Identification of degradation and manufacturing issues using multi-parameter mapping of organic solar cells

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Advanced Characterization Methods for PV – 14^{th} January 2016

Agenda

- Short introduction to NPL
- Challenges for organic solar cells
- Why mapping at different scales is important?
- Examples
  - Nanoscale photocurrent map
  - Nanoscale multiparameter
  - Microscale PL, Raman, Photocurrent
  - In-situ photocurrent mapping
- Final remarks

National Physical Laboratory - UK

NPL National Physical Laboratory | Centre for Carbon Measurement

- UK's metrology institute established in 1900
- World-leading National Measurement Institute (Top 3 among ~100)
- 650 staff, 450 Graduate/PhD scientists - multidisciplinary

36,000 m^2 national laboratory

Photovoltaics at NPL

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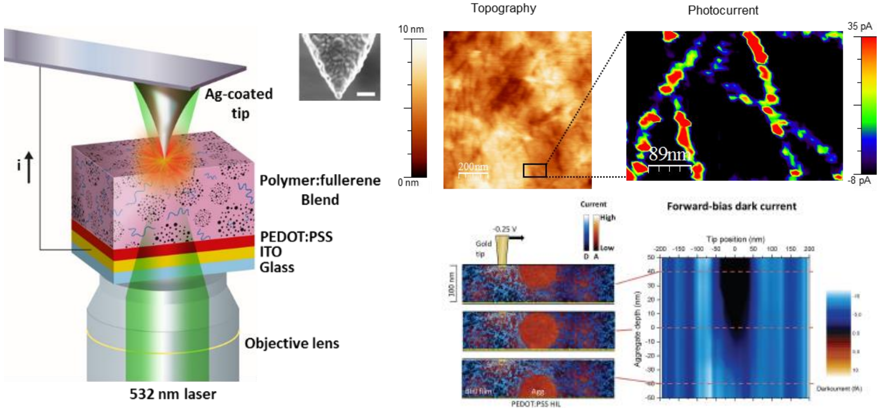
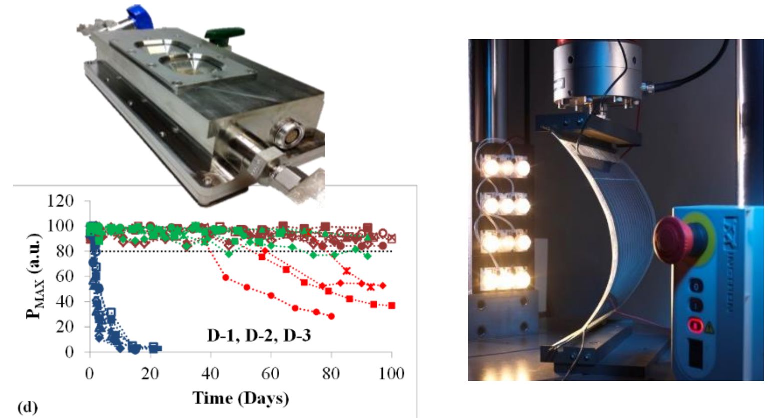
Nanoscale functional characterisation

Novel mapping methods & innovative modelling



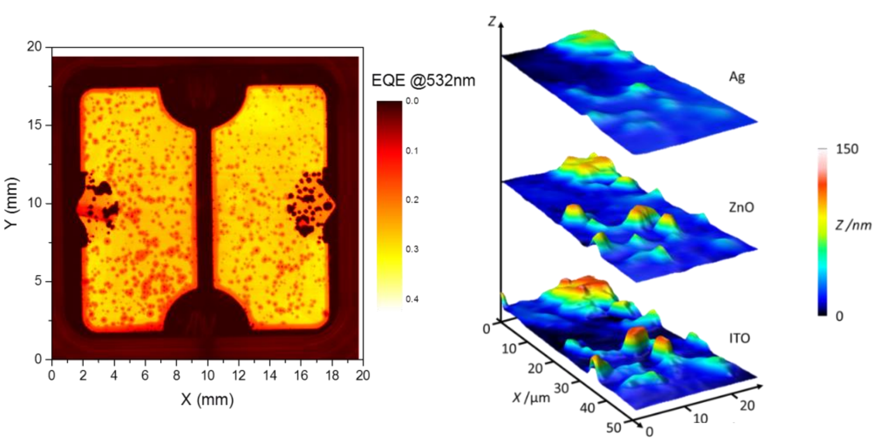
Stability (in-situ characterisation)

Novel in-situ characterisation & accelerated tests



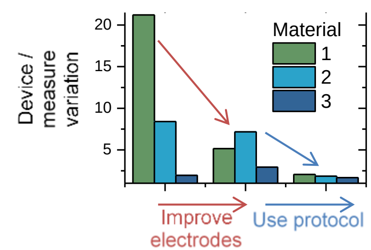
Quality control

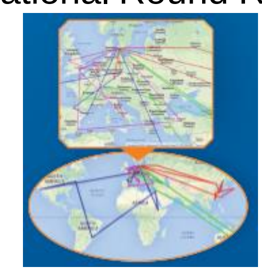
Advanced defect characterisation



Standardisation

Measurement protocols International Round Robins





Collaborations:

Stakeholder groups: oe-a, VAMAS, EERA, bsi., IEC

Companies: MERCK, Eight19, CANATU, TÜVRheinland, SEFAR, FOM Technologies

R&D/NMIs: EMPA, specific, imec, ECN, cea, leti, JRC, VSL, INMETRO, PTB, Fraunhofer

Universities: Imperial College London, University of Surrey, Loughborough University, DTU Technical University of Denmark, Universitat de València

Why Organic PV?

- Mechanical Flexibility / Weight reduction (e.g. 0.5 Kg/m^2)
- Design Flexibility (color, transparency, shape…)
- Low environmental burden

Image from Heliatek

Image from Heliatek

Recent examples from OPV industry

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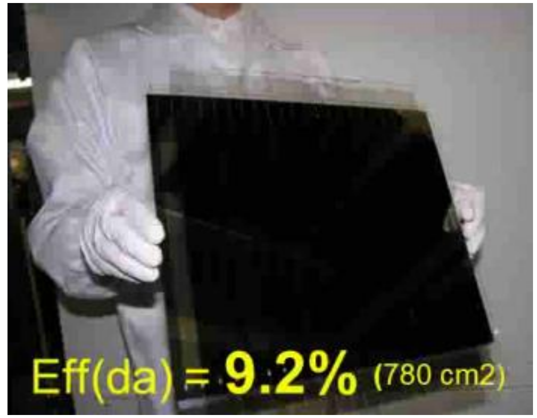
TOSHIBA
Leading Innovation >>>



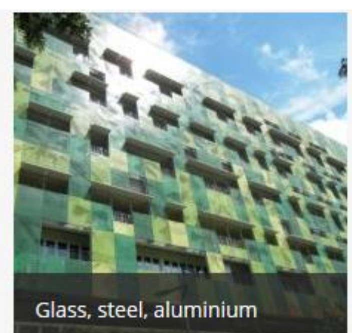
JIS C 8938
Environmental and endurance test methods for amorphous solar cell modules (corresponding to IEC 68-2-2, IEC 68-2-21, IEC 68-2-52)

Tests	Relative Reduction in PCE $= (PCE_{initial}-PCE_{after})/PCE_{initial}$
(B-1) Dry heat test 85°C, 1000 hours	3%
(B-2) Damp heat test 85°C, 85%RH, 1000 hours	0%
(A-1) Thermal cycling test 90°C ←→ -40°C, 200 cycles	4%
(A-2) Temperature/humidity cycling test 85°C 85%RH ←→-40°C, 10 cycles	2%
(A-5) Light soaking test 255 W/m² (300~700 nm), 63°C, 500 hours	9.5%

BELECTRIC®

African Union building
445 Belectric OPV solar modules installed in 5 days!

Heliatek®
The future is light



Mechanically stable Organic Solar Cells

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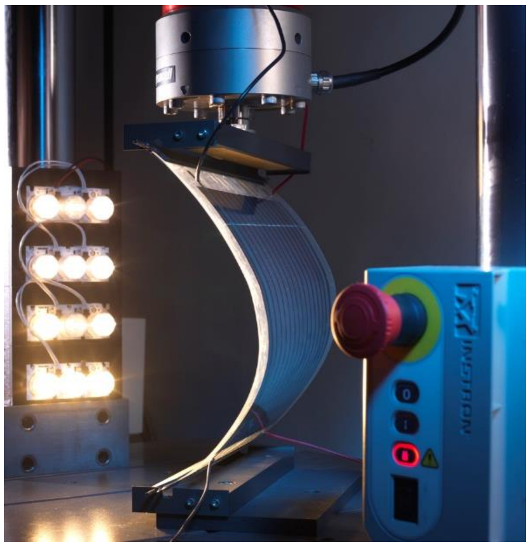
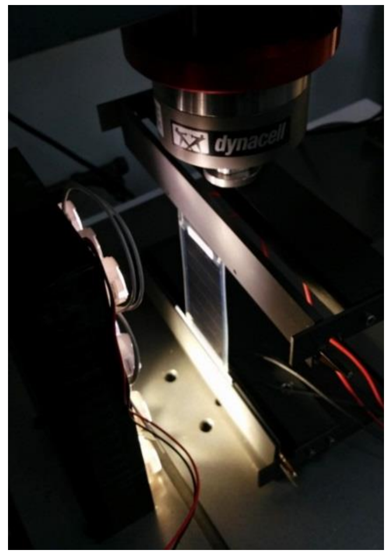
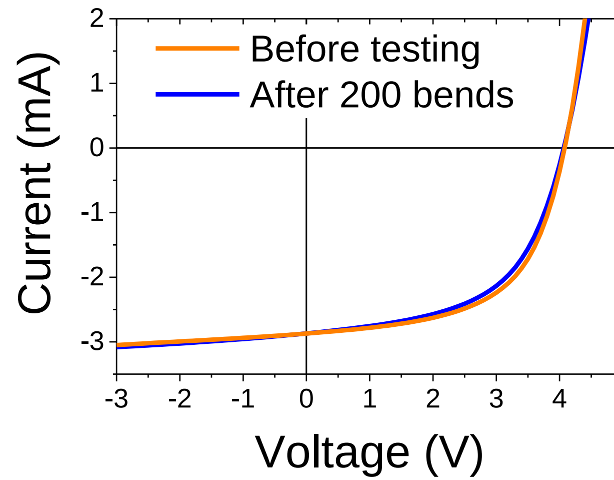




OPV module fabricated by Eight19 Ltd and characterised at NPL

Module was constantly illuminated at 10% of 1 sun intensity (100 W/m^2)



Current-voltage curves were measured in-situ after each bend.

Bend radius down to 25 mm.

Eight19

Co-funded by the European Union under grant agreement n° 314068

TREASORES

Main challenges

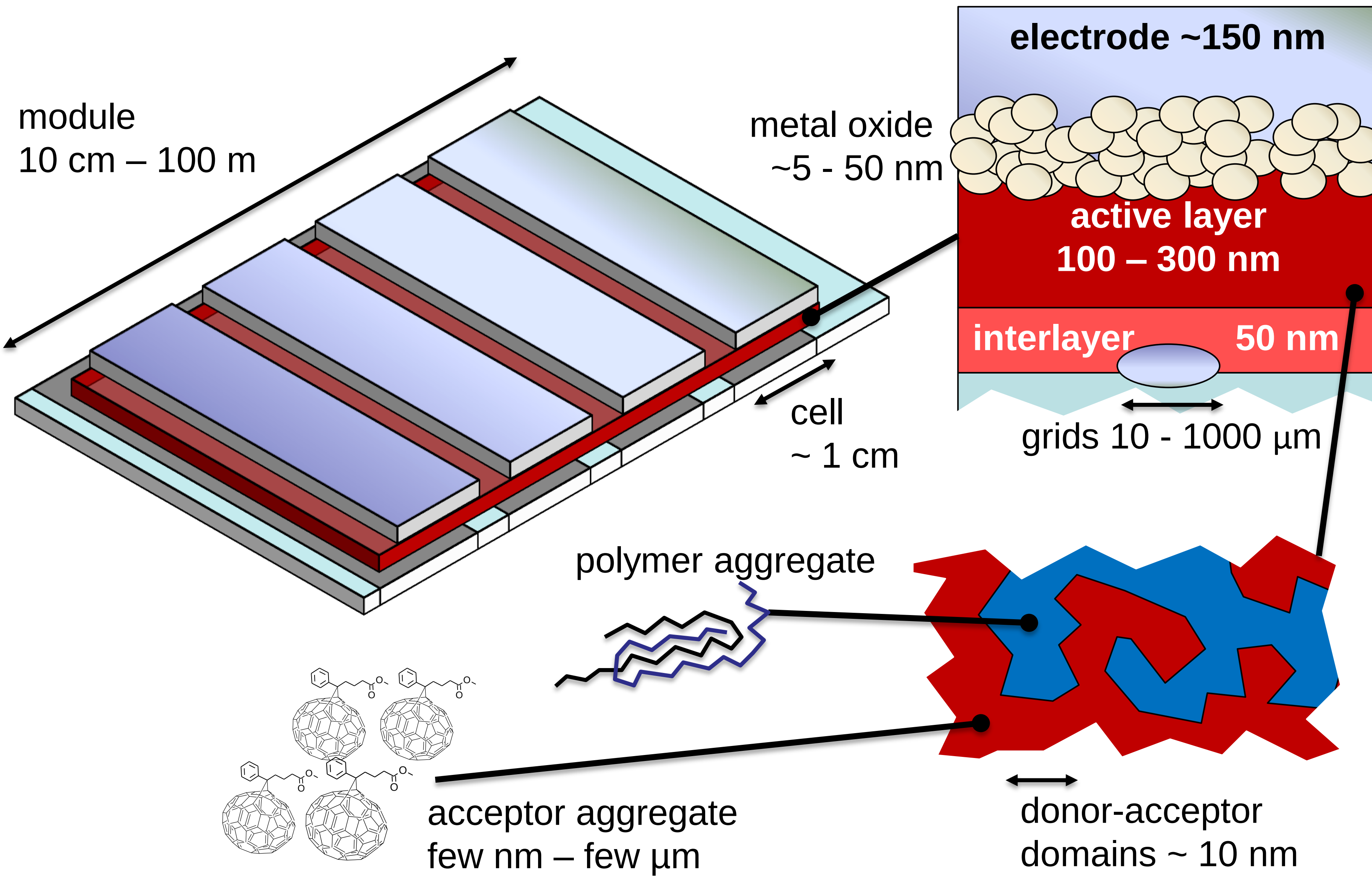
OPV is not a single technology!

Hundreds of possible active layer materials
Different stack configurations (regular – inverted)
Numerous module design options
Many different deposition methods, substrates, interlayer materials…
Companies use proprietary materials

Key issues:

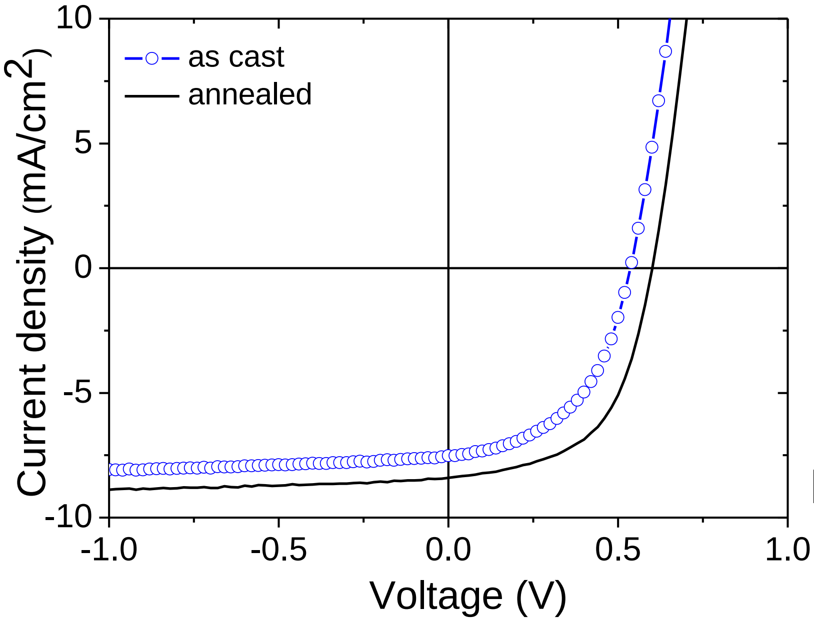
- Defect characterisation in multiple scales
- Identification of degradation mechanisms

Length scales of OPV

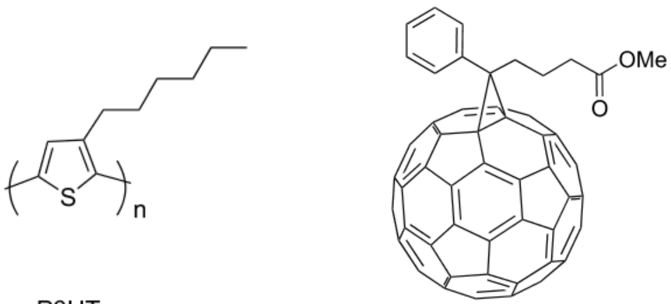


Example 1

Nanoscale characterisation



Semiconductors



P3HT

PCBM

Increased efficiency upon thermal annealing

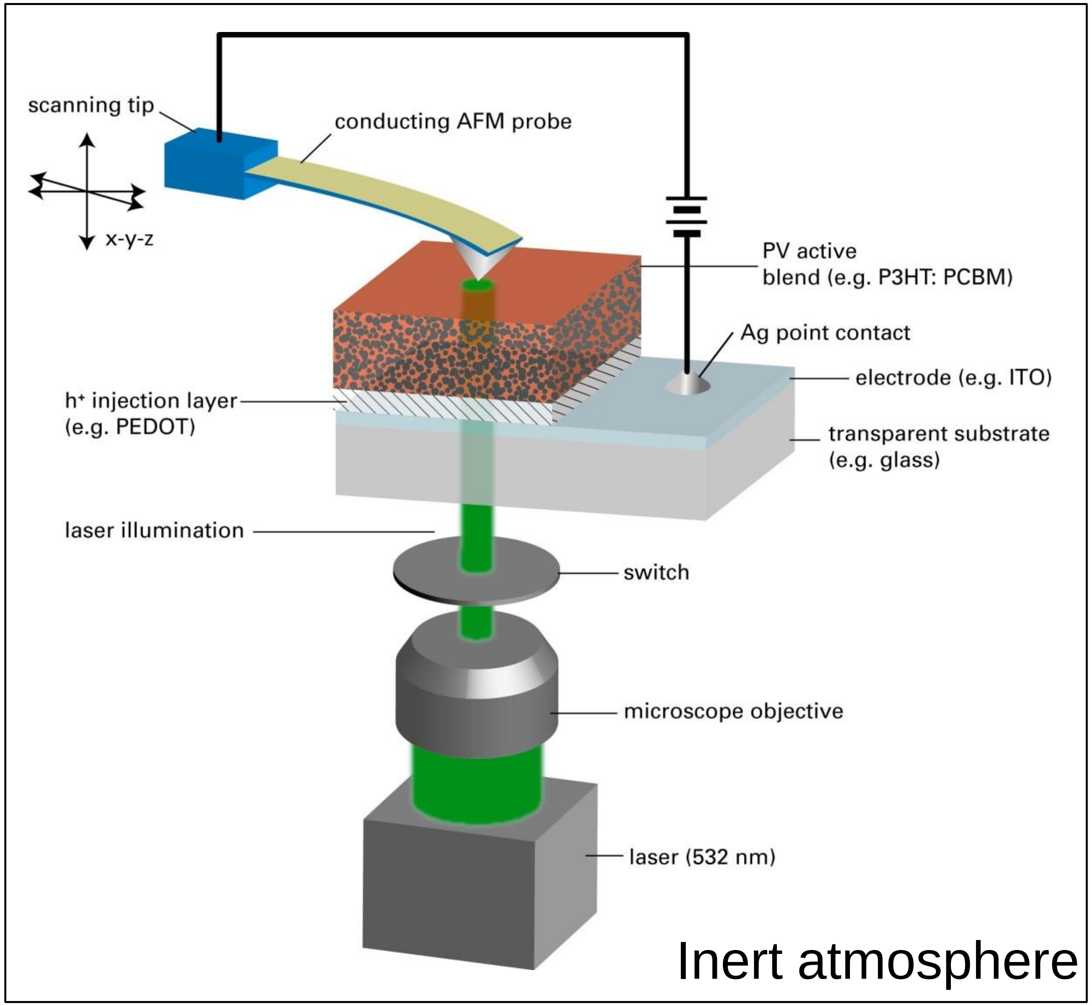
Why?

Sample: P3HT Nanowires : PCBM

Nanowire width ~ 20 nm

Example 1a

Photoconductive-AFM

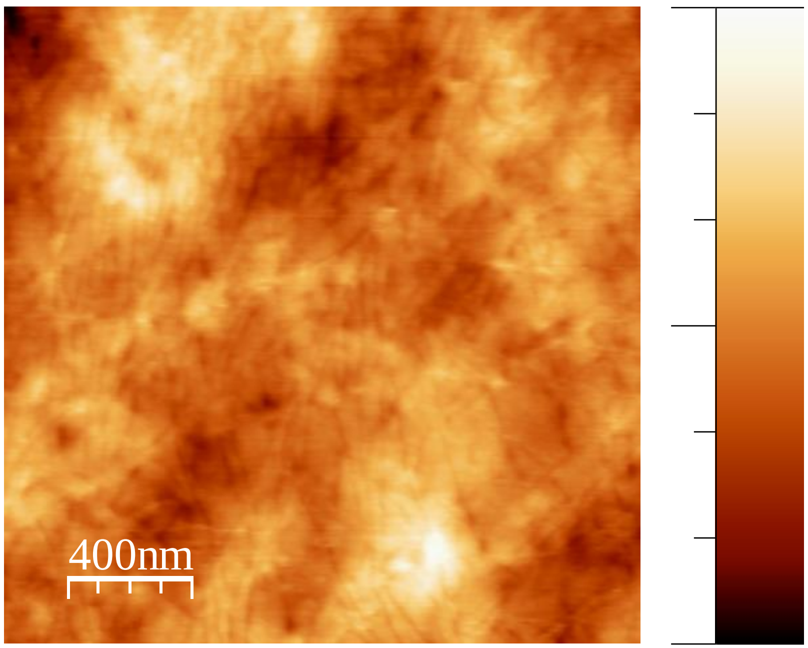


Nicholson and Castro, Nanotechnology **21** (2010) 492001 (review)
Tsoi et al. Energy Environ. Sci., **4** (2011) 3646

Photoconductive-AFM data on operating organic solar cell

Topography

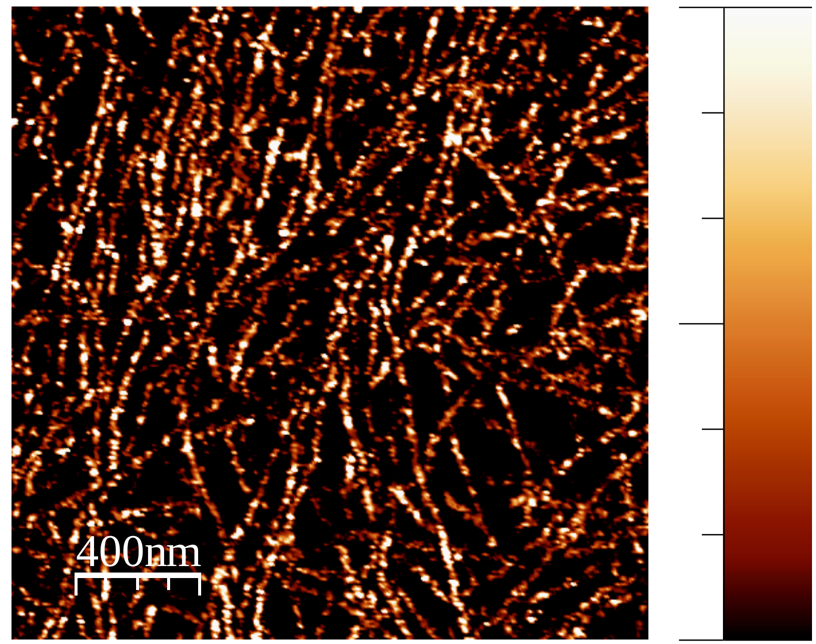
18 nm



0 nm

Photocurrent

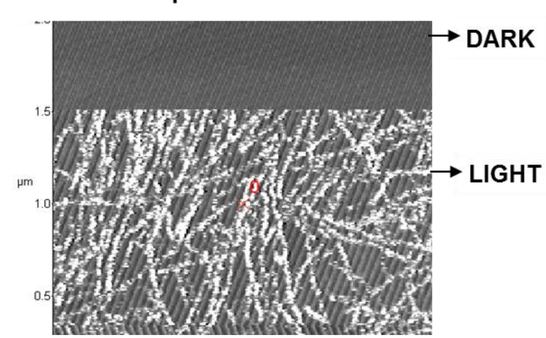
30 pA



-30 pA

Topography: Very flat (RMS roughness ~ 2 nm)
Nanowires are embedded in the 80 nm thick film

Real photocurrent



Tsoi, Castro et al. Energy Environ. Sci., **4** (2011) 3646

More than just surface information

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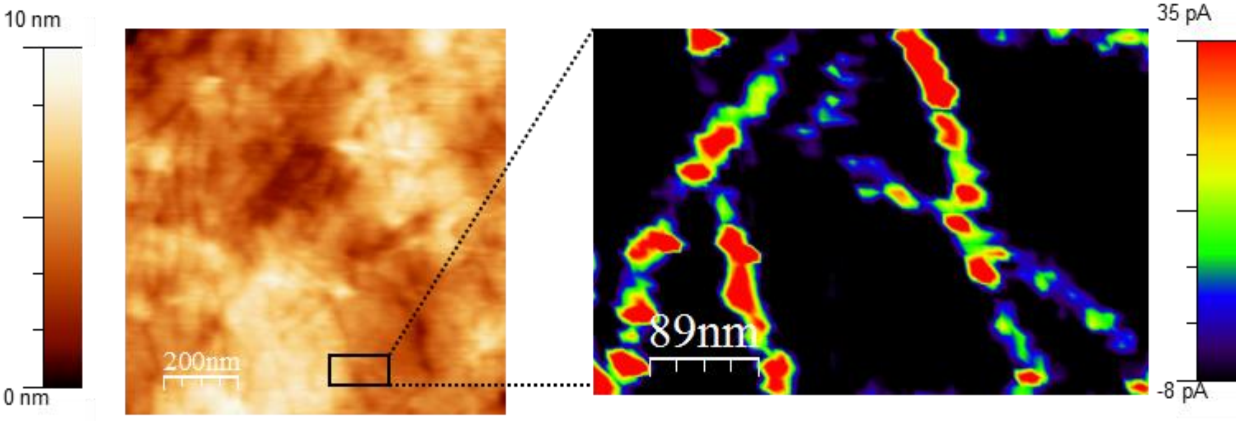
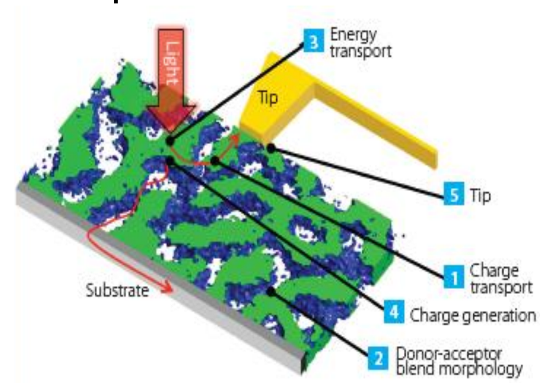
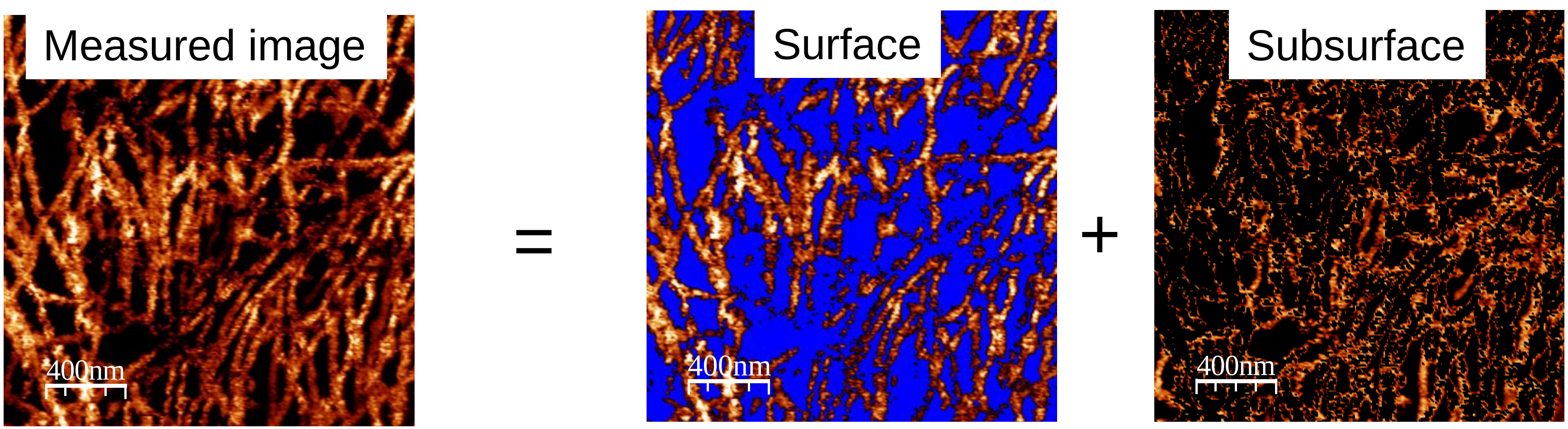


Unique 3D simulation tool



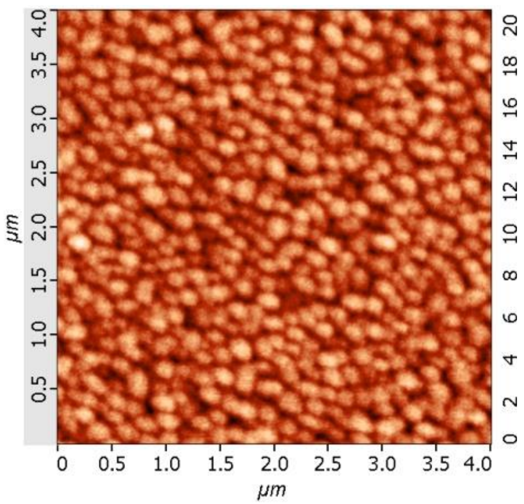
Surface and subsurface signal can be decoupled



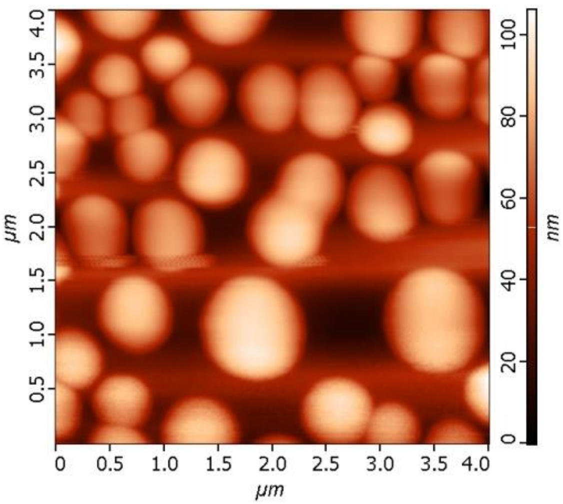
Tsoi Tsoi, Castro et al. Energy Environ. Sci., **4** (2011) 3646
Blakesley and Castro, Phys Rev B **91** (2015) 144202

Example 2

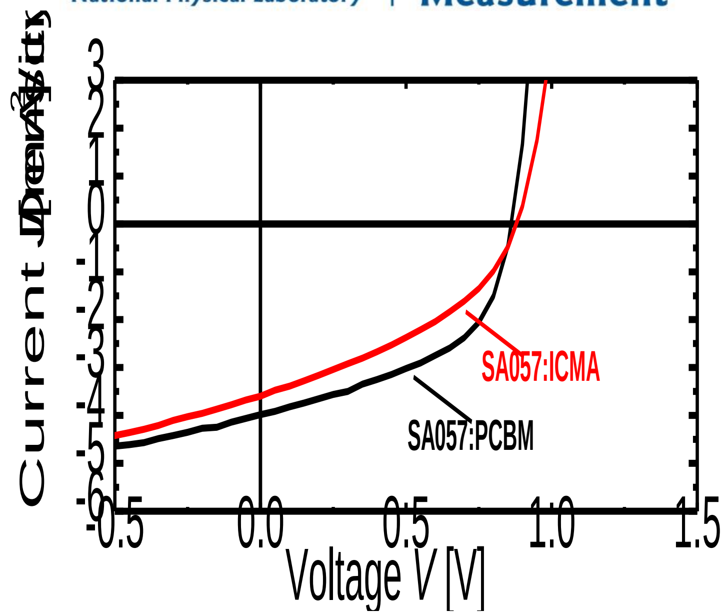
What about samples where features are not obvious?

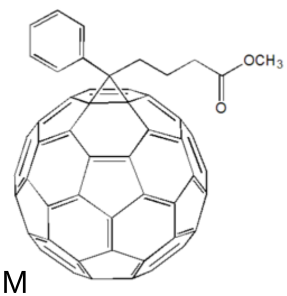


Si TPT-BT:PCBM

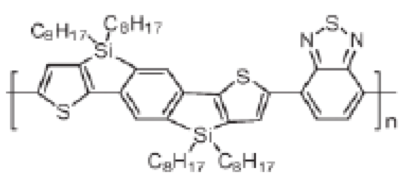


Si TPT-BT:ICMA

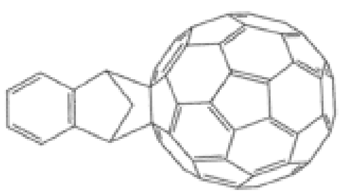




PCBM



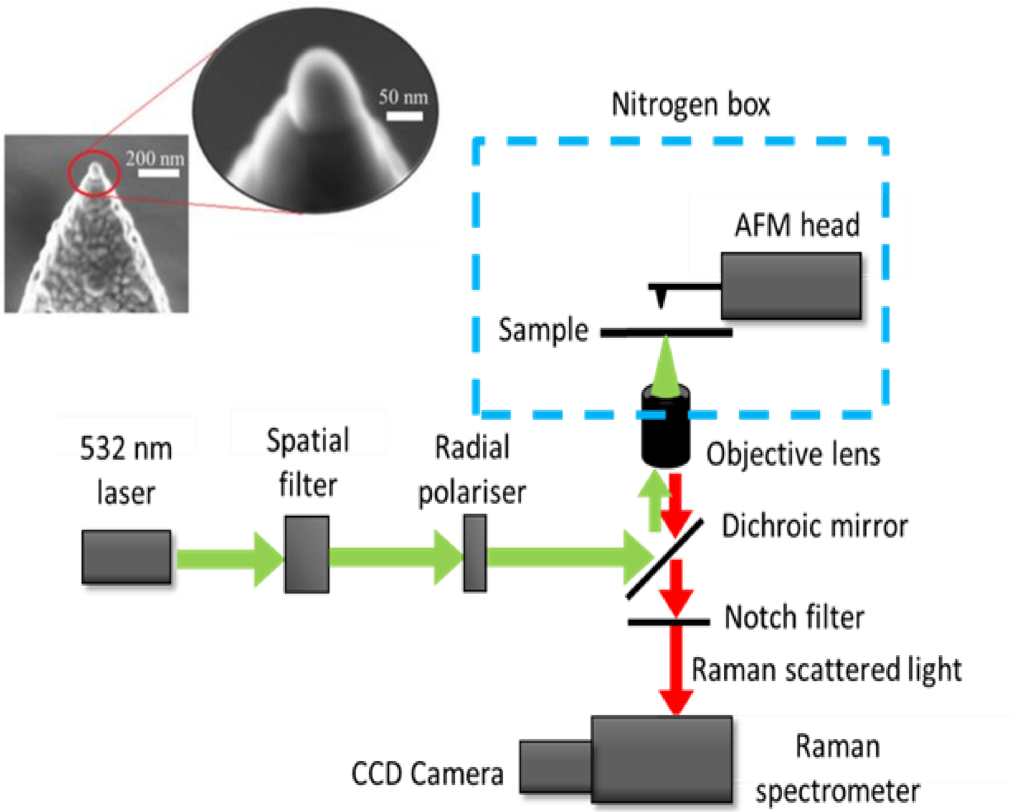
Si TPT-BT

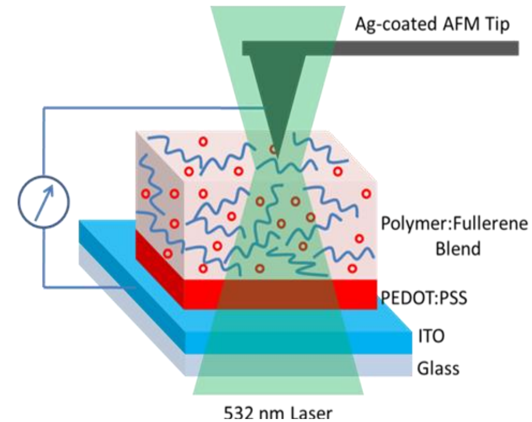


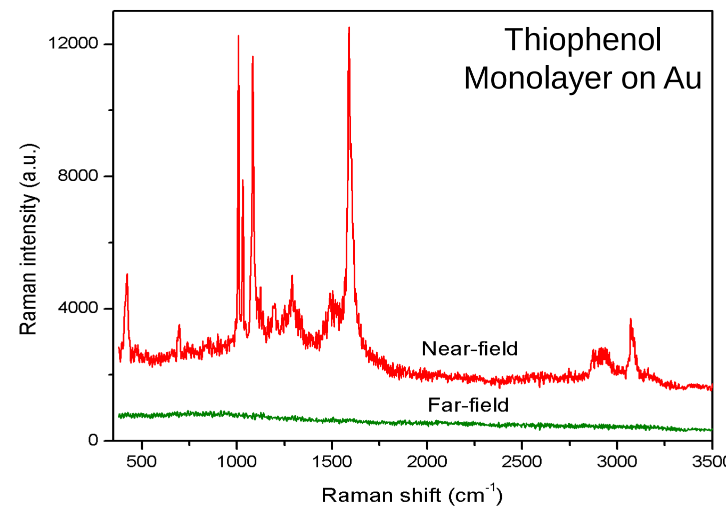
ICMA

Can we get chemical information with nanoscale resolution?

Tip-enhanced optical spectroscopy (Raman, Photoluminescence)







- Laser excites plasmon resonance
- Enhanced electromagnetic field close to the AFM tip

$$EF = \frac{(I_{Tip\text{-}in} - I_{Tip\text{-}out}) / A_{NF}}{I_{Tip\text{-}out} / A_{FF}}$$

Naresh et al, submitted (2015)

Tip-enhanced optical spectroscopy (TEOS)

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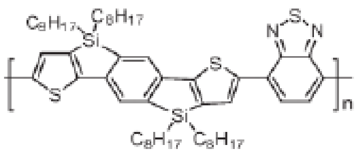
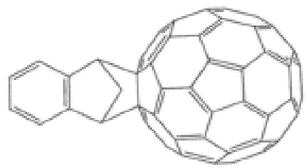
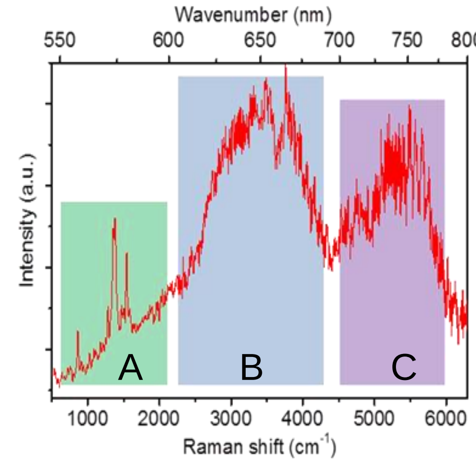


Si TPT-BT

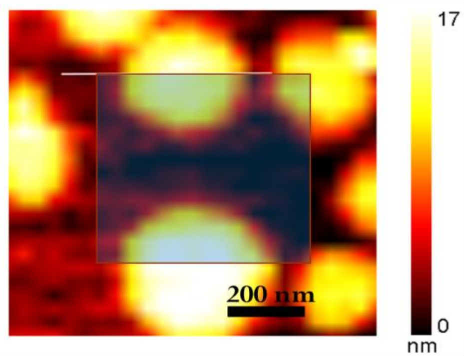


ICMA

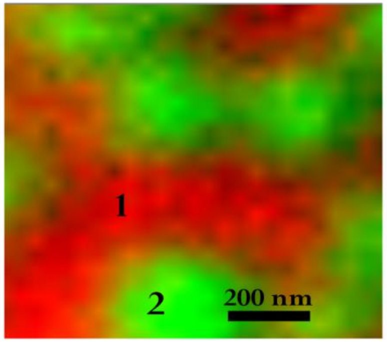


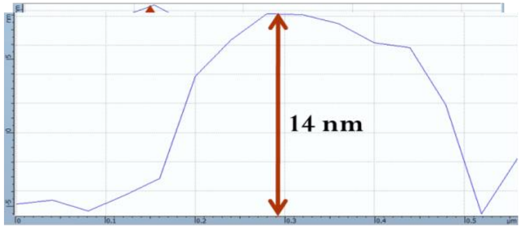
A: Raman peaks from polymer
B: Photoluminescence from polymer
C: Photoluminescence from ICMA

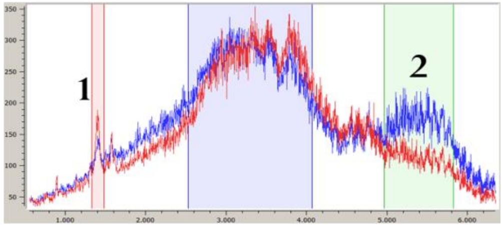
Topography



TEOS







Green: Polymer Raman
Red: Fullerene PL

Naresh et al, submitted (2015)

First simultaneous PC-AFM and TEOS

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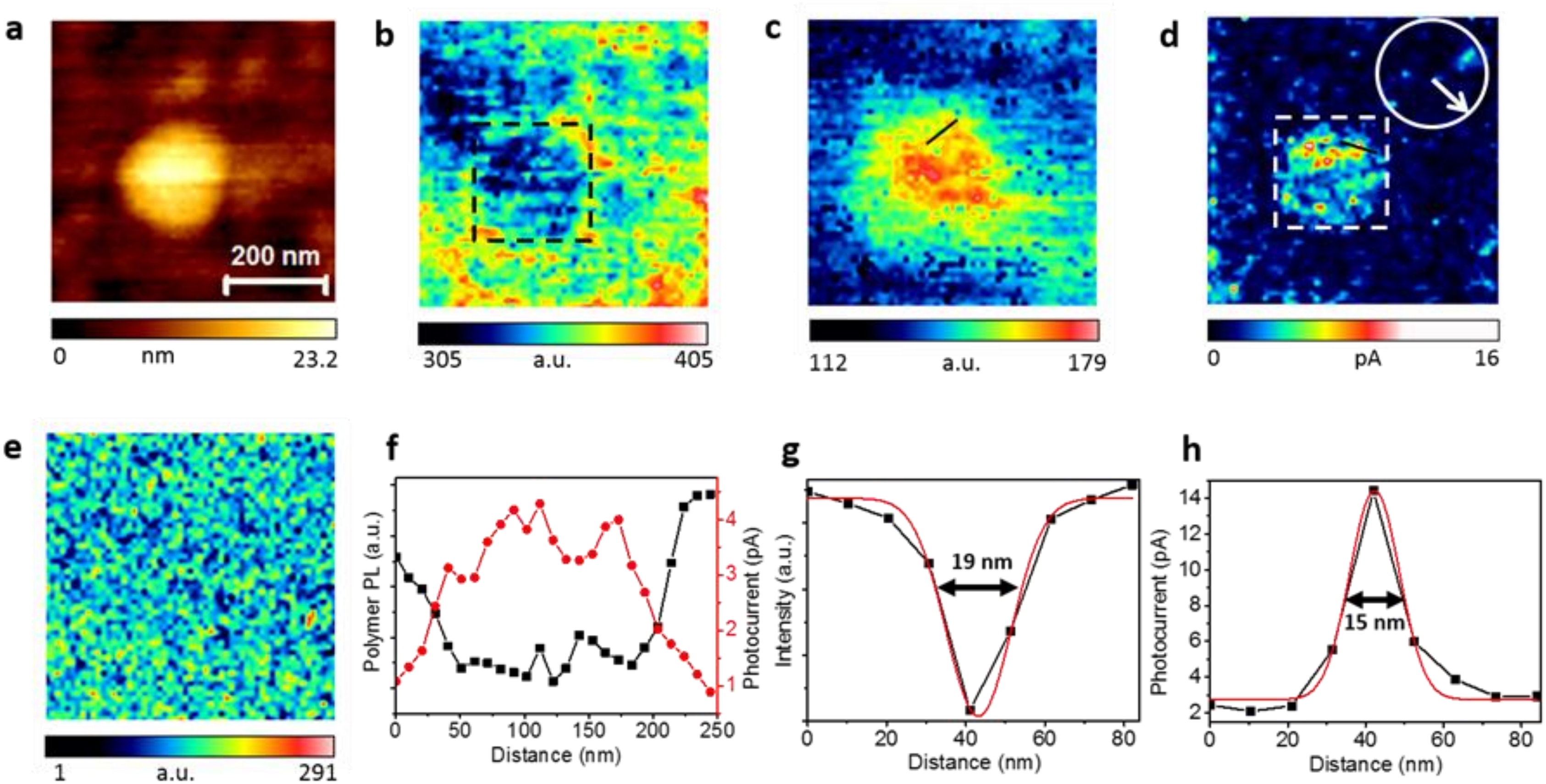
Topography | Polymer PL | Fullerene PL | Photocurrent



Polymer Raman

Indication of measurement resolution

Kumar et al, submitted (2016)

Example 2

Larger area multi-parameter mapping

Provides information about:
- Processing issues
- Resistive losses over large areas
- Degradation

Example of methods:

Photoluminescence
Raman
Photocurrent (LBIC)
Transmittance

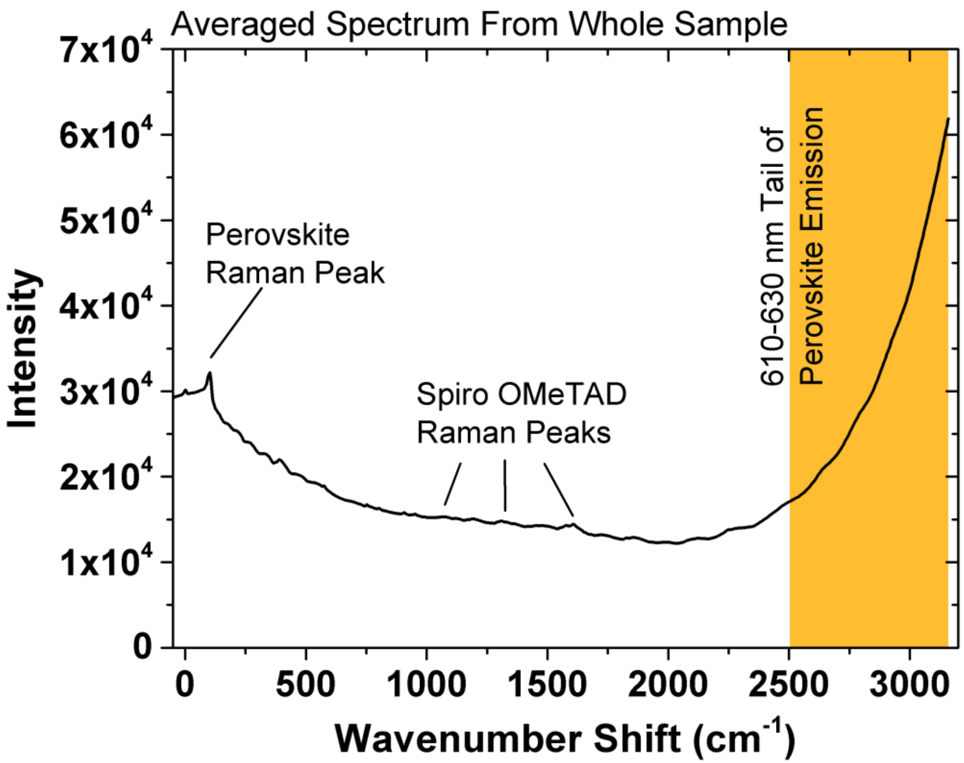
(Photoluminescence, Raman, Photocurrent (LBIC), Transmittance: Can be combined in one experiment.)

Electroluminescence
Thermography
…

Example 2a: Manufacturing issues

Perovskite Solar Cell

Device Structure: glass/FTO/TiO2/Mixed Halide Perovksite/SpiroOMeTAD/Gold



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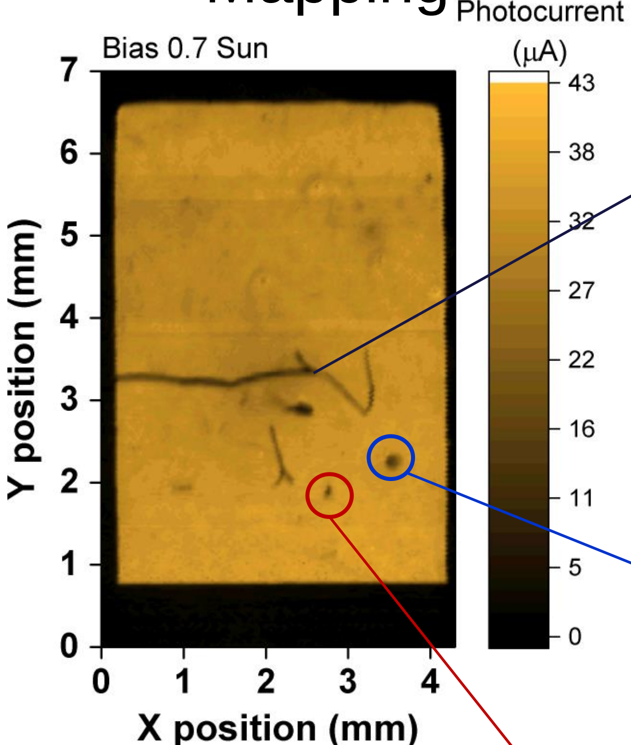
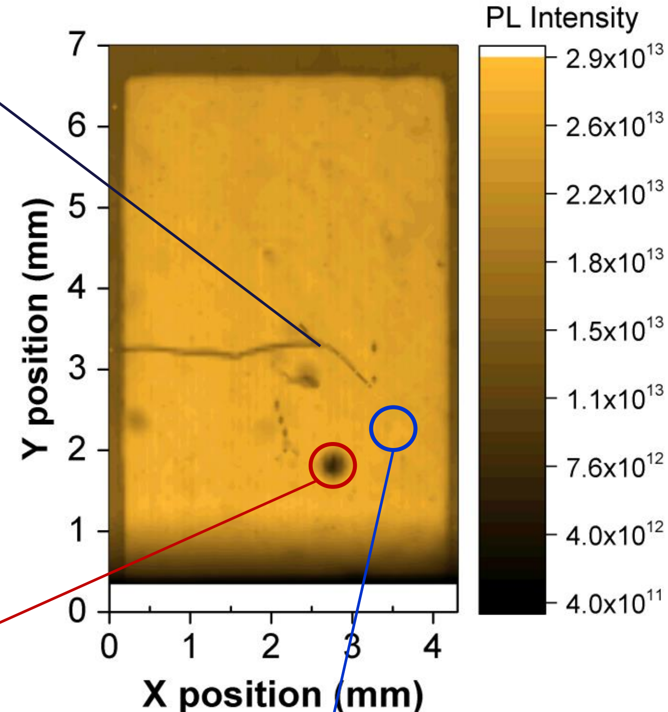
LBIC – Photocurrent Mapping



Scratch reduces photocurrent and PL intensity

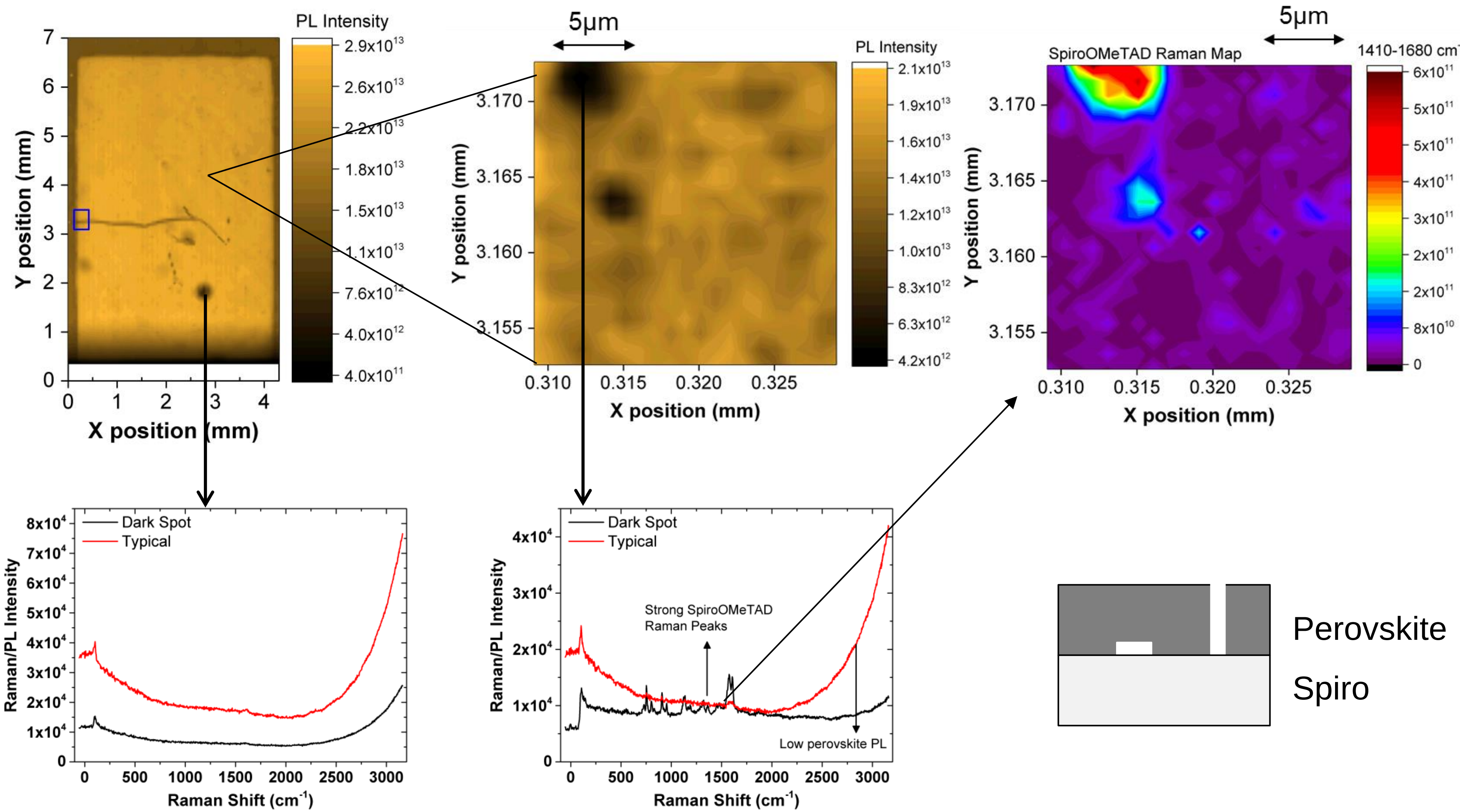
Perovskite PL Mapping



Loss of photocurrent matches reduced PL suggesting reduced active layer coverage.

Loss of photocurrent but no reduction in PL. Possible shunt.

micro PL/Raman Mapping

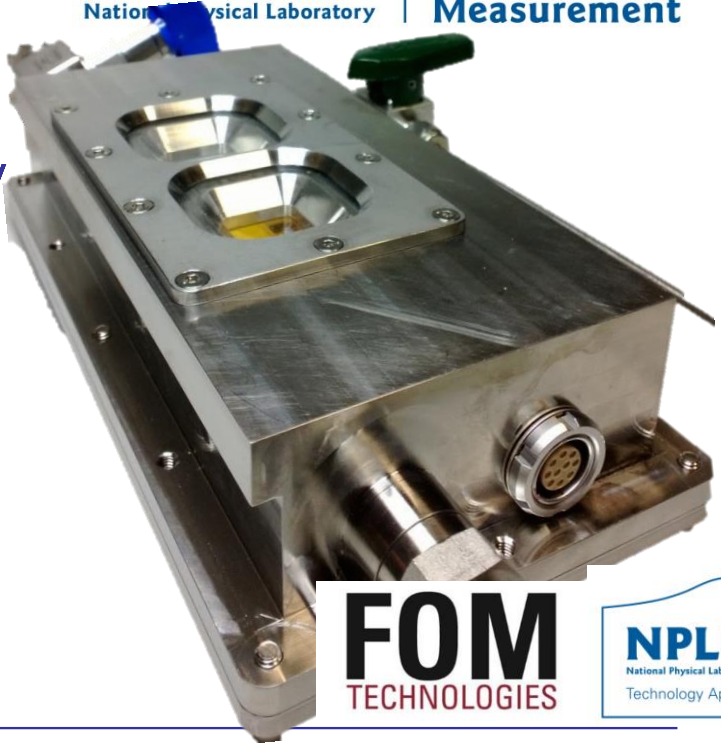


PL/Raman mapping can identify micrometre-scale defects: here the strong Raman signal from Spiro and low Perovskite PL suggest a hole in the perovskite layer capped with Spiro.

Example 2b: Degradation issues

NPL portable environmental chamber

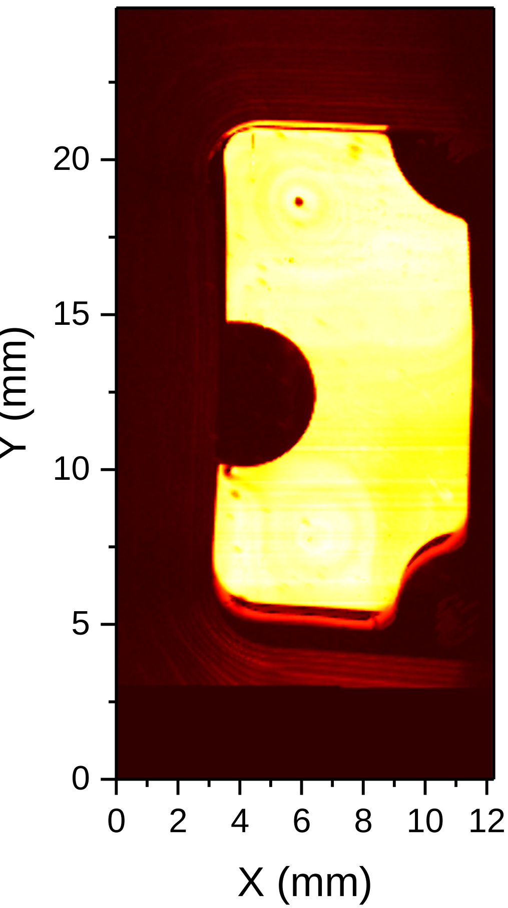
- Simulates encapsulation environment
- Independent control of oxygen and humidity (selective stress testing)
- Automated testing and data acquisition with programmable environments
- *in-situ* characterisation using imaging techniques, µ-Raman, µ-PL, EQE, TPV/TPC etc.



Parameter	Range	Accuracy
Oxygen concentration	0.5 ppm to 21 % (>5 orders of magnitude)	± 10 % traceable
Humidity	1.0 ppm to ~10 % R.H. (>3 orders of magnitude)	± 20 % traceable
Temperature	+ 20 ° C to + 50 ° C	± 1 ° C
Light	AM 1.5 AAA Xe lamp solar simulator, traceable	
Balance gas	99.9999 % Nitrogen	

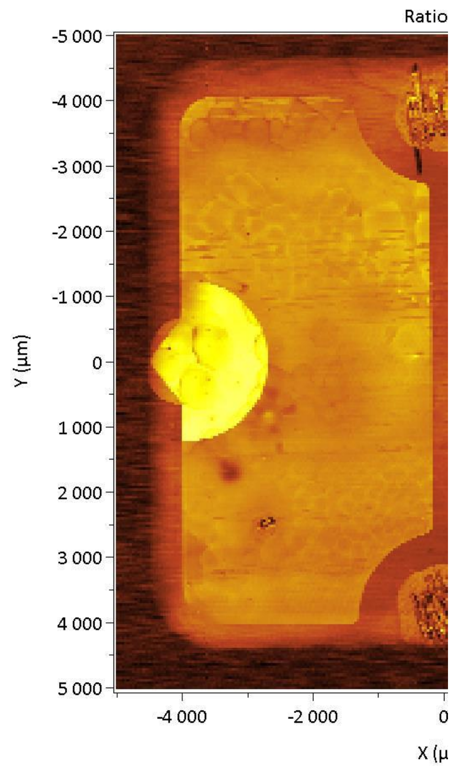
Complementary information

LBIC

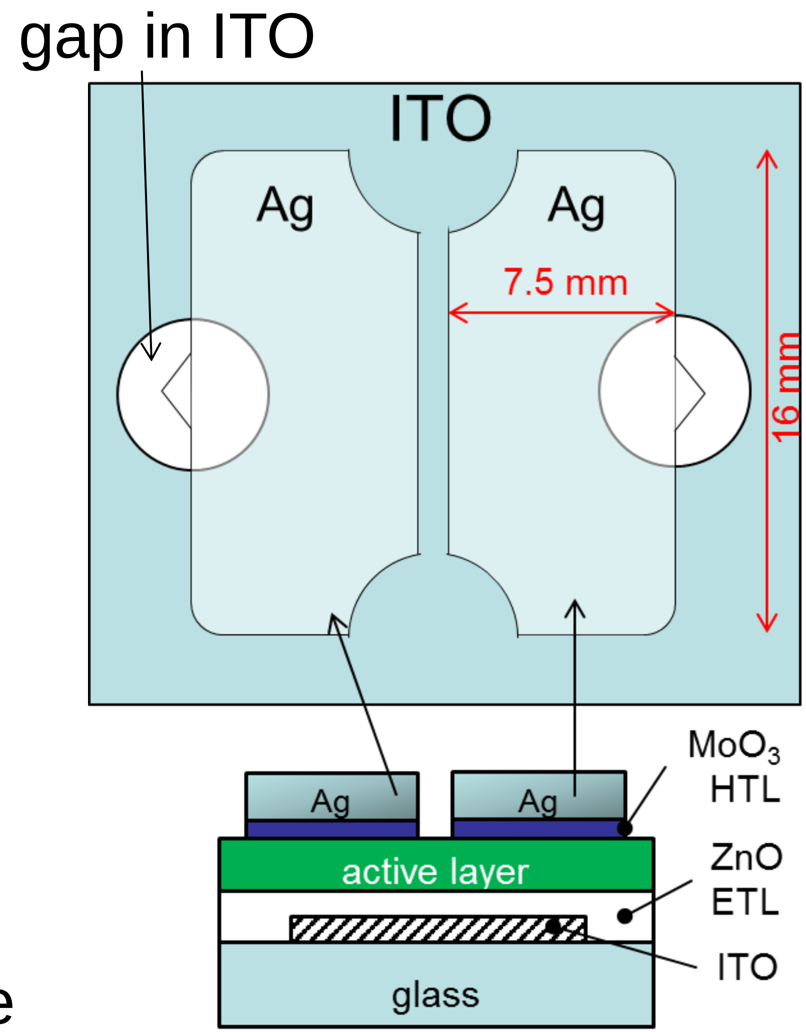


MoO_3 device not exposed

PL

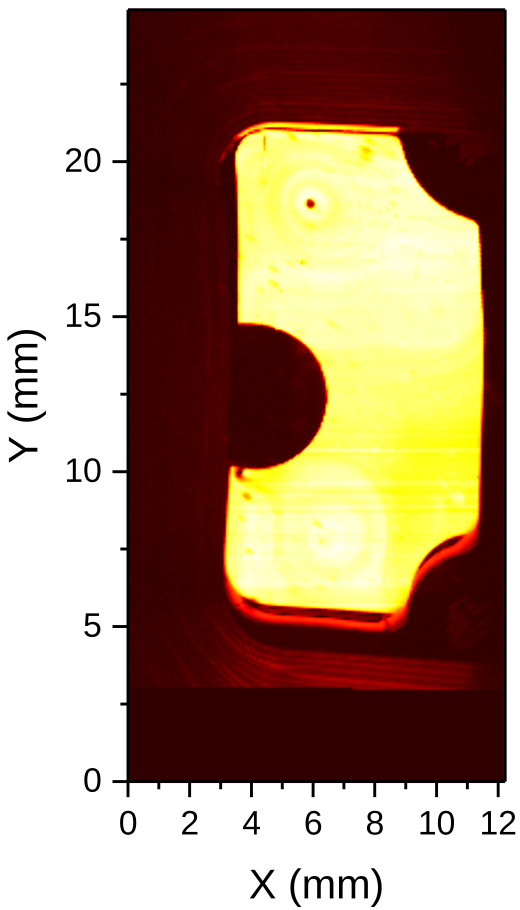


Micro-Photoluminesce mapping

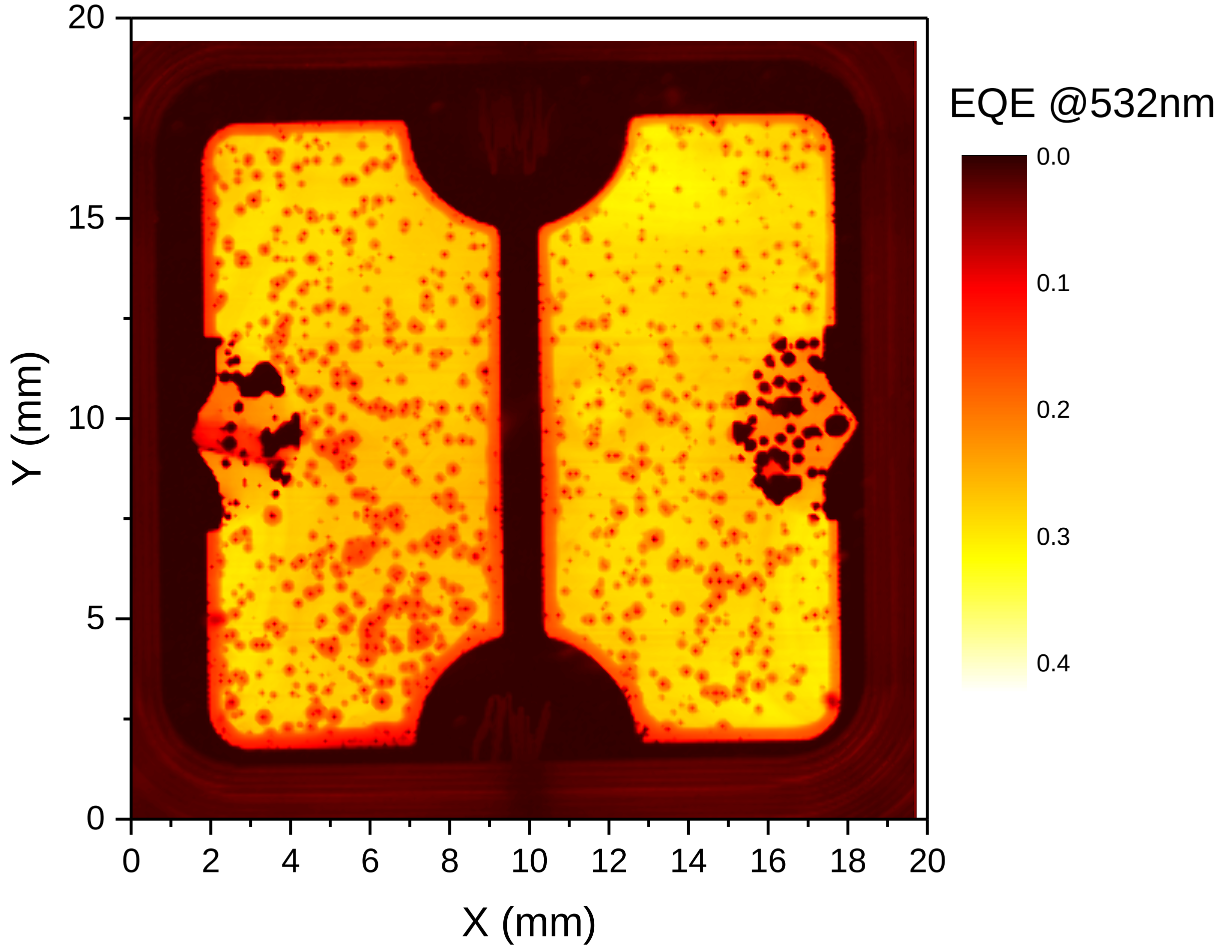


active area = 1 cm^2

Photocurrent map (MoO_3)



In N_2 atmosphere



Unprotected device after long term exposure to O_2

Final summary

- Still growing interest in OPVs. Key issues: defect characterisation in multiple scales / identification of degradation mechanisms
- Mapping/Imaging is key to provide insight into manufacturing and degradation issues
- Single methods are very limited. Combination of methods is preferred.
- Multiparameter (simultaneous) or in-situ characterisation avoids possible unwanted contamination/degradation between tests

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