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Surface defects in water vapour barrier layers for structured plastic electronics

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The NanoMend project has received funding from the European Community's Seventh Framework Program (FP7/2007-2013) UNDER Grant Agreement No. 280581

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The paper presents results from the first stages of Nanomend

NanoMend

European Framework 7 Programme
– NMP-2011 NanoSciencies, NanoTechnologies, Materials and New Production Technologies.

€7.25million, 4 year long project

14 European Partners

Mend project has received funding from the European Community's Seventh Framework Program (FP7/2007-2013) UNDER Grant Agreement No. 280581

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Consortia

NPL National Physical Laboratory; University of Huddersfield; cpi ...the future inspired; Fraunhofer EMFT; Fraunhofer IVV; Flisom Flexible Solar Modules; storaenso; IBS Precision Engineering; TNO innovation for life; KITE Innovation Europe; Tampere University of Technology; Isovoltaic; ISRA Vision; Open your mind. LUT. Lappeenranta University of Technology; Microsharp Corporation Limited Innovators in Light Management Technology

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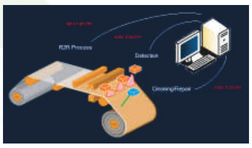
Project Ambition

To develop technologies that are able to detect and correct micro and nano-scale defects in Roll to Roll produced films, without slowing production speed.



In order to improve product performance, yield and lifetime.

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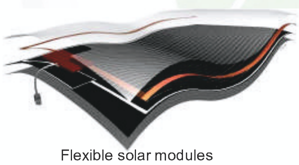
Applications

NanoMend will tailor its technology to the specific needs of the following applications:



Flexible solar modules

The food packaging

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Why is this project necessary

- Thin films can take the form of:
  - Functional layers within a product (flexible photo-voltaics).
  - Protective coatings (used to weather proof flexible photo-voltaics, food packaging, digital displays other applications).

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Why is this project necessary

- Defects within these films reduce the yield, performance and life time of the products:
  - By reducing their resistance to environmental conditions.
  - By increasing the scrap rate
- Reducing the proportion of defects will make a range of products more competitive.

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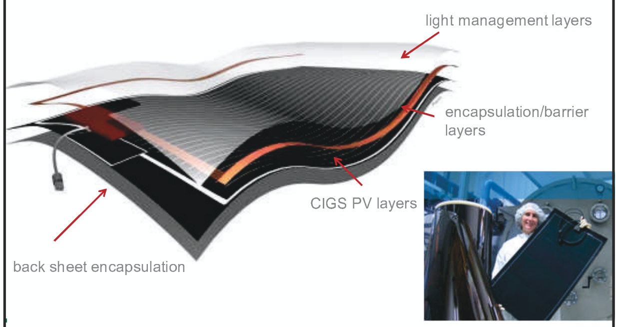
NanoMend Flexible Solar Modules; basic layer groupings



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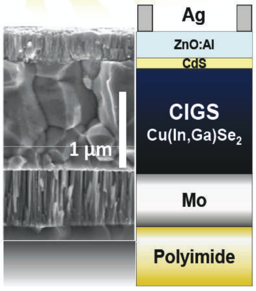
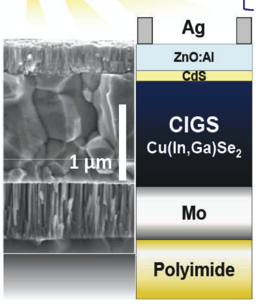
Functional elements of flexible photovoltaic cells



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

Front end processes

Functional elements of flexible photovoltaic cells



Barrier film: Al_2O_3, polymer

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

Front end processes

Encapsulation 1

- Encapsulation of the PV layer by polymer film layers is designed to protect the PV modules from water ingress through the polymer layers to the cells which reduces efficiency over time
- The most expensive element of PV cells per m^2 is the barrier layer
- ALD layer of Al_2O_3 40nm thick on a planerised polymer substrate

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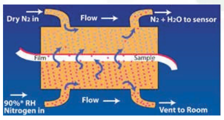
Encapsulation 2

- Defects; "pin holes" and particles in the ALD layer are thought to significantly affect the barrier properties
- Test substrates were produced at CPI and measured using a MOCON Water Vapour Transmission Rate (WVTR) test.



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Defects density and its correlation with WVTR

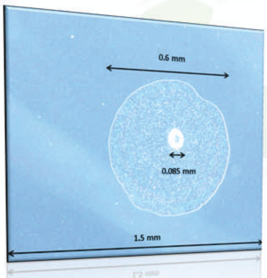
- Water vapor transmission rate (WVTR) for 40nm film at specified conditions 38ºC @90% RH

Water vapor transmission rate (g/m²/24 hr)	
Sample 2701	1.1x 10^{-3}
Sample 2702	1.3 x 10^{-3}
Sample 2705	4.1x 10^{-3}
Sample 2706	2.0x 10^{-3}

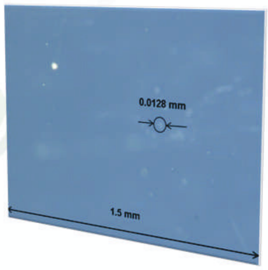
- From the above table it can be observed that sample 2705 has the highest value of WVTR.

Visualisation of defects

Scale of large defects



Scale of small defects

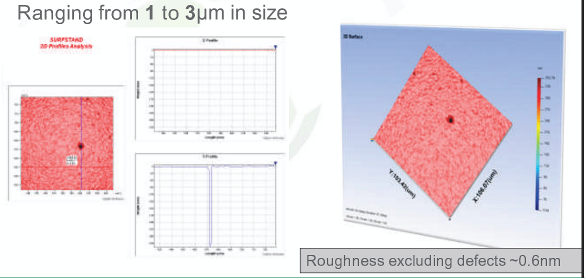


Optical microscope images
× 200 lens magnification

Types of defects 1

➢ Pinholes

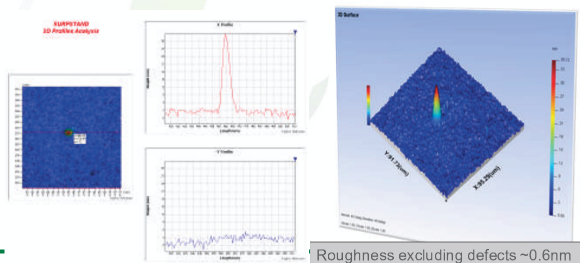
Ranging from **1** to **3**μm in size



Roughness excluding defects ~0.6nm

Types of defects 2

➢ **Peaks/particles** of ≤ 30 nm height

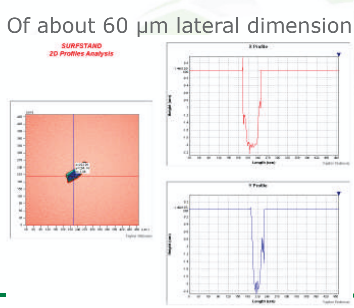


Roughness excluding defects ~0.6nm

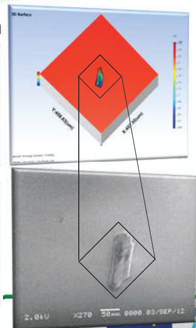
Types of defects

➢ **Holes**

Of about 60 μm lateral dimension



Roughness excluding defects ~0.6nm



SEM picture

Defining significant peaks and dales

- Density of peaks - *Sds/mm²*
- Density of dales (pits) -*Sdd /mm²*
- Density of significant defects -*Sfd /mm²*

Possible defect counters

When counting all of defects there was no correlation between WVTR and possible defect density or types

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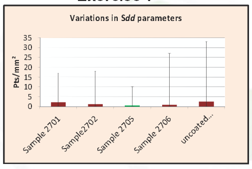
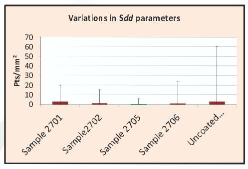
Density of dales, *Sdd*

- A dale is defined as a region around a pit such that all maximal downward paths end at the pit (ISO 25178-2:2012 (E)).

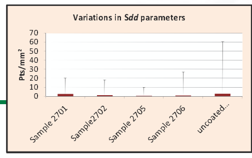
Exercise 1



Exercise 2



Exercise 3



Sdd parameters mean value (pts/mm²)

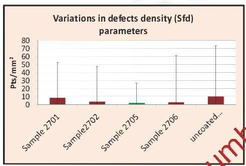
Sample No	Exercise 1	Exercise 2	Exercise 3
Sample 2701	2.26	3.120	2.667
Sample 2702	1.25	1.572	1.472
Sample 2705	0.556	0.556	0.585
Sample 2706	0.96	1.052	1.059
Uncoated /S	2.66	3.215	3.056

Significant defects density, *Sfd*

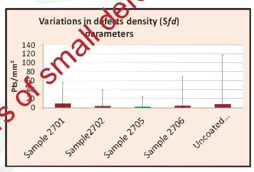
- *Sfd*= (density of peaks + density of dales)

Relatively large numbers of small defects

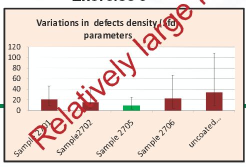
Exercise 1



Exercise 2



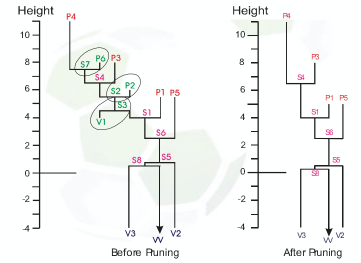
Exercise 3



Sfd parameters mean value (pts/mm²)

Sample No	Exercise 1	Exercise 2	Exercise 3
Sample 2701	8.498846	9.267278	20.964
Sample 2702	3.767269	3.995331	15.72026
Sample 2705	1.938746	1.985845	9.019053
Sample 2706	2.803999	4.361767	23.22805
Uncoated /S	10.01236	8.250714	34.74597

Structured Feature 'Filtering' -Wolf Pruning



Noise and Measurement errors can also create artificial "small" critical points

Function splits features into functionally significant and insignificant sets

Exercise 4

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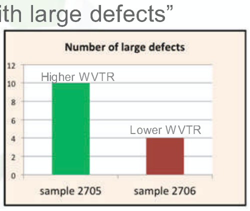
"Number of data files with large defects"

- **Exercise 4-** A comparison of defects on sample 2705 and sample 2706.
- More than 500 locations were inspected at a magnification of X 20 on the CCI for both samples.
- Only large defects (6σ (Sq=0.8nm) height & width > 15um) (i.e. area and height pruning/segmentation)



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

- **Small numbers of larger defect seem to have the dominant effect on WVTR (no clear distinction between peaks and dales)**

Super-resolution

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- Clearly many defects are smaller than the diffraction limit any may affect WVTR.
- A priori data can be used with super-resolution techniques to measure (or simply detect) sub-resolution features
- NPL developing instrumentation along with phase-retrieval techniques
- Investigating the use of optical singularities

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Structured Surface Analysis in Flexible PV metrology

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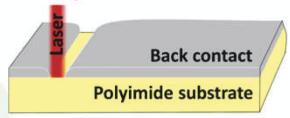
Laser Cell scribing in Mo back contact

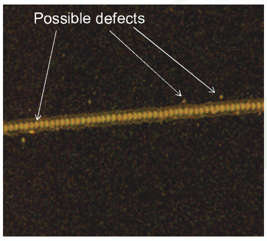
Optical & CCI analysis

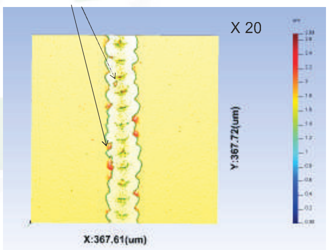
- The PV cell back connect is made from a layer of Molybdenum. After the coated polymer web leaves the vacuum chamber, it passes over a laser that scribes lines into the metallic layer to delineate the individual solar cell back-contact.



Laser Cell scribing in Mo back contact

Possible defects





Defects “bridging” the call gaps can give rise to shorts across cell reducing overall efficiency

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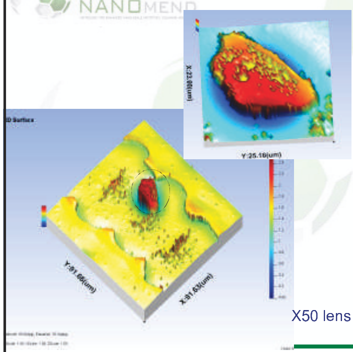
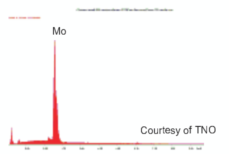
Interferometer analysis of defect

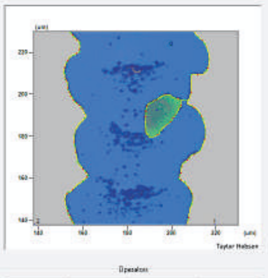


- Particle inside the scribe line.
- Height 1 um.
- Width about 18um
- EDAX analysis confirms Mo



X50 lens magnification

Step Height Segmentation across defect area



No.	Group	Datum	Mean (um)	Max (um)	Min (um)	Pt (um)	Area
0		D	-0.041	0.936	-1.524	2.460	36900
1	1	D	0.315	0.864	-0.003	0.867	26126
2	1		0.315	0.864	-0.003	0.867	26126
3			1.304	1.863	0.438	1.425	1518

Set trough bottom to be zero and use

- Relative heights
- Trough width
- Defect width as % of trough width

As a defect detector

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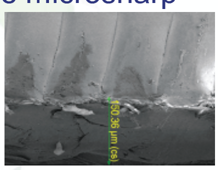
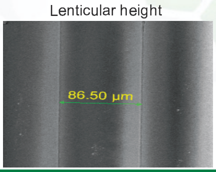
Light Management Film Dimensions insert picture microsharp

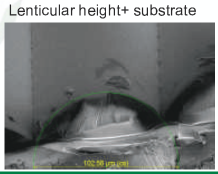
Lenticular height



Lenticular height+ substrate



Pitch



Diameter

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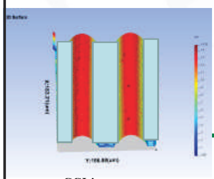
Original surface structure

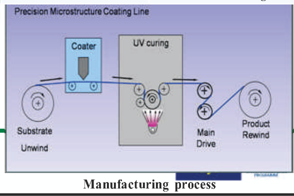
- A roll to roll, UV casting process that produces micro structure to extreme accuracy is implemented.

Lenticular Structures; Slope deficit

Lenticular structures- design parameters	
Lenticular structure height	5-25 um
Pitch	75-400 LPI
Prism Shape	Spherical and A spherical
substrates	PET, PMMA, PC
Reel width	Up to 1000 mm
Prism orientation	Parallel to reel length

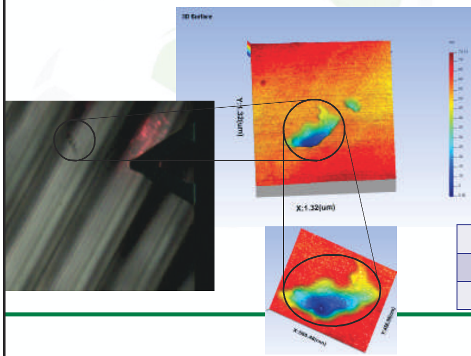


CCI image



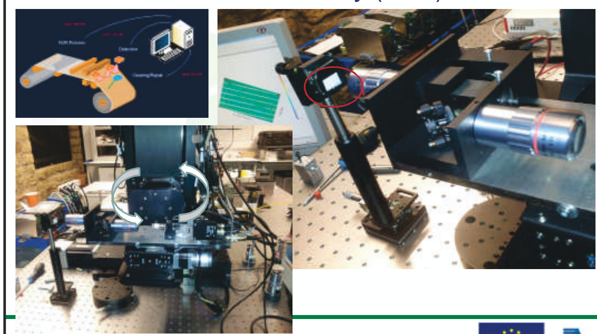
Manufacturing process

Defective in optical film (AFM)



Defect size scale	
Width	0.57um
Depth	60nm

In Process Systems Wavelength scanning Interferometry (WSI)



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Conclusions

- Flexible PV cells critical functionality depends of barrier properties
- Defect density seems to correlate with WVTR
- Structured surface approach useful in monitoring defect presence in all layers
- In process sensors needed!

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Acknowledgements

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