Organic and Printed Electronics

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Examination OPE Micro-505

Date: June 30th & July 1st 2025

Room: CM 013

Duration: 20 minutes with preparation (15 min just before, no notes allowed)

Format: Oral with 2 questions

Content: Lectures

Schedule: Available on the moodle

Revision: Questions can be sent by email

OPE course content and schedule

Dates	Lectures	Lecturers
20.02	Introduction	D. Briand
27.02	Physics of printing I	V. Subramanian
06.03	Physics of printing II	V. Subramanian
13.03	Materials for large area electronics	V. Subramanian
20.03	Thin film transistors fundamentals	V. Subramanian
27.03	Thin film transistors devices & Circuits	V. Subramanian
03.04	Organic light emitting diodes	V. Subramanian
10.04	Solar cells	V. Subramanian
17.04	Flexible and printed sensors	D. Briand
01.05	Energy storage & Encapsulation	D. Briand
08.05	Integration & Smart Systems	D. Briand
15.05	Sustainable electronics	D. Briand
22.05	Case study	D. Briand

Lesson 9 – Energy storage & Encapsulation

Dr. Danick Briand

Reference book 2nd ed. on OPE: Chapters 8 & 10

Objectives and content: Energy storage

Objectives

- Learn about the working principles of batteries and supercapacitors
- Fabrication techniques for printed energy storage components
- Identify the challenges

Content

- Batteries vs Supercapacitors: operation and characteristics
- Printed batteries
- Printed supercapacitors

Energy storage

Purpose

- The purpose of an energy storage device is to provide electrical energy when the main source of power does not deliver the needed energy or when energy is needed.

Storing principles

- In electrochemical energy storage devices the energy can be stored in two different ways:
  - In the volume of the electro-active electrode materials such as in batteries
  - And on the surface of the electrode materials such as in supercapacitors

Parameters are commonly used to describe the performance and functionality of electrochemical energy storage devices:

- Storage capacity or charge density (C/l or C/kg)
- Energy density (J/kg or Wh/kg)
- Power density (W/kg)
- Voltage efficiency, ratio of output (discharging) voltage and charging voltage
- Lifetime, shelf-life (time of becoming unusable), or cycle
- Lifetime (charge/discharge cycles)
- Operating temperature range
- Environmental aspects

Battery

In **battery technology**, different electrochemical systems are available.

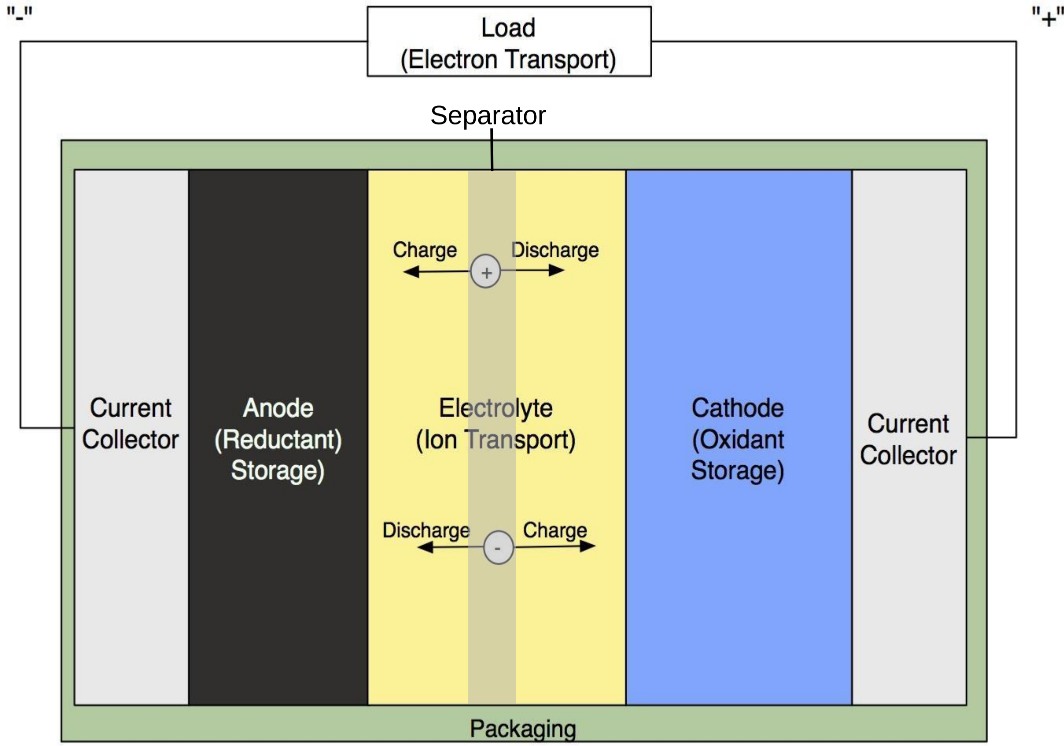
An electrochemical system consists of:

- An anode material (negative terminal)
- A cathode material (positive terminal)
- An electrolyte: liquid (wetting the separator) or solid (safer)
- Separator (conduction of ions only to avoid short cut of the electrodes)

Because of these combinations and the structure of the cell, the electrical properties vary over a wide range.

Most important properties are:

- Cell voltage
- Charge contents (capacity)
- Load capability
- Peak load capability
- Cycle ability for rechargeable (secondary) cells



Basic structure of an electrochemical energy storage device

Battery form factor: Thick/Thin film storage

Int. J. Energy Res. 2012; **36**:1139–1150 © 2012 John Wiley & Sons, Ltd.

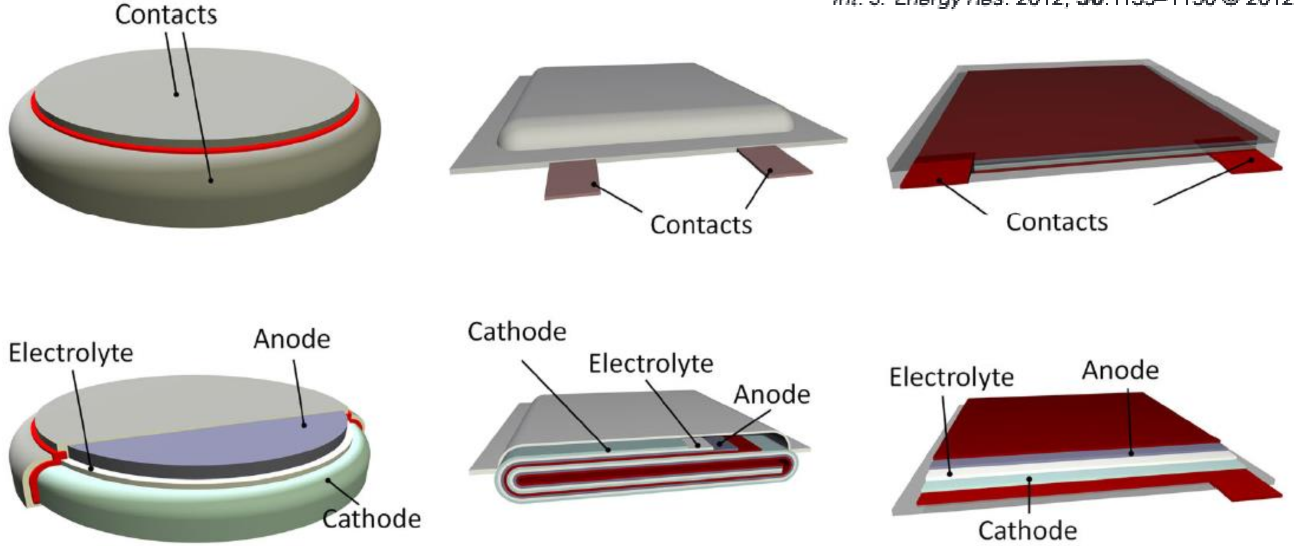


Figure 6. Schematic layout of three different micro-batteries: button cells (left), pouch cells (center) and thin film batteries (right). On the top image, the full battery is shown, whereas an opened battery is displayed at the bottom to indicate the electrode configuration.

- **Emerging (thin film printed) storage systems are being introduced**

Thin-film-flexible

Lithium-flexible

Lithium-coin

Printable

Supercapacitor

Capacitors

Super capacitor, ultracapacitor, electrochemical capacitor

- Standard capacitors can provide significantly higher power densities than batteries, energy density lower by about 2 to 3 orders
- Supercapacitor: higher energy density than standard capacitor and retain long life and short charging time
- Supercapacitor store ionic charge in an electric double layer to increase their effective capacitance

CAP-XX offers a very low profile.

- **Energy density 1 order of magnitude higher than standard capacitor and 1 to 2 orders of magnitude lower than rechargeable batteries**
- **Larger operating temperature range (-40 to 85 °C) than a battery**
- **Low impedance source for peak current loads**

Supercapacitor

Supercapacitors are capacitors that use an electrochemical double layer (EDL) instead of a dielectric layer were developed. In the EDL the ions in the electrolyte accumulate to the close vicinity of the opposite electrode surfaces.

The separation of charges in the EDL (also known as the Helmholtz layer) is very small, in the nanometer range, which leads to very high capacitances.

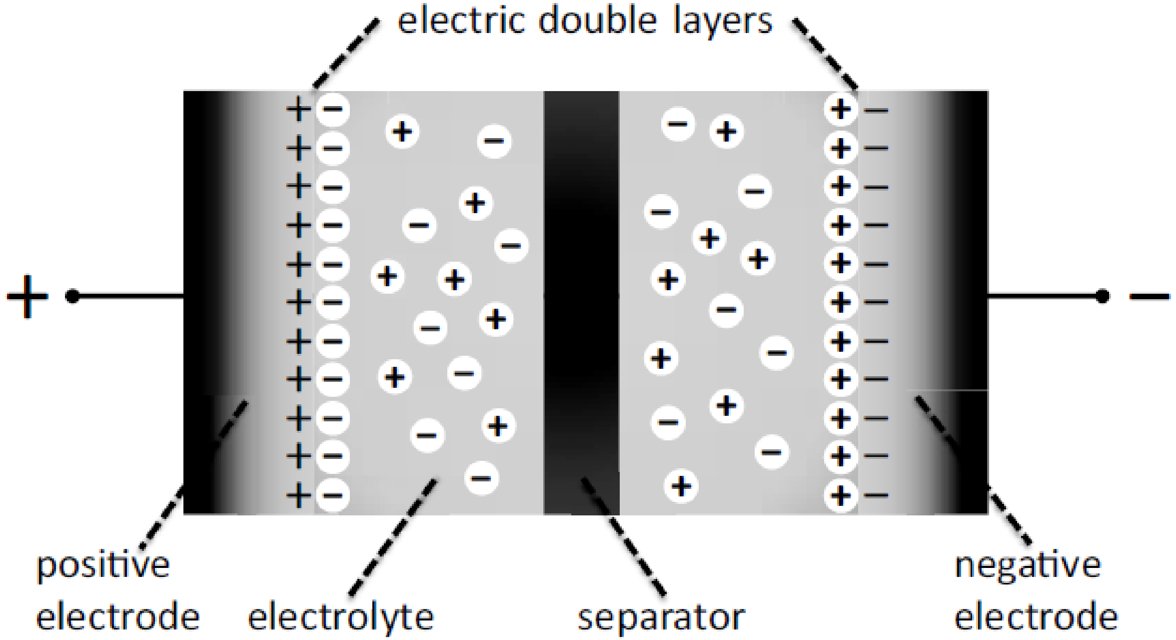


Figure 8.2 Structure of a supercapacitor.

From OPE reference book

Supercapacitor

Supercapacitors consist of two electrodes, an electrolyte between them, and usually a porous separator layer (ion membrane). The ions in the electrolyte are able to move in the electrolyte and through the separator while the supercapacitor is charging.
The specific capacitance (C/A) of an EDL is usually of the order of 10 µF/cm^2.

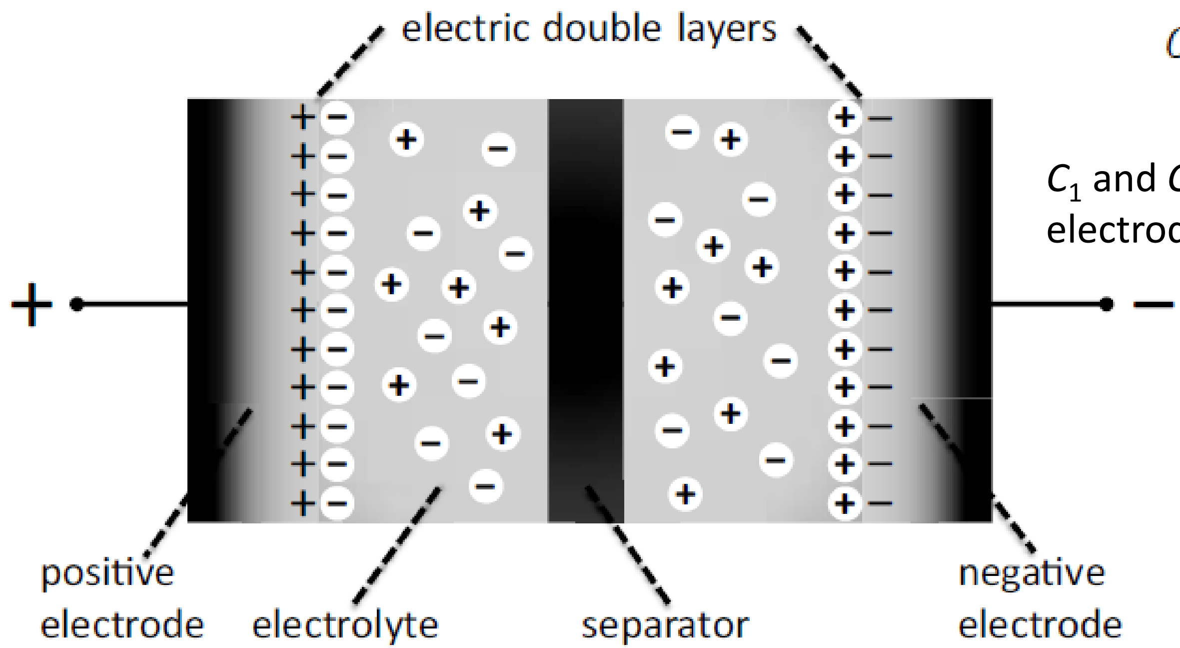


Figure 8.2 Structure of a supercapacitor.

$$C = \frac{C_1 C_2}{C_1 + C_2}$$

C_1 and C_2 are located on the electrode–electrolyte interface

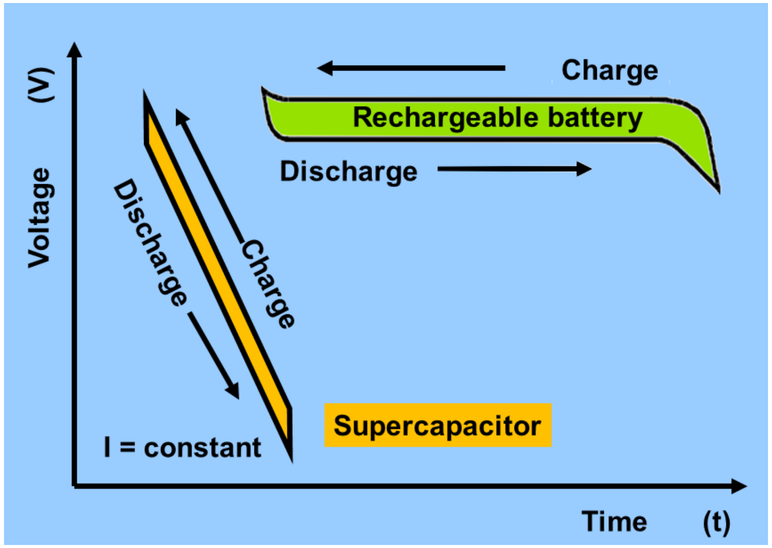
$$P_{max} = \frac{V^2}{4R_S}$$

Internal resistance R_S (equivalent series resistance: ESR)

From OPE reference book

Supercapacitors

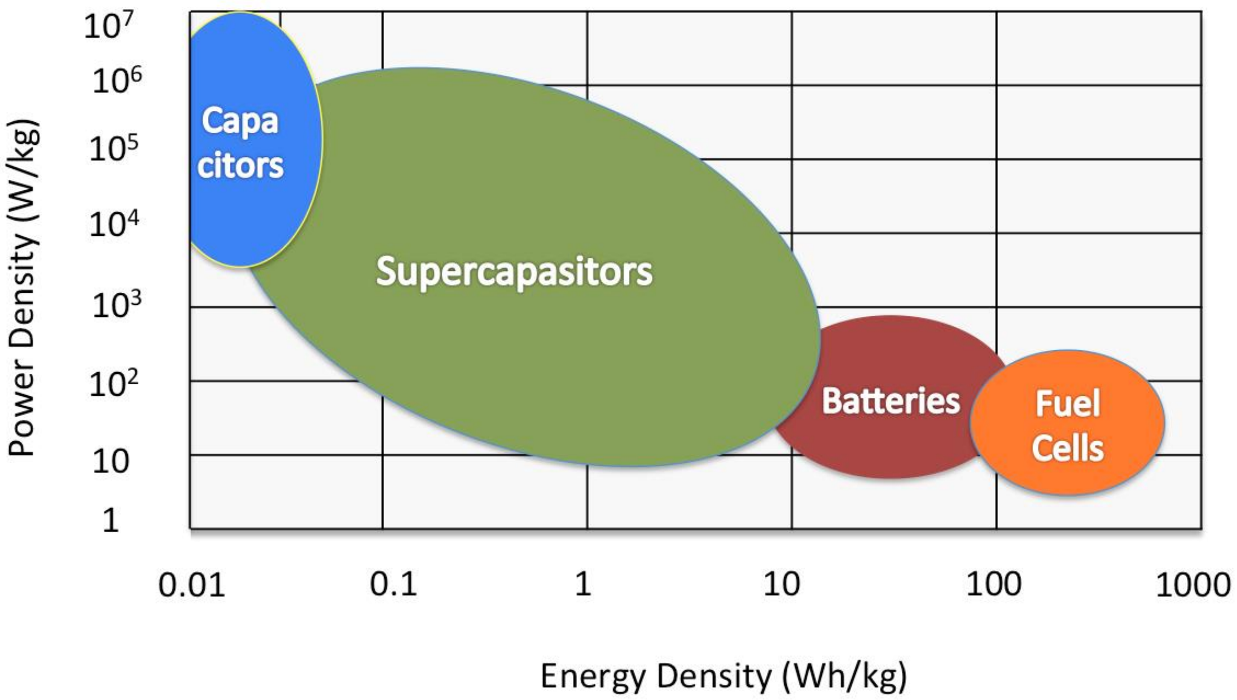
- **<u>Supercapacitors</u> are mainly used to provide enough current for the transmissions in cases where the energy source cannot provide current pulses**
  - They have quite low volumetric energy density but can supply a lot of energy in a very short impulse (high specific power) with “infinite cycles”



  - They can make a good combination with primary battery cells providing enough energy for the transmission current peaks
  - A <u>drawback of the supercapacitors is their relatively high self-discharge current</u>

Battery vs. Supercapacitors

- **Comparison**



Battery vs. Supercapacitors

Parameters are commonly used to describe the performance and functionality of electrochemical energy storage devices:

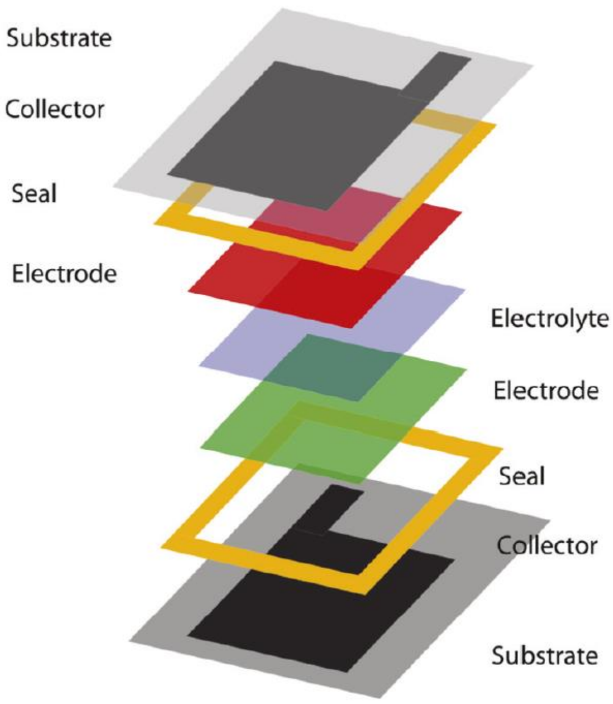
Difference in operation causes some difference in their performance.

- A slower charge-capturing mechanism in the case of batteries results in lower power output when compared to supercapacitors, where chemical reactions do not take place.
- On the other hand, batteries can have higher energy densities than supercapacitors because the ions can penetrate into the electrode material in large quantities.
- Further, the lifetimes of batteries are lower because the volume changes caused by the penetration of charges into the electrode material induce structural fatigue to the device structure.

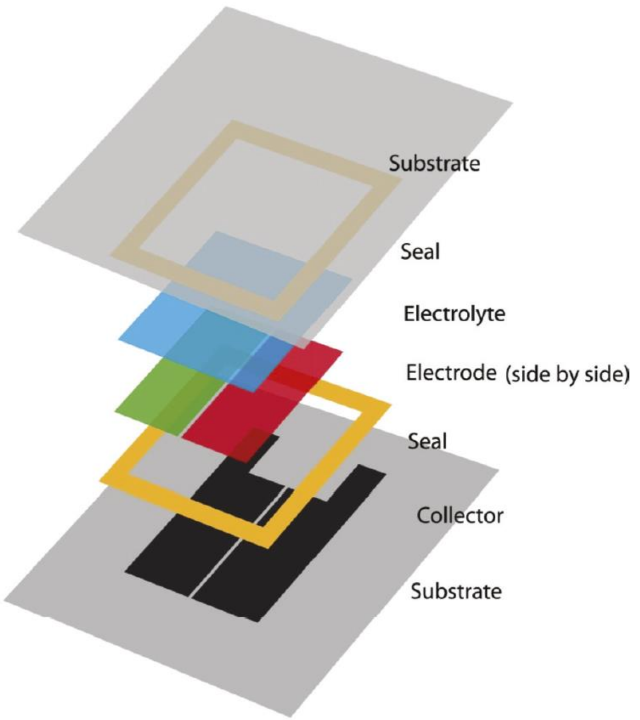
Printed battery assembly

- The performance of a battery strongly depends on the construction. Especially the length of the ion path in the electrolyte is important for the DC resistance.

Stacked assembly vs. **Co-planar assembly**



See chapter 8 for processing details



Mainly screen printing is used in relation to thickness and materials inks

Printed battery assembly

Stacked assembly vs. Co-planar assembly

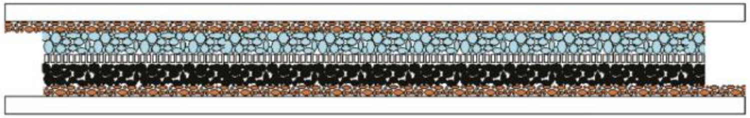


Figure 8.9 Assembly of the electrodes and separator/electrolyte in a stacked configuration.

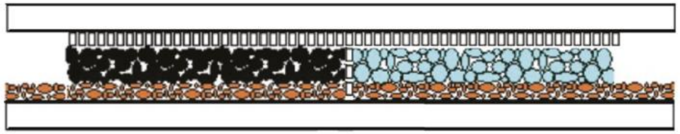


Figure 8.12 Assembly of the electrodes and separator/electrolyte in a co-planar configuration.

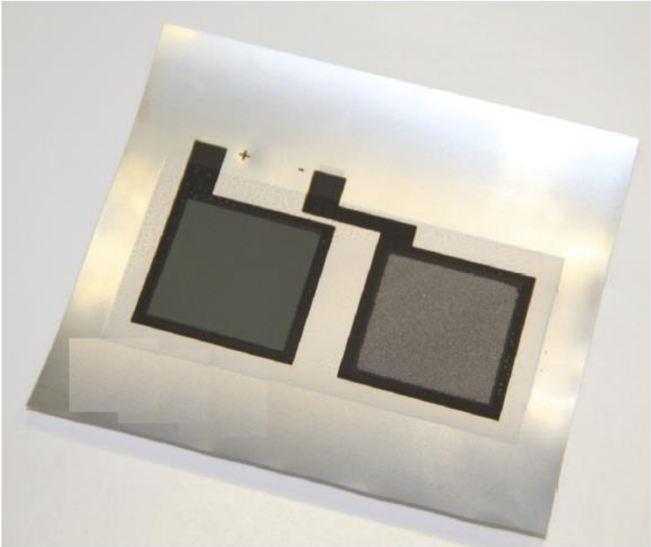


Figure 8.10 Example of a printed stacked nickel/metal hydride battery. The device was fabricated in Hochschule der Medien (HdM), Stuttgart, Germany.

Figure 8.13 Example of a printed co-planar nickel/metal hydride battery. The device was fabricated in HdM, Stuttgart, Germany.

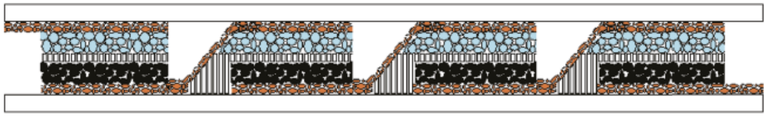


Figure 8.14 Serial connection of stacked cells.

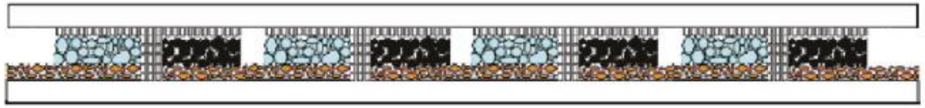


Figure 8.15 Serial connection of co-planar cells.

Printed battery assembly

Stacked assembly vs. **Co-planar assembly**

The advantages and disadvantages of stacked and co-planar battery configurations are compared in Table 8.1. A serial connection is easily possible for both cases.

Table 8.1 Comparison of stacked and co-planar constructions

	Stacked	**Co-planar**
Advantage	Low internal resistance, high rate capability	Easy to print, thin construction, flexible
Disadvantage	Thick and unflexible	High internal resistance, strong decay in the discharge curve

Printed battery materials

Table 8.4 Typical battery electrolyte materials

Electrolyte system	Primary	Secondary (rechargeable)
Water-based electrolyte	KOH solution (alkaline) Zinc chloride solution (neutral)	KOH solution
Organic electrolyte	Lithium perchlorate in EC/DME	Lithium phosphor fluoride in EC/DEC

Typical battery anode materials

Electrolyte system	Primary	Secondary (rechargeable)
Water-based electrolyte	Zinc	Metal hydride (MH)
Organic electrolyte	Lithium (metal)	Lithium (metal) Lithium in carbon Lithium titanate Lithium in silicon

Table 8.3 Typical battery cathode materials

Electrolyte system	Primary	Secondary (rechargeable)
Water-based electrolyte	Manganese dioxide Silver oxide Nickel oxy Hydroxide Oxygen (air)	Nickel hydroxide
Organic electrolyte	Manganese dioxide	Lithium cobalt oxide (LCO) Lithium nickel mangan cobalt oxide (NCM) Lithium iron phosphate (LFP)

Challenges in fully printed energy storage

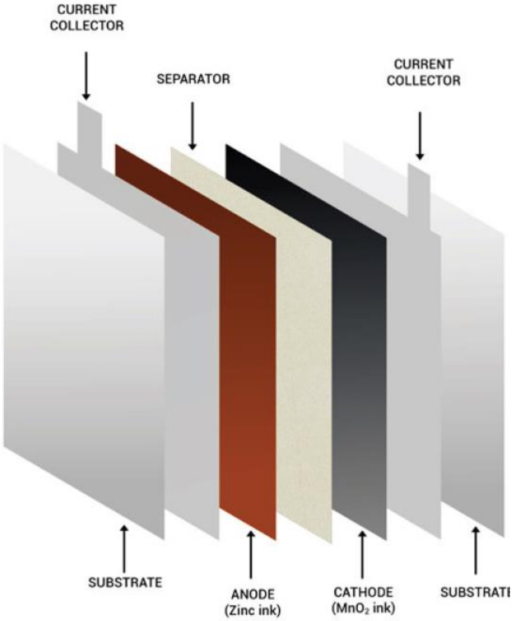
- Porous electrodes can be easily printed. After drying, the electrodes made of electro-active materials with a binder form a porous body that can act as an electrode.
- Cells using an organic electrolyte are difficult to print because they require an inert atmosphere and need to be tight sealed.
- The encapsulation should have high barrier properties in the order of 10^{-6} g/m²day H_2O permeation.

Table 8.5 Overview of battery technologies and their printability

Primary batteries	V_{max}	Printability issues
Zinc/manganese dioxide	1.5 V	Easy to print, open system
Zinc/air	1.4 V	Complicated cathode, alkaline electrolyte
Zinc/silver oxide	1.5 V	Alkaline electrolyte
Lithium/manganese dioxide	3.0 V	Affected by water
Secondary batteries (rechargeable)	V_{max}	Printability issues
Nickel/metal hydride	1.2 V	Alkaline electrolyte
Lithium ion	3.7 V	Affected by water

Challenges in fully printed energy storage

- One of the main challenges is printing the combination of electrolyte and separator, since the commonly used electrolytes require a completely sealed shell. The most common solution is to convert these into a printable paste.
- However, there are some challenges such as the hygroscopic nature of many electrolytes, which makes them hard to adapt to printing technologies, and the low ionic conductivity arising from the high viscosity needed to print relatively thick layers. There is also the probability of having pinholes that can cause short circuiting of the electrodes.



Printing Zinc MnO_2 batteries (from CENTI, Portugal)

Printable supercapacitor architectures

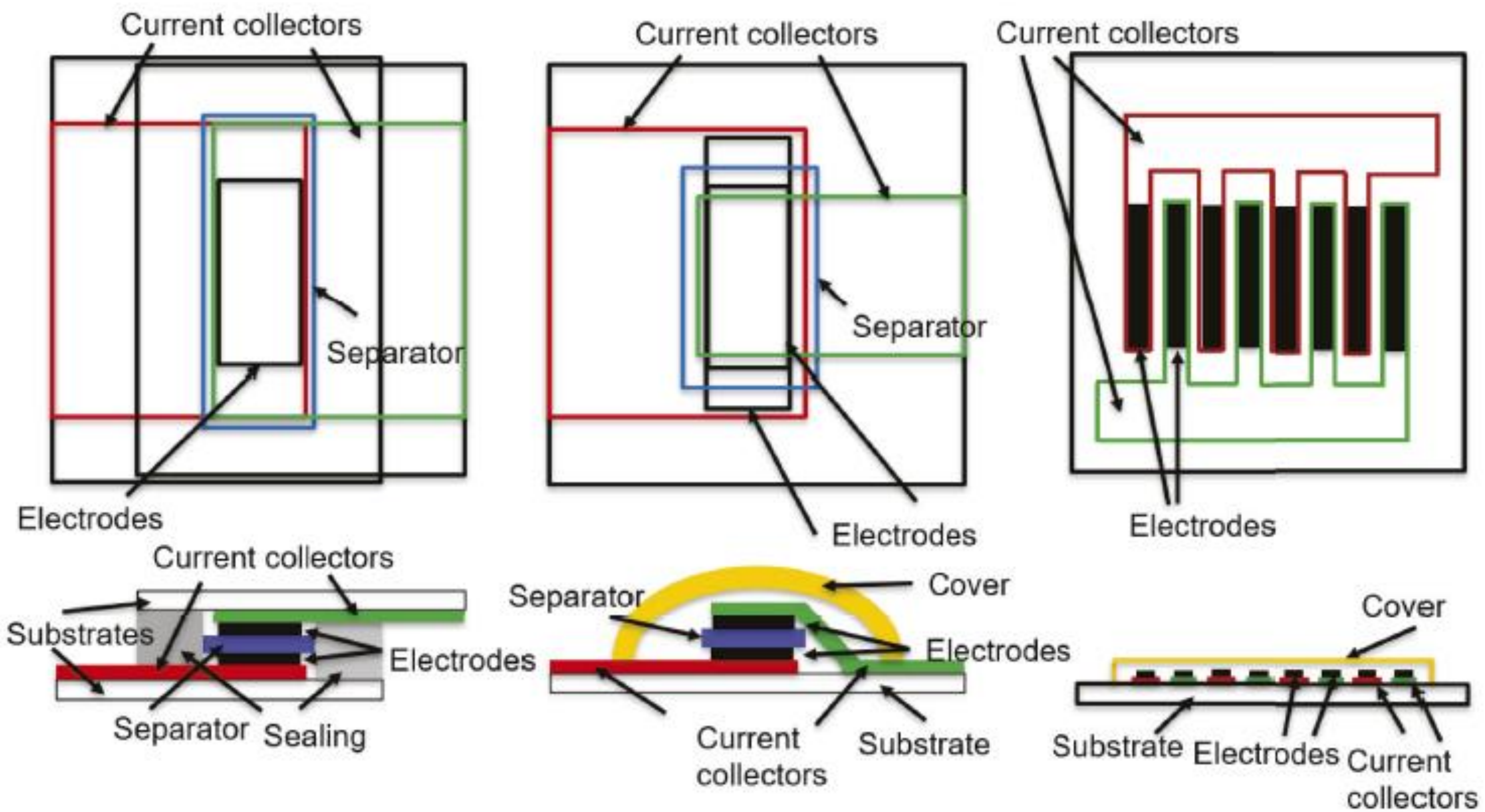


Figure 8.16 Supercapacitor structures: Stacked face-to-face (left), monolithic (middle), and interdigitated (right).

Printable supercapacitors

- Carbon nanomaterials, mostly CNTs and graphene, whose high electrical conductivity and nanoporous structure allow for the electrode to function as a current collector itself.

- Various solution-processing methods, such as inkjet printing, screen printing, spray coating, doctor blading, bar coating, dip coating, painting, and brush on coating, have been demonstrated.

- Printable supercapacitors have been recently fabricated, for example, from activated carbon, CNTs, graphene carbon black, and carbon fibers, as well as their composites with conducting polymers.

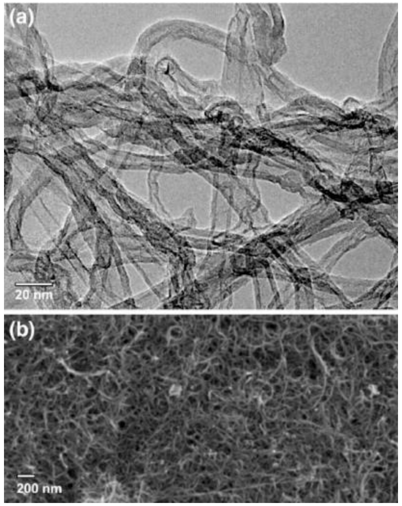


Figure 8.15 An example of new printable nanocarbon-based high-surfacearea materials used in supercapacitor electrodes.
(a) TEM and (b) SEM images of CNT/xylananocomposite ink.

Printable supercapacitors

- There are several demonstrations of printed supercapacitor electrodes, but to have a fully printable supercapacitor, the separator film also should be printable, except in the case where electrodes are printed directly on the separator film.
- Further, application of the electrolyte and device encapsulation has to be done using scalable methods.
- One promising approach toward fully printed supercapacitors was recently demonstrated by Tuukkanen et al., who used nanocellulose film as a printable separator in a CNT-based supercapacitor.

See next slide…

Printable supercapacitors

- The high-surface-area electrodes, which simultaneously act as current collectors, are fabricated from solution-processable CNT nanocomposite ink.

  (a) The assembly of the device is done by sandwiching two CNT electrodes on a cellulose-based separator soaked with aqueous NaCl electrolyte.

  (b) Photograph of a bent CNT supercapacitor. A commercial paper separator was used.

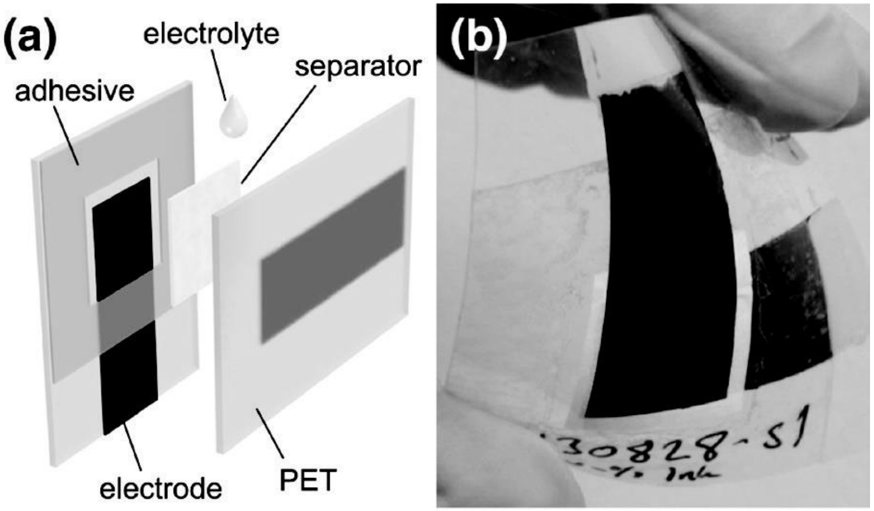


Figure 8.16 An example of printable and flexible CNT-based supercapacitors.

Lehtimäki, S., Tuukkanen, S., Pörhönen, J., Moilanen, P., Virtanen, J., Honkanen, M., and Lupo, D. (2014). Low-cost, solution processable carbon nanotube supercapacitors and their characterization. *Appl. Phys. A*, 117(3), p. 1329.

Power sources: some printed examples

Printed batteries

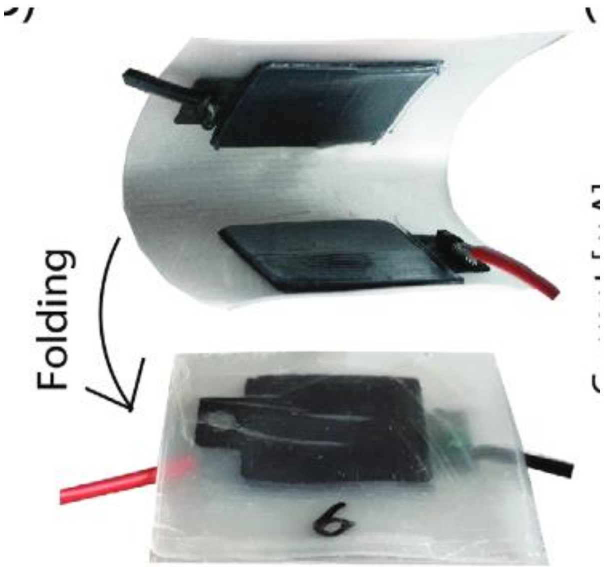
- Li-ion printed batteries

  http://www.greenbat-project.org

  - goal: environmentally friendly printed Li-batteries with 3 mAh/cm^2 capacity

Zinc-Maganese dioxide on paper

3D printed supercapacitors



Disposable Nanocellulose-Carbon

From Empa (CH)
Adv. Mater. 2021, 33, 2101328

Some questions about Energy storage

- Battery vs. Supercapacitor
- Architectures and configurations
- Provide examples of materials involved ?
- How can they be fabricated by printing ?
- What are the important considerations ?
- What are the challenges ?

Objectives and content: Encapsulation

Objectives

- Gain familiarity with encapsulation, materials and methods for organic electronics
- Link degradation mechanisms to encapsulation materials

Content

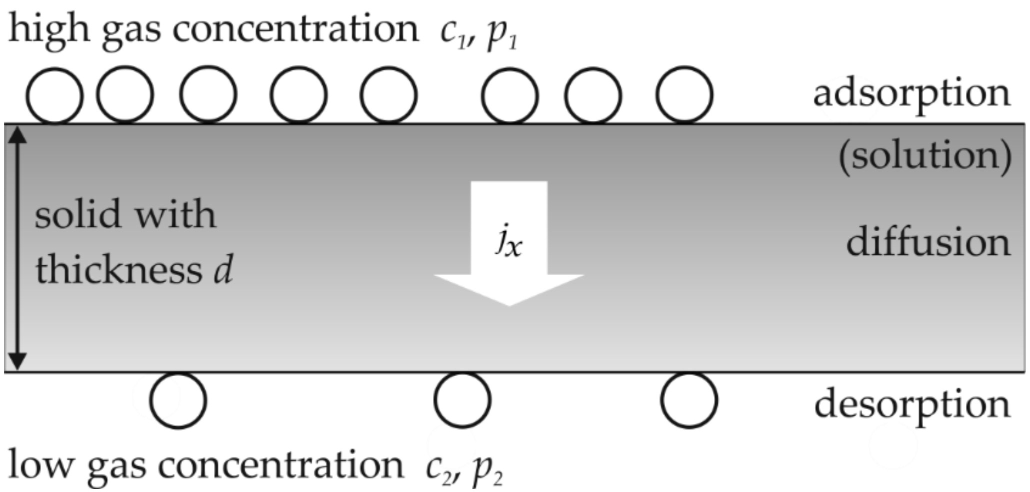
- Basics on permeation, permeability, and diffusion
- Introduce different types of materials. Inorganic/ organic barriers, role of point defects. Selants. Getters. “thin film encapsulation” .
- How to measure and evaluate encapsulation materials
- OLED case

Cases

- We will work and discuss together some cases relevant for OLED/OPV technologies. Other device cases can be extrapolated from these (e.g., batteries).
  - Please Read chapter 9 & keeping in mind the points below
  - From the previous classes – try to note:
    - What are the degradation drivers for OLED? For OPV ?
    - Which layers / materials can be affected ? Which molecules/ gasses create damage ? Which other factors?

    → work out measures one could take to reduce OLED and OPV degradation (and increase lifetime).
  - What are the basics of permeation / permeability / diffusion?
    - Section 9.3; definitions of sorption, diffusion, permeation. Driving force of diffusion; permeation vs partial pressure and temperature
    - Order of magnitude a) how much water can go through a 100 m^2 foil at 10^{-6} $g/m^2/day$, same for a 10 m^2 foil at 10^{-1} $g/m^2/day$.
  - Which materials can you use to encapsulate a device?
    - Substrates materials: polymers, glass, metal
    - Glues - Getters
    - Thin film barriers: processing. Fig 9.8 – Properties: figure 9.10: - Table 9.2
    - Which materials can you use
  - Which methods can you use to characterize & measure those materials?

Some basics to start



$$\vec{J} = -D\Delta\vec{c} = -D\,\frac{c_1 - c_2}{d}$$ Fick's law

$$c = S \cdot p_g$$ Henry's law

c: concentration
p_g: partial pressure at the surface

Permeation coefficient → "1/resistance"

$$P = D \cdot S$$

Diffusion coefficient
- Material property
- Temperature (activation energy)

Sorption coefficient
- Material property

$$J_x = -DS\,\frac{p_1 - p_2}{d} = -P\,\frac{p_1 - p_2}{d}$$

J_x: particle current density
gas particle flow

NB: here a "solid" is a homogeneous material. An object with defects (holes) is different

Some basics to start

- **Partial pressure of the permeate gas**
  - Partial pressure for oxygen permeation equals 20% of the total air pressure.
  - For water, partial pressure and concentration on the air side depends on temperature and relative humidity:

$$\text{r.h.}\,[\%] = \frac{p_{vapor}}{p_{saturation}} \cdot 100$$

  - The temperature dependance of water vapor saturation pressure is given by Magnus Fomulare (ϑ :-45 to 60°C)

$$\ln p_s = \ln(611.2\ \text{Pa}) + \frac{17.62 \cdot \vartheta}{243.12\ °\text{C} + \vartheta}$$

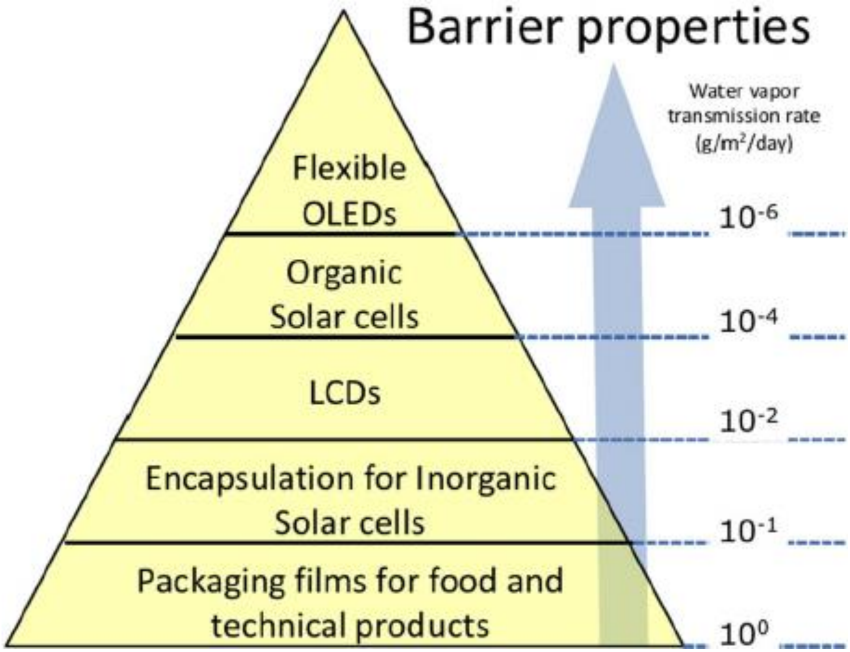
- **Temperature dependence of permeation**
  - Fickian diffusion is a thermally activated process following an Arrhenius equation for temperature dependence.
  - As both diffusion and sorption depend exponentially on temperature the permeation coefficient can be determined by :

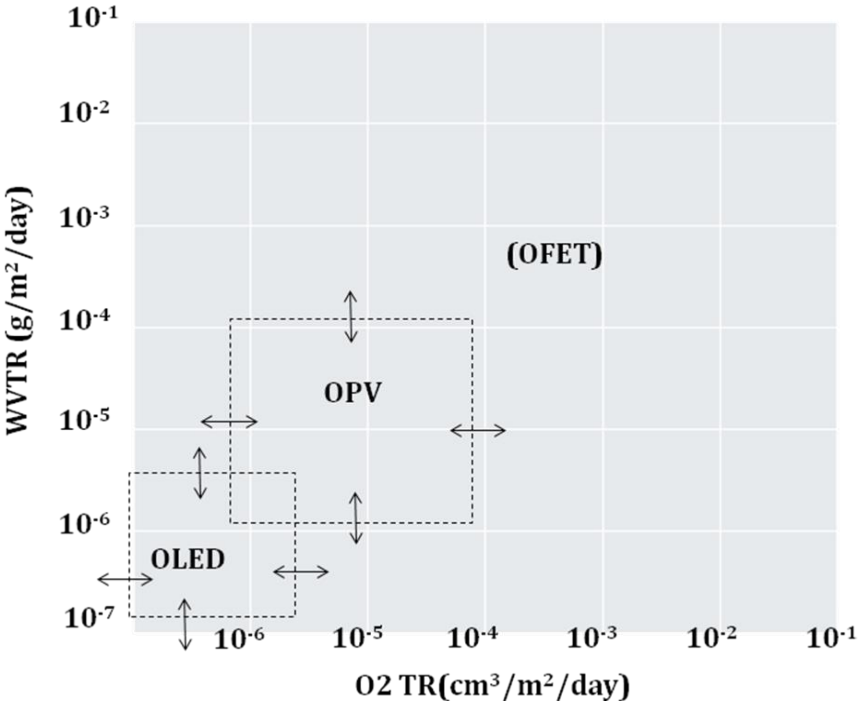
$$P = P_0 \cdot e^{-\frac{E_A}{RT}} \quad \text{with} \quad (E_A = E_D + \Delta H_S)$$

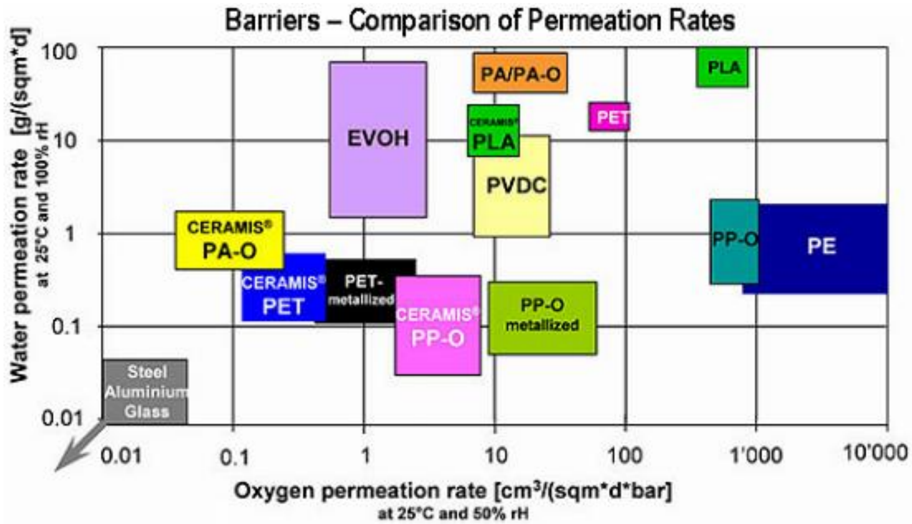
E_D: activation energy gas diffusion
ΔH_S: activation energy of sorption

"**WVTR**": water vapour transmission rate in "**steady state**"
$g/m^2/day$ at given temperature, relative humidity

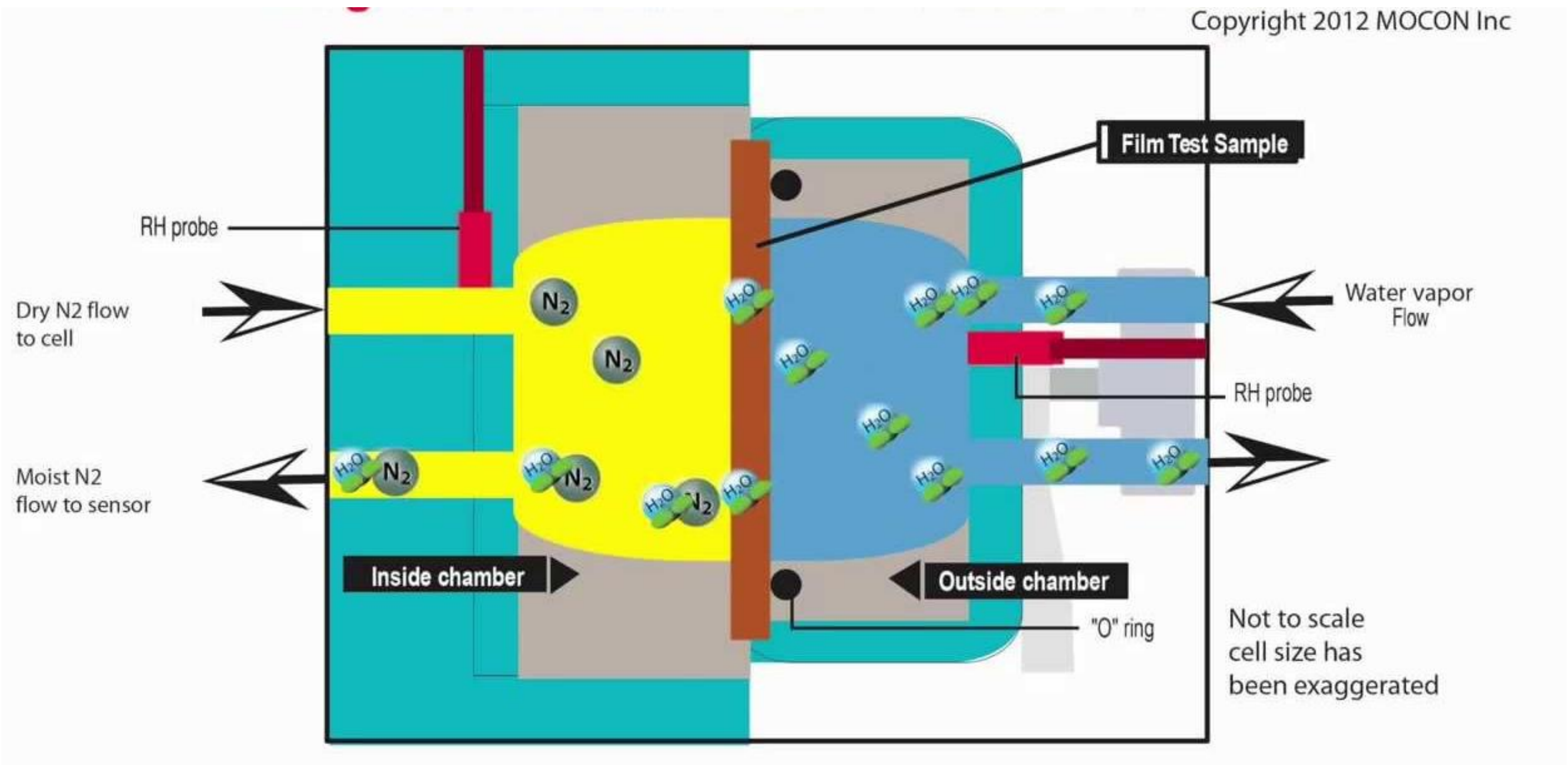
Materials and barriers







Water vapour transmission measurement – Test cell example



Thin film layers and WVTR

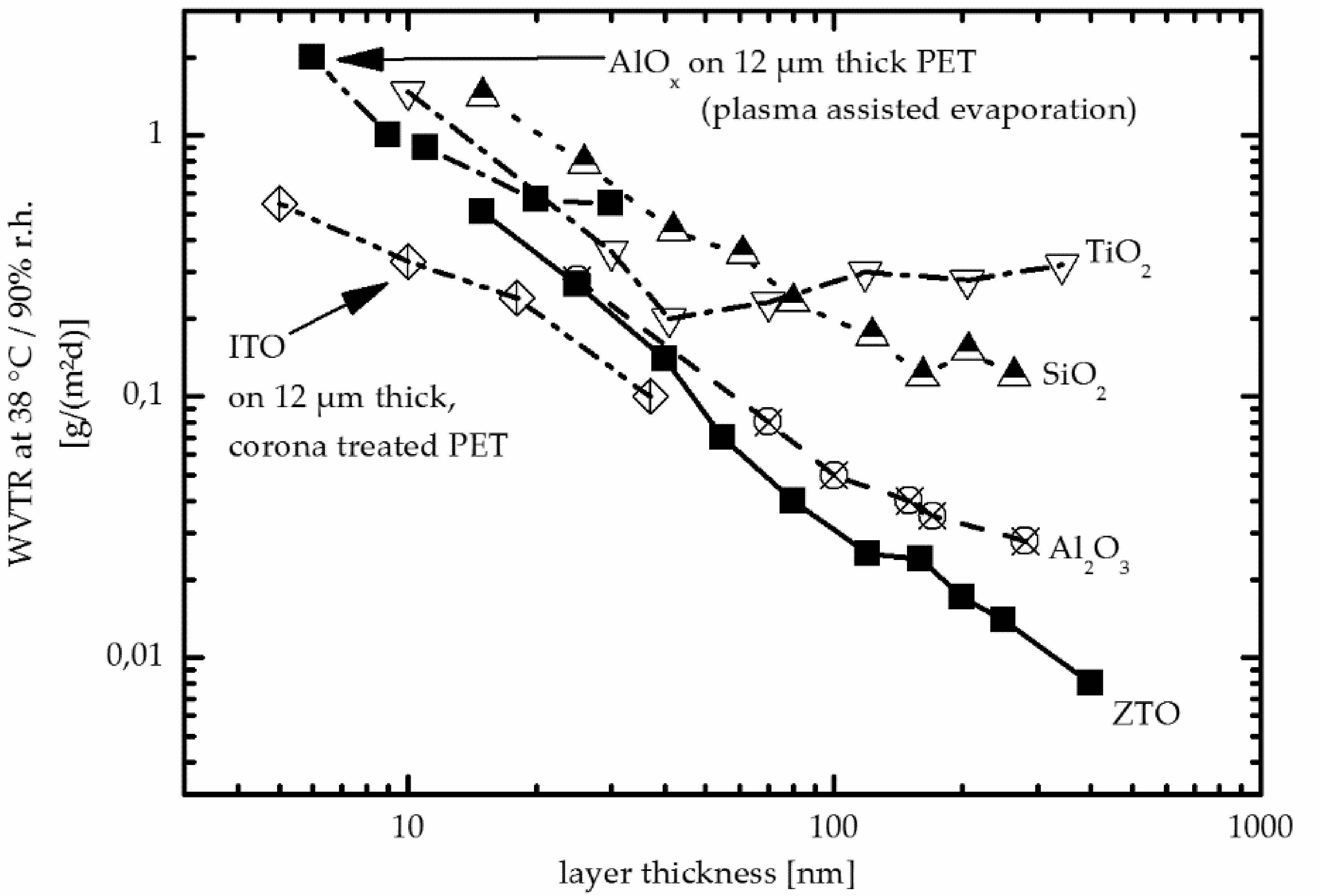
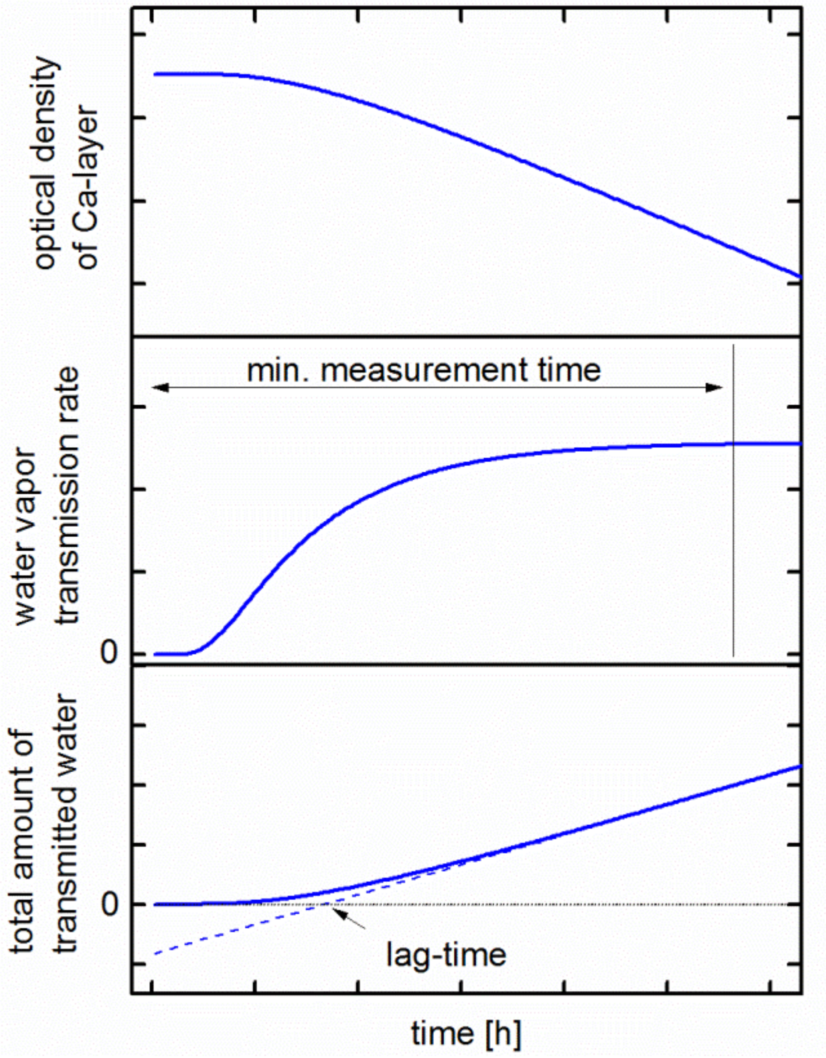
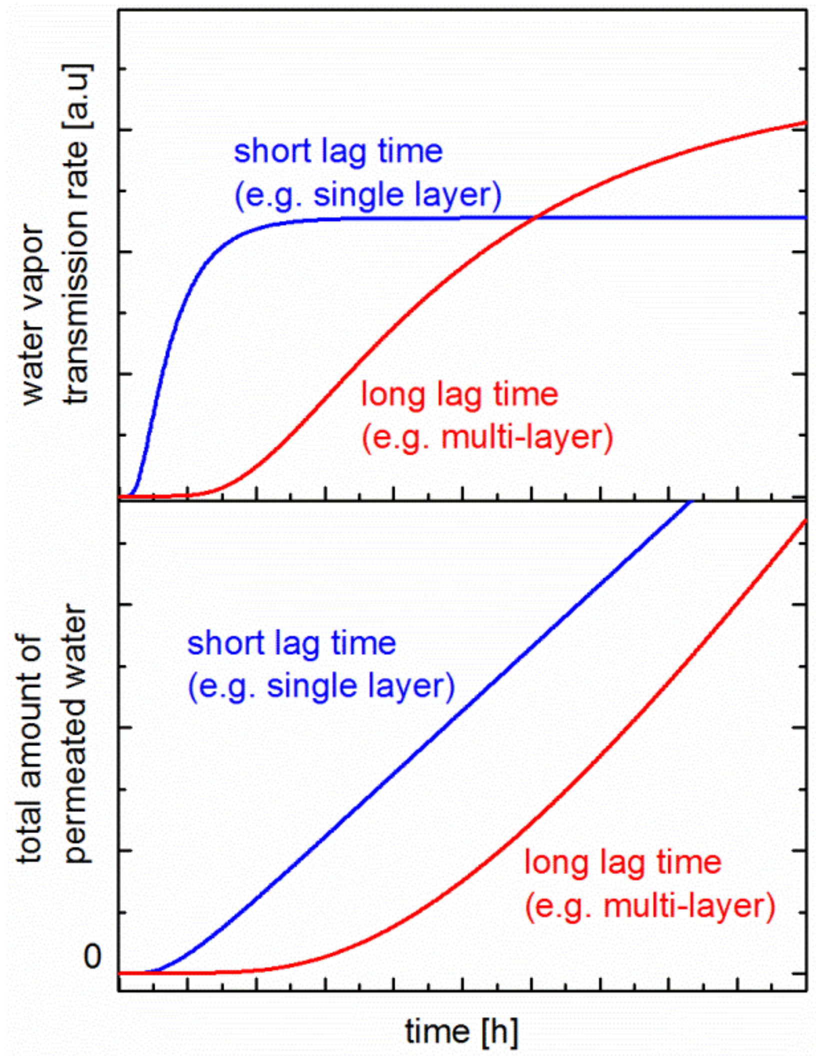


Figure 9.10 Water vapor transmission rates of different single-barrier layers on PET Melinex 400 CW at 38°C/90% r.h.

Water vapour transmission measurement – lag time

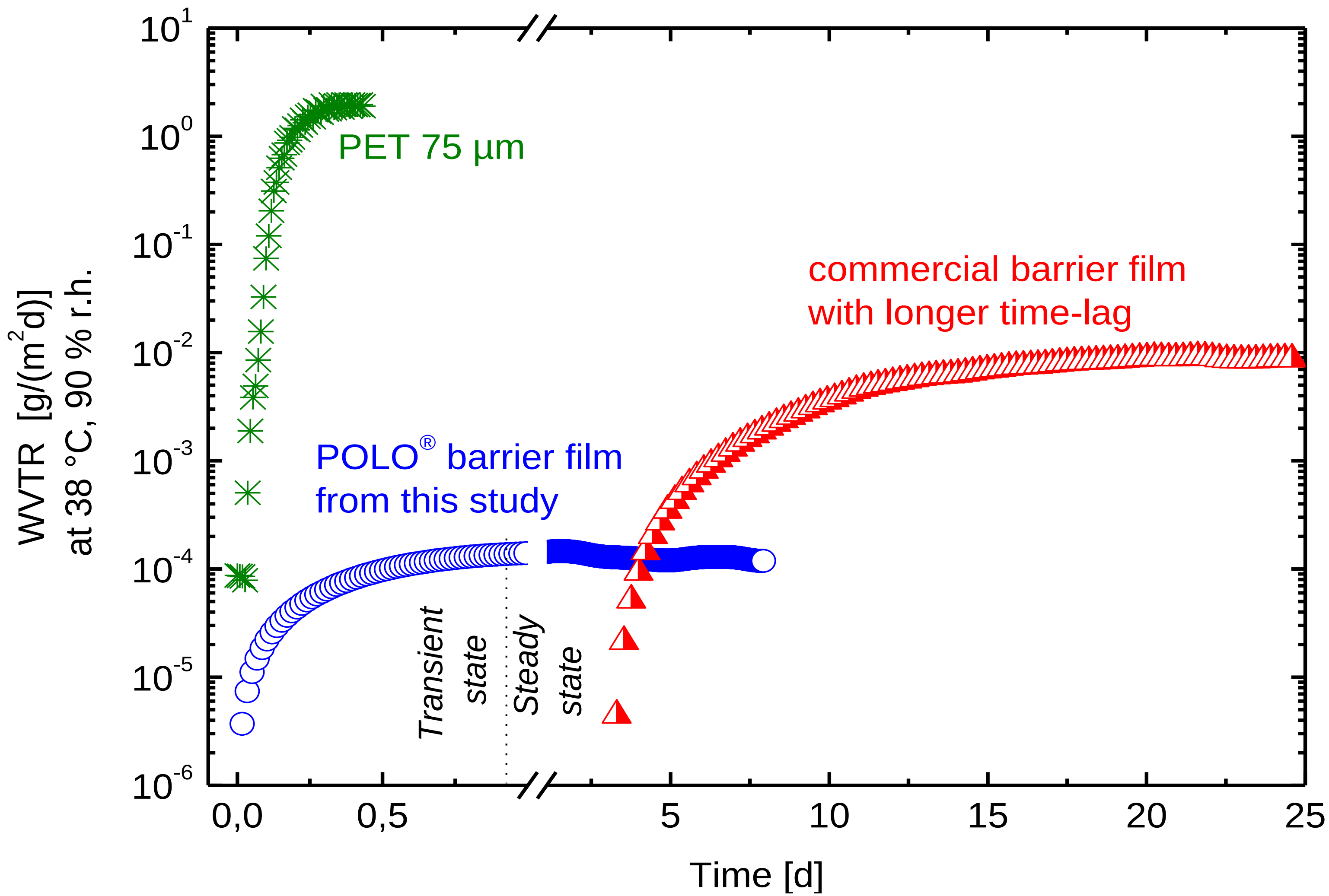




NB: for many devices: what matters is the **total amount** of e.g., water that enters the packaging → integration vs time!

Organic Electronics 15 (2014) 3746–3755

Testing barrier films – lag times - WVTR



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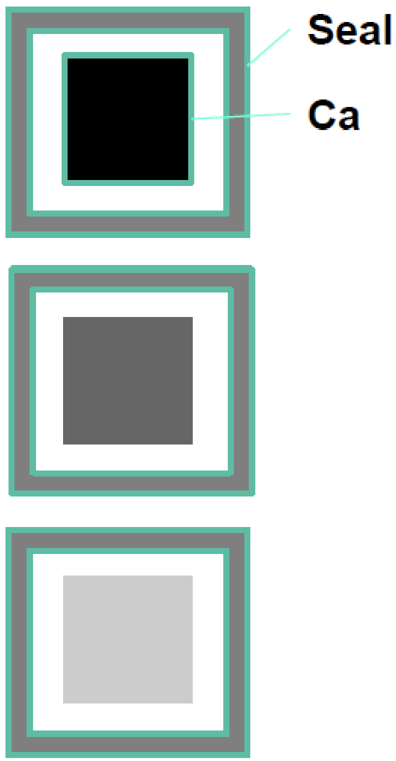
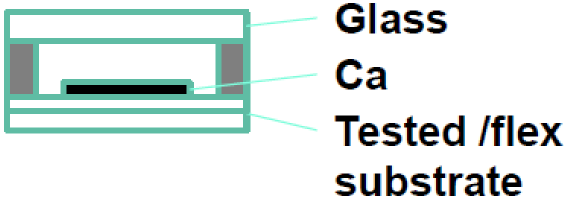
Permeation - Ca test



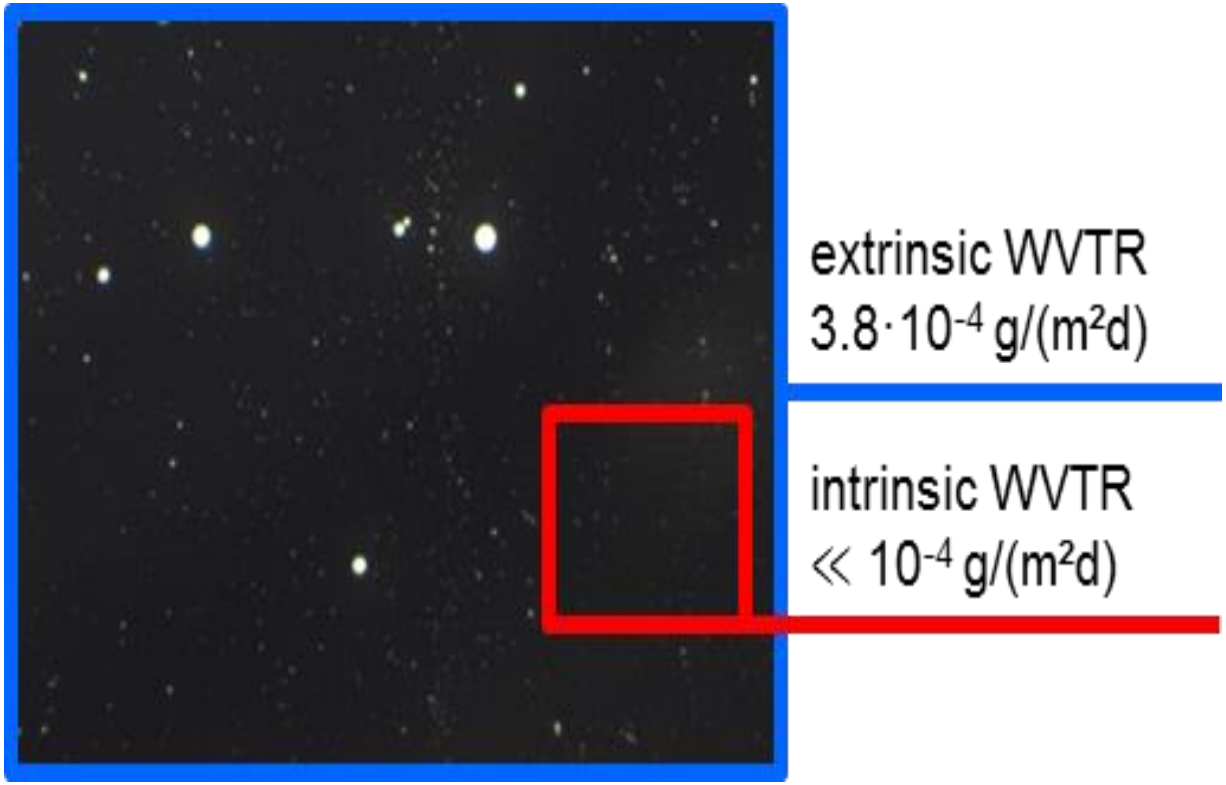


$$Ca + 2H_2O \rightarrow Ca(OH)_2 + H_2$$

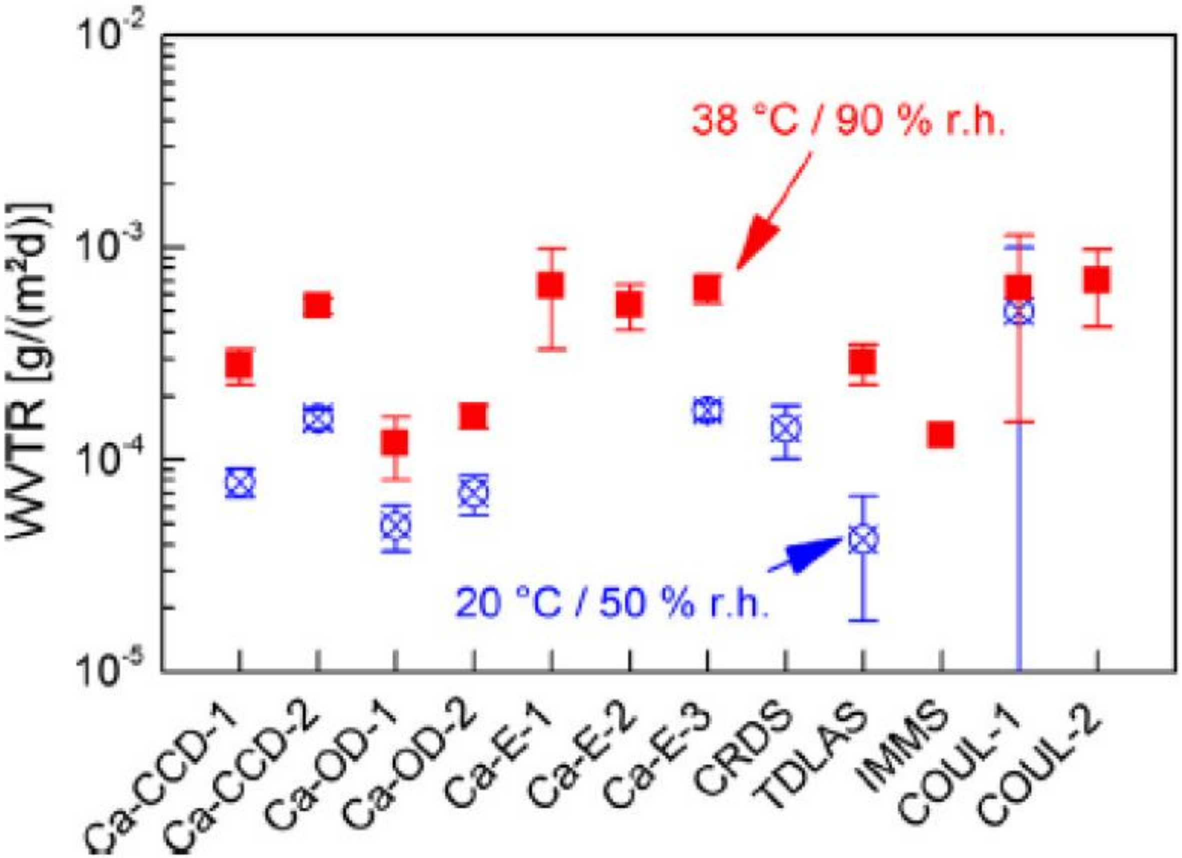
- Metallic calcium is (hydr)oxidized as H_2O enters the cavity – does not measure O2
- Transparency and electrical resistance increase
- Optical/elecrical properties translated in WVTR if relevant/wished
- Can be used to measure sealants, substrates, thin film packaging
- Can be used to identify/qunatify pinholes, if relevant

Permeation - barrier with and without defects

Ca test



Water vapour transmission tests: Comparison of techniques



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Encapsulation Processing

Encapsulation:

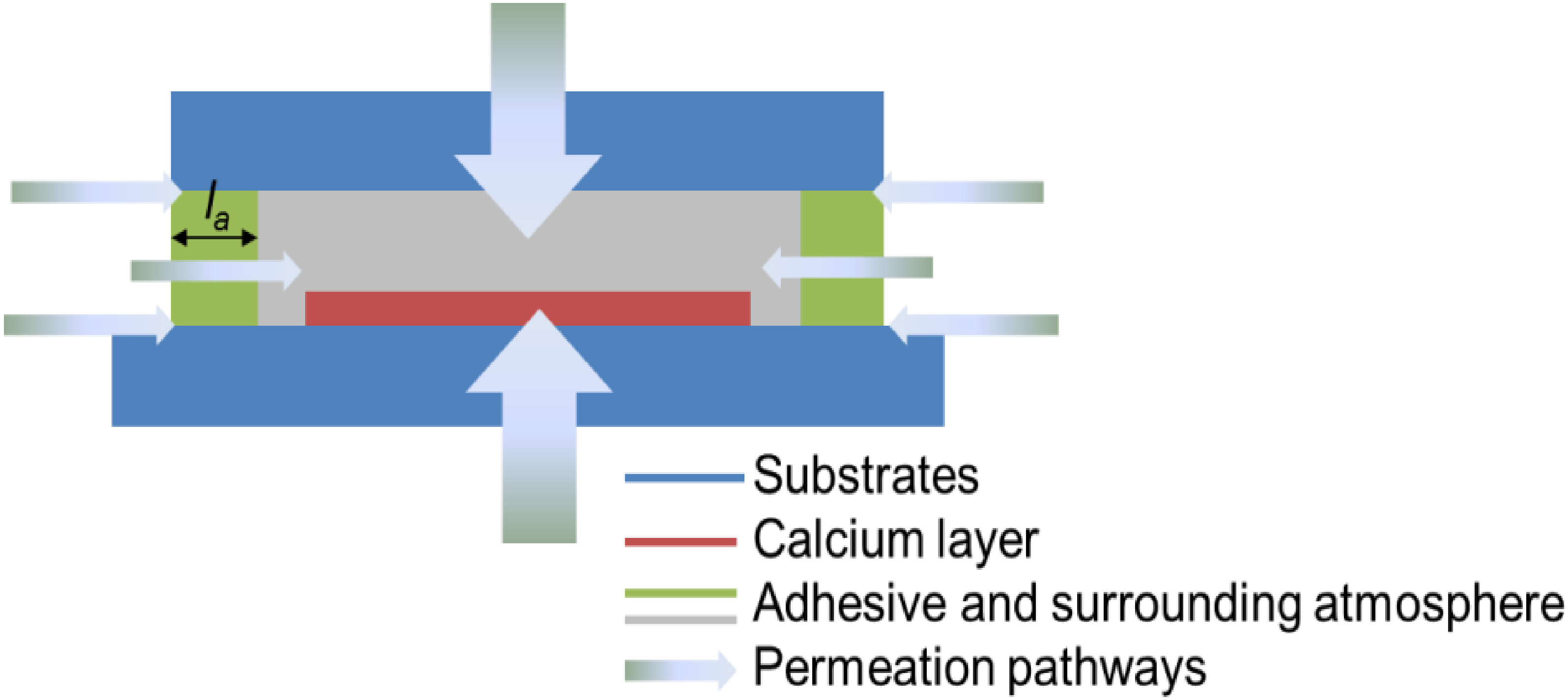
→ **packaging materials**

→ **packaging processes (Session 9.5)**

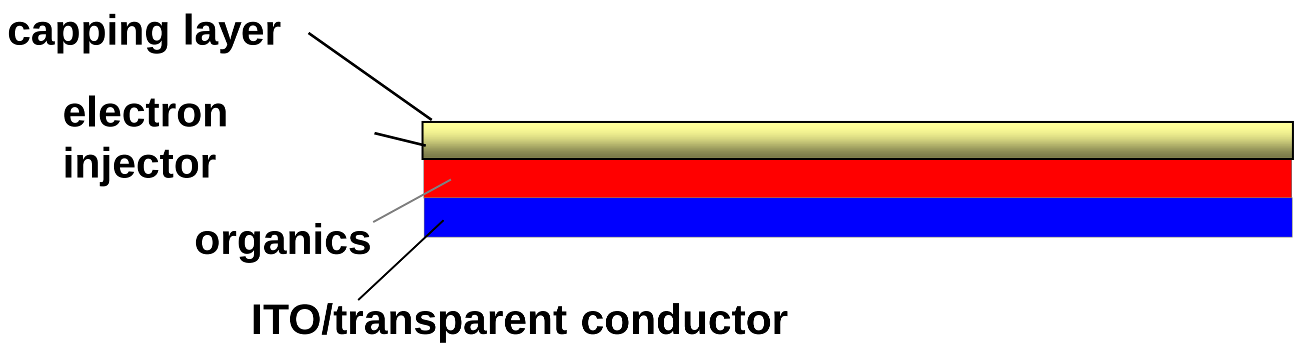
- **Barrier film and Device Preparation Application of Adhesives**
  - **Coatings and prinitng**
  - **Lamination**
- **Substrate – and Device – Handling Requirements**

Device packaging- permeation pathways?

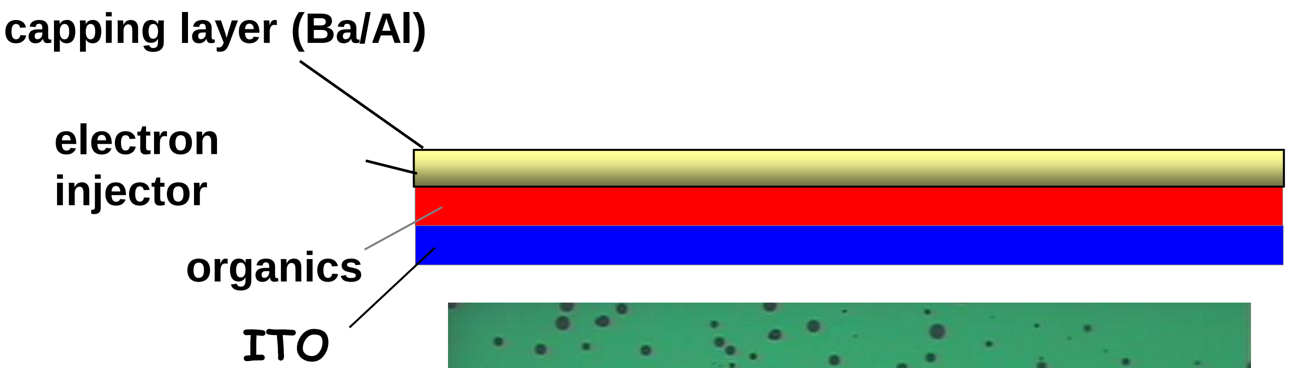
Imaging of the Permeation paths

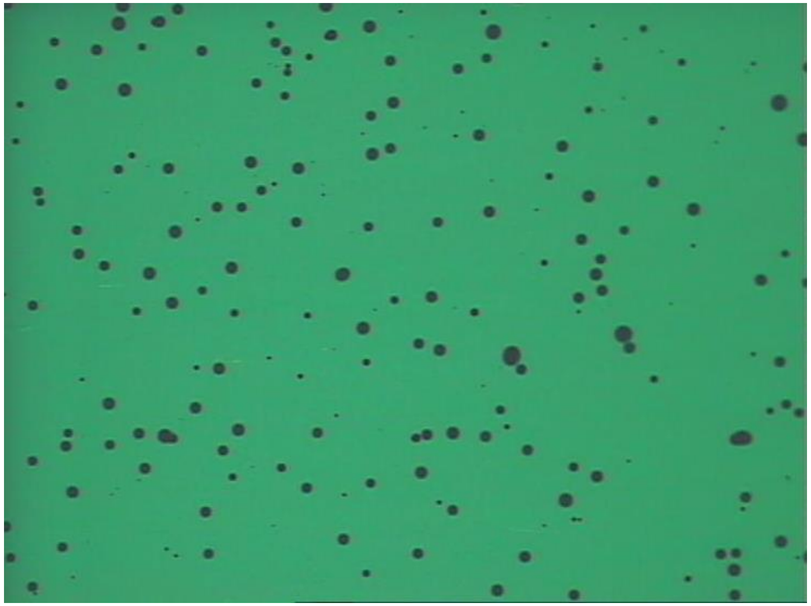


OLED - basic cross section



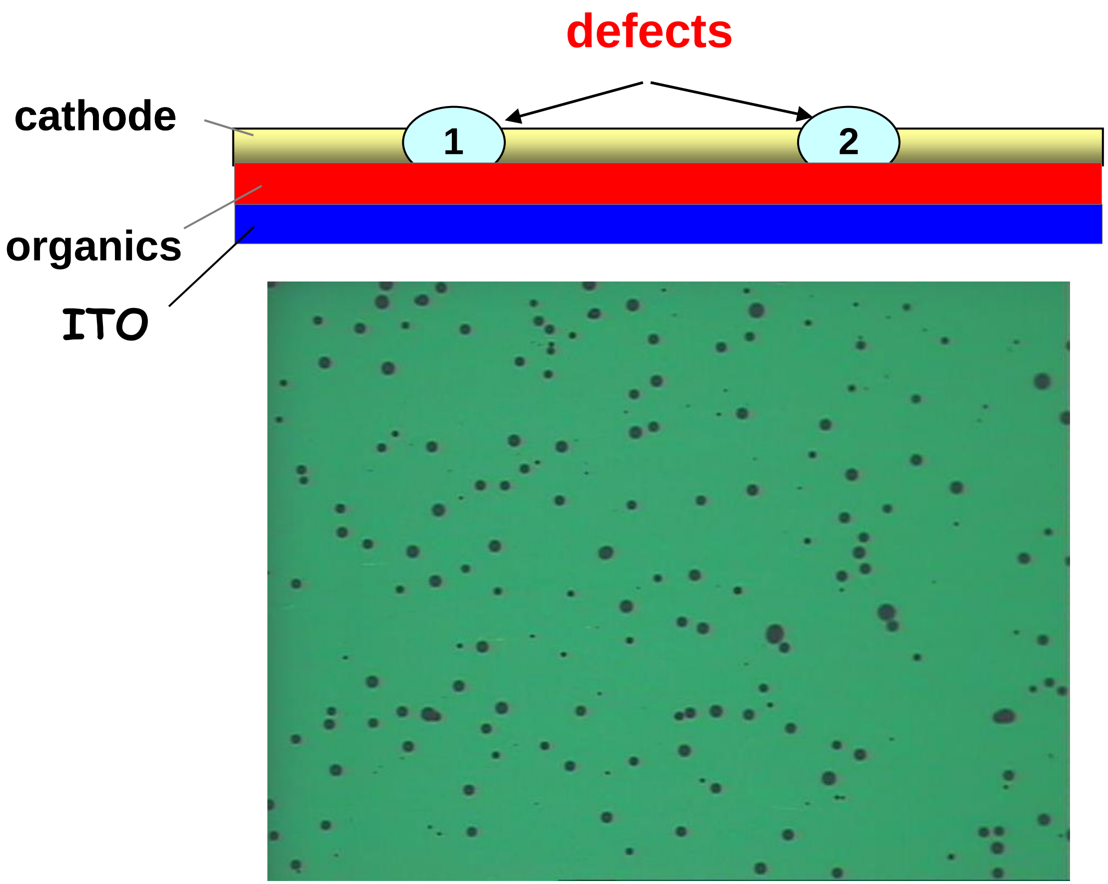
OLED - basic cross section





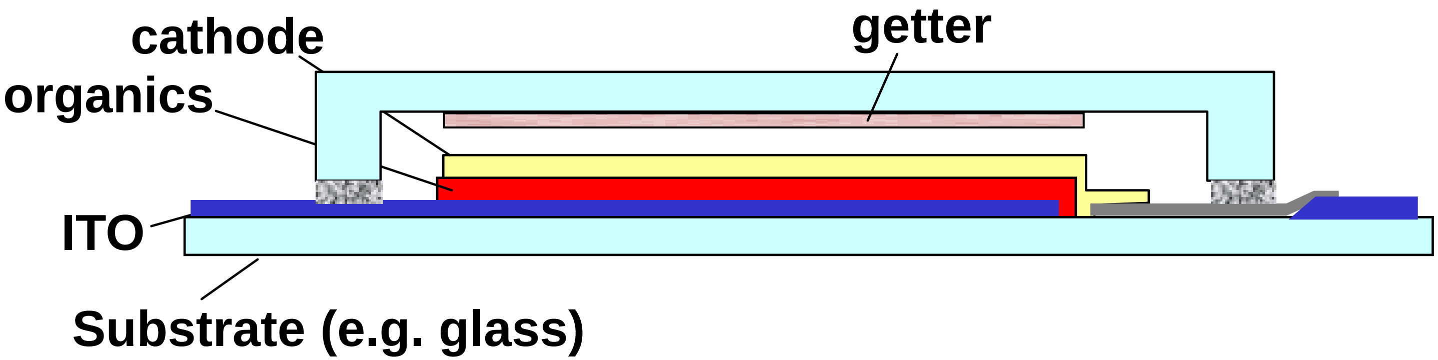
Ba/Al cathode: 10^7 black spots /m^2

OLED - basic cross section



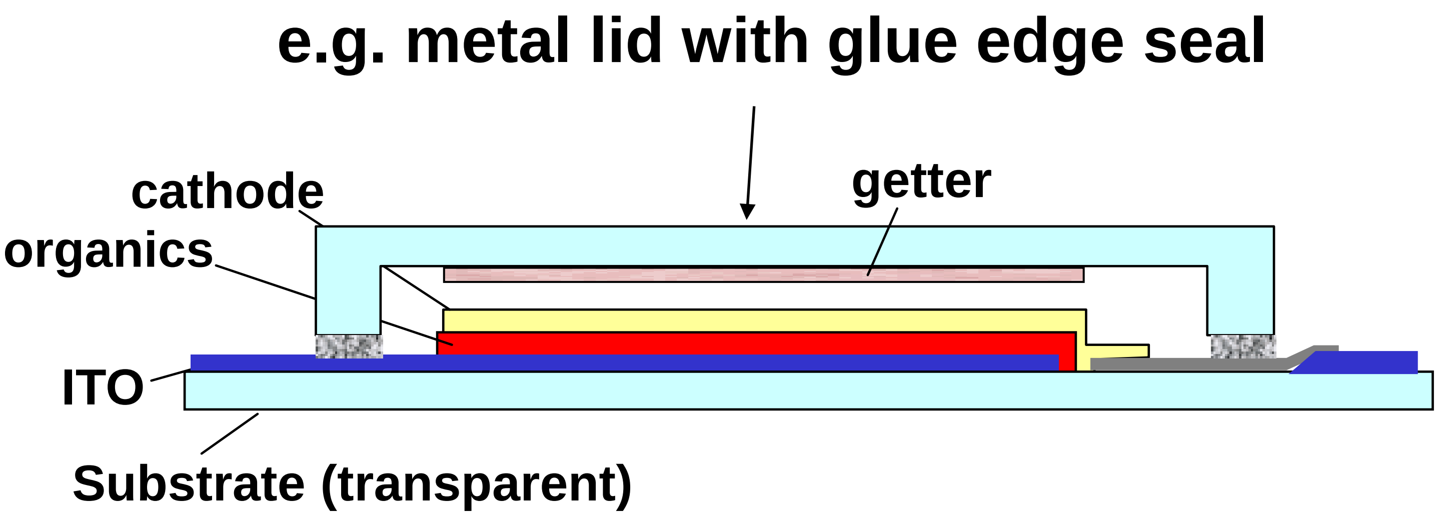
Ba/Al: 10^7 black spots /m^2

OLED packaging - metal lid with glue edge seal



- Proven concept
- Quality of encapsulation (glue edge, getter) is independent of quality of sample (pinholes)
- Benchmarking: onset of black spot formation at specified climate

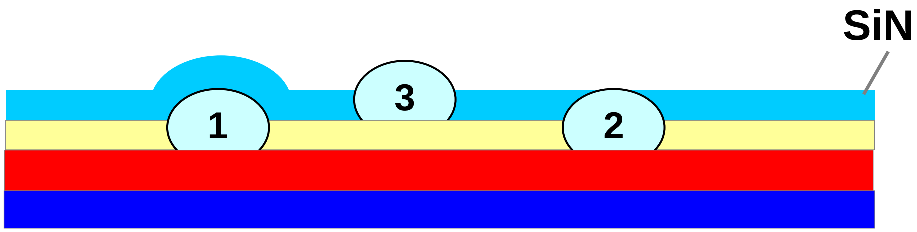
OLED packaging - metal lid with glue edge seal



Conventional encapsulation not applicable for

- flexible devices
- general lighting (low-cost requirement)

Thin film coating / encapsulation



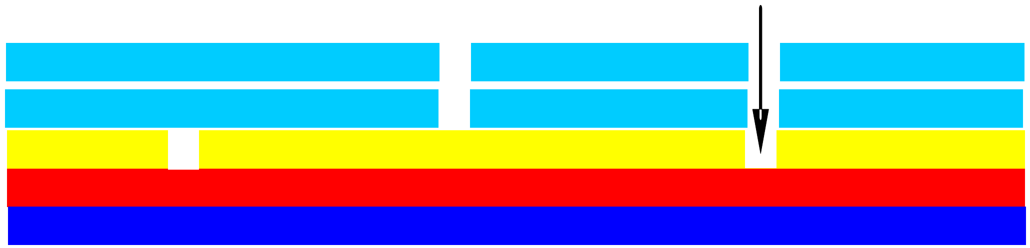
SiN: - WVTR < 10^{-6} g/m^2/day:
no black spots in 10 years at 20C/50%RH
- effective pinhole coverage 99 %: 10^5 black spots/m^2

Thin film encapsulation (TFE) – multiple layers

Improvement TFE :

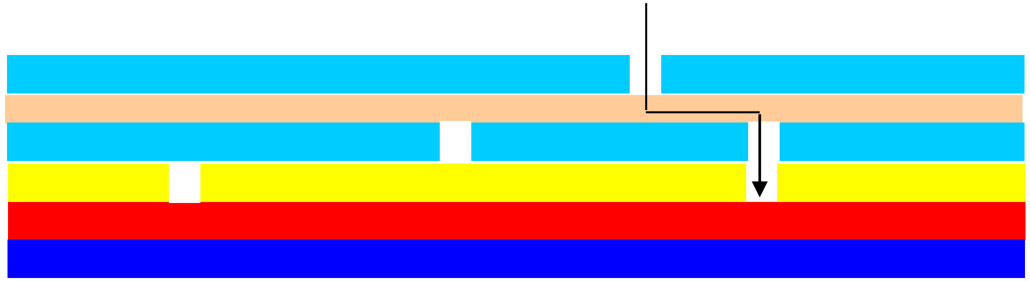
- increase thickness of SiN:

  no reduction of black spots



- stacking of layers:

  decoupling of pinholes in subsequent SiN layers



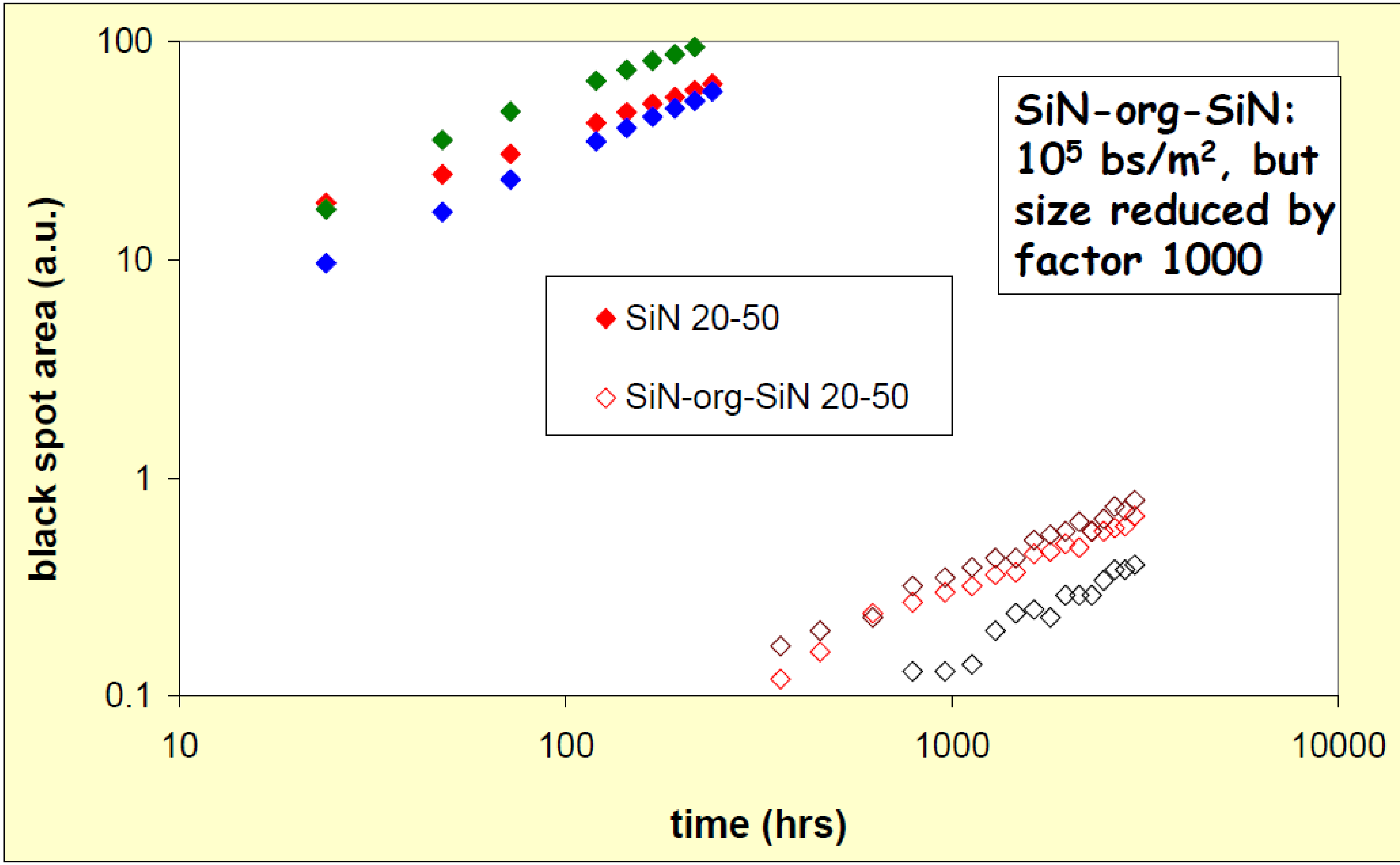
Thin film encapsulation (TFE) – multiple layers

stacking of layers:

barrier – organic coating - barrier

- No reduction of number of black spots wrt single barrier
- Delay of black spot growth rate depends on distance between pinholes in upper and lower SiN
- Quality of TFE depends on quality of sample !!

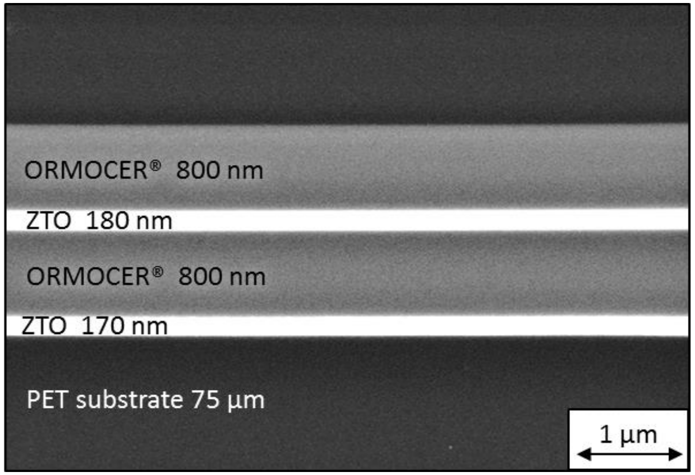
Thin film encapsulation (TFE) – multiple layers



Multi-layer / Multi-material barriers

Commonly, **polymer layers and oxide barrier layers are stacked alternately** on the substrate. While the oxide layers have low gas permeability but contain layer defects, the polymer layers are permeable but have the capability to interrupt defect growth and cover particles on the substrate or in the layers below.

ORMOCER® short for Organic Modified Ceramics describes a group of hybrid polymer materials. They are composed of inorganic oxidic structures, that are cross-linked or substituted by organic groups. UV curable.



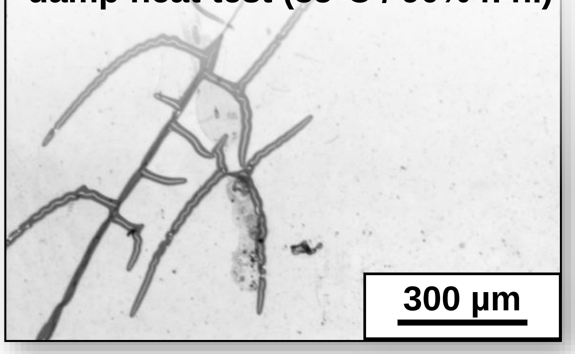
SEM cross-section image of the multi-layer barrier structure of the Fraunhofer Fraunhofer Alliance POLO.

Barrier mechanics during R2R processing

Strain in processing of coated polymer webs:

- **web-tension in roll-coaters**
  - 200 N on 400 mm wide Melinex 400 CW (75 µm):
    - at 20 °C: 0,16 % strain
    - at 120°C: 0,64 % strain
- **bending on rollers**
  - 3.75 cm bending radius on 125 µm PET (centred neutral axis) = 0,17 % strain on outside
- **mismatch in thermal expansion coefficients**
  - PET: $\alpha = 7 \cdot 10^{-5}\ K^{-1}$: 20°C … 120°C -> 0.7 % strain
- **shrinkage of polymer webs**
  - PET Melinex 400 CW at 150 °C: 1 %

200 nm Al_2O_3 on PET after 100 h damp heat test (85°C / 90% r. h.)



John Fahlteich, Fraunhofer FEP

Barrier mechanics : failure mechanisms

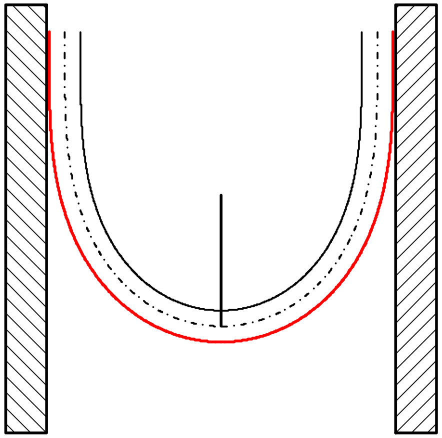
Two dominant failure mechanisms:

tensile ➔ crack formation (above critical strain ~ 1 %)

compressive ➔ buckling (adhesion is key)

“Cylindrical” deformation allowed

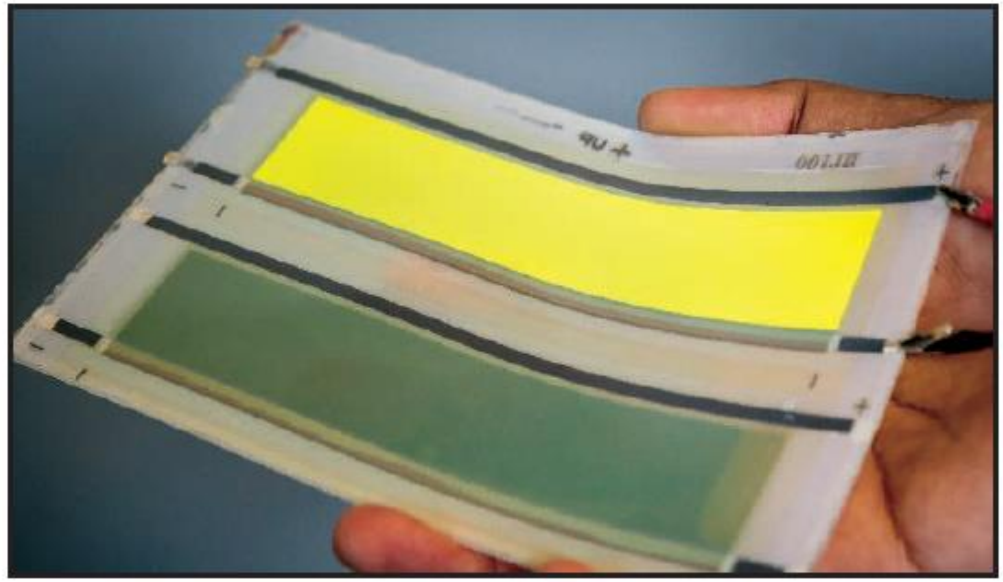
3D - deformations or device folding is very tough!



Piet Bouten, Philips

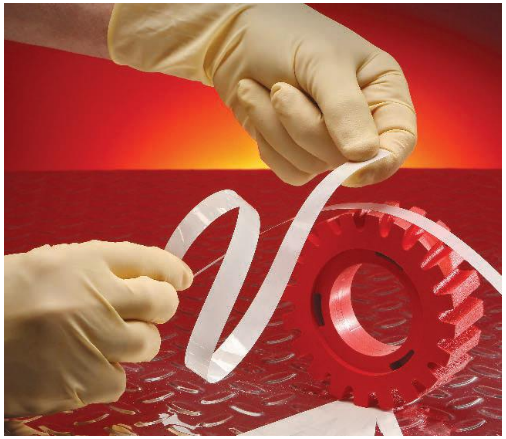
New packaging materials

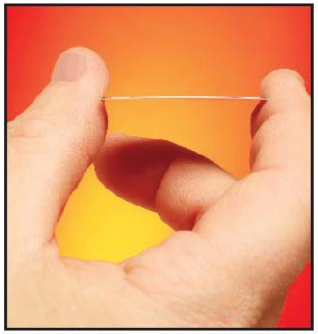
- **Ultra-Thin, Flexible Zirconia Ceramic by Thin E-Strate®**
  for Solid State & Thin Film Devices, Flexible Hybrid Electronics or Sensors:
  - Ultra barrier
  - Durable
  - Lightweight
  - Translucent
  - Wear resistant
  - Corrosion resistant
  - Biocompatible



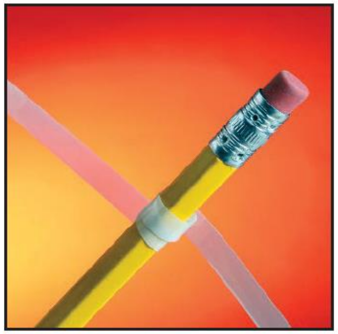
OLED Photo Courtesy of Holst Centre

Zirconia Ribbon Ceramic
World's 1st Continuous Roll-to-Roll Ceramic





Thin E-Strate® as support and seal in Flexible Solid State Lithium Batteries and OLEDs.



20µm thick ceramic

Self reflection questions

- Why do we need encapsulation in (organic) electronic devices?
- Can you name some examples of mechanisms or effect that are the root cause of performance degradation ?
- Which materials can be used for managing the lifetime of a printed/organic electronic device?
- Can you name some quantities / units / concepts that can be useful when addressing lifetime issues?
- Which methods can you use to evaluate encapsulation materials and processes ?

QUIZ

- **Smart phones**
  - **iPhone**
  - **Android**

  } **Download and install the App "*PointSolutions*"**

- **Laptops / Tablets**
  - ***https://ttpoll.eu***

- **Join session – micro505**

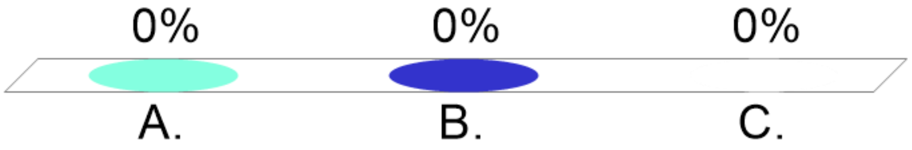
- **If asked – Enter anonymously (not your real name)**

Q1: Which component has the highest power density and energy density?

A. **Battery higher power density / Supercap higher energy density**

B. **Supercap higher power density / Battery higher energy density**

C. **Both are the same**



Q2: What is the main limitation in fully printing battery / supercap

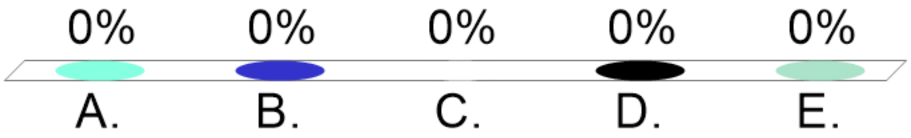
A. Two many layers to stack

B. Printing the electrodes

C. Printing the separator

D. Printing the electrolyte

E. Their encapsulation



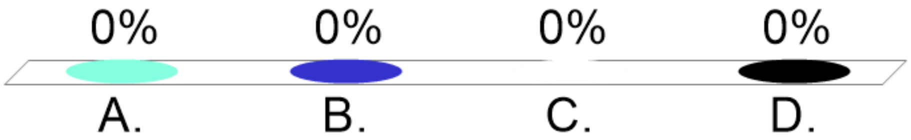
Q3: Rank the devices in terms of encapsulation permeability requirement

A. OTFT > OPV > OLED

B. OLED > OTFT > OPV

C. OPV > OLED > OTFT

D. OLED > OPV > OTFT

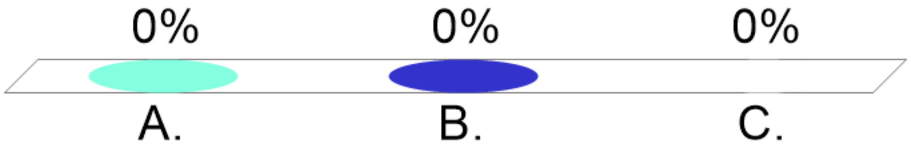


Q4: Is WVTR, water vapor transmission rate, enough to determine failure time ?

A. Yes

B. No

C. It depends



APPLICATION, MARKET, ROADMAP

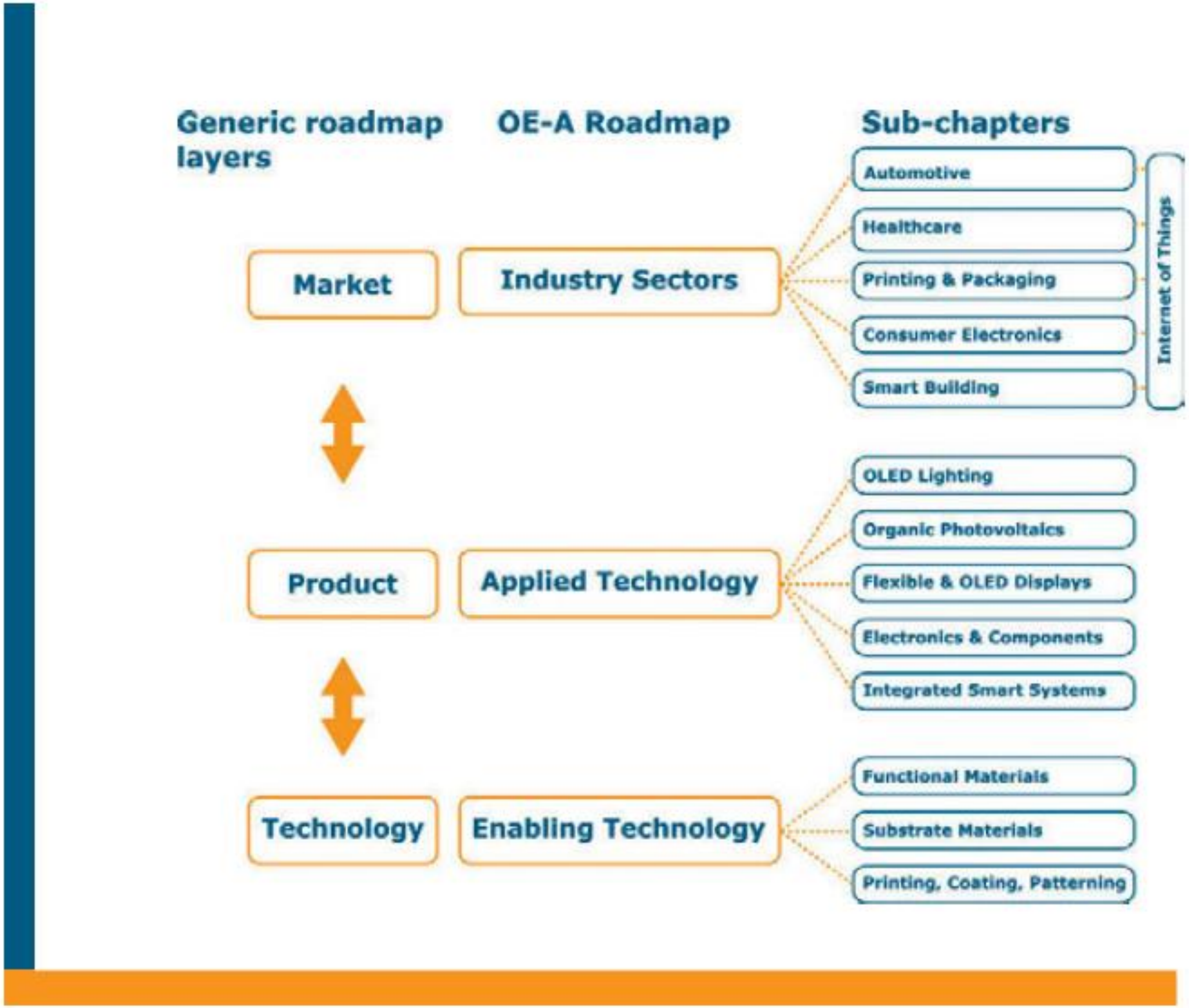
As a complement

Reference book on OPE: Chapter 14
OE-A Roadmap 8th Edition, 2020

Technology readiness level (TRL)

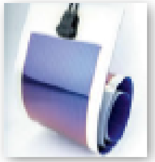
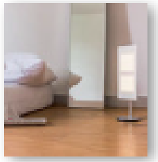
OE-A Terminology	TRL	EU Framework Program 2020 Terminology
Lab demos	TRL 1	Basic principle observed
	TRL 2	Technology concept formulated
Demonstrator	TRL 3	Experimental proof of concept
	TRL 4	Technological validity in a lab
Prototype	TRL 5	Technology validated in relevant environment (industrially relevant environment in the case of KETs – key enabling technologies)
Pilot production	TRL 6	Technology demonstrated in relevant environment (industrially relevant environment in the case of KETs)
	TRL 7	System prototype demonstration in an operational environment
Small scale production	TRL 8	System completed and qualified
Mass production	TRL 9	Actual system proven in operational environment (competitive manufacturing in the case of KETs; or in space)

The Concept of Technology Roadmap



OE-A Roadmap 8th Edition

OE-A roadmap OPE

	Existing 2020	Short Term 2021-2023	Medium Term 2024-2026	Long Term 2027+	
	Foldable displays for phones; Reflective EPD	large flexible OLED-Displays; rollable TV; curved display for automotive interior	In-mold electronic (IME) Displays;	Flexible QD-Displays; flexible µLED-Displays	**Flexible & OLED Displays**
OPV	OPV objects; portable chargers; OPV-R2R products	Opaque OPV for BIPV; Large area OPV foil; OPV power supply	Semitransparent OPV for BIPV; OPV for autonomous sensors	Color and shape on demand; OPV on "all" surfaces (e.g. wallpaper, mobile devices) combined with thin film battery	
	Printed devices: memory, RFID antenna, primary battery, active backplane, piezoelectric elements; Sensors: glucose, pressure, temperature, humidity; printed phone case integrated antenna; thin flexible Si-chips	light sensor; stretchable conductors / resistors; 3D touch sensors; OTFT backplanes for low energy displays and OPD; 3D & large area flexible electronics; active touch sensors	Printed secondary ion battery; printed super caps; gesture sensors	Complex stretchable electronics; Printed complex logic;	**Electronics & Components**
Integrated Smart Systems	Smart label sensors (humidity, temperature); Sensors for blood analysis; NFC labels; Hybrid systems (printed components + flexible ICs); HMIs (sensors)	Ambient monitoring (e.g. humidity); sensors embedded in molded parts (automotive); on-skin human monitoring patches for sports; ambient intelligence (connected); Sleep disturbance monitoring;	On-skin human monitoring patches in clinical environment; Single article tagging (food)	Smart labels with geo localization; Breath analyzer for medical prevention	
	Flexible white OLED modules; rigid red OLEDs for automotive applications	Flexible red OLEDs (segmented) for automotive applications; transparent OLEDs; OLEDs for interior lighting of automotive	3D OLEDs; OLED signage; OLED for medical applications	OLED for aircraft and railway interior application	**OLED Lighting**

(c) OE-A

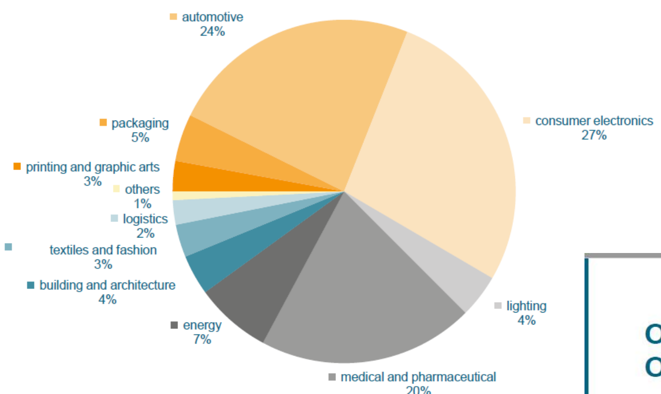
OE-A Roadmap 8th Edition

OE-A Business Climate Survey

OE-A Business Climate Survey on General Trends in Organic and Printed Electronics, February 2022

Targeted End-User Industry

Share of companies in %



Source: OE-A, answers weighted by number of employees, multiple entries possible, figures rounded

Printed Electronics in Automotive
Great potential for printed electronics components

oe-a

"Potential applications include antennas, body parts, cockpits, loudspeakers, mounted structures and sensors. Flexible electronics can be incorporated into bumpers, head-up displays, instrument panels, seats, tires, windows and many other auto parts."

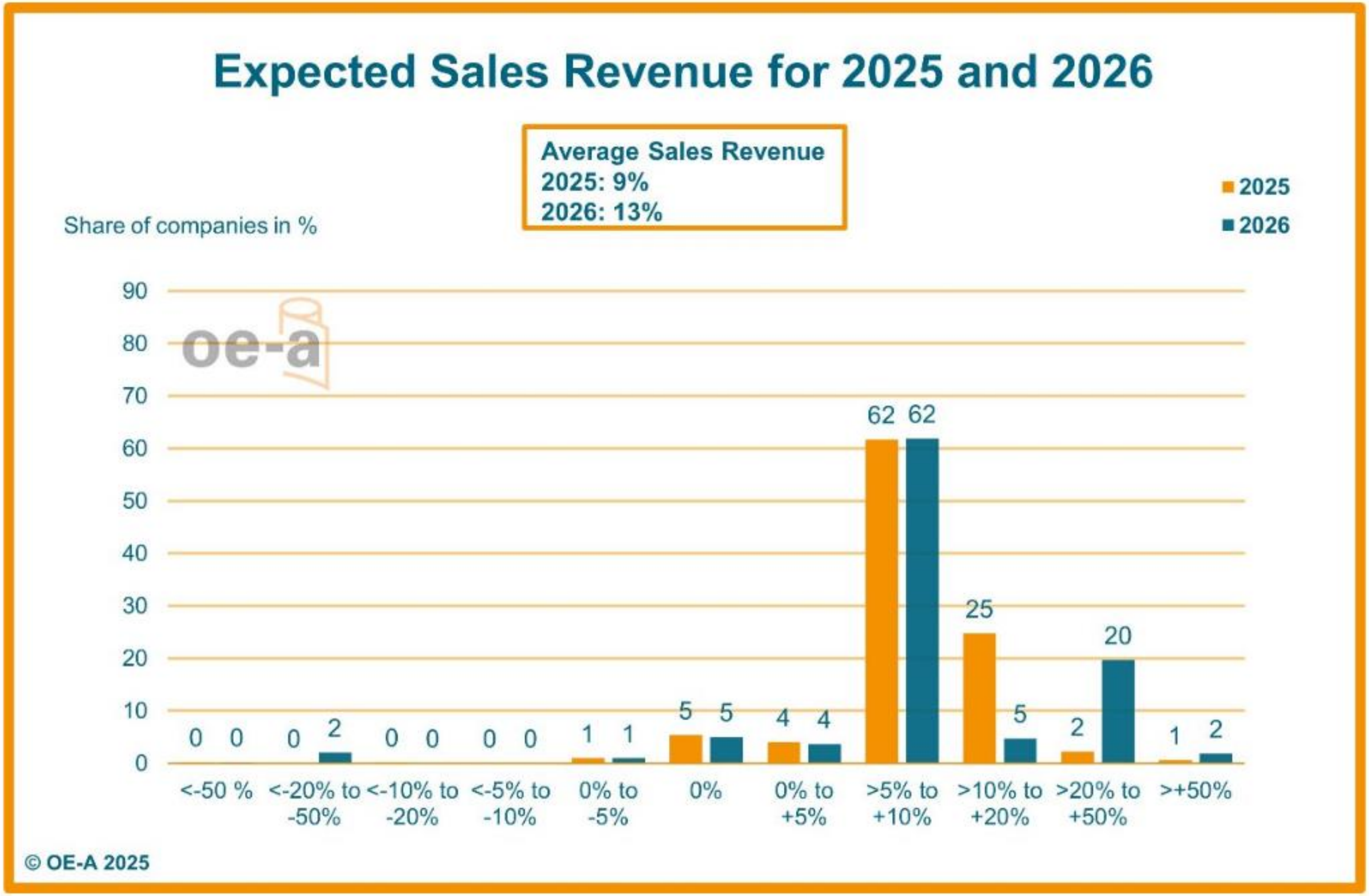
Electronics content (classical and printed electronics) in car's total production costs

OE-A Business Climate Survey on General Trends in Organic and Printed Electronics, February 2022

oe-a

Most important targeted end-user industries:

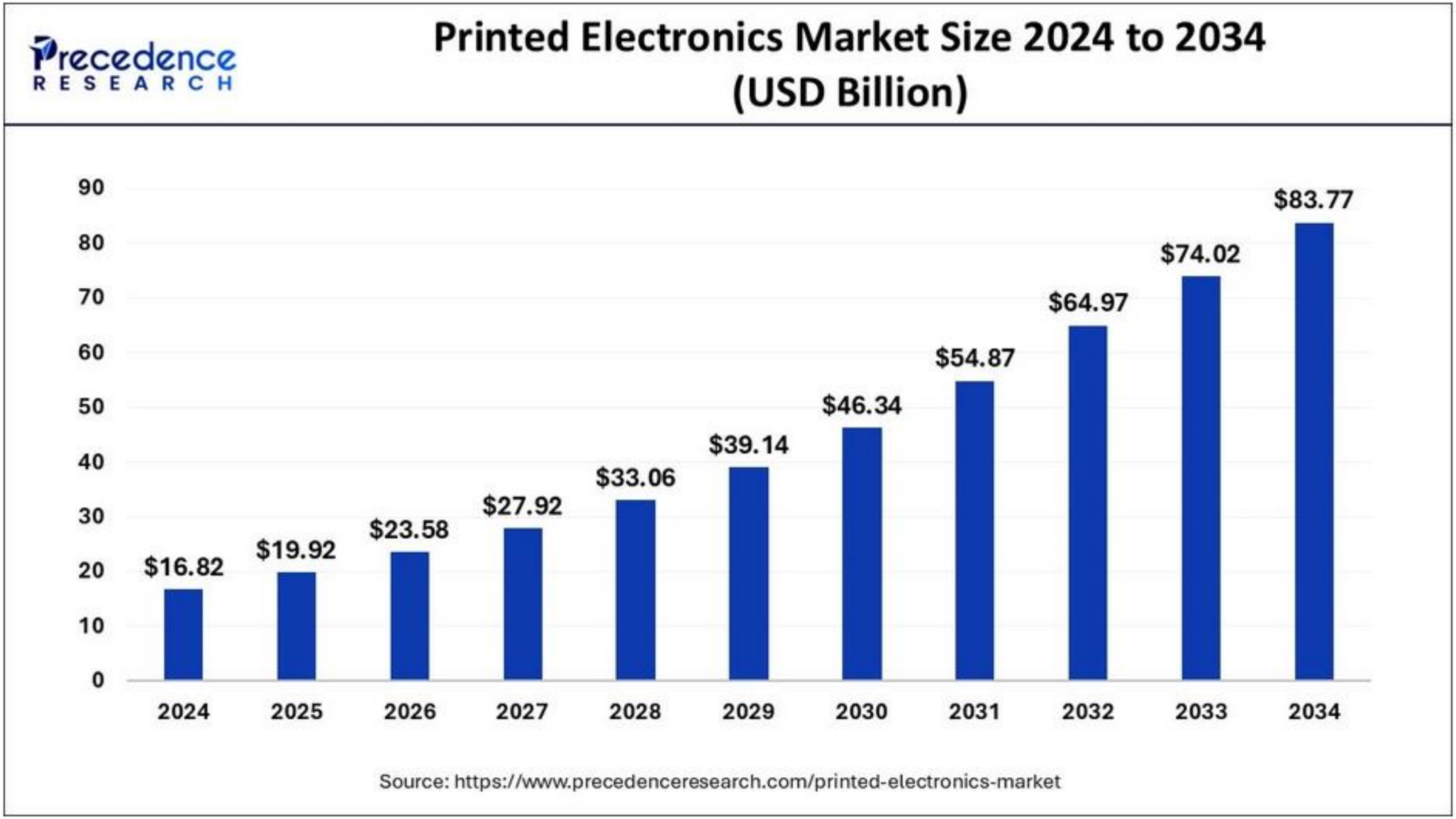
OE-A Business Climate Survey



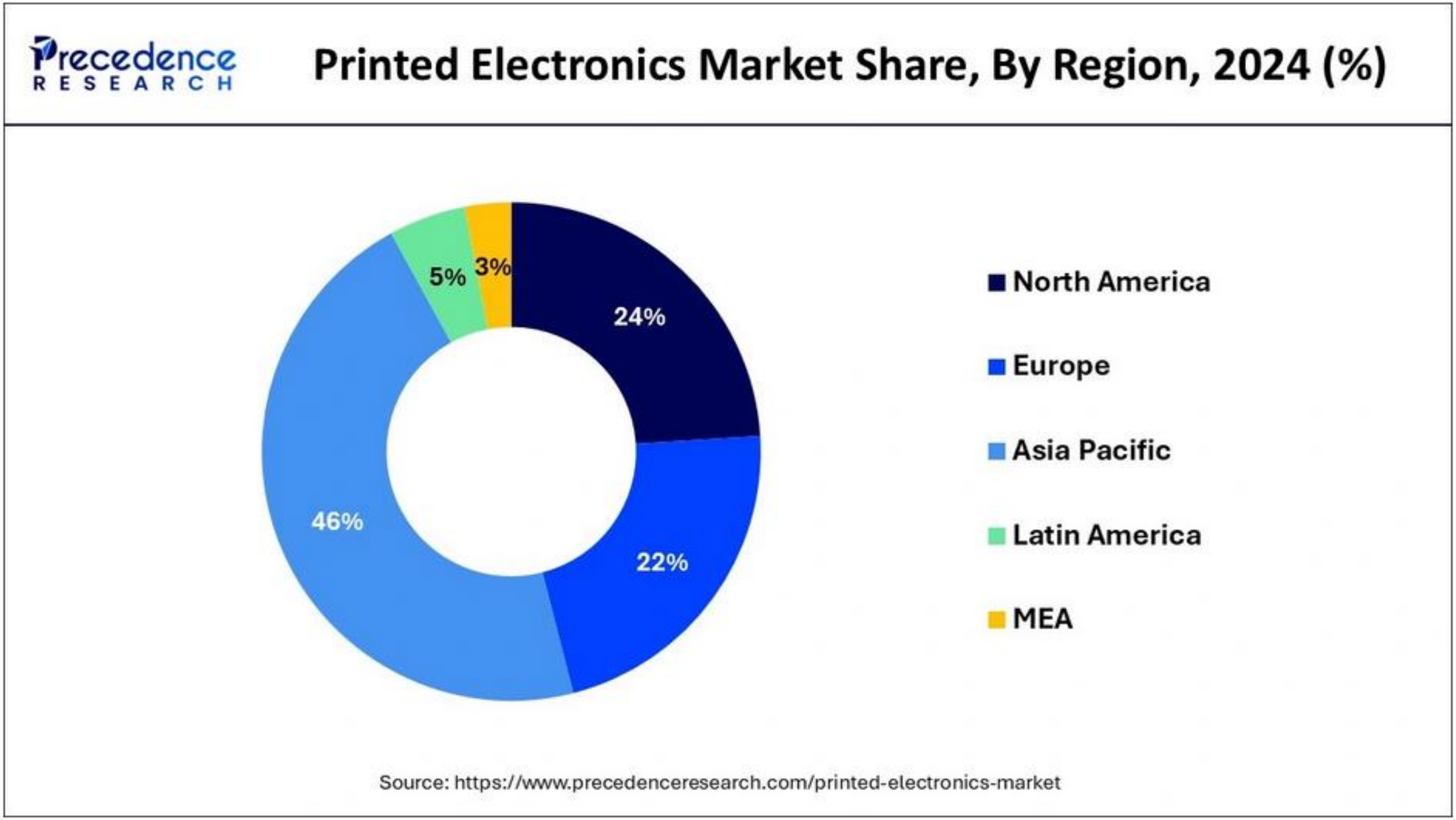
The OE-A business climate survey forecasts an 9 % increase in turnover for the industry this year.

For 2026 a plus of 13 % is expected. © OE-A (image in higher resolution)

PE market size evolution



PE market share



PE market share by technology