Flexible organic devices: Towards ubiquitous electronics

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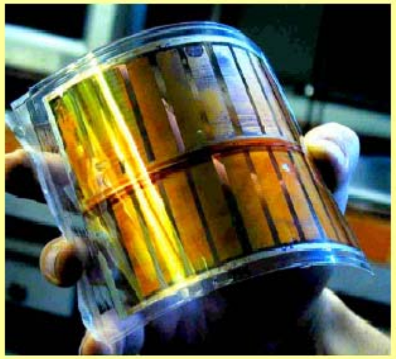
IEEE TTM, May 2012

Organic Semiconductors

- Large area & flexible substrates possible
- Large variety of materials
- Low cost

Organic materials

Organic light emitting diodes

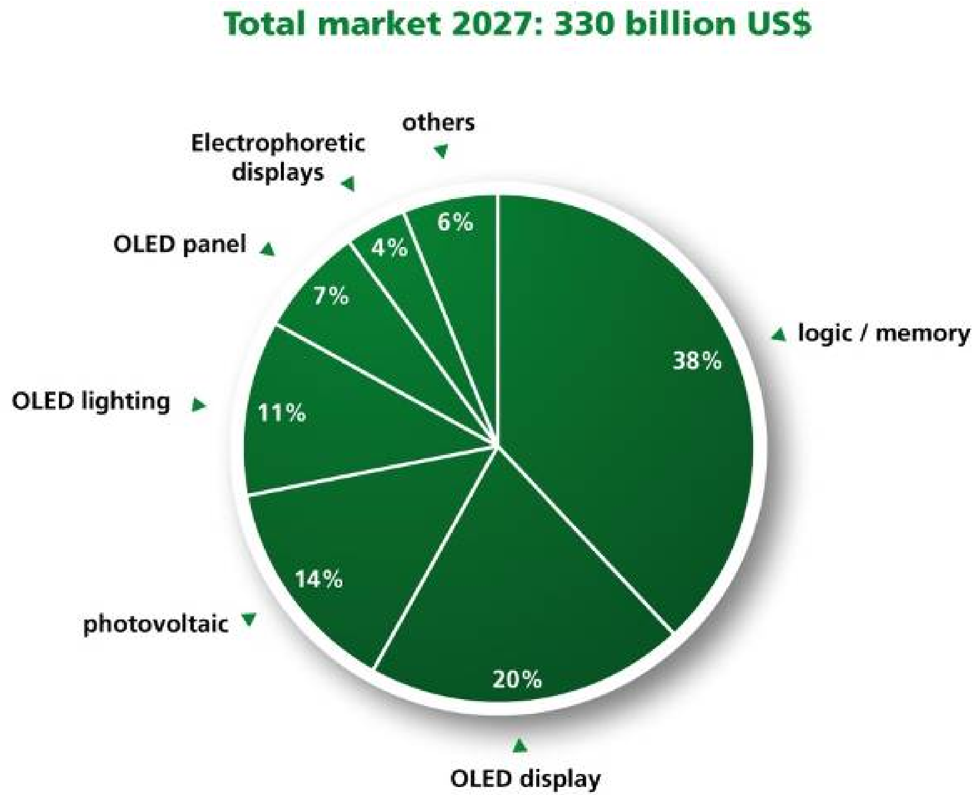


Photovoltaic cells

Transistors and memory

Future Markets for Organic Devices

- IdTechex study:
- 330 billion US$ in 2027
- Most important markets:
  - Logic/Memory
  - OLED-Display
  - Photovoltaics



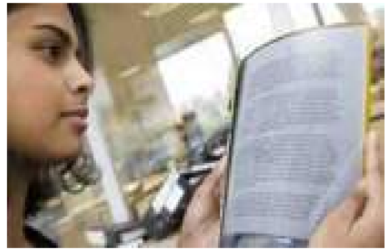
Progression of Organic Products

1st wave: OLED Displays

2nd wave:
OLED lighting

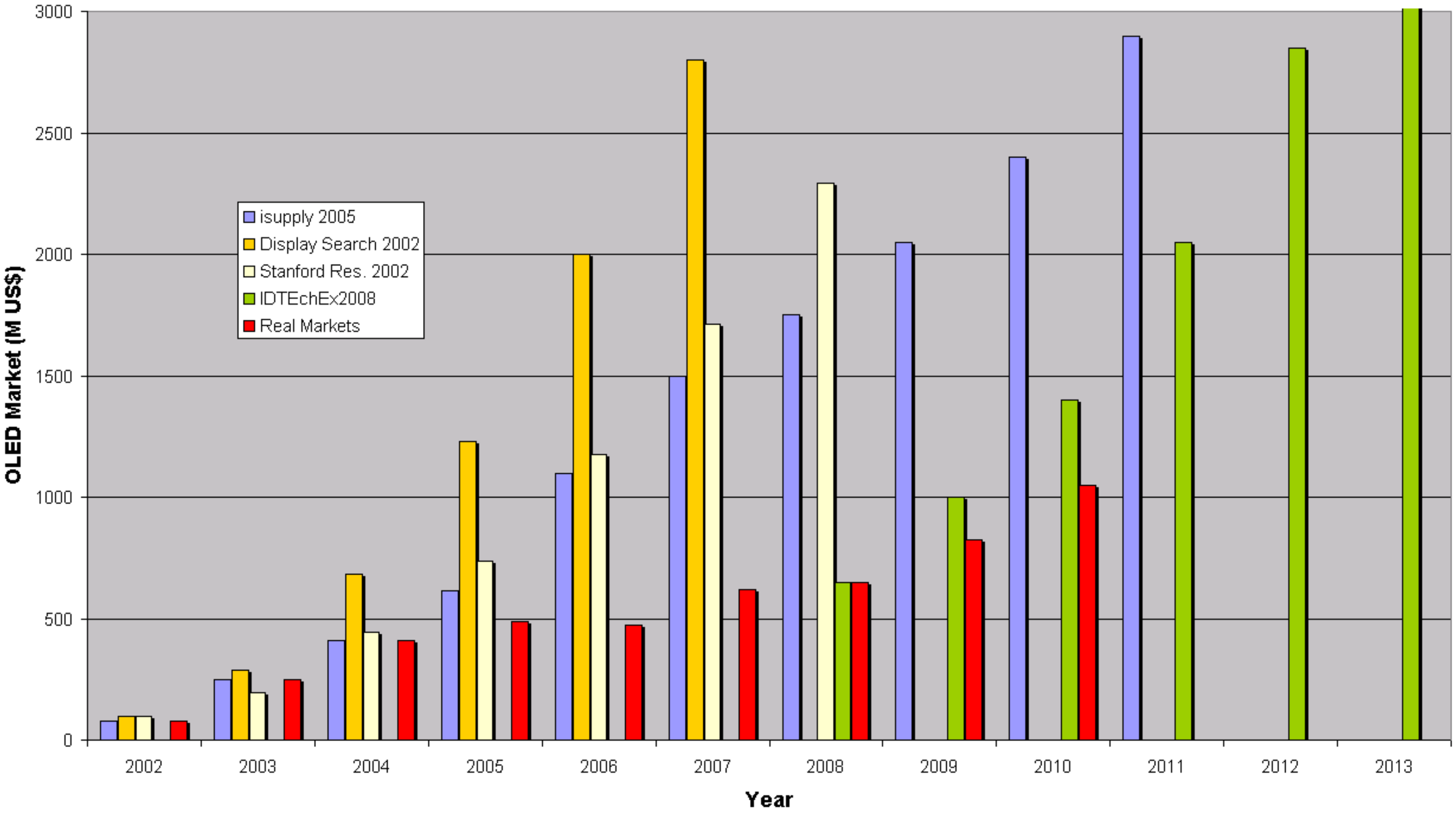
3rd wave:
Solar cells

4th wave:
Organic electronics

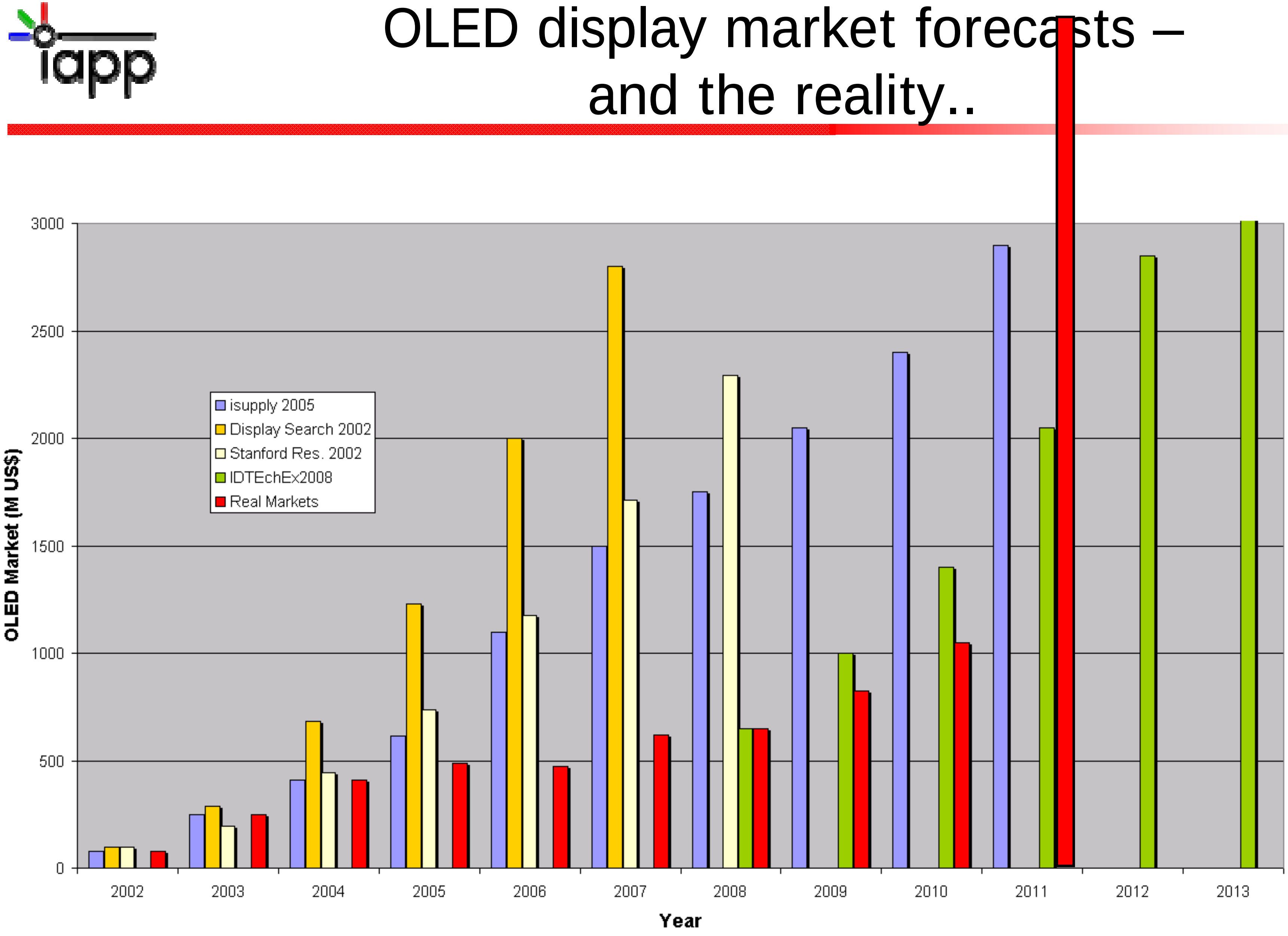


Time

OLED display market forecasts – and the reality..

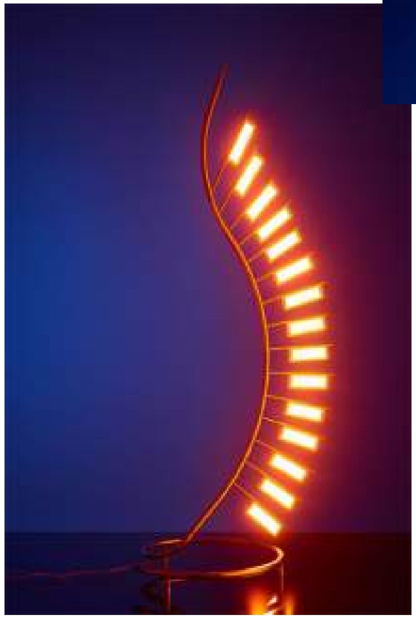


OLED display market forecasts – and the reality..



The OLED 55‘ TV is coming...

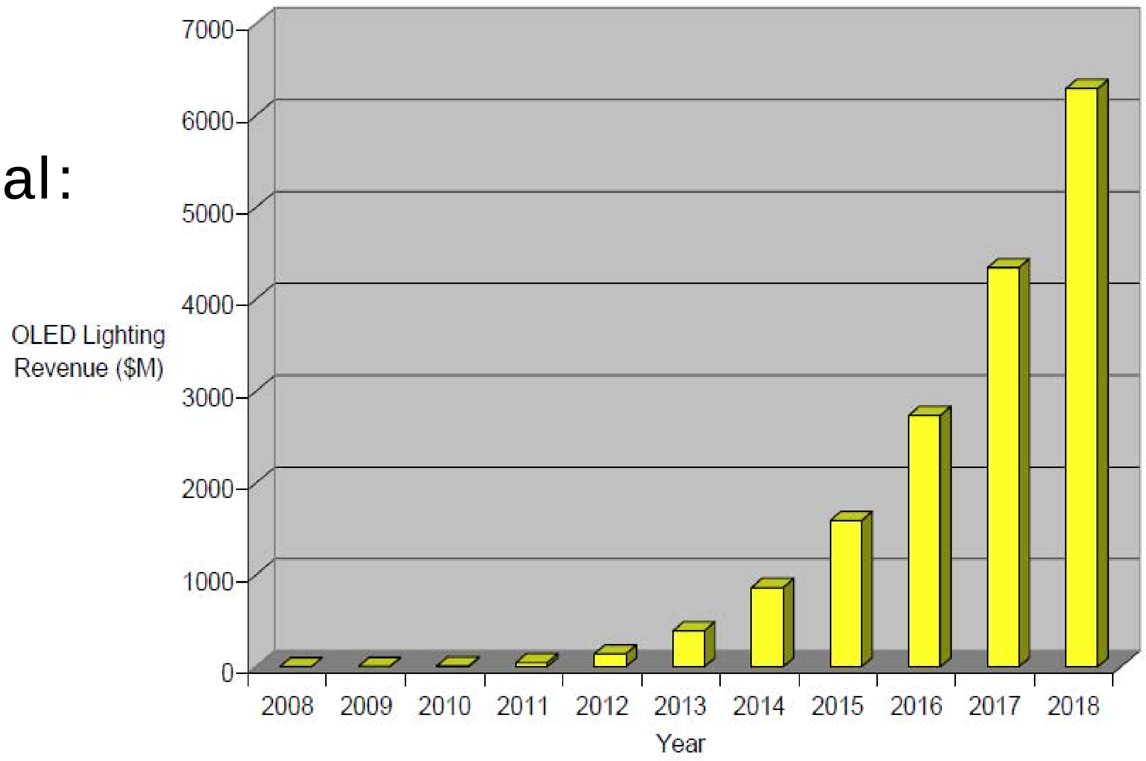
OLED Lighting Demonstrators



Source: Novaled

OLED lighting market forecasts

- OLED soon multibillion market?
- High efficiency crucial: 20-30lm/W reached >50lm/W required
- Brightness at least 1000, ideally up to 5000 Cd/m^2



Source: Displaysearch

Carbon: the influence of dimensionality

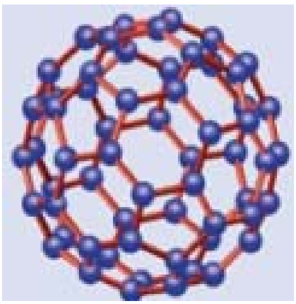
10^4

10^1

10^{-2}

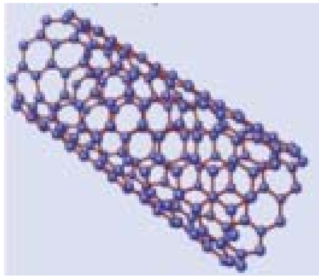
mobility

Van der Waals-
coupling:
Narrow bands



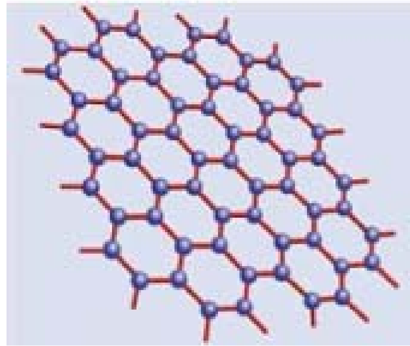
0D

1D covalent:
broad bands



1D

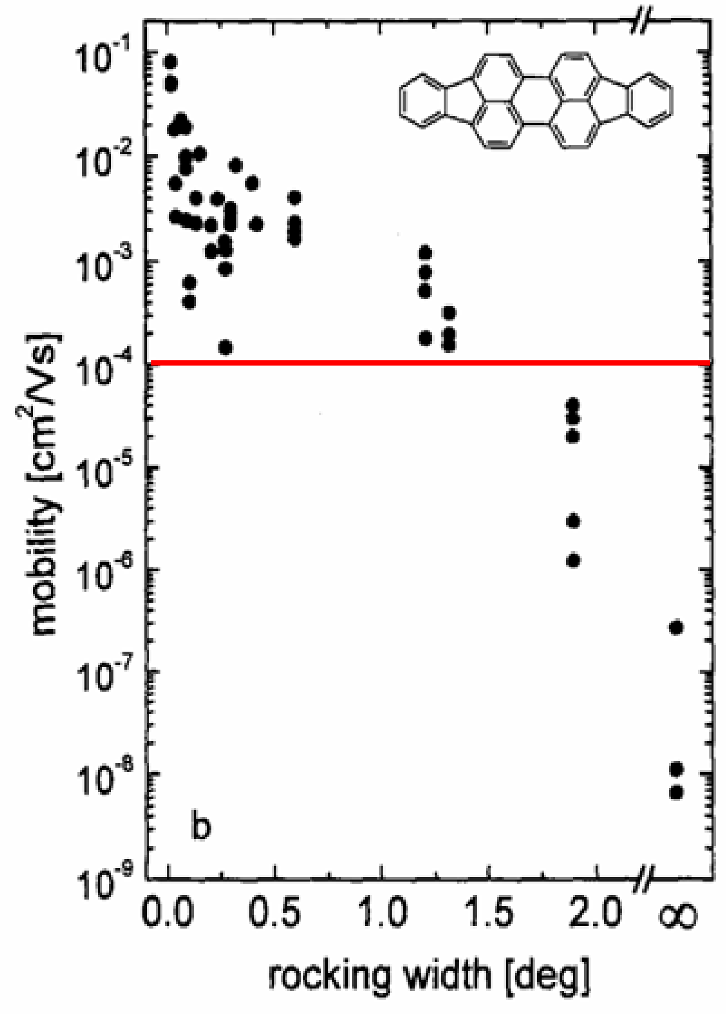
2D covalent
broad bands



2D

Source: Castro Neto, Geim et al.

Mobility as a function of disorder



Typical OLED today!

N. Karl et al. 2001

- Rocking width correlates with mobility
- Even small disorder reduces μ strongly
- Conductivities are accordingly low

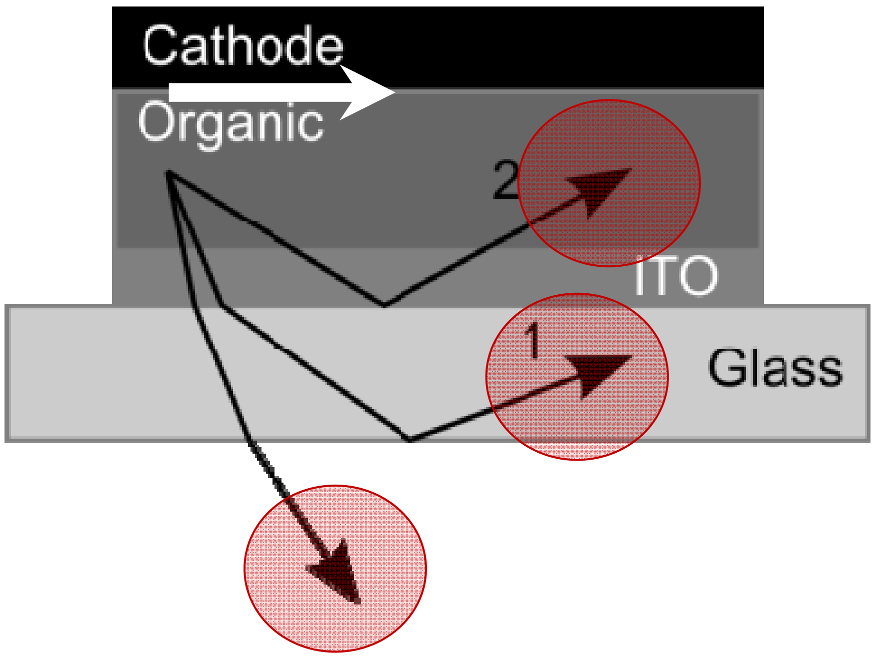
What determines OLED efficiency?

$$\eta_{external} = b_I \times \frac{h\nu}{eU} \times \eta_{recomb} \times \eta_{optical}$$

Outcoupling efficiency

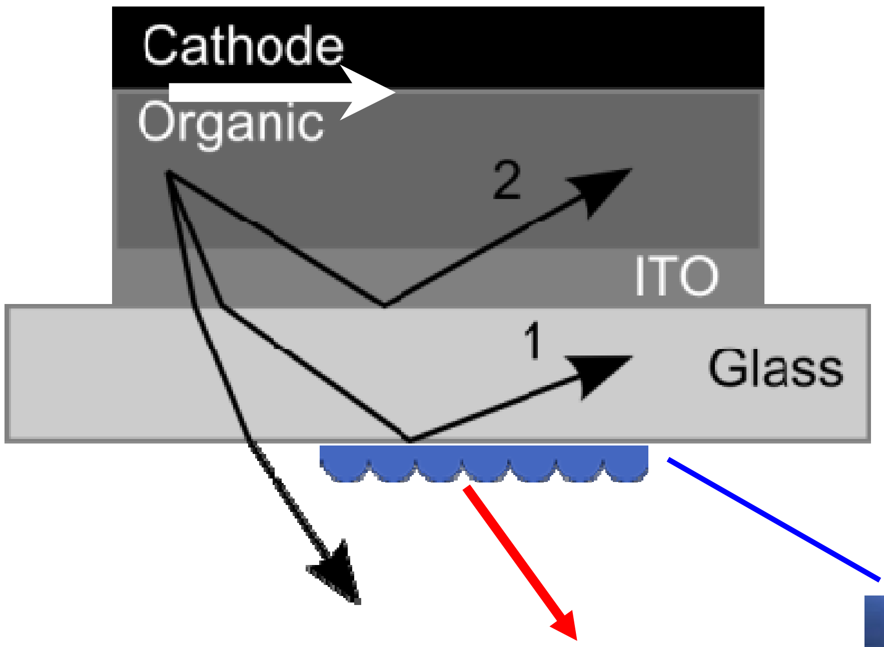
- b_I: Electron and hole current balance: 1 can be reached √
- eU: Operating voltage should be ≈ photon energy √
- η_{recomb}: 75% Triplet, 25% Singlet excitons: 0.25 for fluorescent emitter: Use phosphorescent emitters (Forrest/Thompson), optimize recombination zone √
- $\eta_{optical}$: about 20% in flat structure: 80% lost to wave guide modes

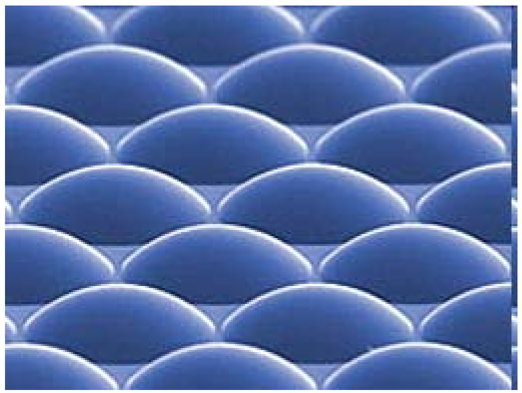
Distribution of Power in Modes



- **Outcoupled** modes
- **Substrate** modes (1)
- **Organic** modes (2)
- **Plasmonic** losses (3)

Substrate Modes: Outcoupling easily achieved

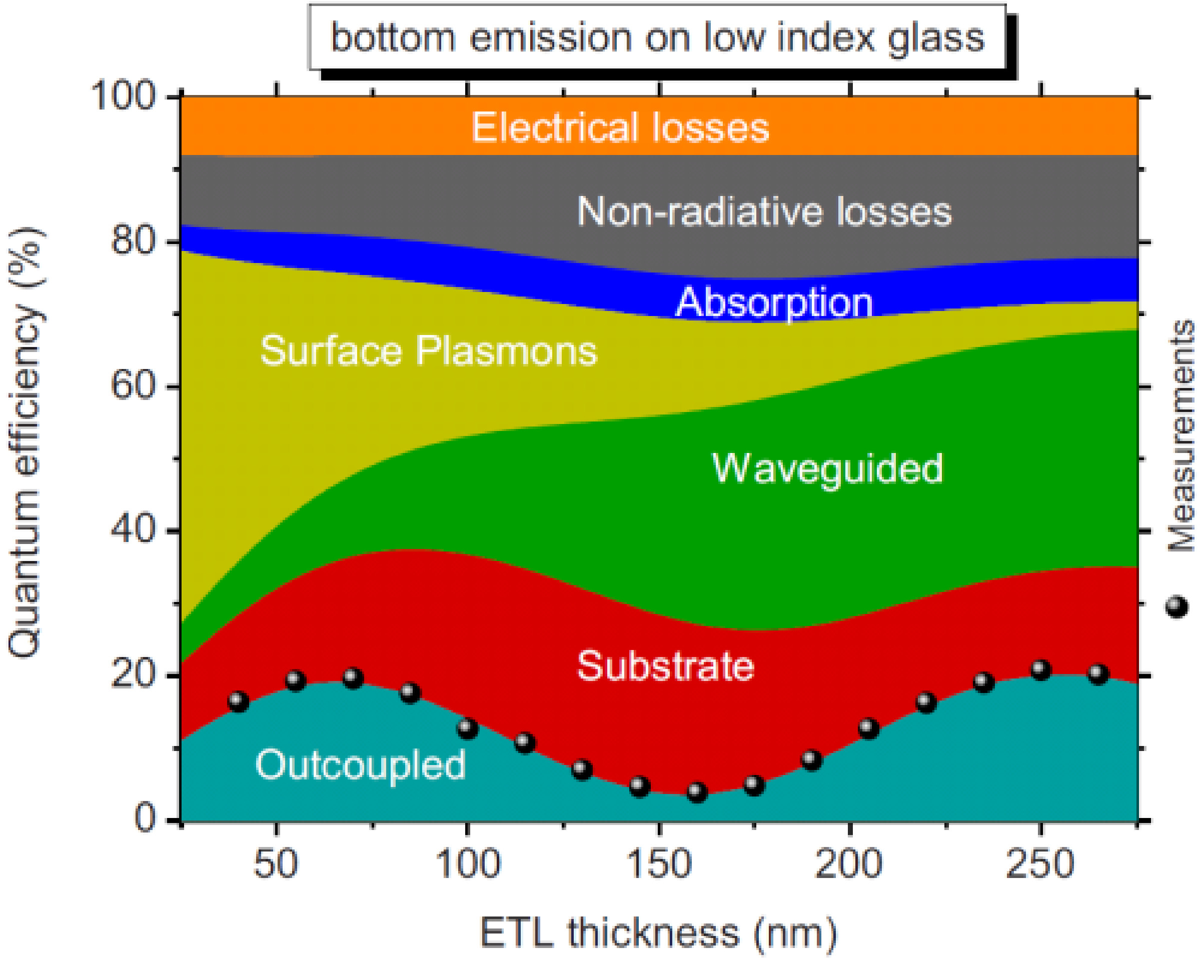




Source: Temicon

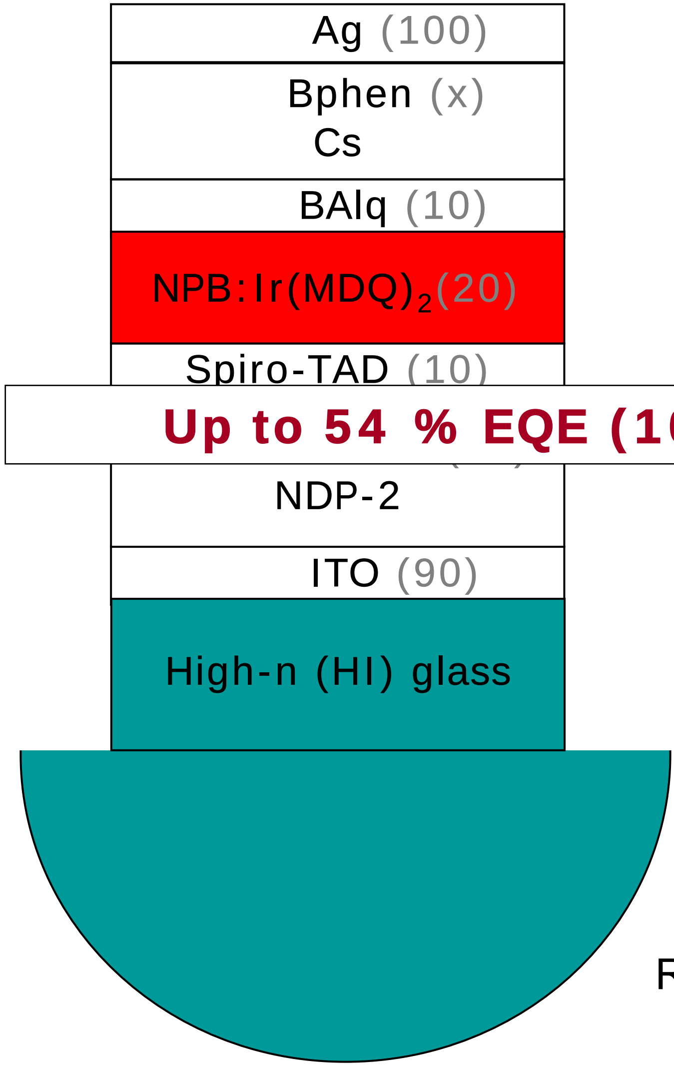
Distribution of power into different modes

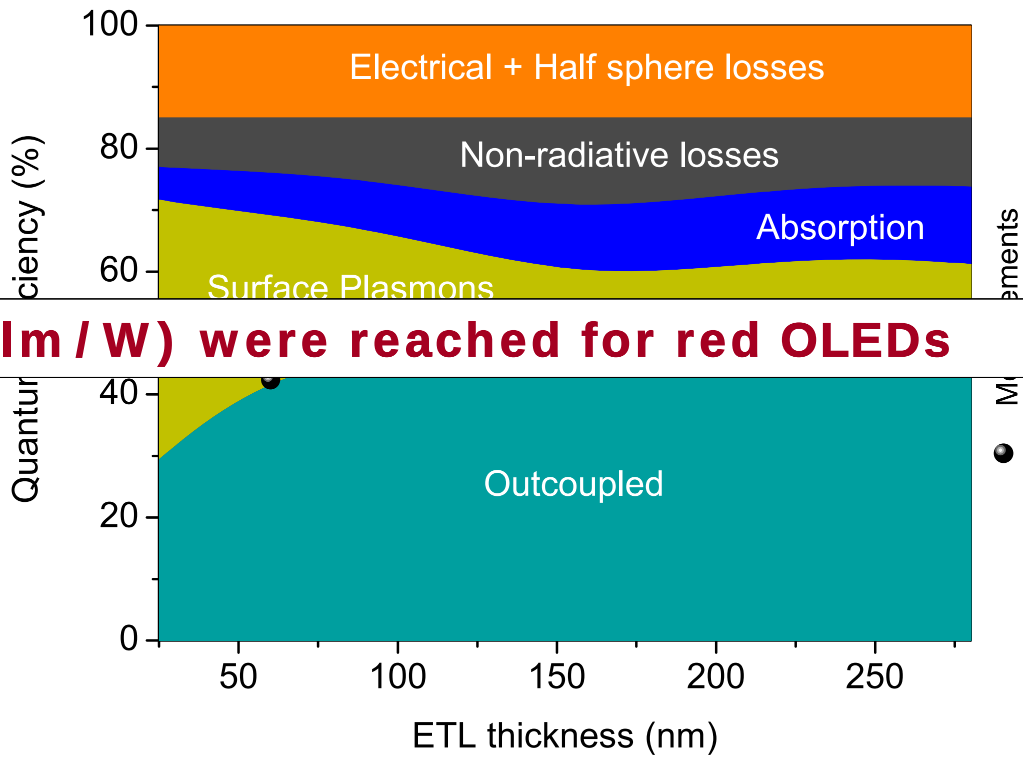
- Calculations by Mauro Furno (M. Furno et al. Proc. SPIE **7617**, 761716 (2010); Phys. Rev. B **85**, 115205 (2012))
- Model includes Purcell effect
- Model can be tested by variation of electron transport layer thickness



R. Meerheim et al., Appl. Phys. Lett. **97**, 253305 (2010)

Experiment: High Index Glass

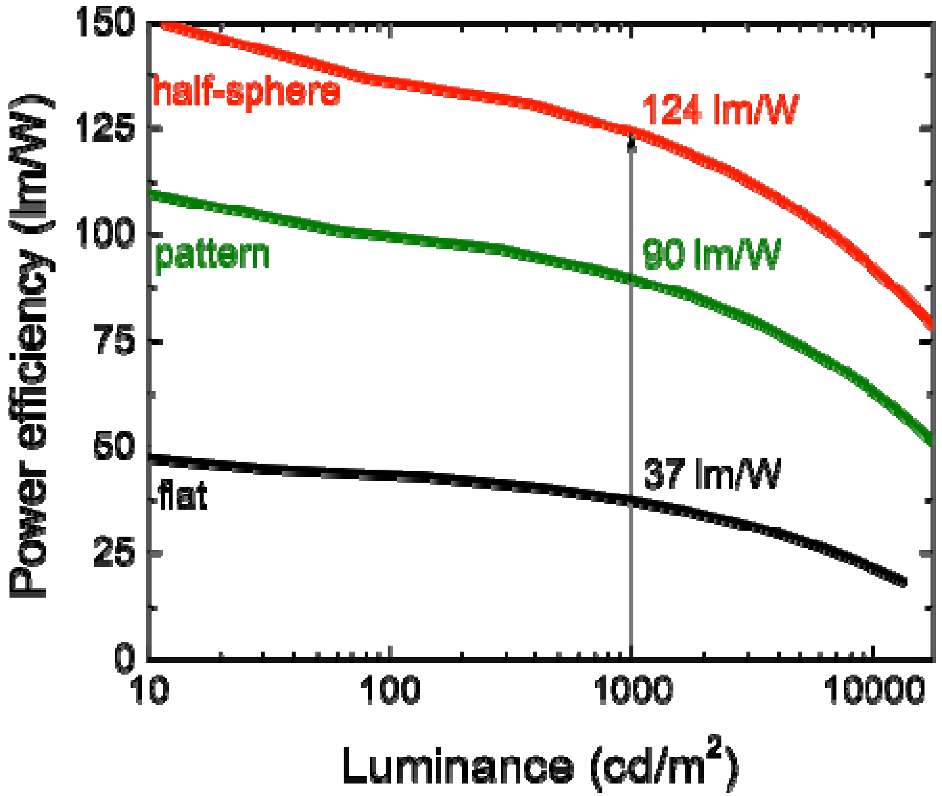


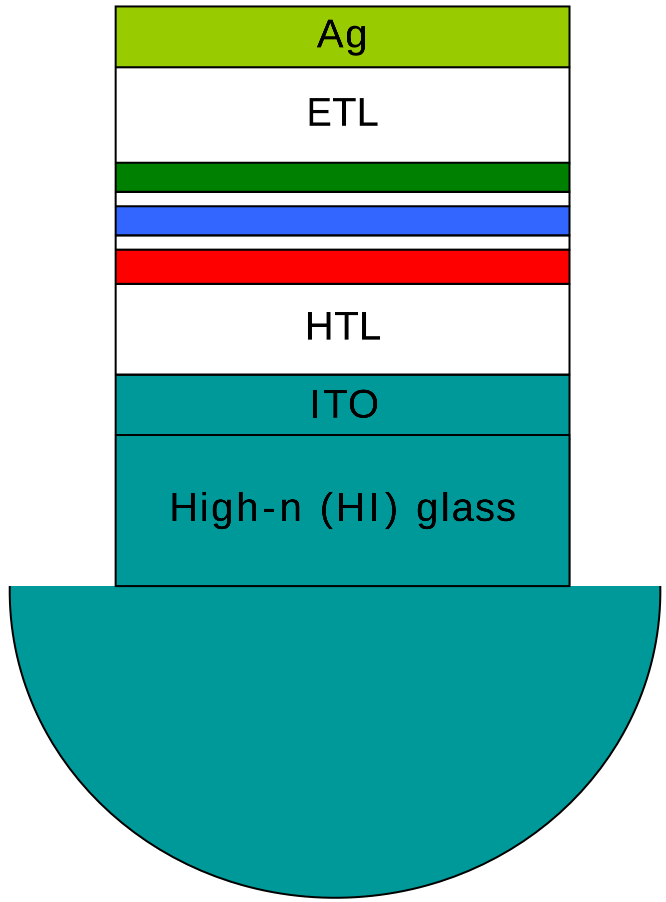


Up to 54 % EQE (104 lm / W) were reached for red OLEDs

R. Meerheim et al., Appl. Phys. Lett. **97**, 253305 (2010)

Results for White OLED





S. Reineke et al., Nature 459, 234-238 (2009)

Results with high-index thin films

nature photonics

LETTERS

PUBLISHED ONLINE: 30 OCTOBER 2011 | DOI: 10.1038/NPHOTON.2011.259

Unlocking the full potential of organic light-emitting diodes on flexible plastic

Z. B. Wang[1†*], M. G. Helander[1†*], J. Qiu[1], D. P. Puzzo[1], M. T. Greiner[1], Z. M. Hudson[2], S. Wang[2], Z. W. Liu[1] and Z. H. Lu[1,3*]

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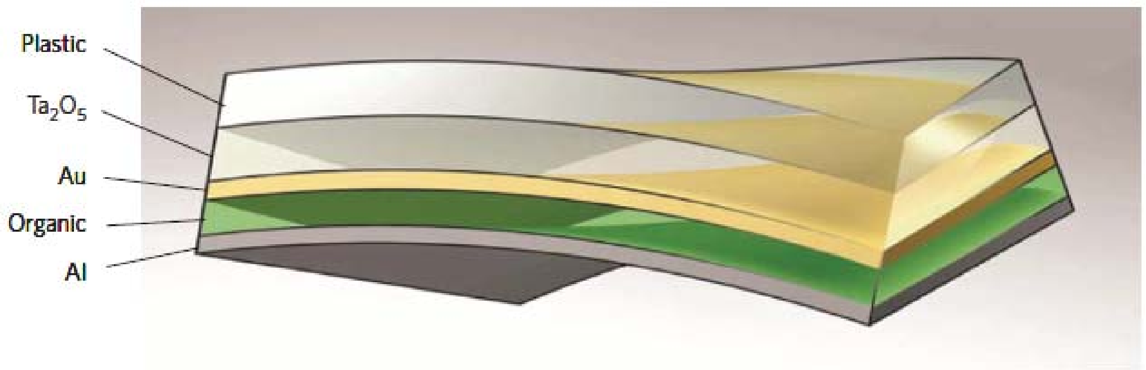
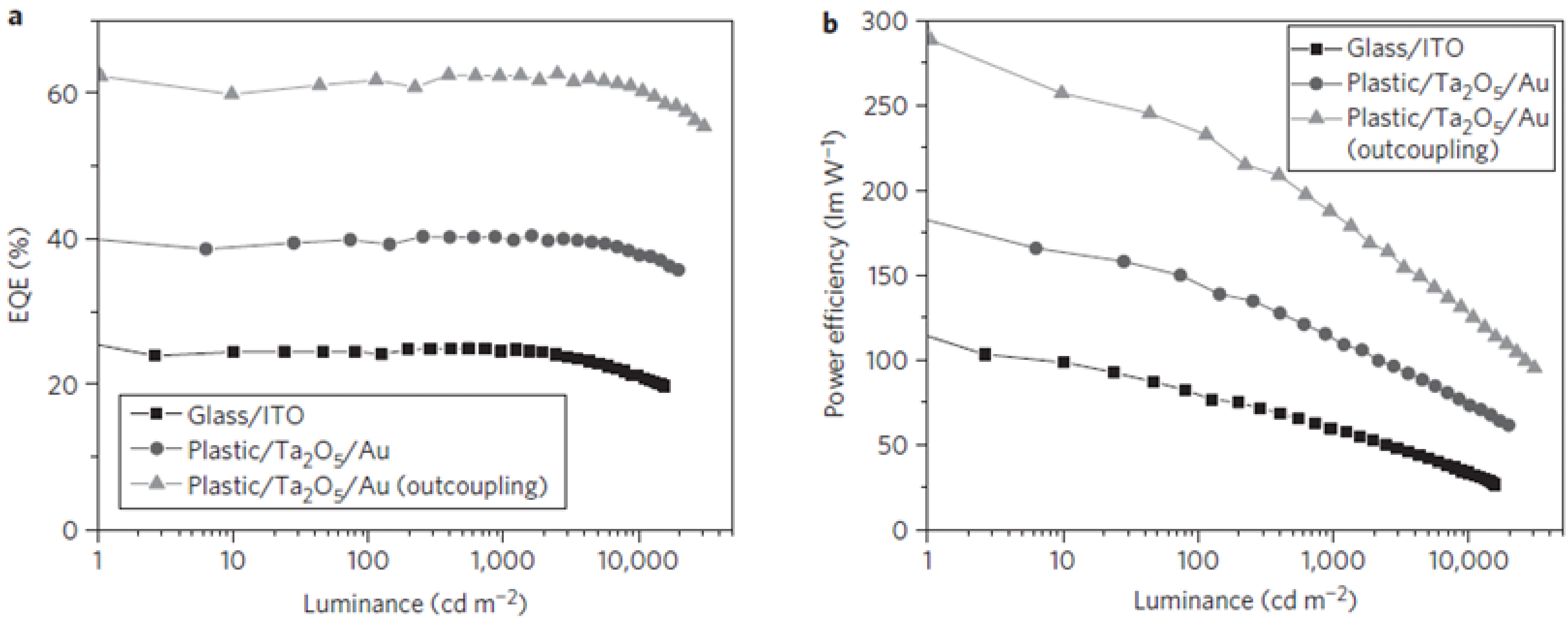


Results with high-index thin films

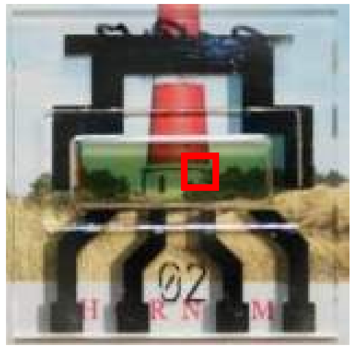


- Extremely high quantum and power efficiency
- Approach not yet proven for white

- Z.B. Wang et al., Nature Photonics **5**, 753 (2011)

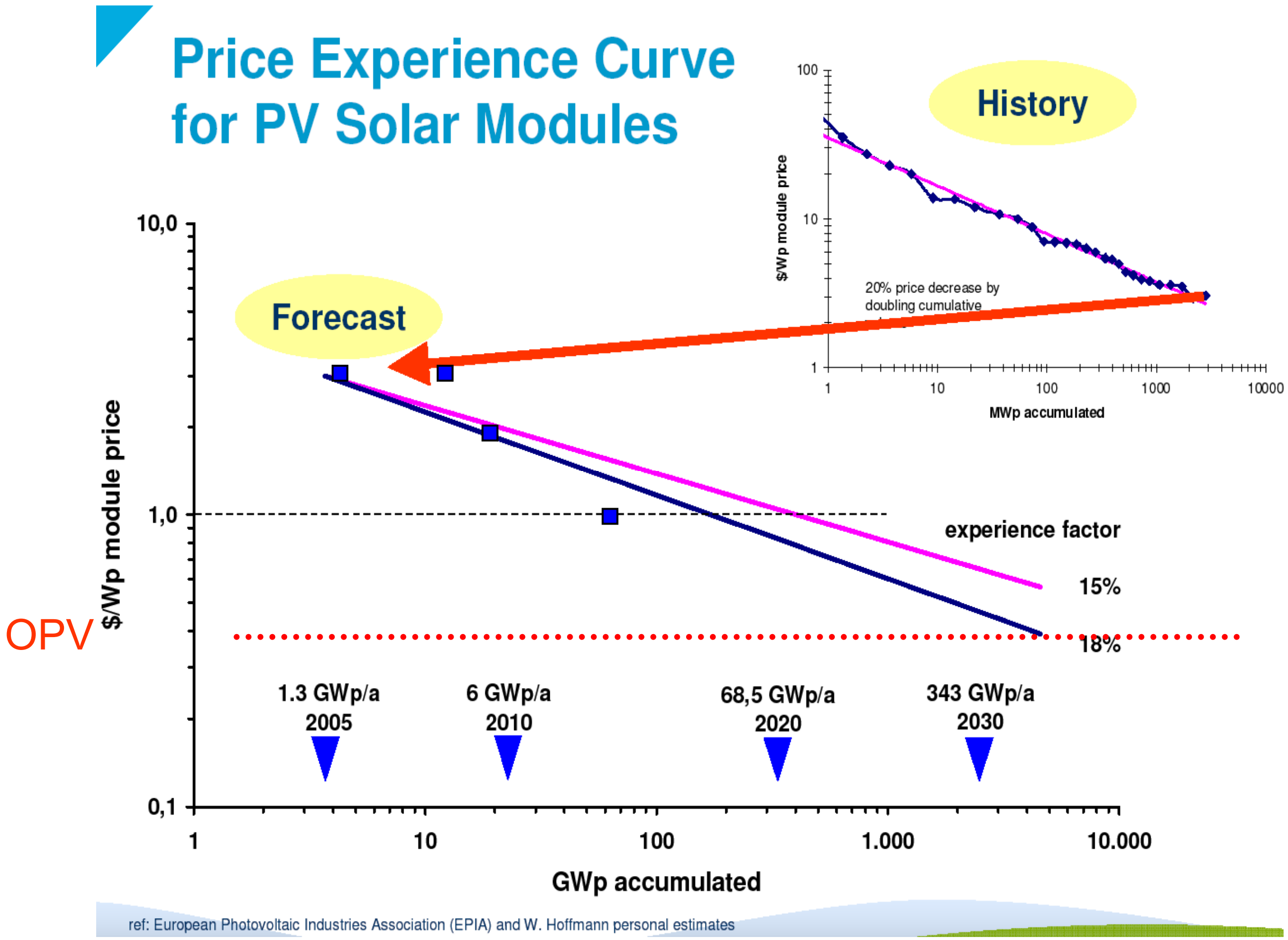
Potential of Organic Photovoltaics

- Flexible plastic substrates and thin organic layers
  - Low material and energy consumption
  - Short energy payback time
- Potentially transparent, color adjustable
- Compatible with low-cost large-area production technologies



Images: Konarka, Neuber, Heliatek, IAPP

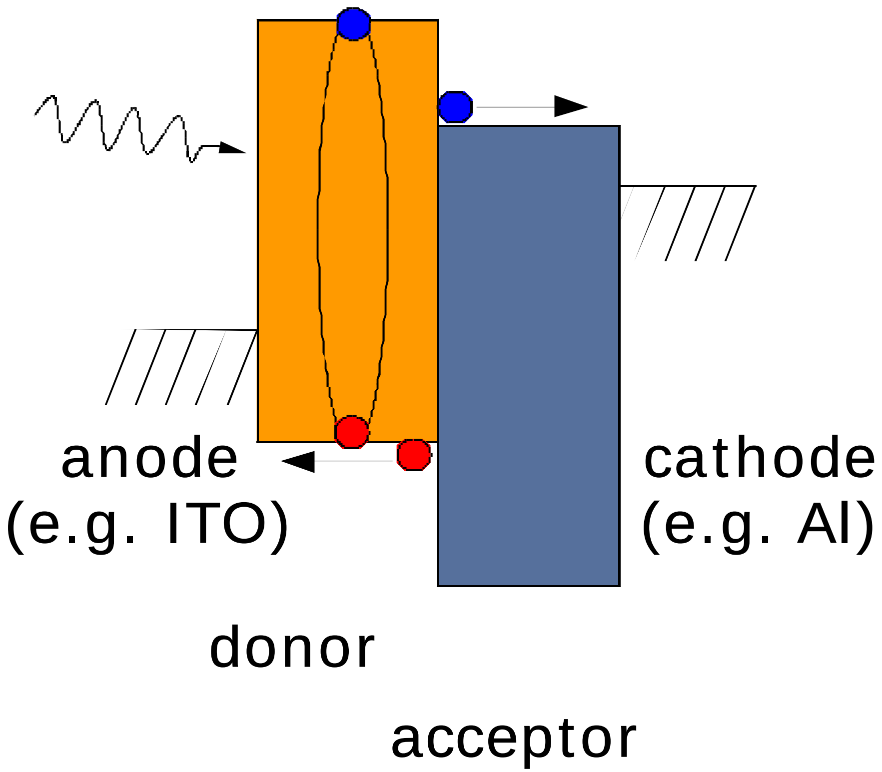
Organic Solar Cells – where is the Market?



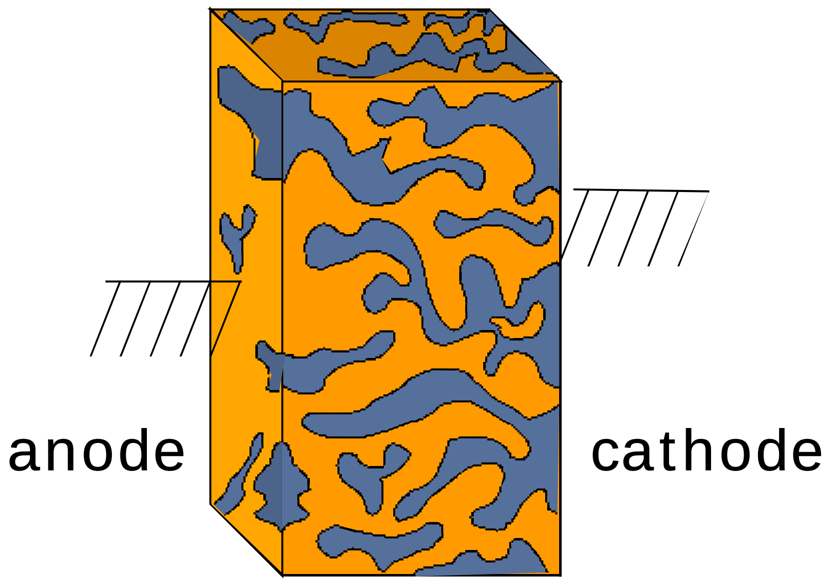
- „Window of opportunity“ in power market: 2015-2030
- What is needed: 10-12% in module = 15-17% in lab
- Lifetime at least 10 years

Exciton separation at a heterojunction

Flat heterojunction (FHJ)

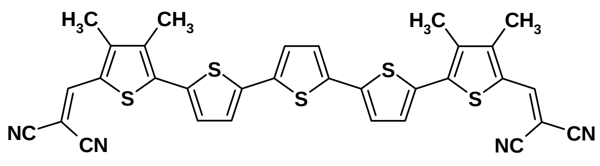


bulk heterojunction (BHJ)

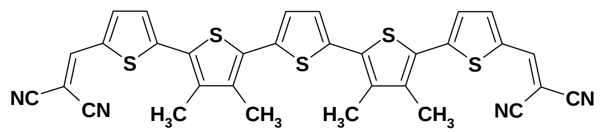


C. W. Tang, Appl. Phys. Lett. 48, 183 (1986)
M. Hiramoto et al., Appl. Phys. Lett. 58, 1062 (1991)
J. J. Hall et al., Nature 376, 498 (1995)
G. Yu et al. Science 270, 1789 (1995)

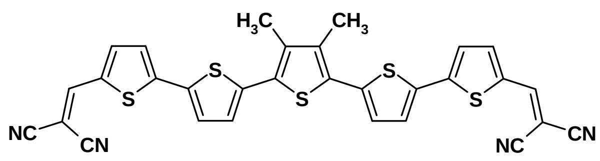
New Thiophenes: DCV5T-Me Series



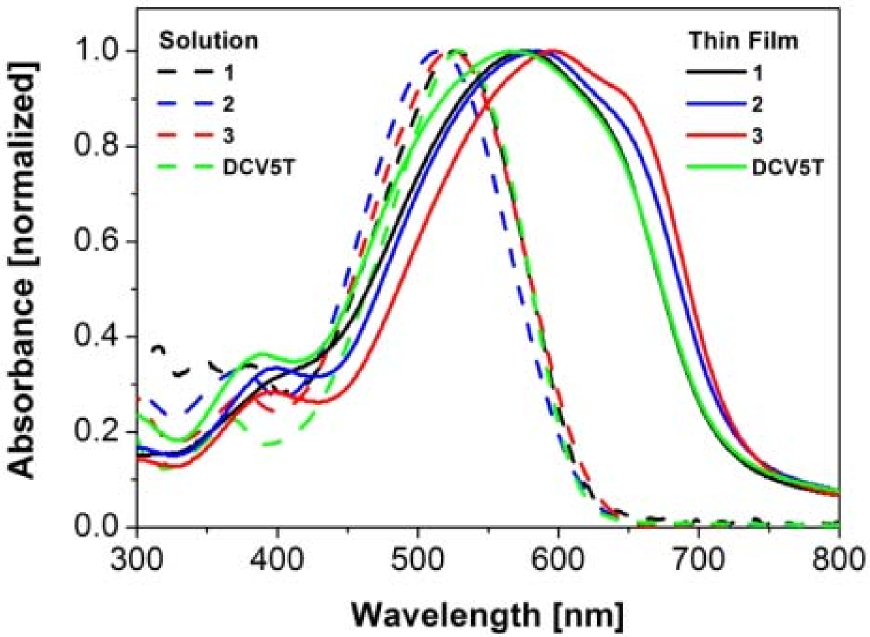
1: DCV5T-Me(1,1,5,5)



2: DCV5T-Me(2,2,4,4)



3: DCV5T-Me(3,3)

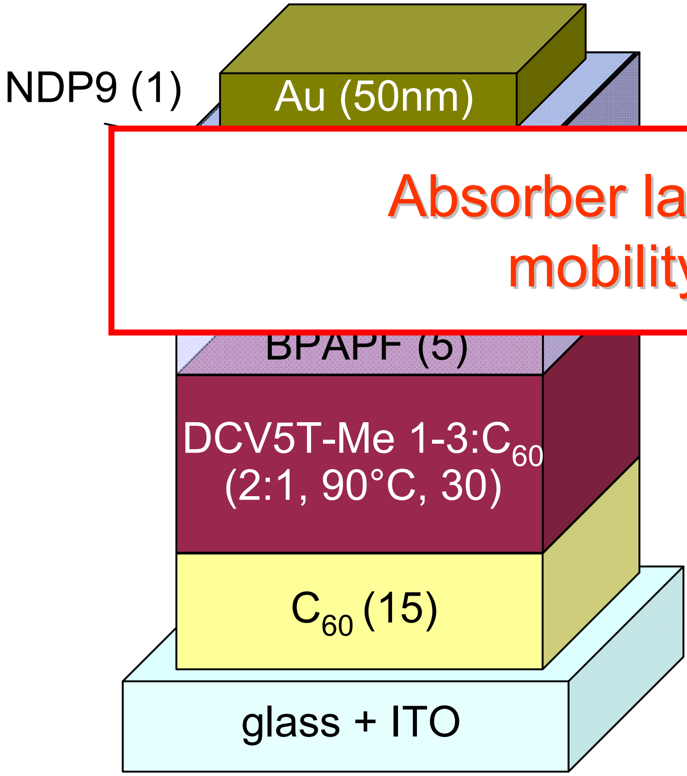


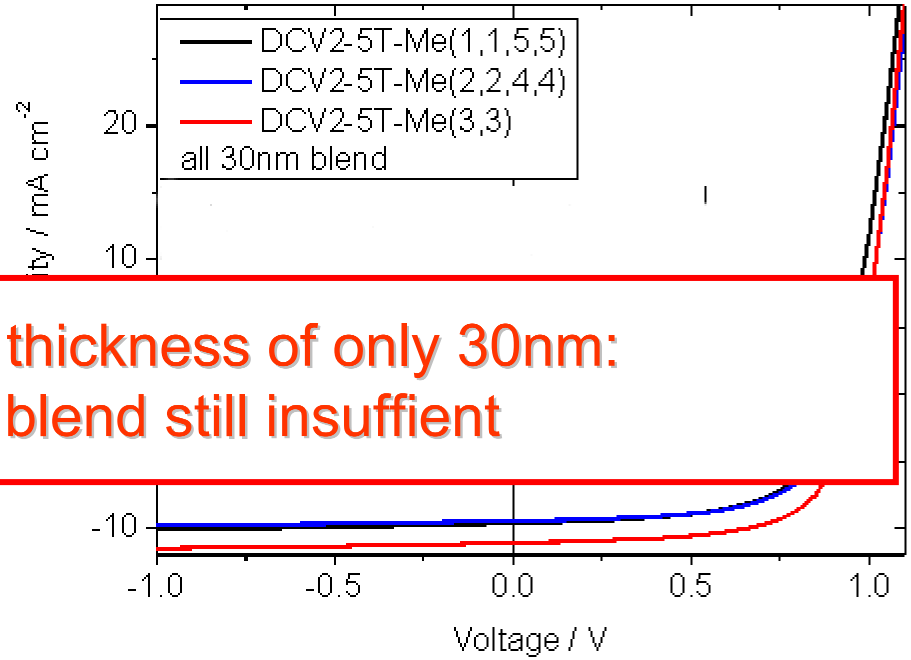
Heliatek

University of Ulm
Department Organic
Chemistry II

R. Fitzner *et al.*, submitted (2012)

DCV5T-Me Results



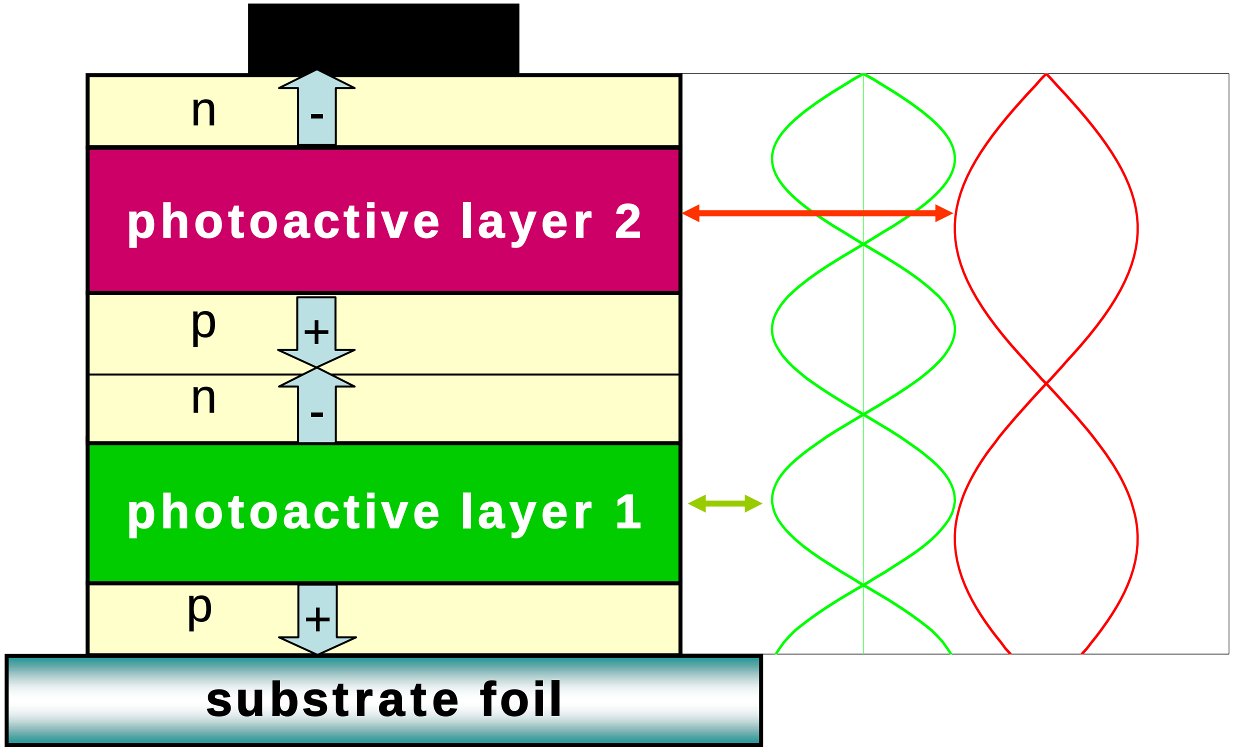


Absorber layer thickness of only 30nm: mobility in blend still insuffient

#	V_{OC} (V)	I_{SC} (mA/cm²)	FF	Eff.(%)
1	0.91	9.6	62.5	**5.5**
2	0.95	9.4	62.1	**5.6**
3	0.96	11.1	65.6	**7.0**

University of Ulm
Department Organic
Chemistry II

Pin-tandem cells:
doped layers are critical for optical optimization



p-i-n tandem cells:

- Pn-junction is ideal recombination contact
- optimizing interference pattern with conductive transparent layers

=>optical engineering on nanometer layer thickness scale

J. Drechsel et al., Appl.Phys.Lett. **86**, 244102 (2005)

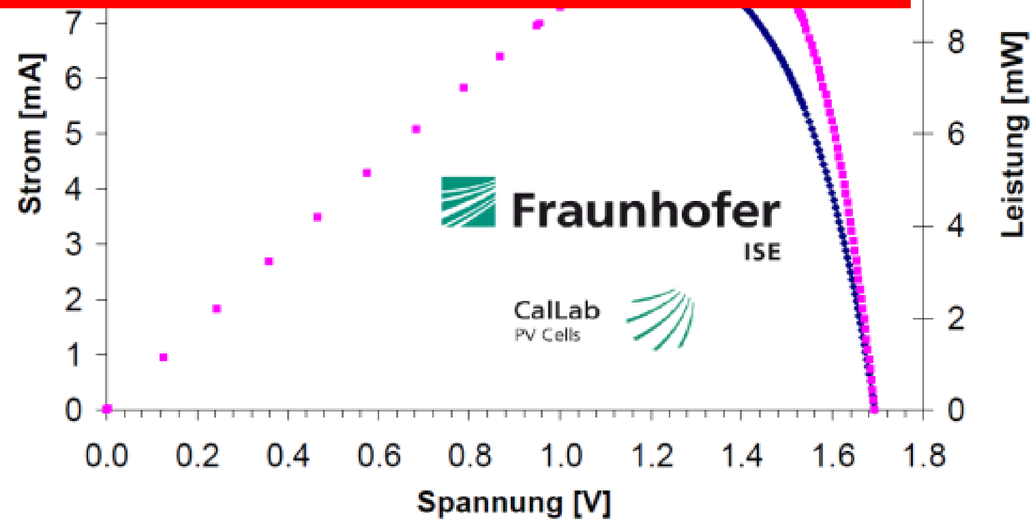
Small-Molecule OPV Record > 1cm²

Leerlaufspannung:	V_{OC}	=	(1.6930 ± 0.0085) V
Kurzschlussstrom:	I_{SC}	=	(9.08 ± 0.23) mA
Füllfaktor:	FF	=	(68.27 ± 0.68) %
Wirkungsgrad:	η	=	(9.75 ± 0.30) %

Latest Result: 10.7% certified by SGS Fresenius

9.7 % on 1.1cm² certified by Fraunhofer ISE, Germany

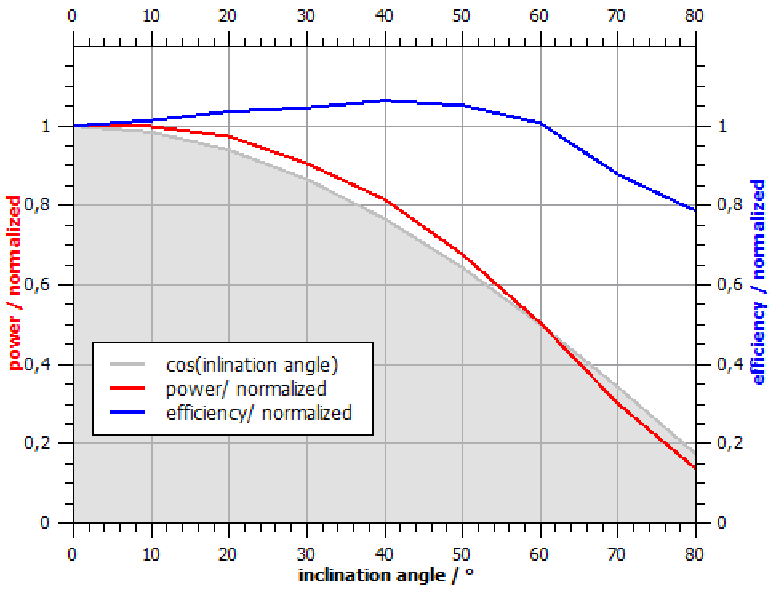
Heliatek®
Say hello to solar. Wherever you are

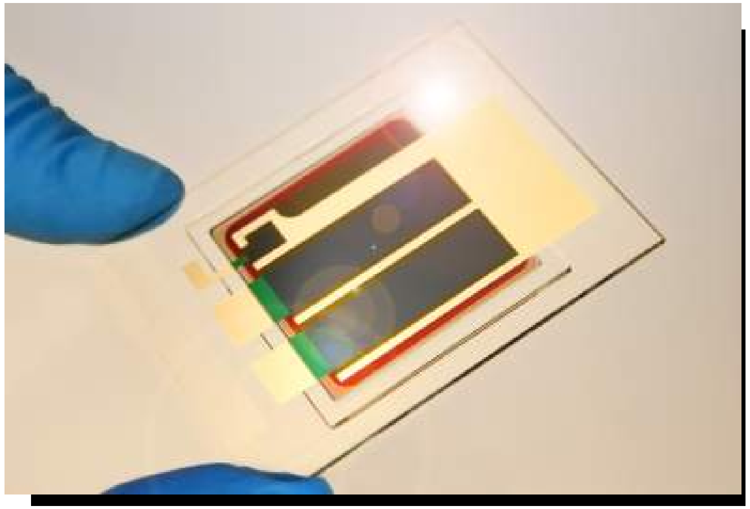


Organics is more: The O-Factor

- Standard measurement: 1 sun, 25 ^{0}C, perpendicular incidence
- Reality: 40-60 ^{0}C, often less than 1 sun, diffuse light
- Organics:
  - Positive temperature coefficient
  - Higher efficiency for lower intensity
  - Special diffuse light responsivity
- Sums up in the O-Factor: approx. 30% better!

Incident Angle Performance



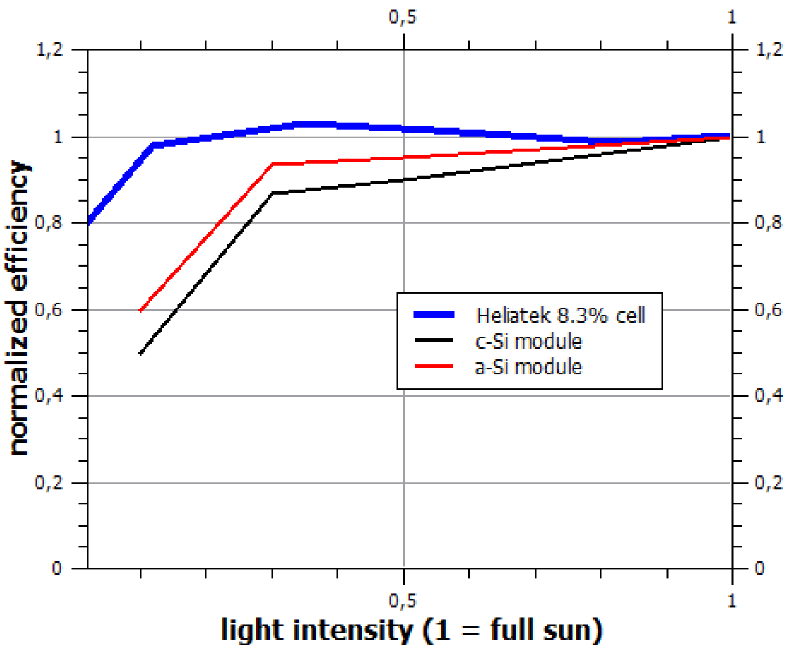


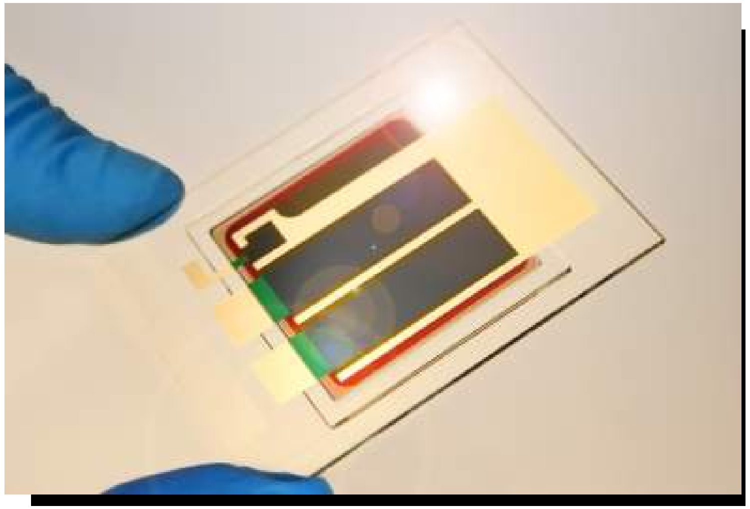
High independence on incident angle:

Efficiency development from 0 to 60° above the expected values of pure geometrical consideration

- Heliatek Absorber
- Certified Efficiency: **8.3 %** (1 cm^2)
- Collaboration of Heliatek und IAPP (TU Dresden)

Intensity Performance





Superior low-light performance:

97 % of full-sun efficiency at 1/10th sun

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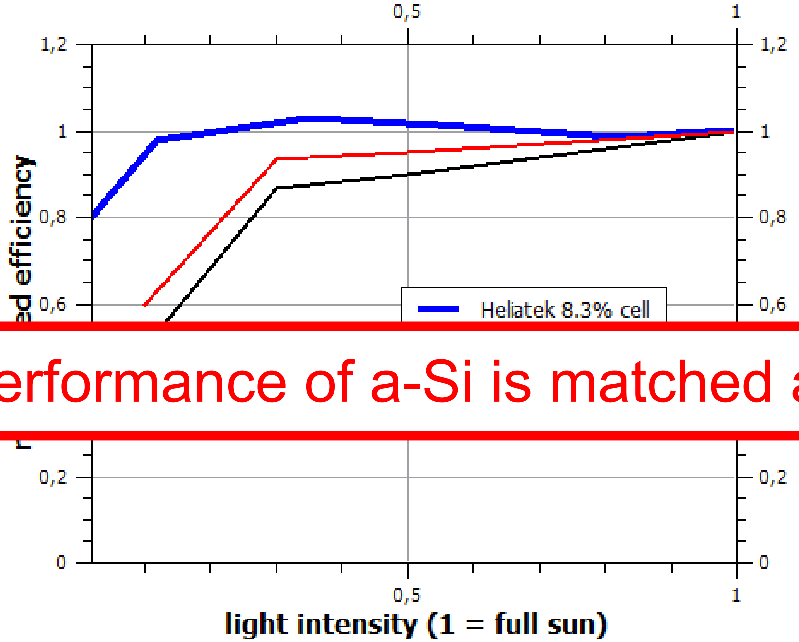
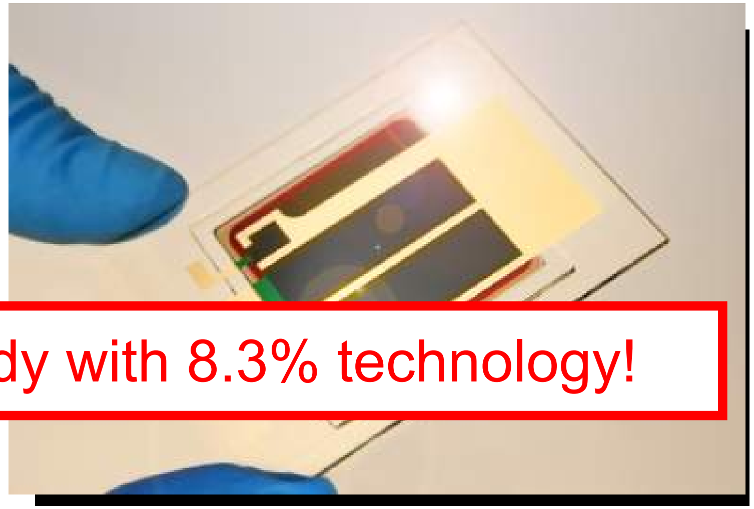
Intensity Performance





Performance of a-Si is matched already with 8.3% technology!

Superior low-light performance:

97 % of full-sun efficiency at 1/10th sun

- Heliatek Absorber
- Certified Efficiency: **8.3 %** (1 cm^2)
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Development of OPV Efficiencies

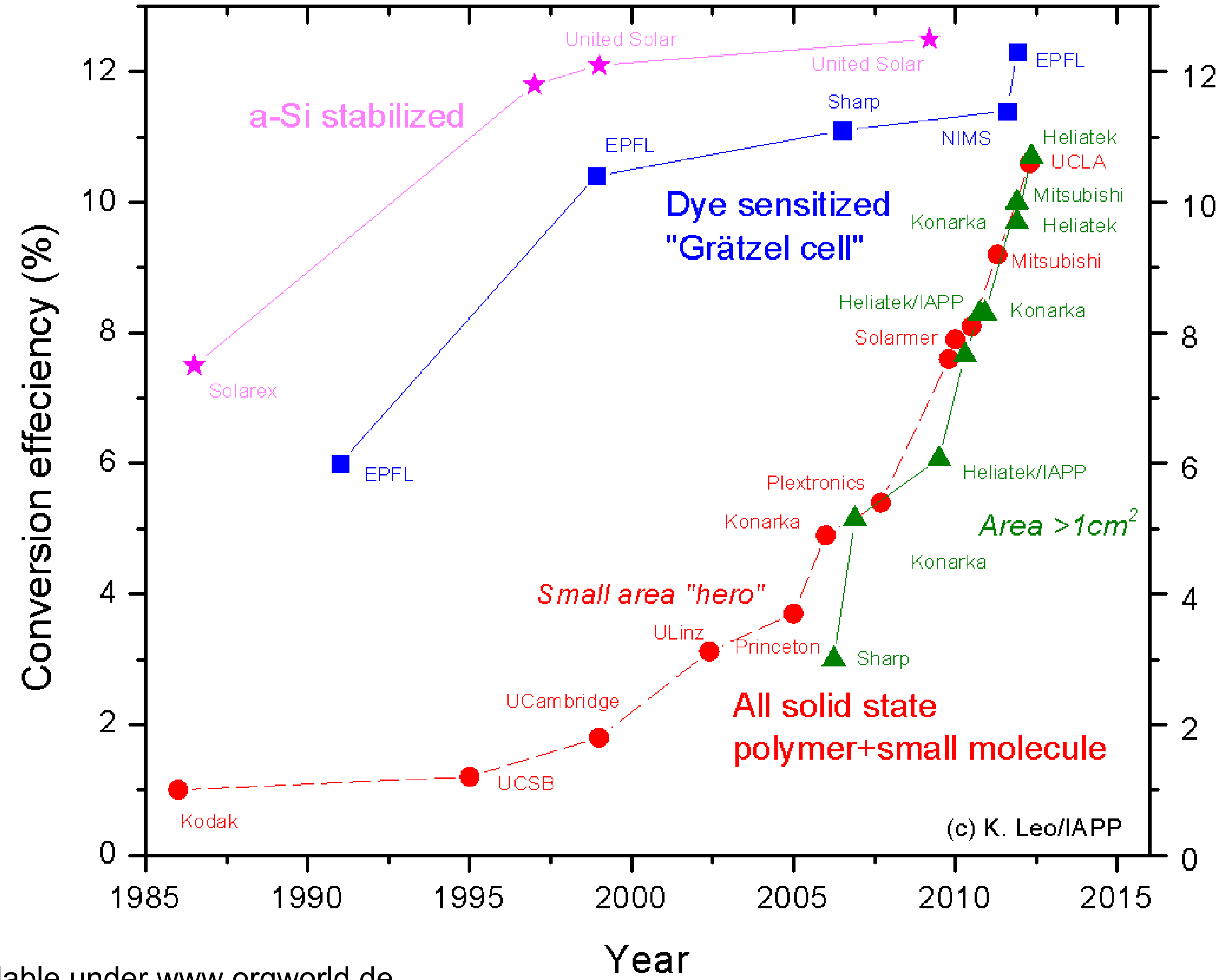
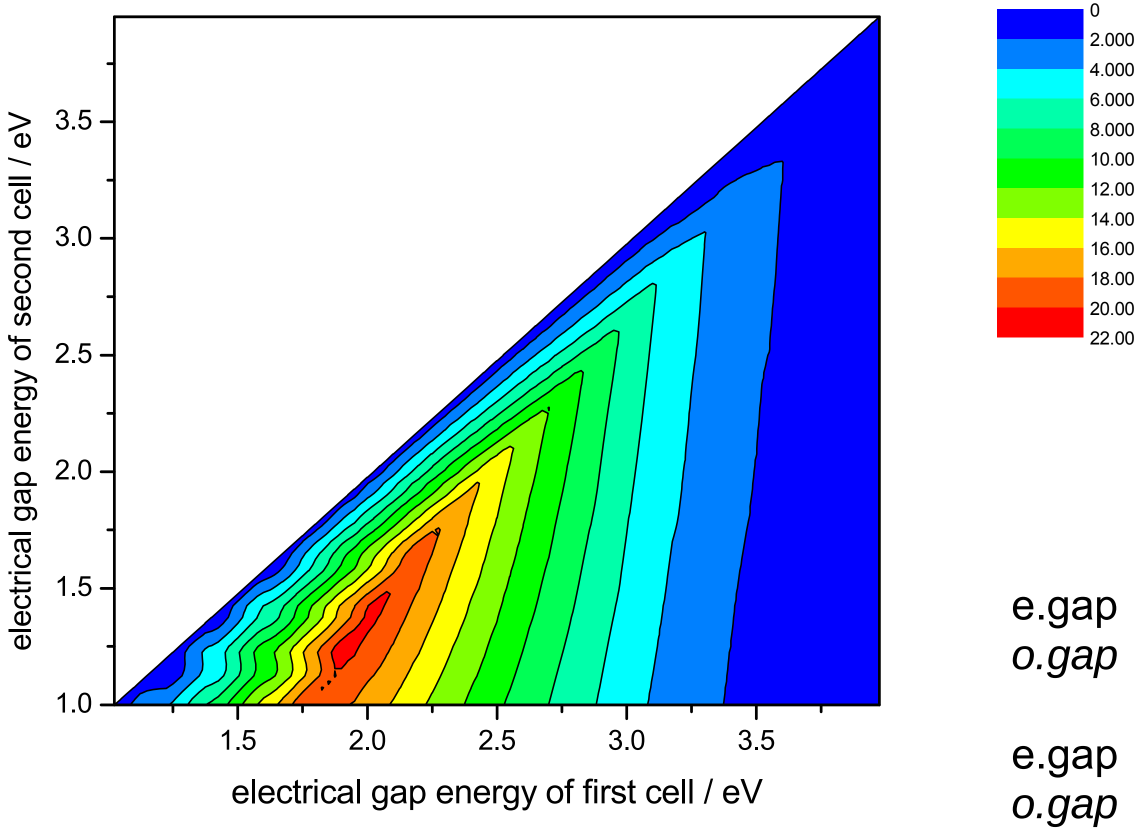


diagram available under www.orgworld.de

Efficiency Outlook for Tandem Cells

Power conversion efficiency of a tandem cell (in %)

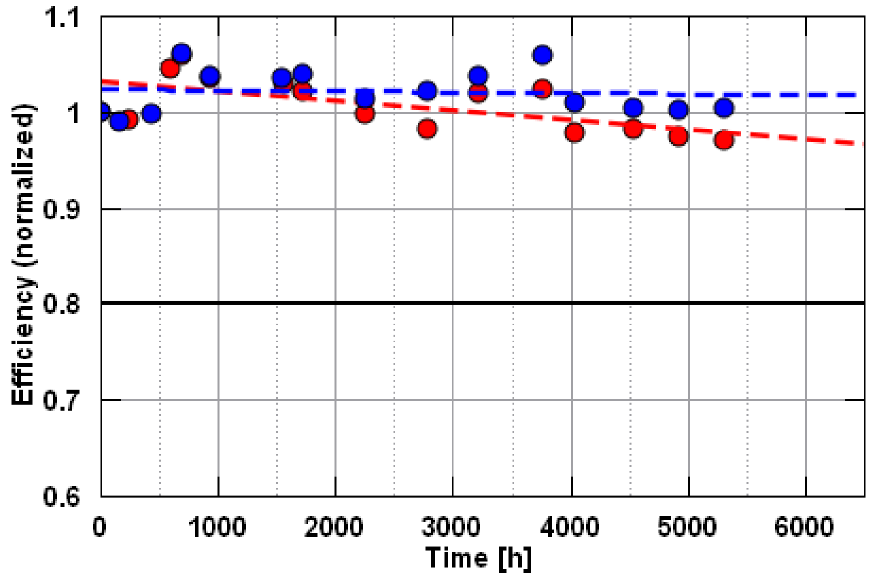


	first cell	second cell	
e.gap	1.9eV	1.25eV	~21%
o.gap	*~770nm*	*~1300nm*	
e.gap	2.1eV	1,5eV	~20%
o.gap	*~690nm*	*~1030nm*	
e.gap	2.225eV	1.7eV	~19%
o.gap	*~645nm*	*~890nm*	

T. Mueller et al.

Lifetime of Thiophene Tandem Cells

- Collaboration between Heliatek & IAPP
- Absorber materials from BASF and Heliatek, dopants from Novaled
- Glass-glass encapsulation
- Halogen light at about 1.5 suns



Stress Conditions	Device Temperature	Integrated Light Dosis	Corresponding Exposure Time in Middle Europe
blue	50°C	8.1 MWh/m²	8 y
red	85°C	dark	

heliatek

Gen2 Pilot Fabrication Line for OLED Lighting at COMEDD

- Including **lithography-free substrate structuring**
- Substrate size **370 x 470 mm² (Gen2)**
- Modular fully automated cluster system
- Plasma pretreatment
- Organic film deposition
  - Vacuum Thermal Evaporation VTE
  - Organic Vapor Phase Deposition OVPD
- Metal film deposition
- Direct connection to encapsulation system

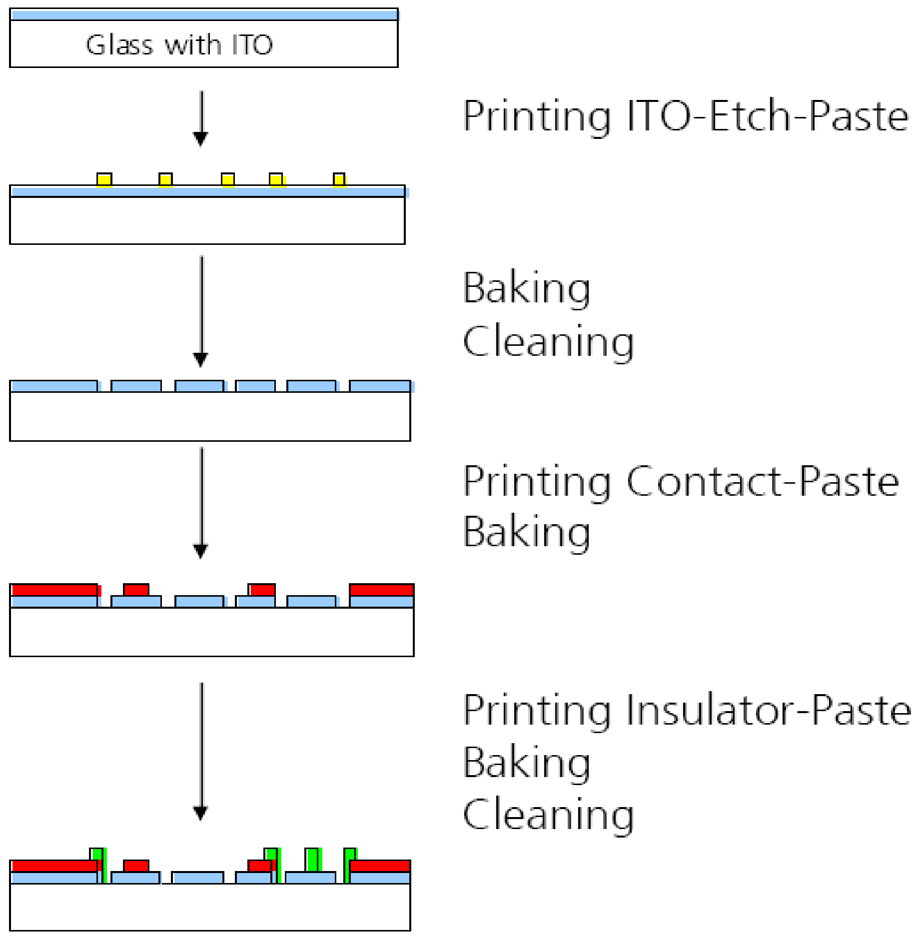
COMEDD Fraunhofer IPMS

Photolithography-free substrates of Gen2 size

ITO structuring:
- Screen-printed etch paste
- Laser ablation

Screen printing of busbars

Screen printing of passivation layers



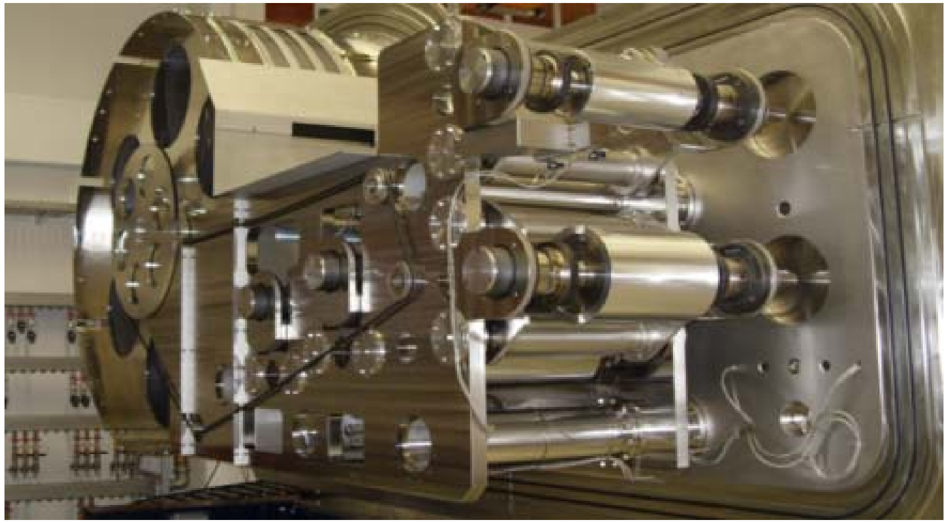
Custom Designed OLED Modules

Roll to roll vacuum coater

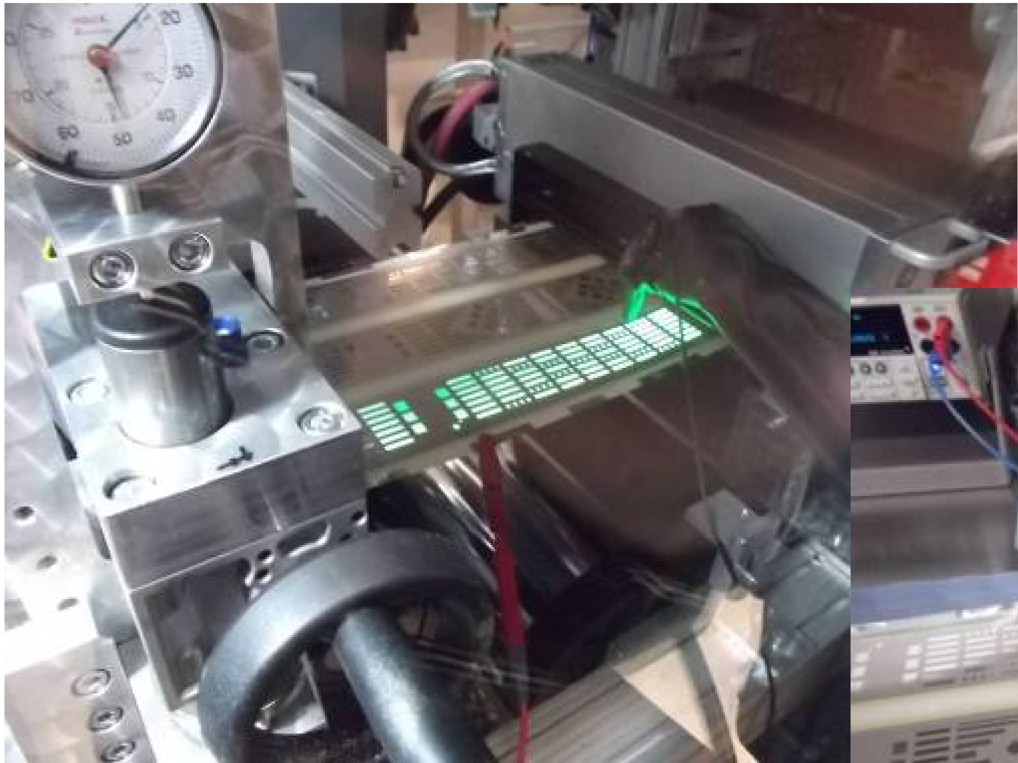
attachement possibility
for a glove box

deposition cylinder

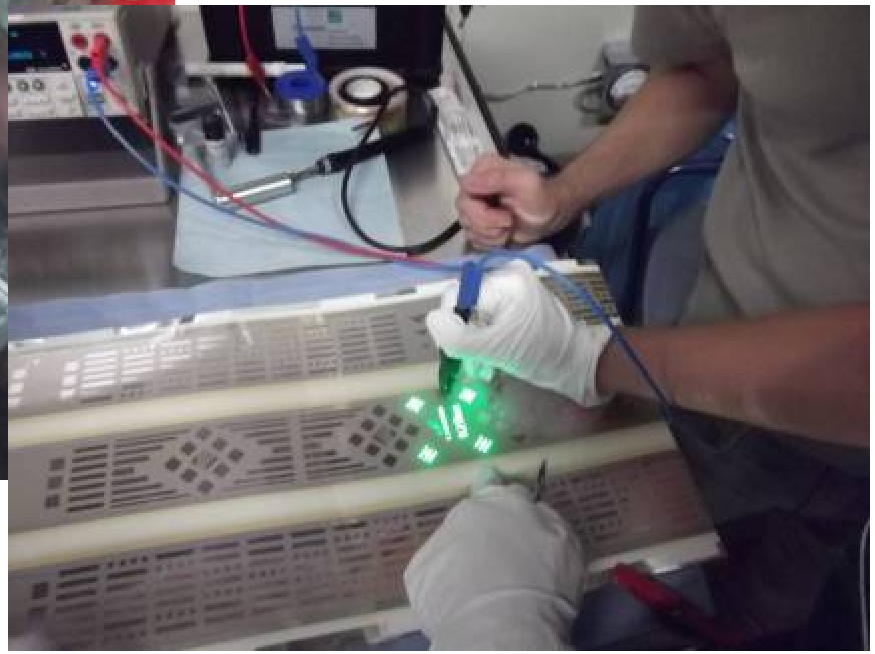
winding units



OLED OPERATION TESTS UNDER INERT CONDITIONS AND AFTER LAMINATION

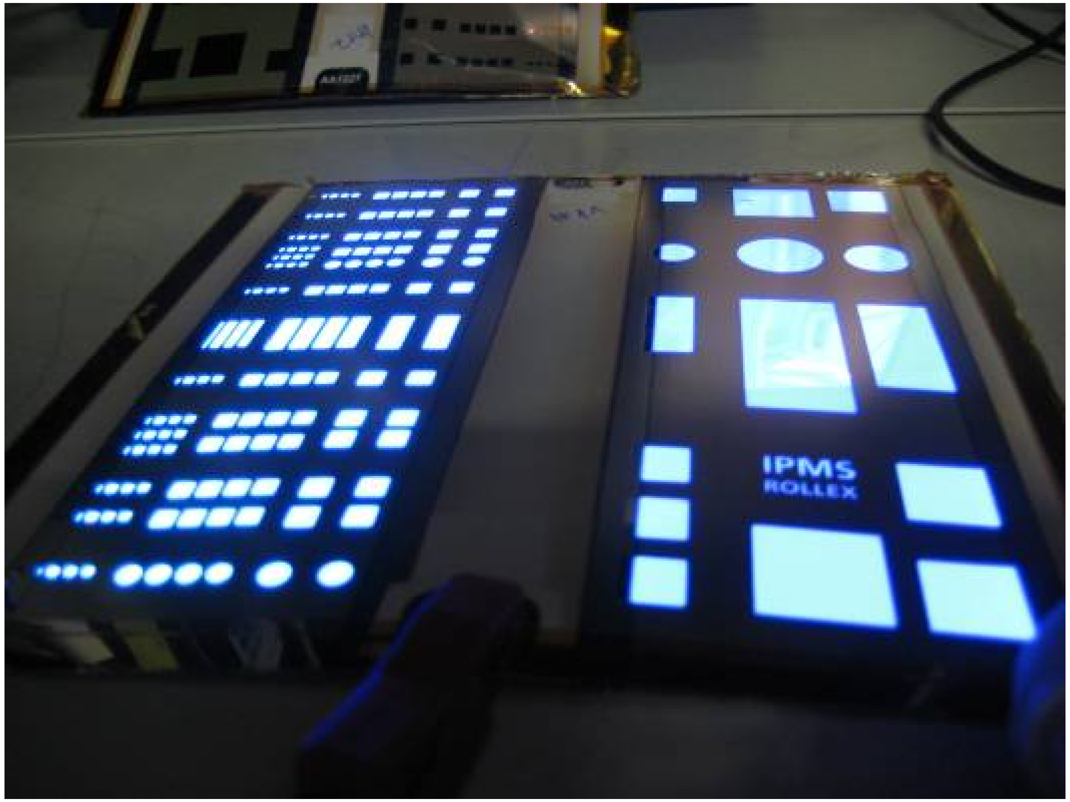


Electrical tests in the inert box



Electrical tests after the encapsulation

WHITE PIN OLED

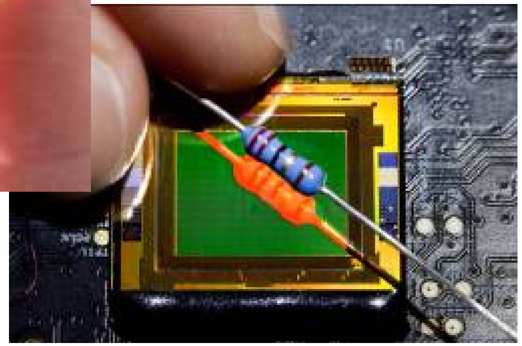


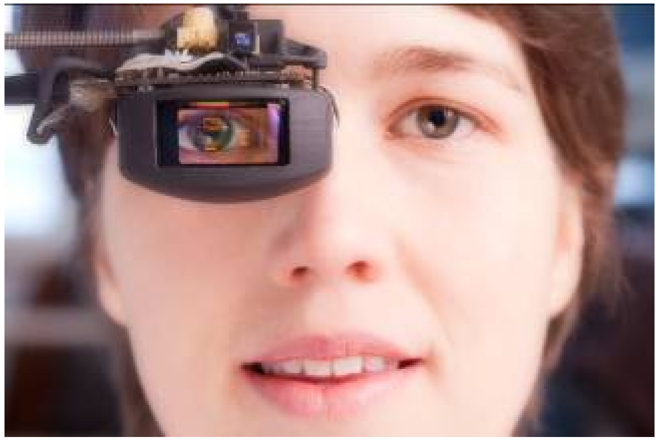
top emitting OLED on metal sheets

Transparent OLED on Polymer web

OLED MICRODISPLAYS AND SENSORICS

- Process development, integration, system integration
  - OLED Microdisplays (small molecules (focus), polymers)
  - bi-directional OLED micro-displays (with embedded image sensor)
  - CMOS backplane IC design and CMOS/OLED interface processing (w/ CMOS foundry)
  - OLED processing (SM and PLED)
  - Encapsulation (wafer-level color filter integration)
  - System design (e.g., see-through near-to-eye display, multimedia I/F & controller)
- Fabrication lines
  - Pilot line OLED-on-CMOS (∅ 200 mm wafer)
  - Pilot line PLED-Microdisplays (ex MED, ∅ 200 mm wafer)





COMEDD Fraunhofer IPMS

- Small OLED Displays have achieved commercial breakthrough
- OLED: Main issue is improving outcoupling
- Organic solar cells: Efficiencies &Lifetimes grow rapidly
- Efficient vacuum roll-to-roll manufacturing demonstrated
- Organic Electronics will be everywhere….

Acknowledgment

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