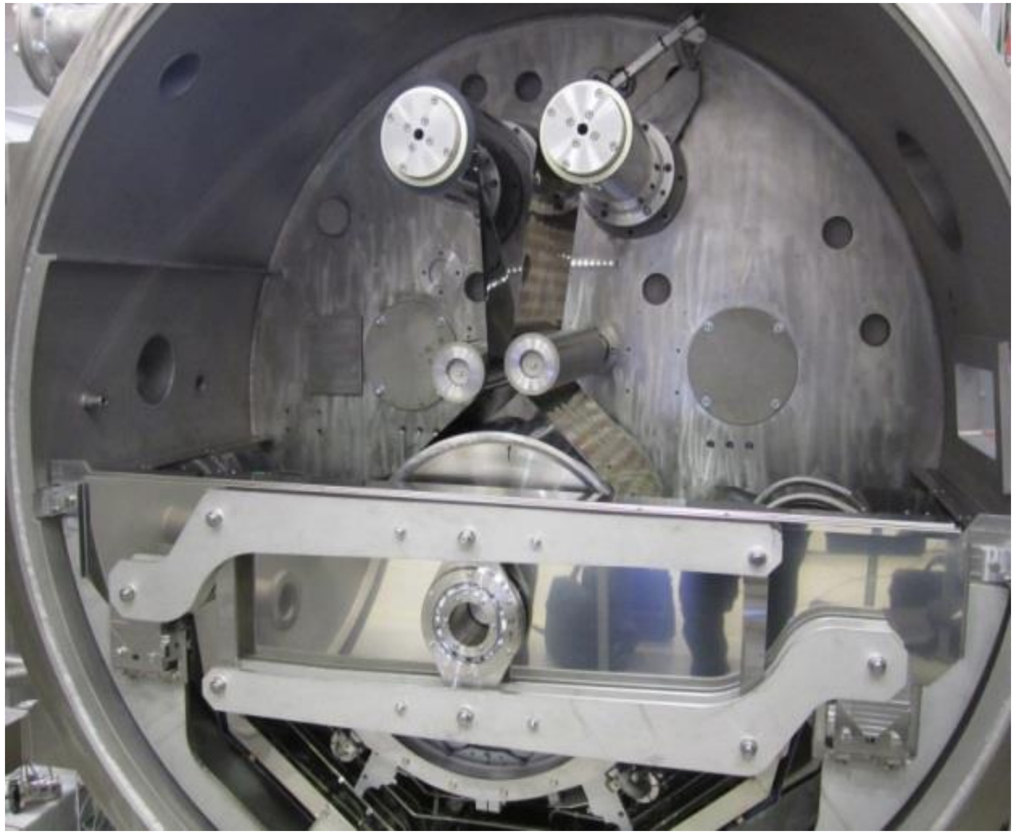
Encapsulated solar cells

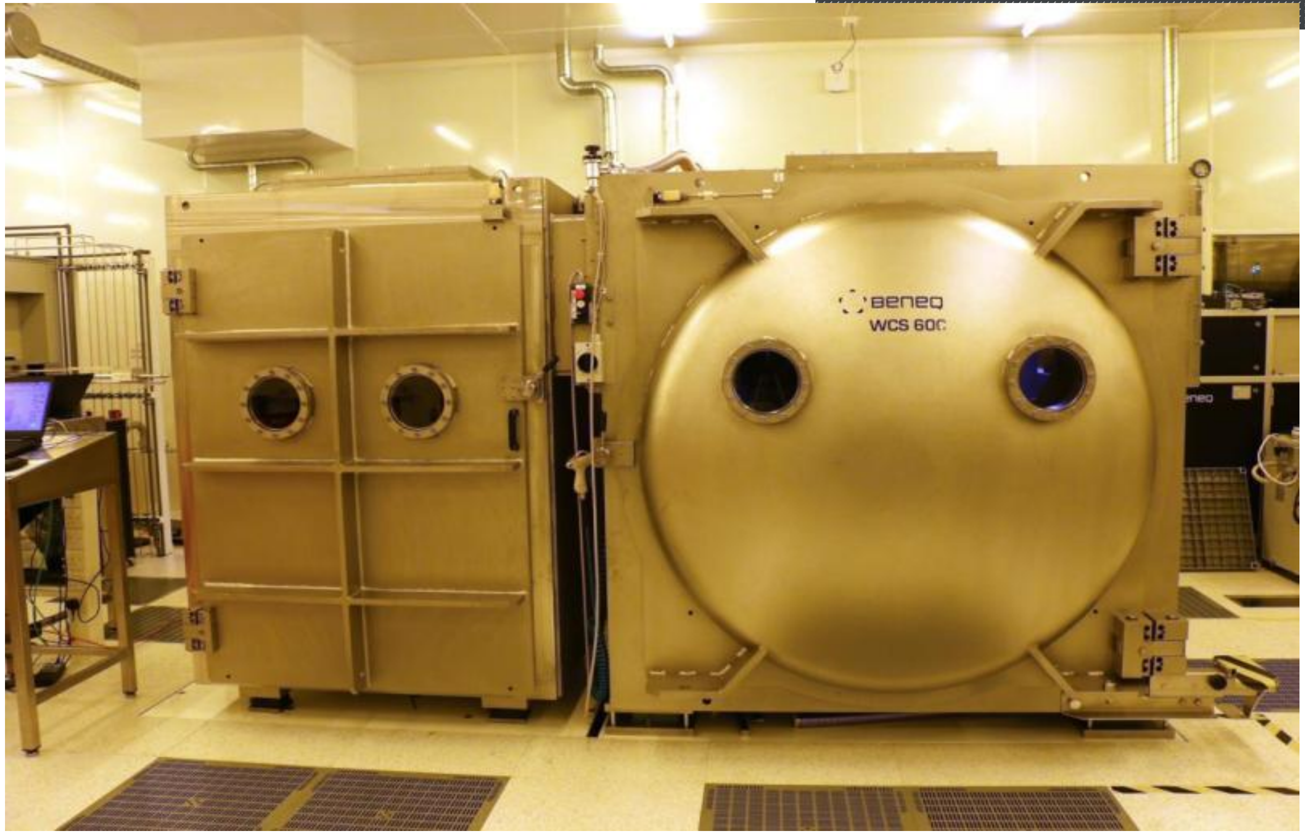
roll

Thin-Film solar cells on flexible substrate



Roll2Roll Atomic Layer Deposition for Barrier Layers, Single Al_2O_3 layer 40nm thick

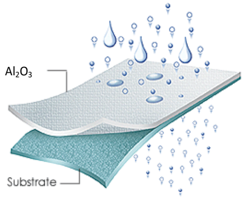




World first demonstration in NanoMend

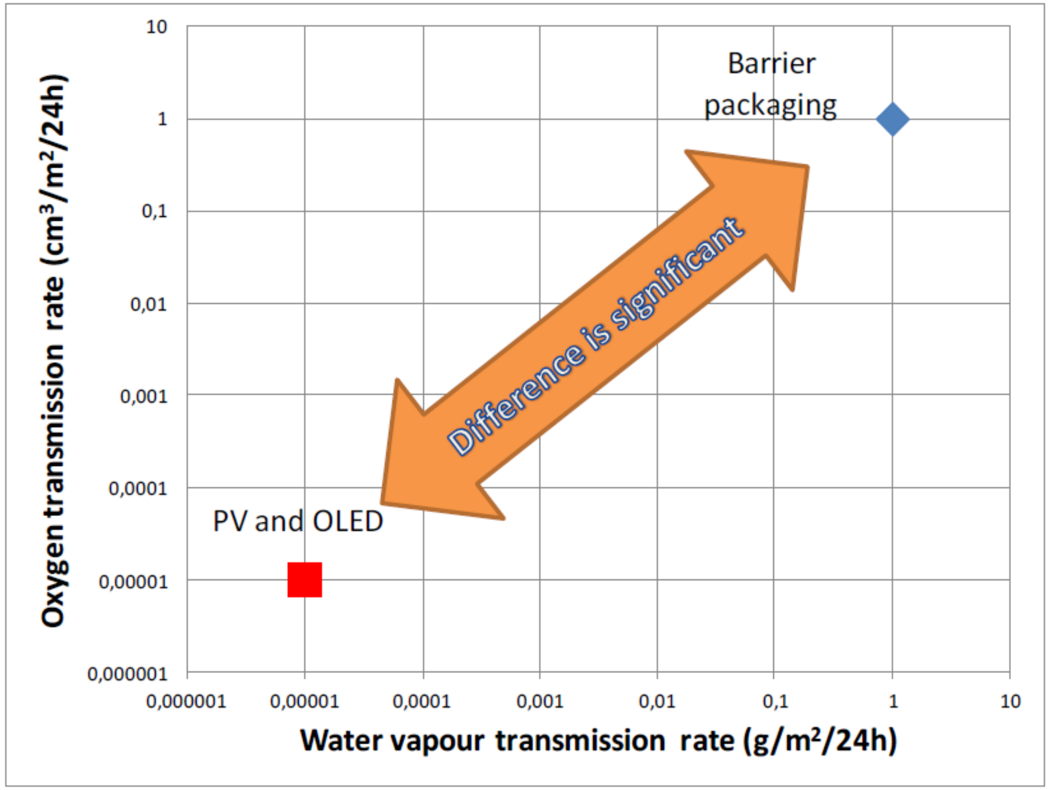
PV Encapsulation Requirements

The Future



- 20 years lifetime needs WVTR @ <10^{-4} g/m^2/day.
- Current single barrier layer capable of ~10^{-1} g/m^2/day.
- A robust, improved and transparent flexible encapsulation method for flexible PV modules is needed.

WVTR= Water Vapour Transmission Rate



IEC61646-2, "British Standards Institution," in Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type approval ed: BSI, 2008, pp. 5-36.

Manufacture of single flexible barrier layer for PV’s

Requires; efficient in-process metrology based on understanding and modeling the function of the the surface to be measured;

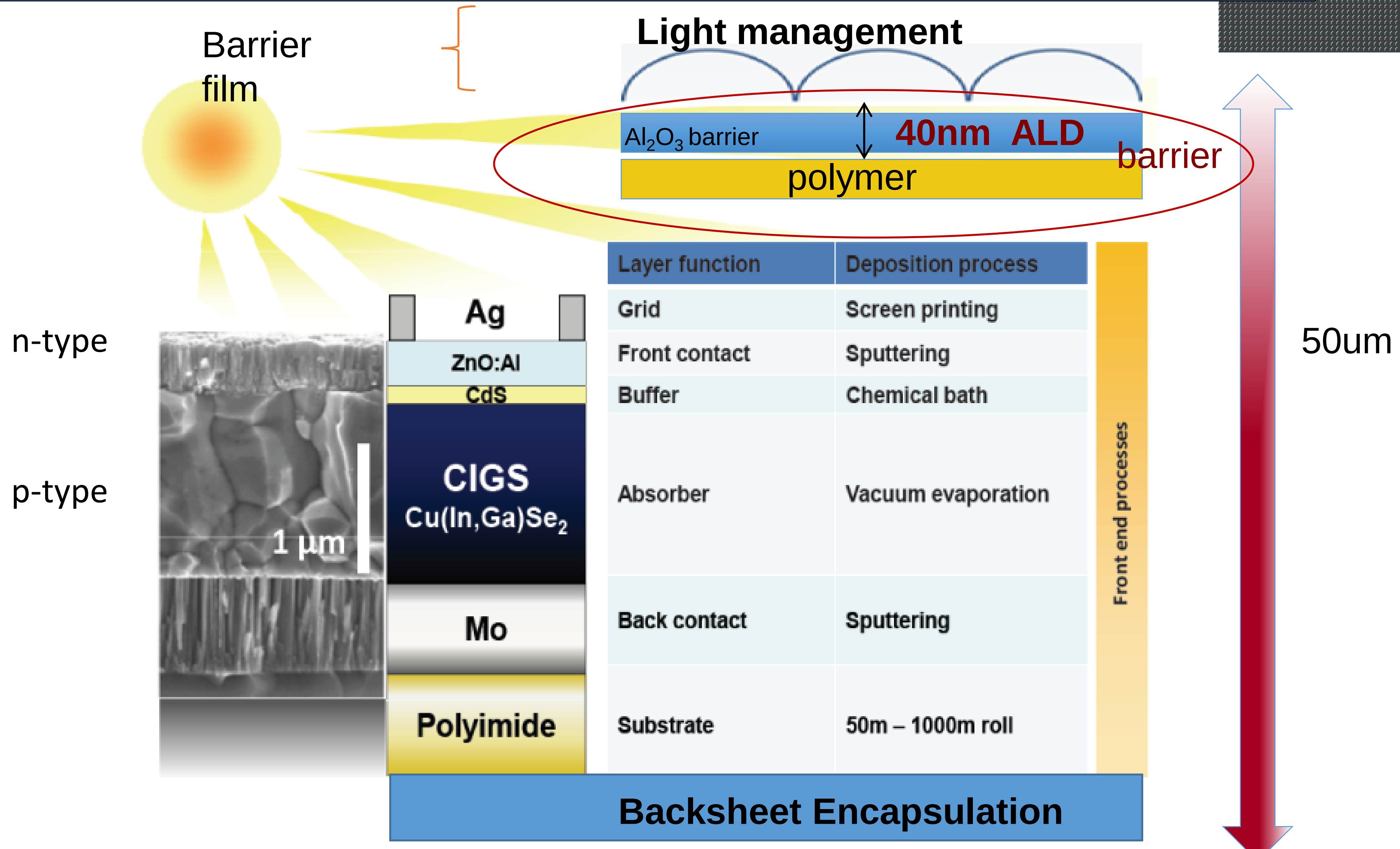
Investigation and correlation of **W**ater **V**apour **T**ransmission **R**ates (WVTR) through defects in barrier substrate as applied to flexible PV’s.

Facilitates in process metrology in R2R manufacture

- Measured and catalogue defects
- Measuring and modeling which defects are most functionally significant
- Tailoring the process measurement

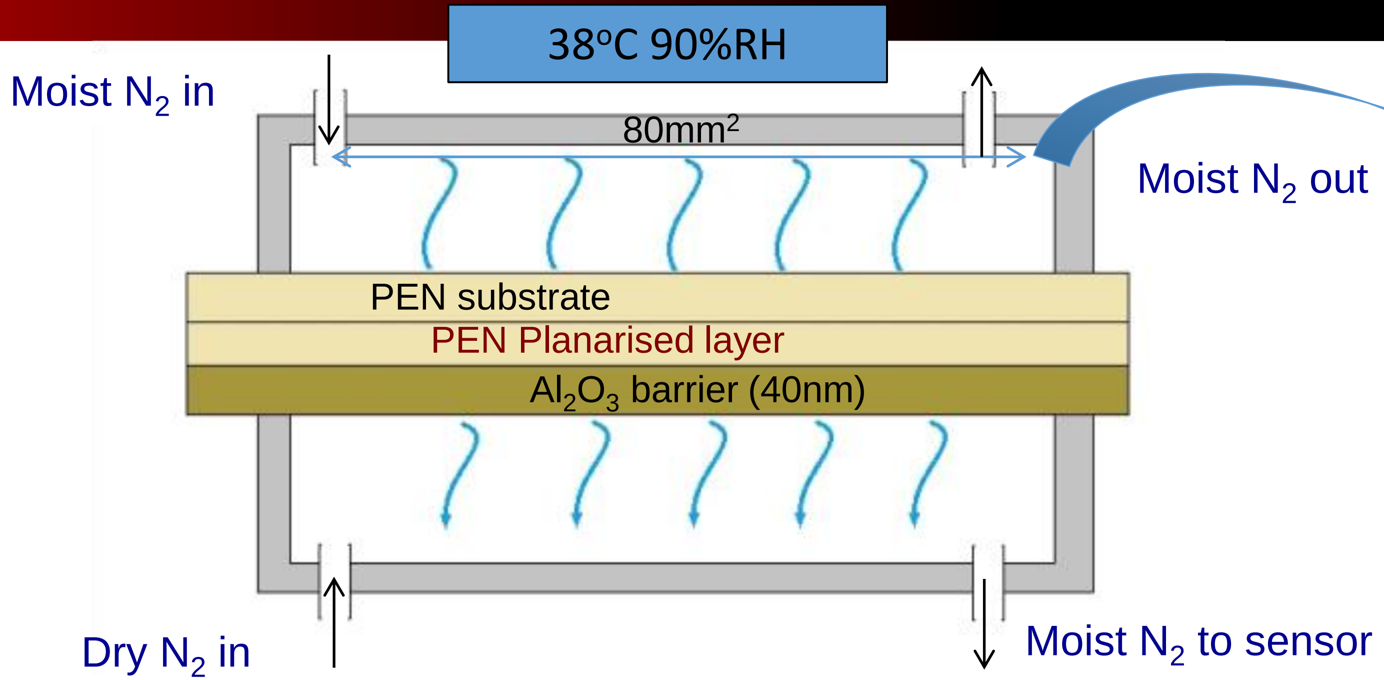
Functional elements of flexible photovoltaic cells

Al_2O_3 barrier layer produced by atomic layer deposition ALD (290 cycles)



Layer function	Deposition process
Grid	Screen printing
Front contact	Sputtering
Buffer	Chemical bath
Absorber	Vacuum evaporation
Back contact	Sputtering
Substrate	50m – 1000m roll

Water Vapour Transmission



38°C 90%RH

Moist N_2 in

$80mm^2$

Moist N_2 out

PEN substrate

PEN Planarised layer

Al_2O_3 barrier (40nm)

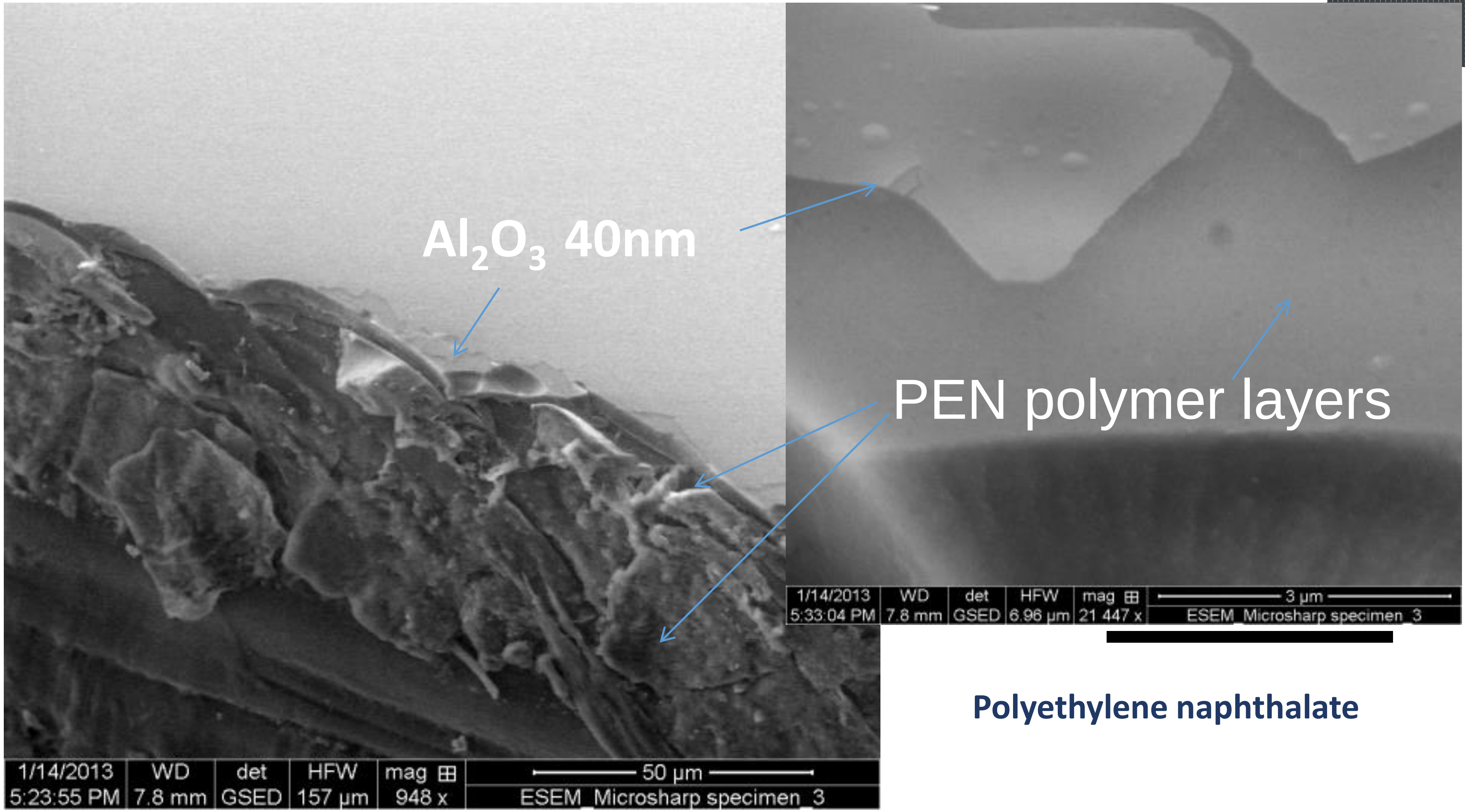
Dry N_2 in

Moist N_2 to sensor

Typical result set

Sample	Water vapour transmission rate ($g/m^2/day$)	Stabalisation time (days)
2701	$1.1x10^{-3}$	11
2702	$1.3x10^{-3}$	11
2705	***$4.1x10^{-3}$***	***5***
2706	$2.0x10^{-3}$	5

Al_2O_3 by Atomic Layer Deposition (ALD) 40nm thickness (ESEM)



[redacted]

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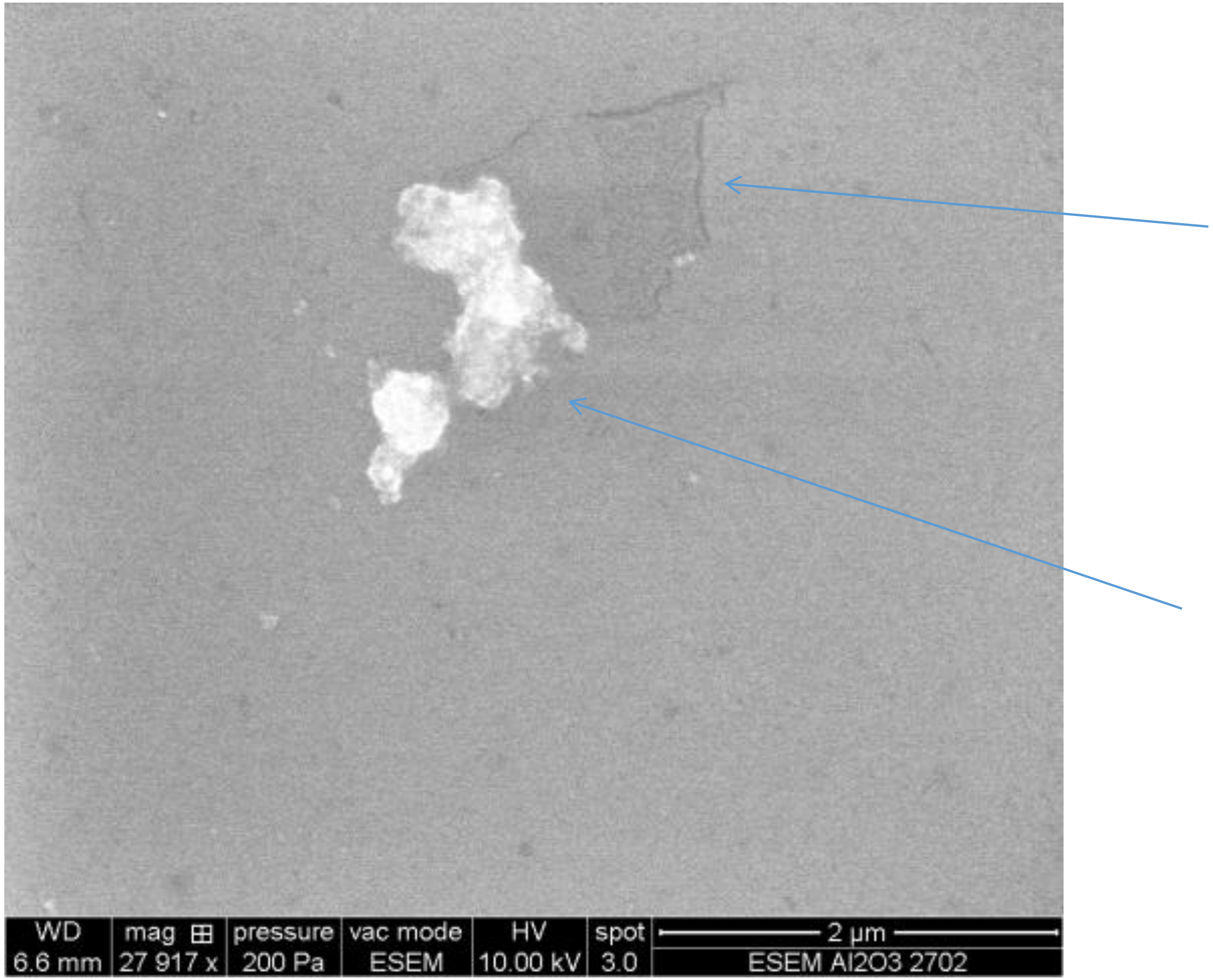
Polyethylene naphthalate

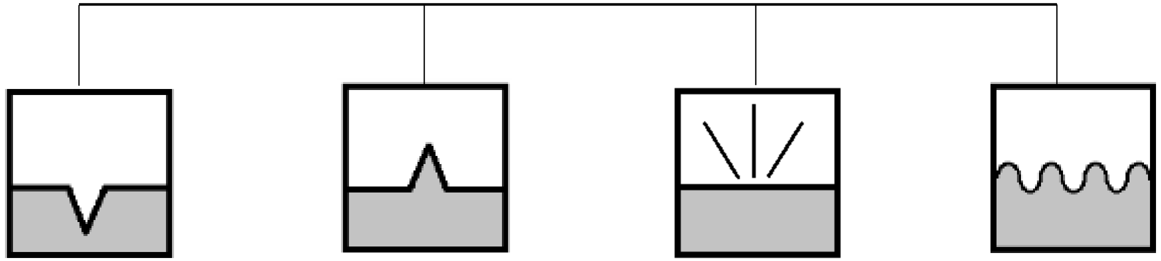
Defects: Particles and Cracks



Cracking

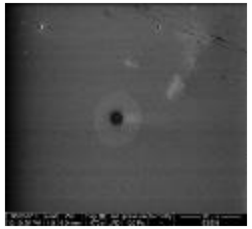
Particulate debris

Defect Classification System



Inwardly directed defect

- Pin holes
- Holes
- Cracks/scratches

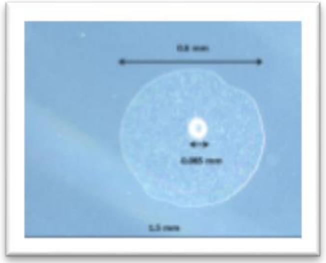


Outwardly directed defect

- Particulate debris

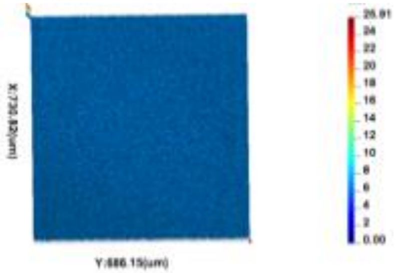
Differing appearance to surroundings

- Delamination

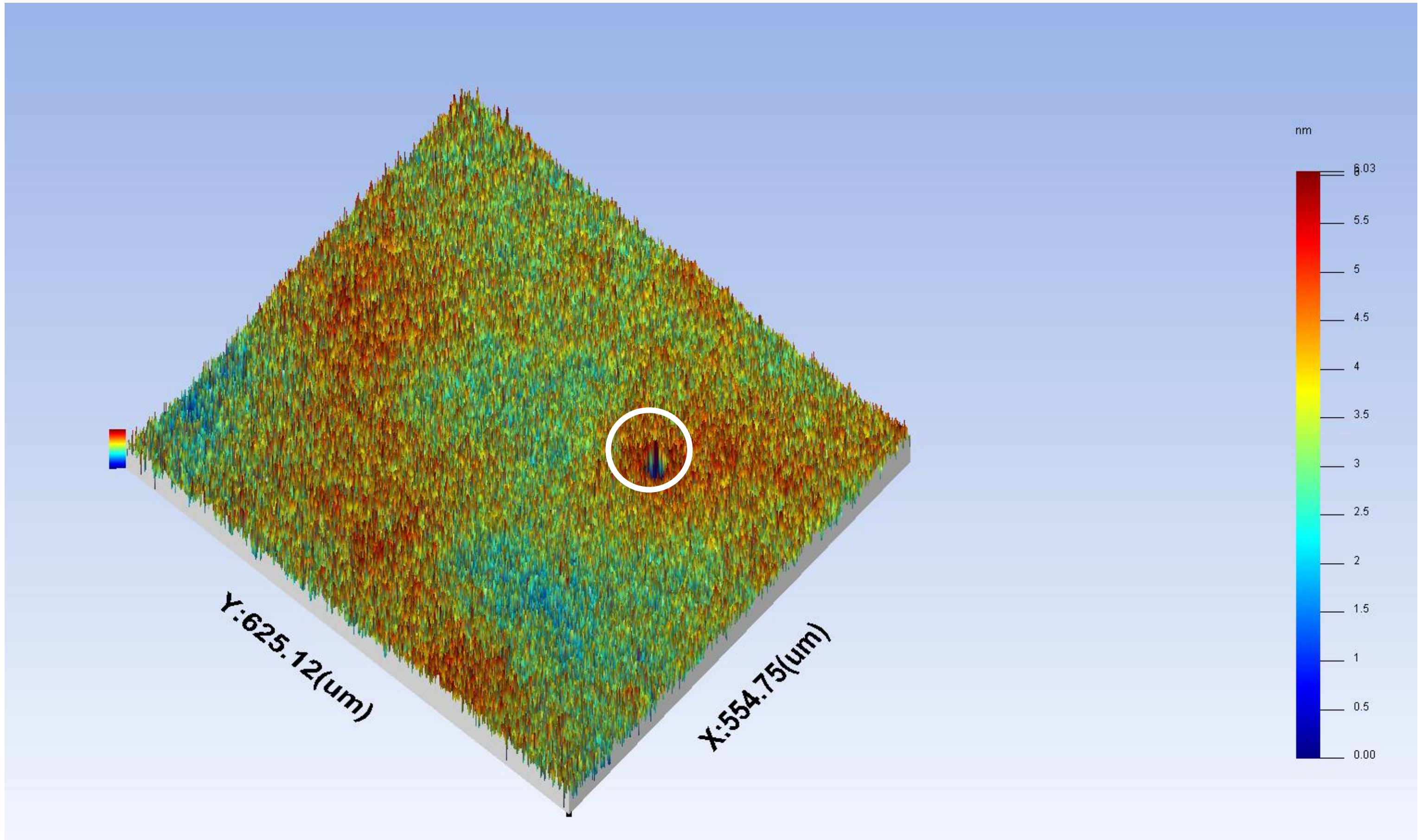


Surface relief

- High roughness



Surface measurement of barrier coating Optical Interferometer



Surface Texture Standards

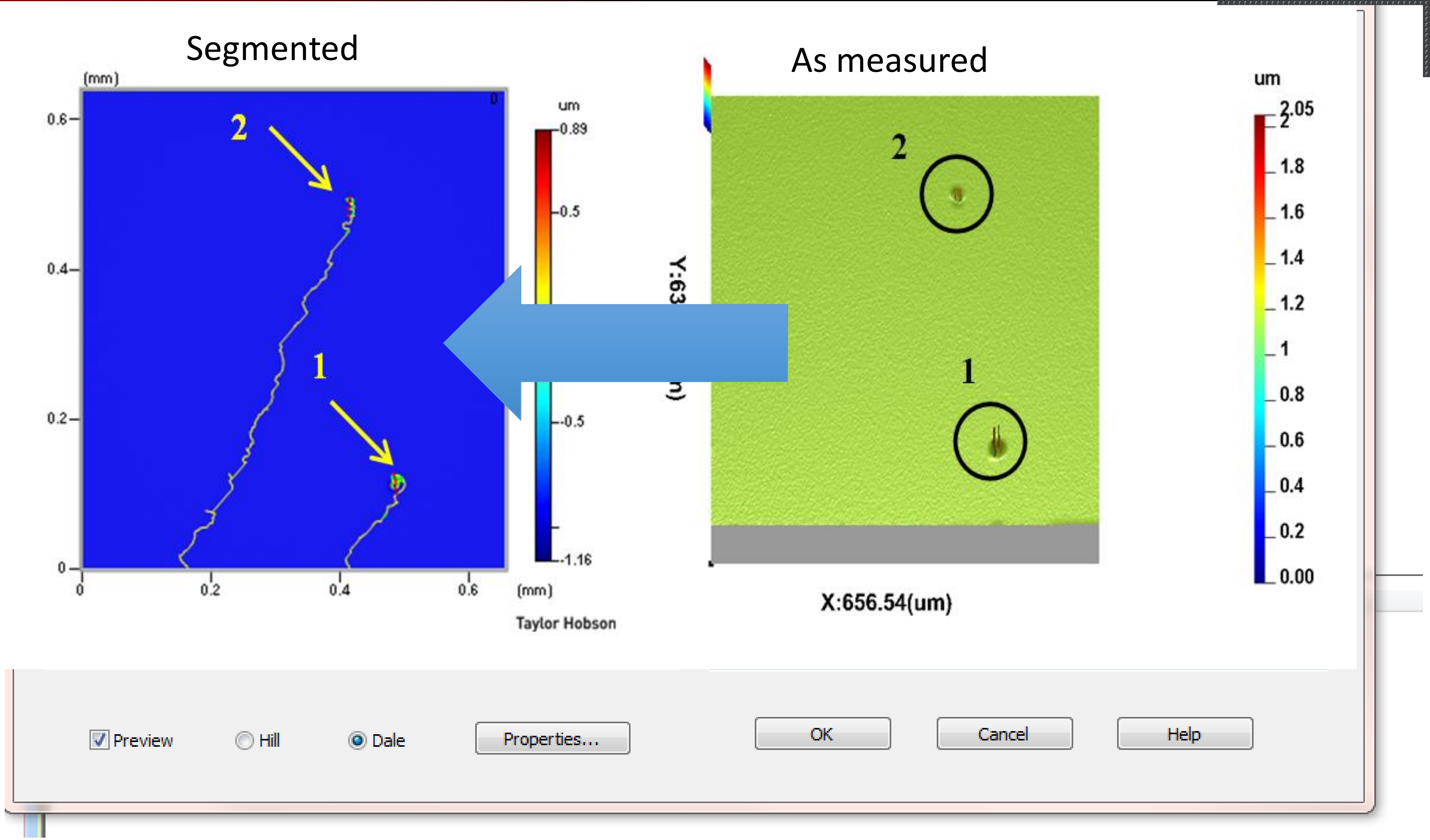
Roughness Parameters (ISO 25178)

Roughness Parameter	Physical meaning
Sa/um	Average areal surface roughness height
Sq/um	Areal root means square roughness height
Ssk	Skewness of surface height distribution (-ve = valley dominated)
Spd/mm^2	Density of Peaks
Sdd/mm^2	Density of dales (pits)
Ssd/mm^2	Density of significant defects Ssd = Sdd + Spd

Feature parameters

- 15% Area coverage ~ on each substrate, 3500 measurements!
- coherence correlation interferometry

Feature Parameter Software ISO 28178

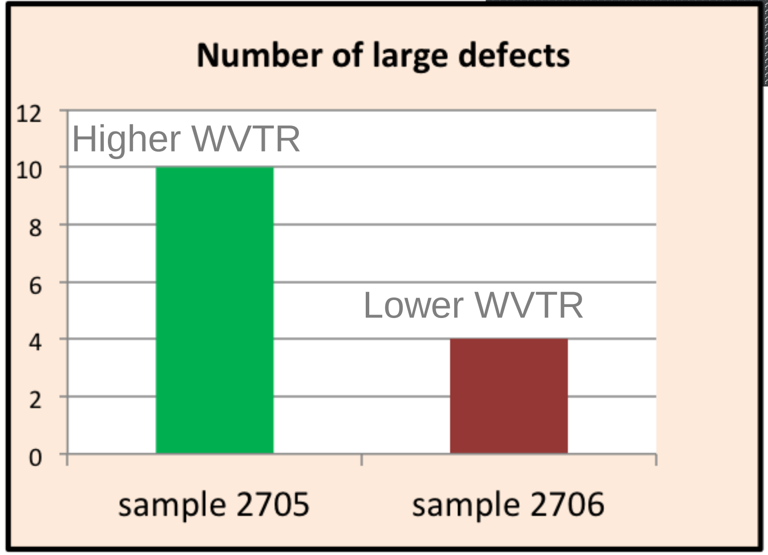


☑ Preview ○ Hill ● Dale

H, Muhamedsalih,, M. Elrawemi, L. Blunt, , X, Lan and H. Martin, (2015) *A computerised data handling procedure for defect detection and analysis for large area substrates manufactured by roll-to-roll process*. In: Laser Metrology and Machine Performance XI, LAMDAMAP 2015. EUSPEN, Huddersfield, UK,

Defect Characterisation Trial :- Feature parameters ISO 25178

Only significant defects (6σ (Sq=σ=0.8nm) height & width > 5um) (i.e. area and height pruning/segmentation) considered significant.

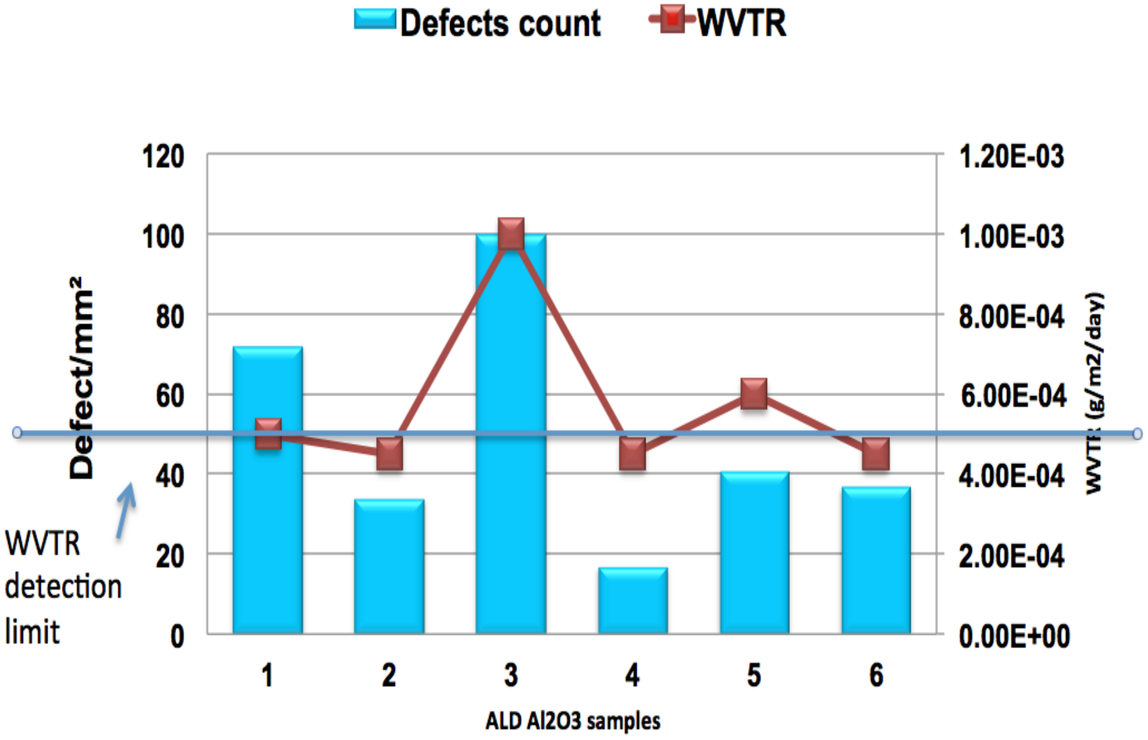


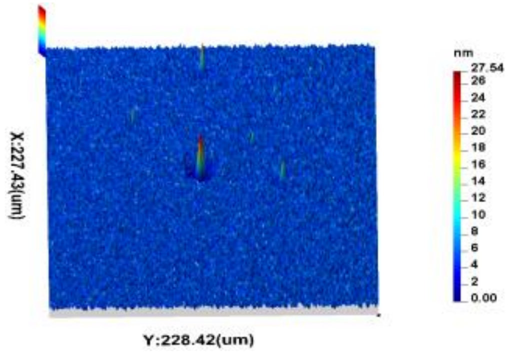
- Sample 2705 has 10 large defects;5 dales+ 5 peaks
- Sample 2706 has 4 large defects 2 dales+2 peaks

- **The presence of small numbers of larger defects seems to correlate with WVTR (no clear distinction between peaks and dales)**
- **Exercise repeated on a several sample sets with same results**

Functional Correlation Defects cf WVTR Trial

The Future





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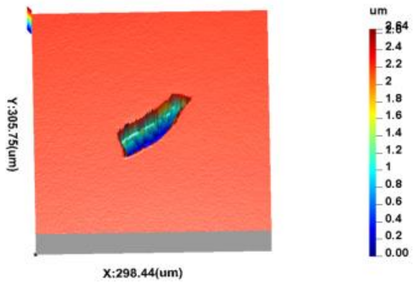
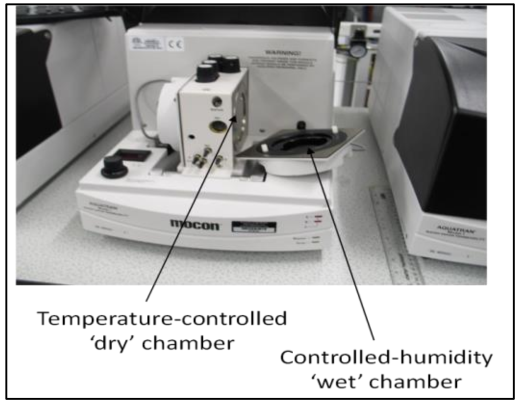


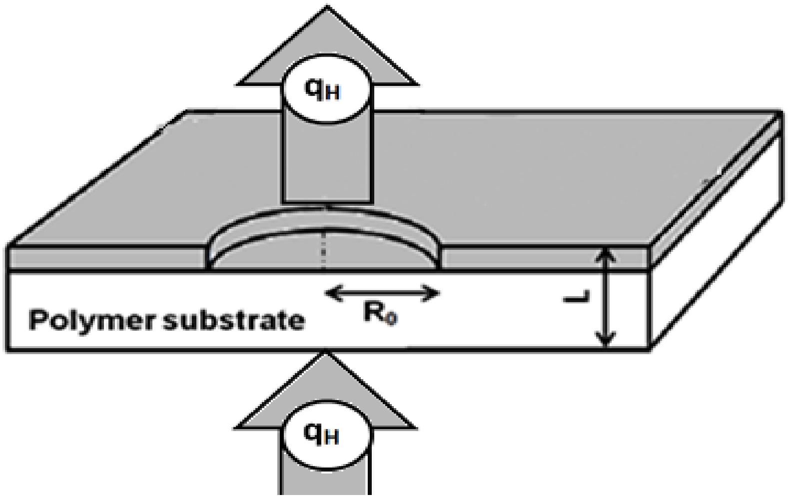


Modeling the WVTR

Can a model approach confirm the experimental WVTR results?

From Da Silva Sobrinho: amount of permeant traversing the polymer and through the hole per unit time, Q

$$Q = \frac{q_H}{t} = \frac{\pi R_0^2 \, D \varnothing}{L}$$



Where R_0 is the hole radius, D is the diffusion coefficient of the film (cm^2/s), Ø is the water vapour concentration (g/cm^3) and L is the combined film thickness, q_H amount of the water vapour, leaving the barrier film

$$WVTR = \frac{Q}{A} \qquad (g / m^2 / day)$$

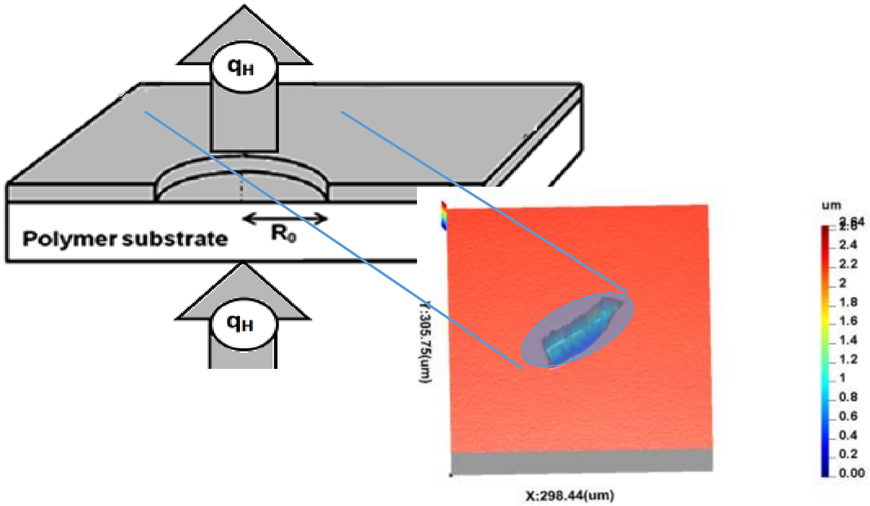
Where; Q is the amount of the water vapour passing through a film at the defect location where the thickness is L and area A during time t being driven by a partial pressure differential P across the film

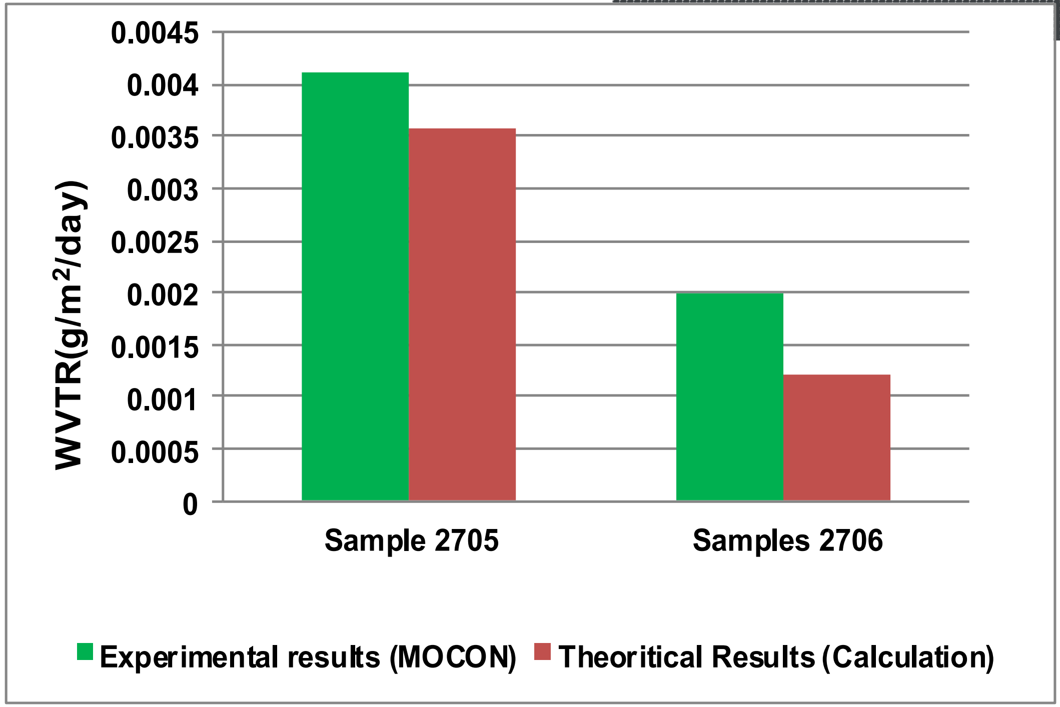
For many defects (real case) then

$$WVTR = \sum_{0}^{N} \left(\frac{Q}{A}\right) \mathrm{N}$$

M. Elrawemi, L. Blunt, L. Fleming, D. Bird, D. Robbins, F. Sweeney *"Modelling water vapor permeability through atomic layer deposition coated photovoltaic barrier defects"*, Thin Solid Film, 570A. pp. 101-106.DOI: 10.1016/j.tsf.2014.08.042, 2014

Modeling the WVTR





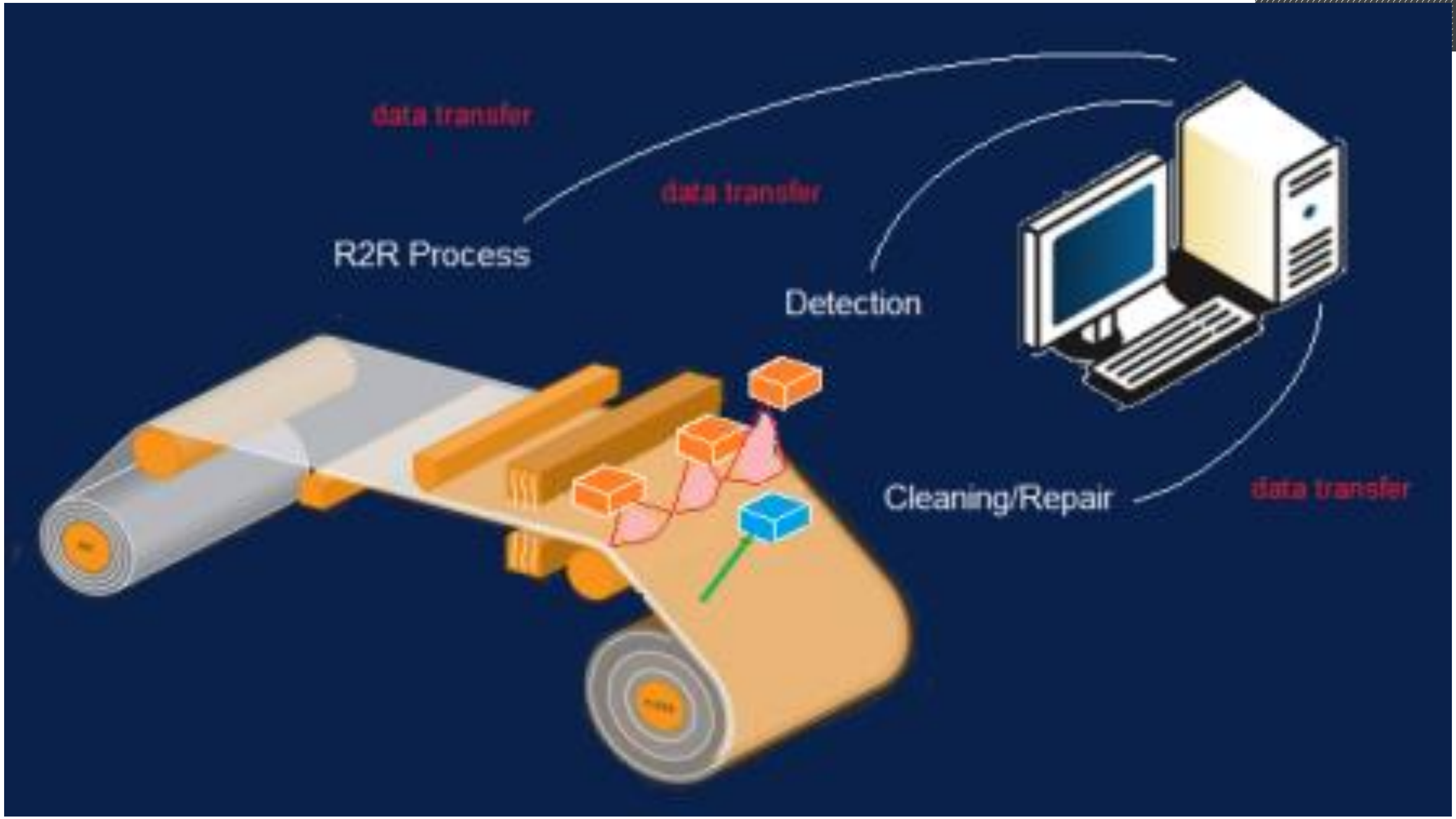
For many defects (real case) then

$$WVTR = \sum_{0}^{N} \left(\frac{Q}{A}\right) N$$

Using surface area of defects calculated from the surface maps give a good correlation

Concentrate on measuring functionally significant defects! < 3um diameter

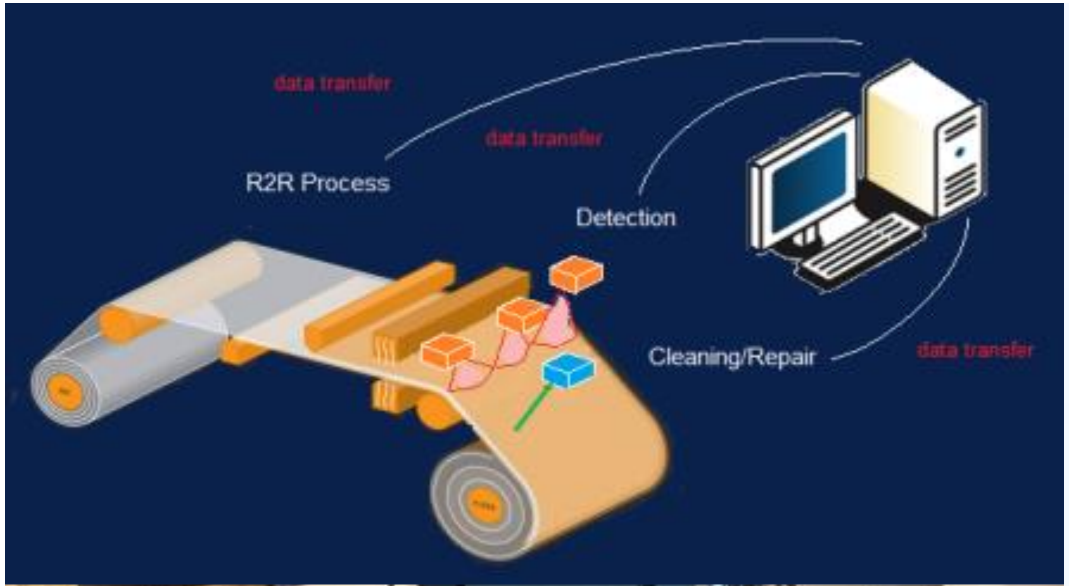
In-process Metrology :– Proof of Concept

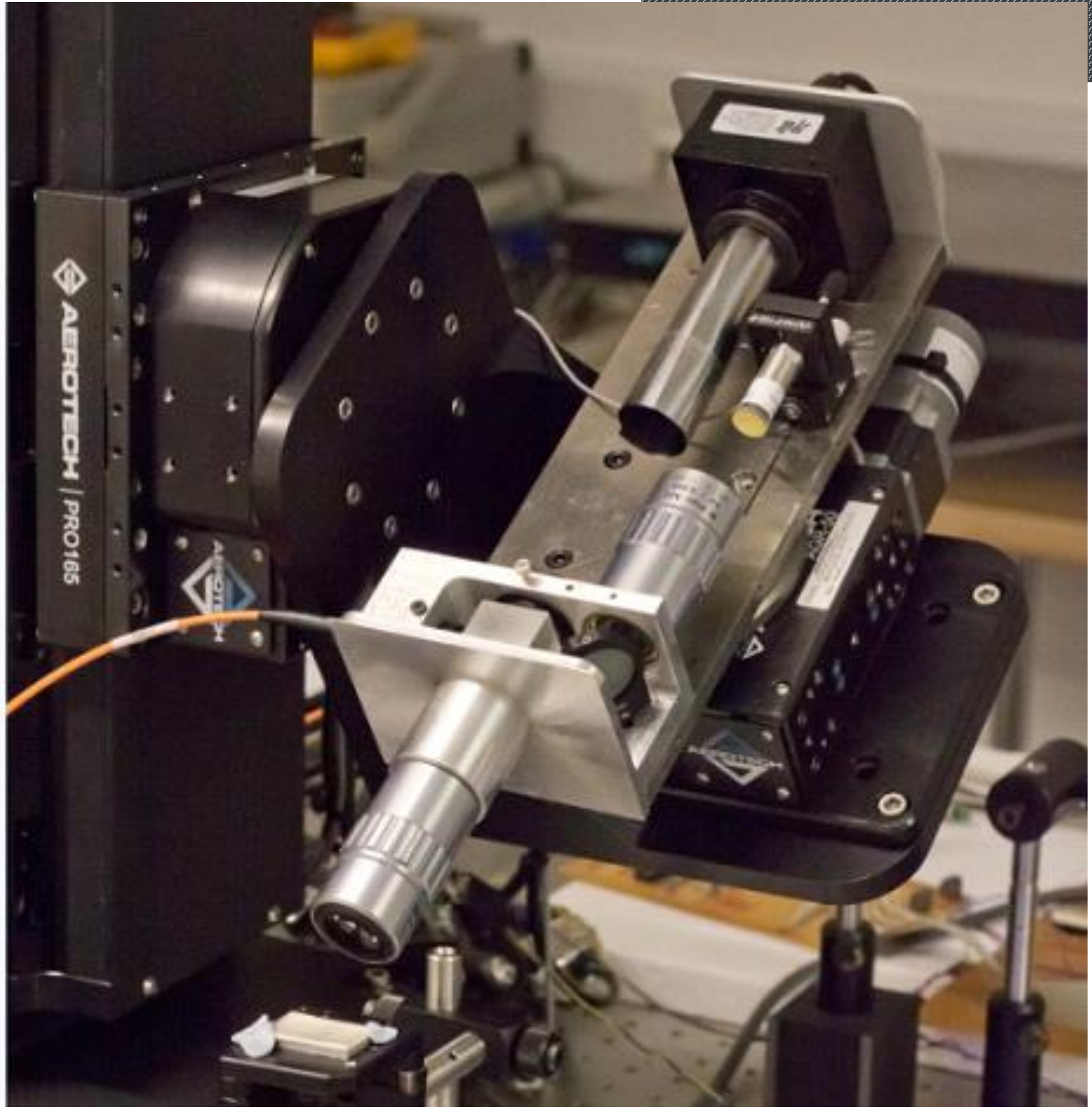


In-process Metrology:- Requirements

- Non Contact
- Fast acquisition ≤ 0.5 sec
- DYNAMIC BETTER
- Robust to environmental vibrations
- Substrate vertical position control
- Auto-focus of optics
- On line calibration
- Massive amounts of data!! (1 strip 900Mb)

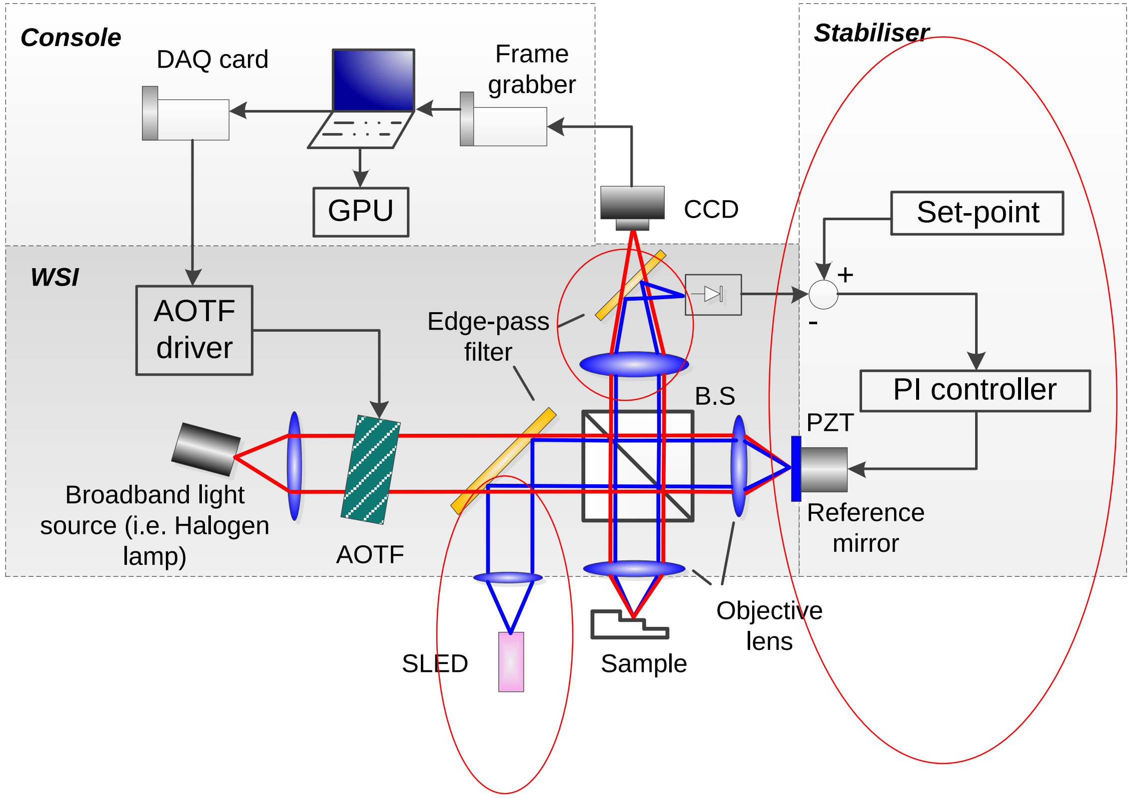
In Process Systems;
Wavelength Scanning Interferometry, WSI





Wavelength Scanning Interferometer

Static Measurement < 2secs



- Varying the wavelength of the incident light using AOTF (530-680nm) 1s acquisition (Acousto-Optic Tunable Filters)
- Dual path system (IR and visible) measurement allows for compensation of environmental vibrations
- GPU and CUDA processing of interferograms

Muhamedsalih, H., Jiang, X. and Gao, F. (2013) 'Accelerated surface measurement using wavelength scanning interferometer with compensation of environmental noise' Procedia Engineering: 12th CIRP Procedia Journal on Computer Aided Tolerancing, 10, pp. 70-76.

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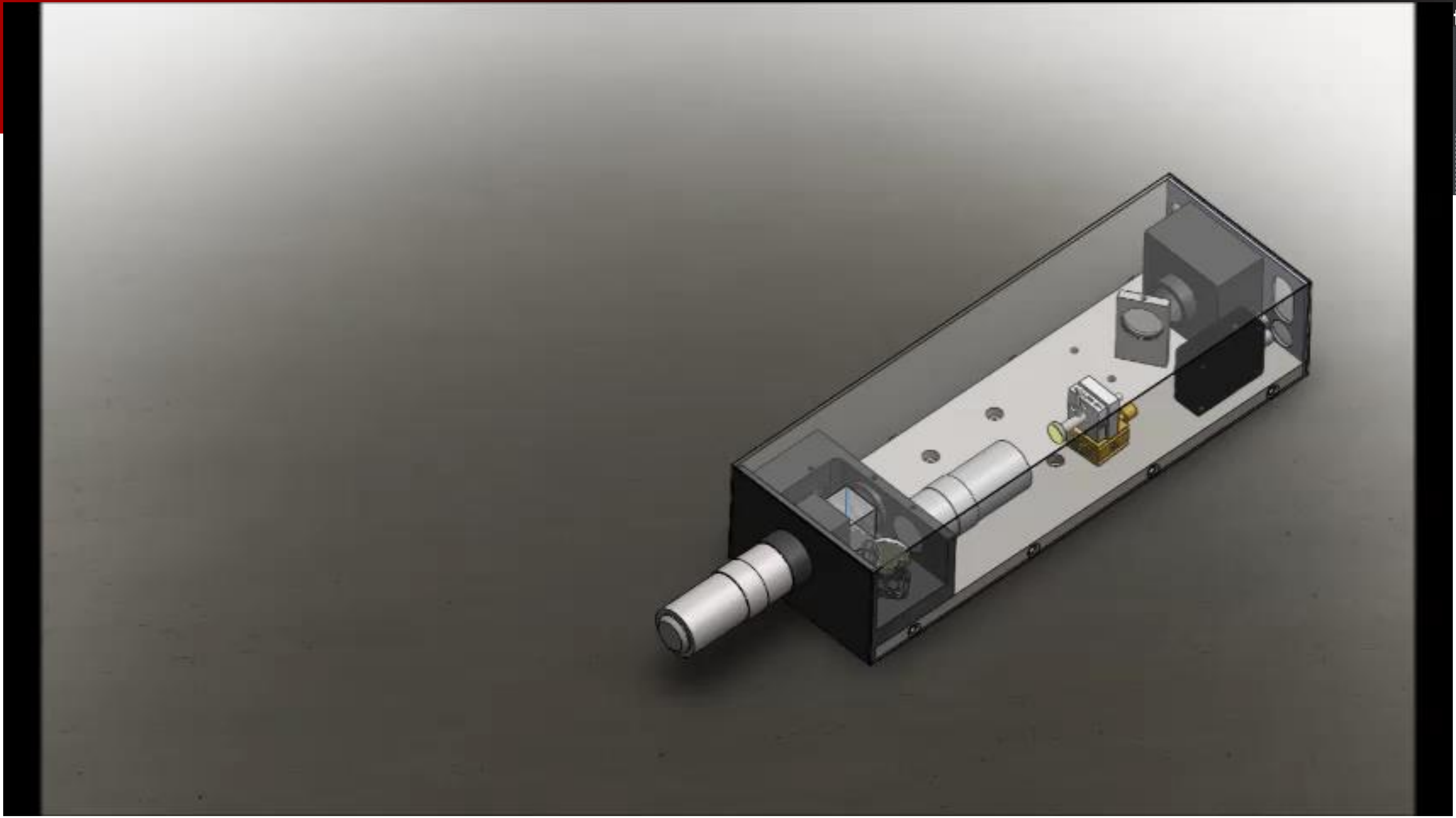
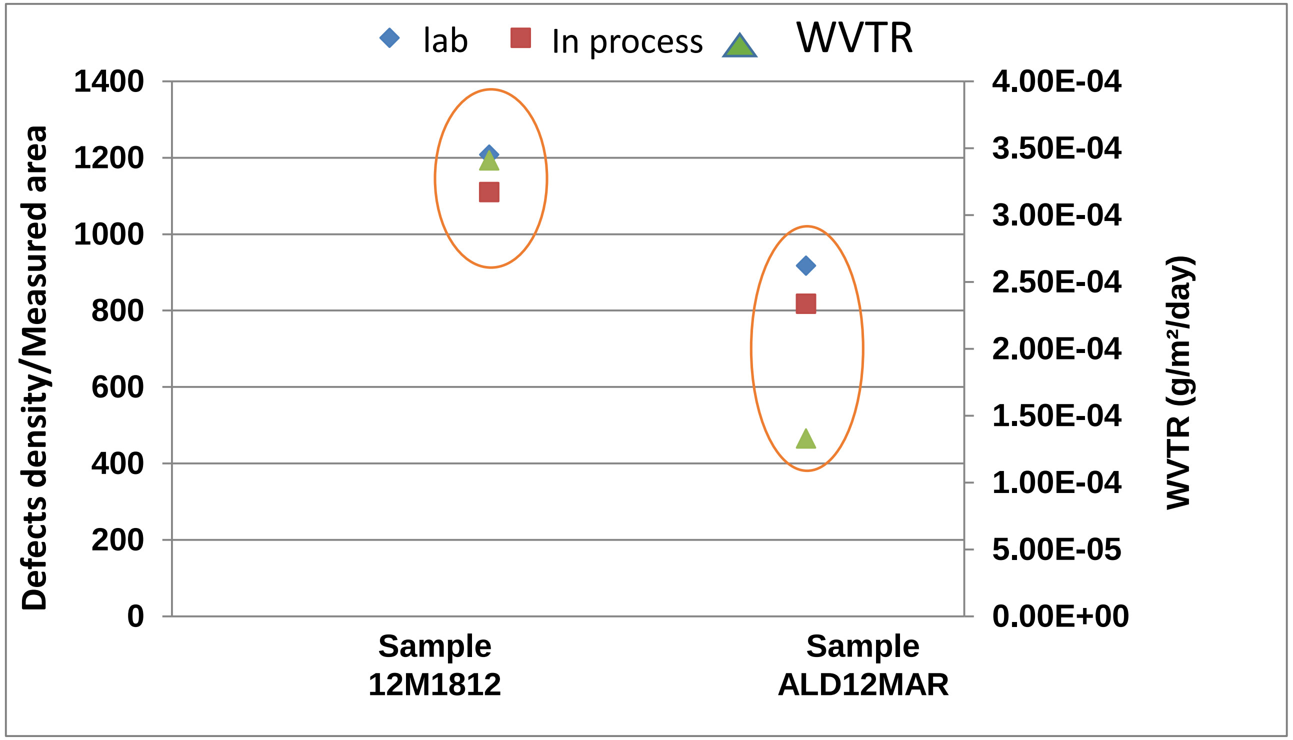


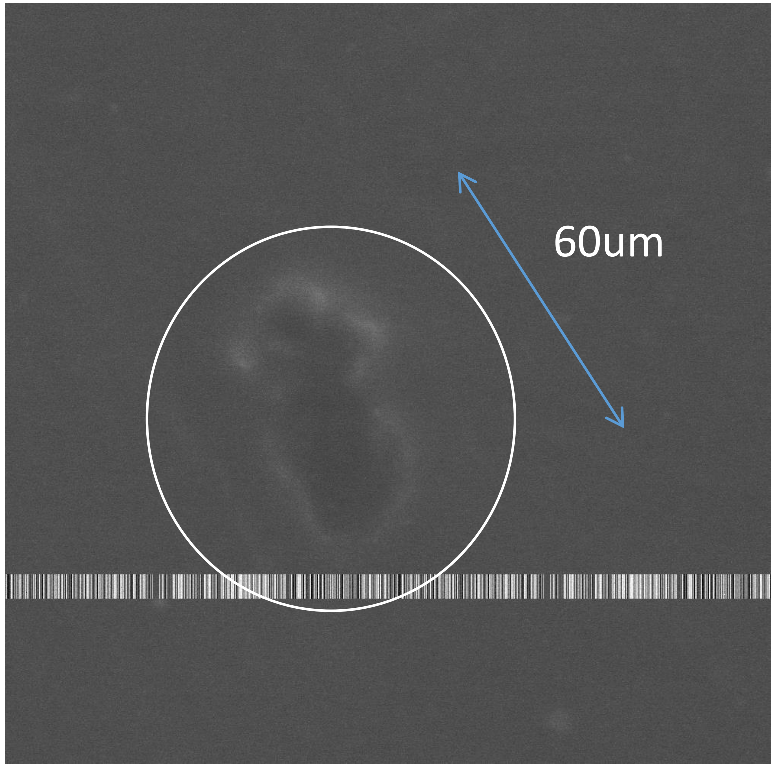
Defects density (2 techniques) vs. WVTR (Trial 3)



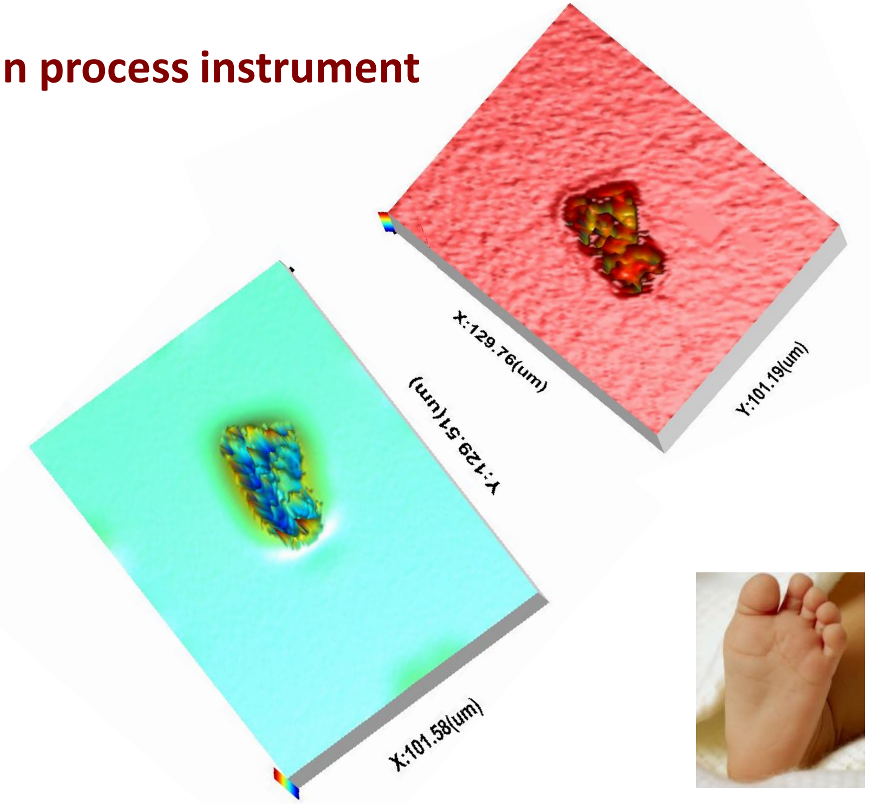
The analysis of the results appears to indicate that the sample with higher density of defects (> 3 µm lateral spacing) exhibits inferior barrier properties. Clear difference in density values for two techniques

Comparative Measurements “baby foot”

ESEM



in process instrument



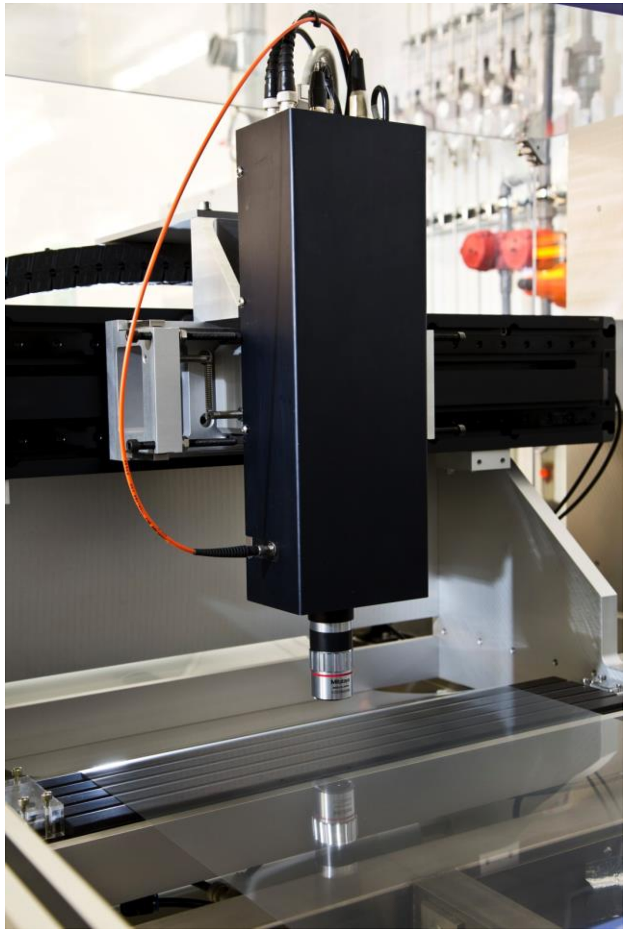
Lab based instrument

Test platform for web inspection of R2R ALD barrier film *(stones)*

The Future

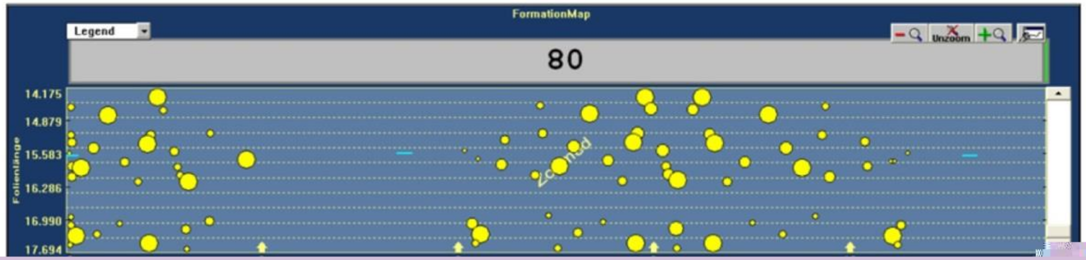
CPI- UK Catapult, Centre for Process Innovation

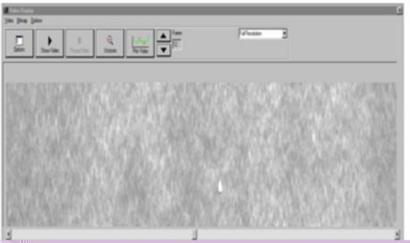
- Roll-to-roll web cleaning platform (CPI)
- Up to 500mm web-width spooling capability (CPI)
- “Substrate holding” system (IBSPE)
- In situ calibration artefact (NPL)



M. Elrawemi, L. Blunt, L. Fleming, F Sweeney, D Robbins, D Bird, “*Metrology of Al_2O_3 Barrier Film for Flexible CIGS Solar Cells*” Int. Jour. of Energy Optimization and Engineering, 4(4), 46-60, October-December 2015

Required Analysis for implementation: Running defect map (mortar)

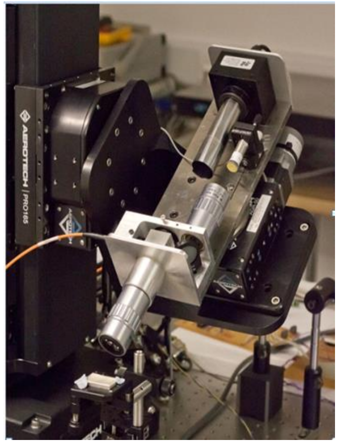




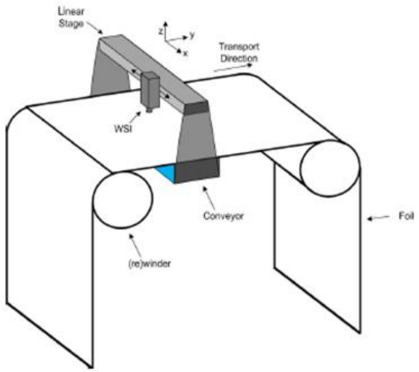
Map and collate defect data for production control or defining areas of substrate rejection

Courtesy of ISRA Vision

WSI development - evolution during the project

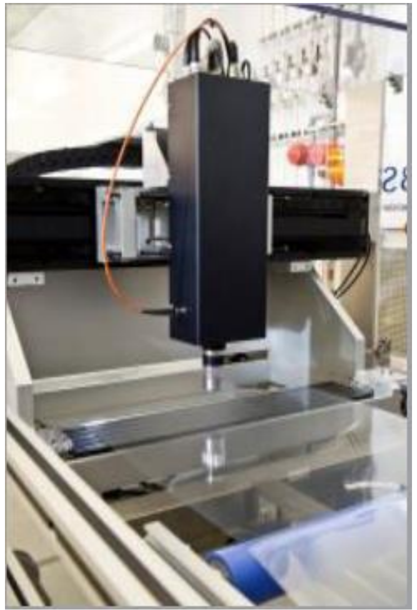


Lab-based system at Hud

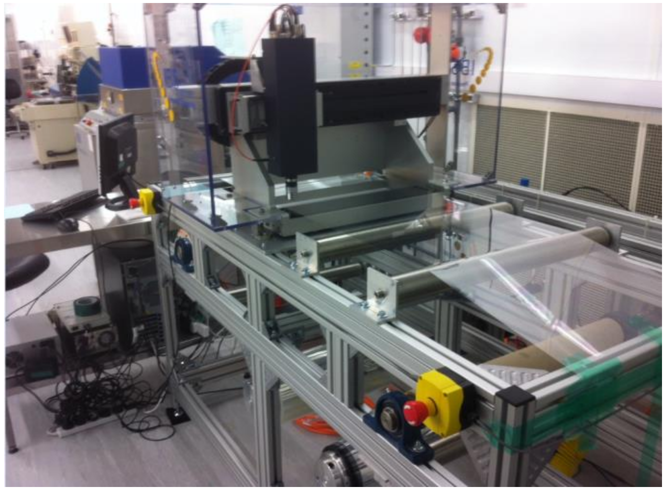


IBSPE development for web hander

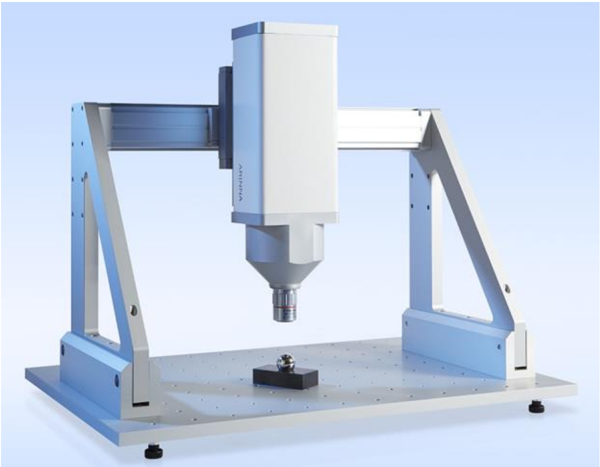
Proof of concept system at CPI

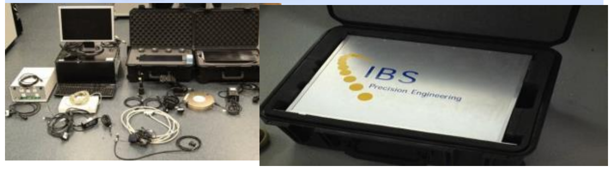


Development of improved web winder at CPI with calibration in line (NPL)



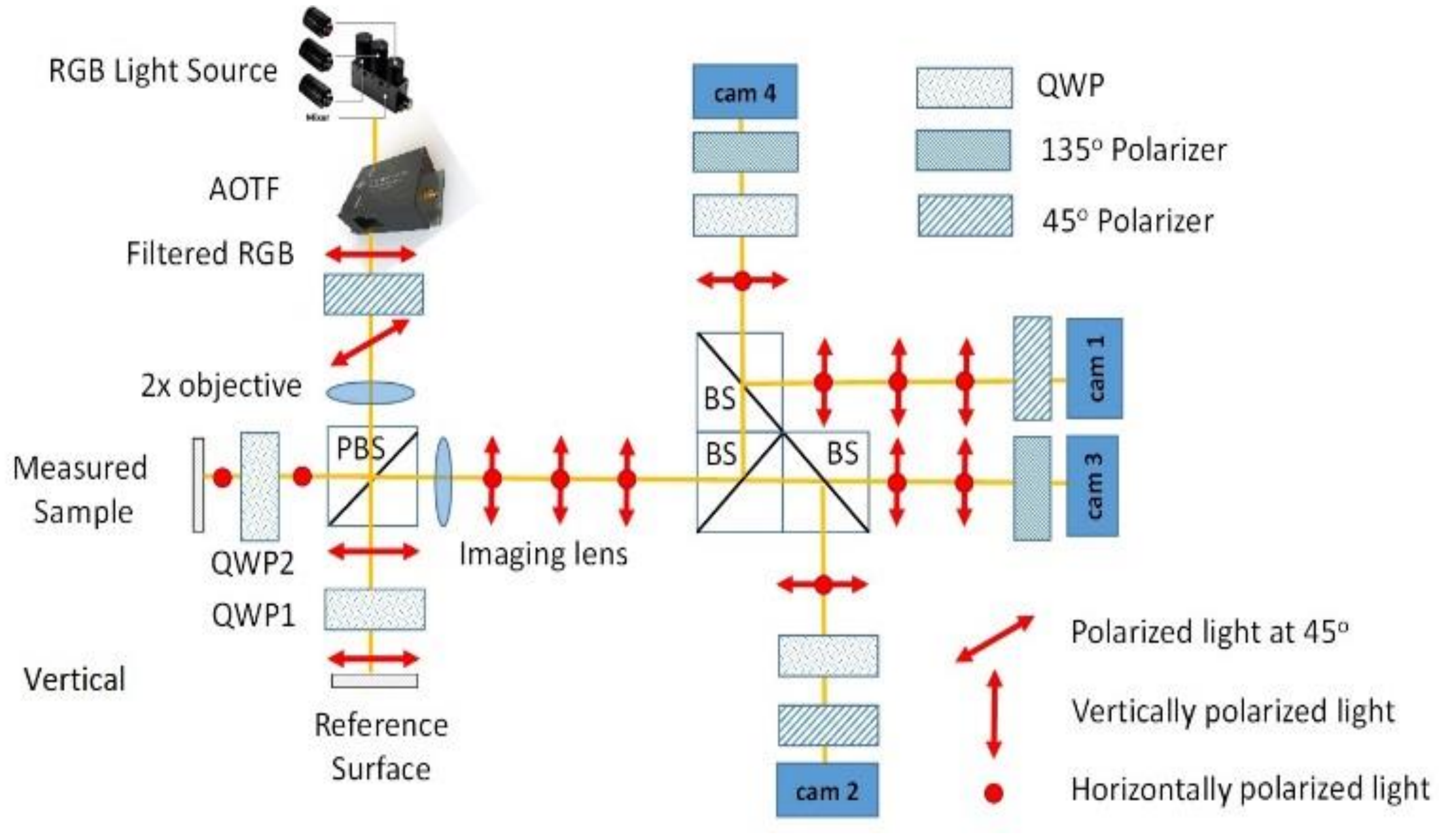
Arinna (IBSPE)





Multi-wavelength Polarising Interferometer

Single Shot Dynamic Measurement



Patent pending

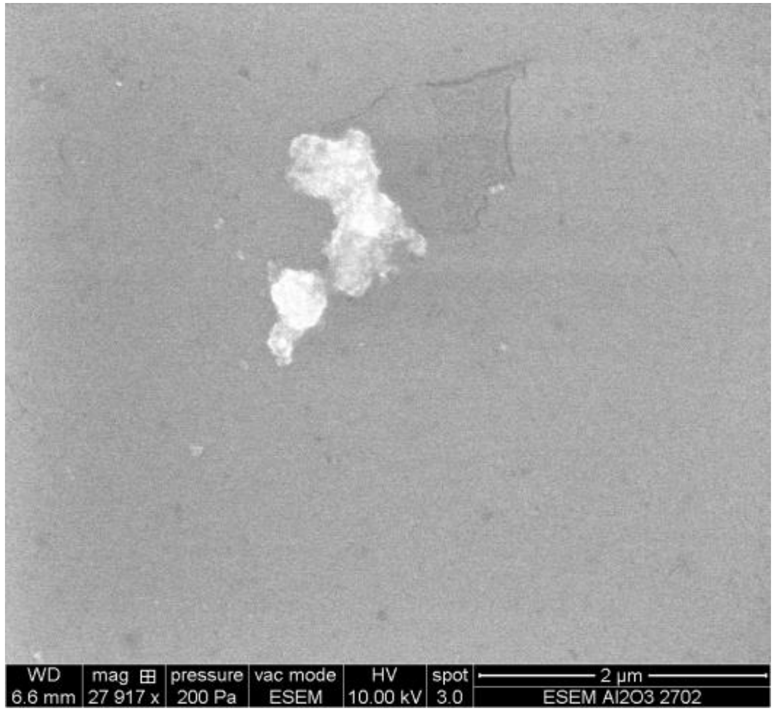
- polarisation technique introduces the essential phase shift
- Each detection arm has a colour CMOS camera placed after a polarization arrangement to generate a single RGB interferogram shifted by π/2 sequentially.
- The polarization arrangement in each arm introduces a phase difference equal to π/2 between the beams and makes them coplanar in order to interfere

Conclusions

- In process metrology for large area substrates a strong technology driver
- Non contact robust measurement the obvious option
- For PV barrier coatings small numbers of large defects correlates with WVTR
- Modelling focuses metrology task
  - Simplifies the number of measurands
  - Reduces the amount of data needed
- Moving Substrates 1-10m/min
- More research needed on data handling

Case Study; Take Home

“Understand what needs to be measured and only measure that”



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EU; Nanomend Grant Agreement No. *280581*

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