Transparent Electronics for Active Matrix Displays

Thomas Riedl

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City: Wuppertal

State: North-Rhine-Westfalia

Pop.: 353.308

Thomas Riedl

Institute of Electronic Devices

since 1863 School of Engineering

1972 Foundation of BU Wuppertal

7 Faculties

14,000 Students

1100 Students

21 Professors

Focus Areas:

→ Automotive Engineering

→ Print & Media Technology

→ Renewable Energy Systems

→ Polymer Electronics

Campus Freudenberg

Institute of Electronic Devices, University of Wuppertal, Germany (T. Riedl)

since : 01.10.2009

former: *Advanced Semiconductors Group*

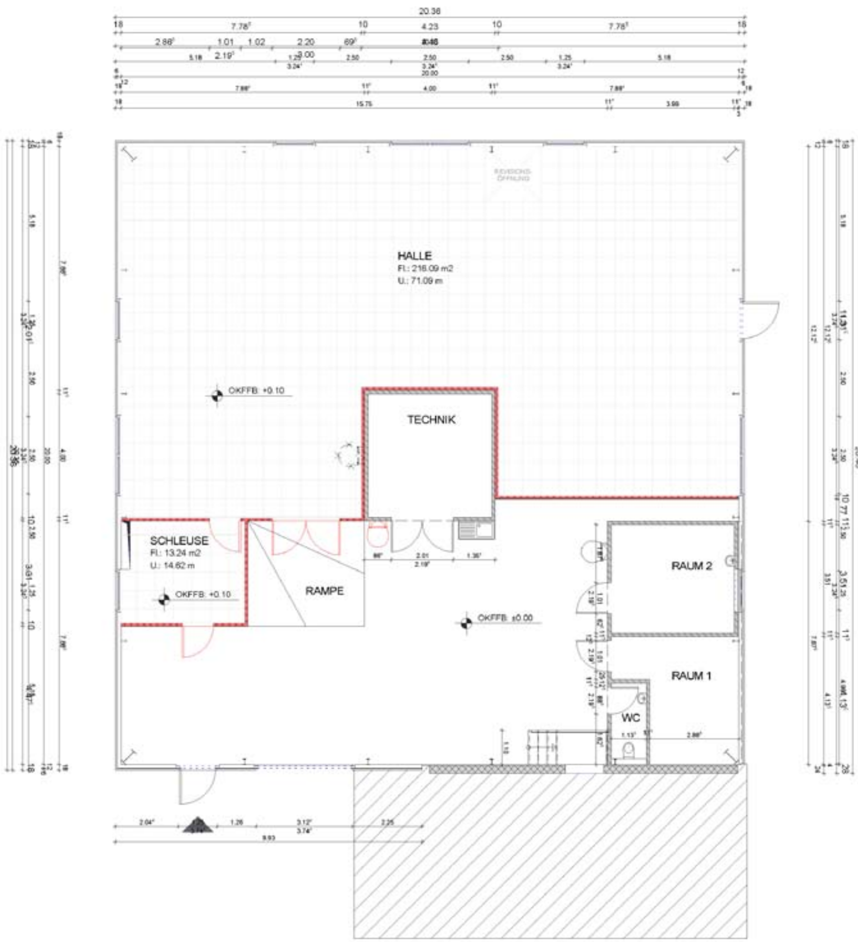
Institute of High-Frequency Technology, TU Braunschweig

New Labs - Institute of Electronic Devices

400 m^2

220 m^2 lab space (clean-room)

Start-up: 2010



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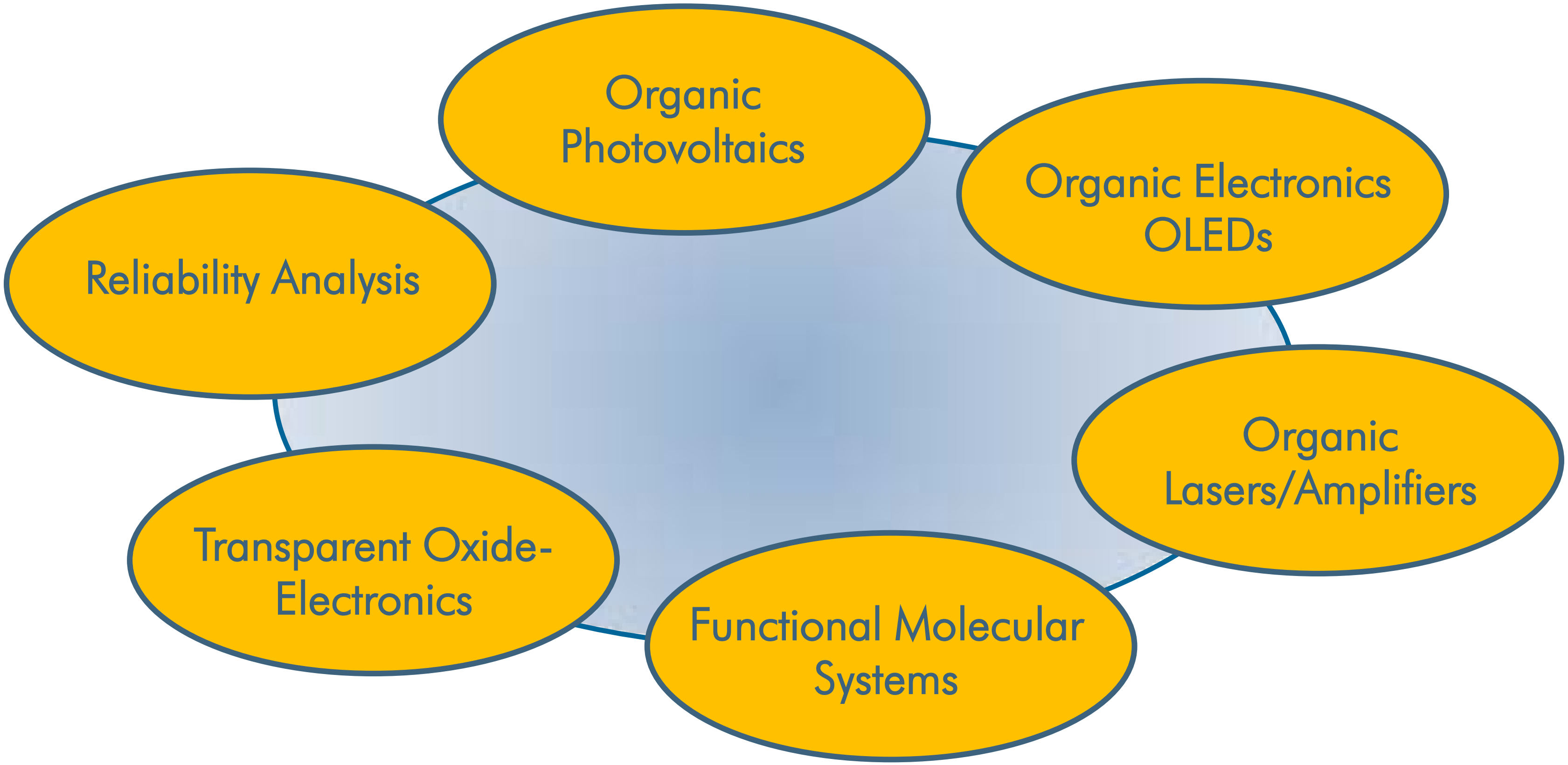
Institute of Electronic Devices, University of Wuppertal, Germany



Metaloxides as Components of AM-Displays

→ Transparent Electrodes (OLED, OPV)

→ Thin-Film Encapsulation

→ Oxide TFTs

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Samsung S8300 UltraTOUCH

LG 15 inch OLED TV (15EL9500)

→ no back-lighting

→ large viewing angle

→ low weight

→ flexible

→ cost effective technology

→ low energy consumption

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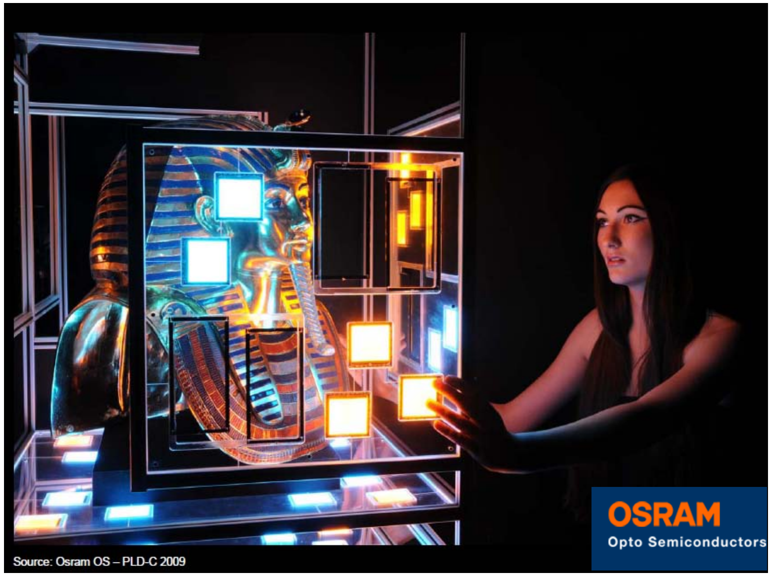
OLED Lighting



OLEDs: next-generation lighting technology

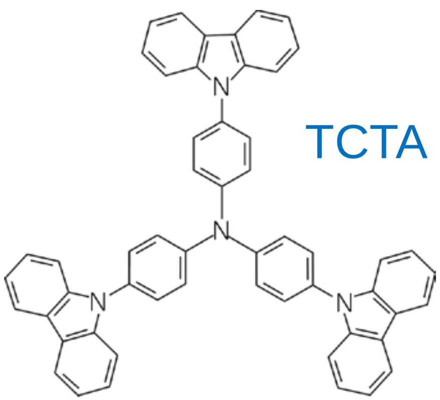
Transparent Displays

Minority Report
TM and © 2002 Twentieth Century Fox and Dreamworks, LLC.

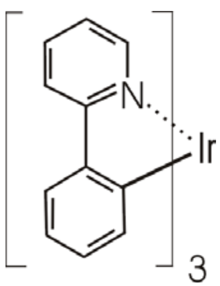
AVATAR TM and © 2009 Twentieth Century Fox

Transparent OLED

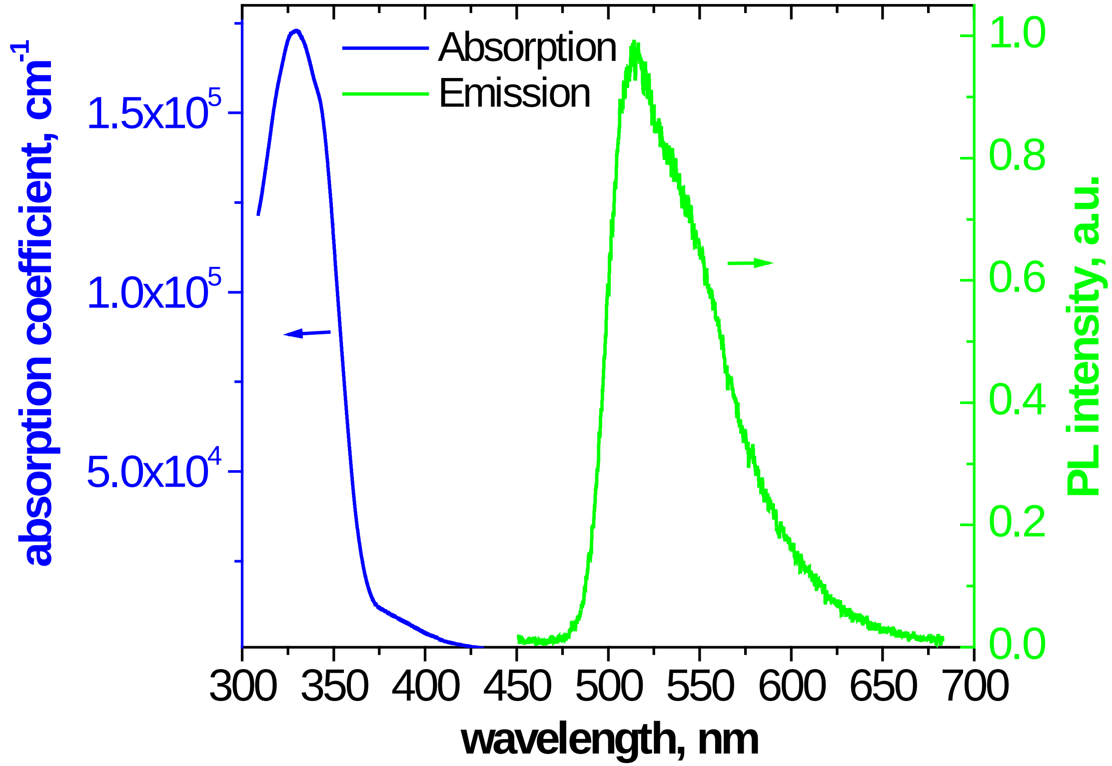
guest-host systems



TCTA



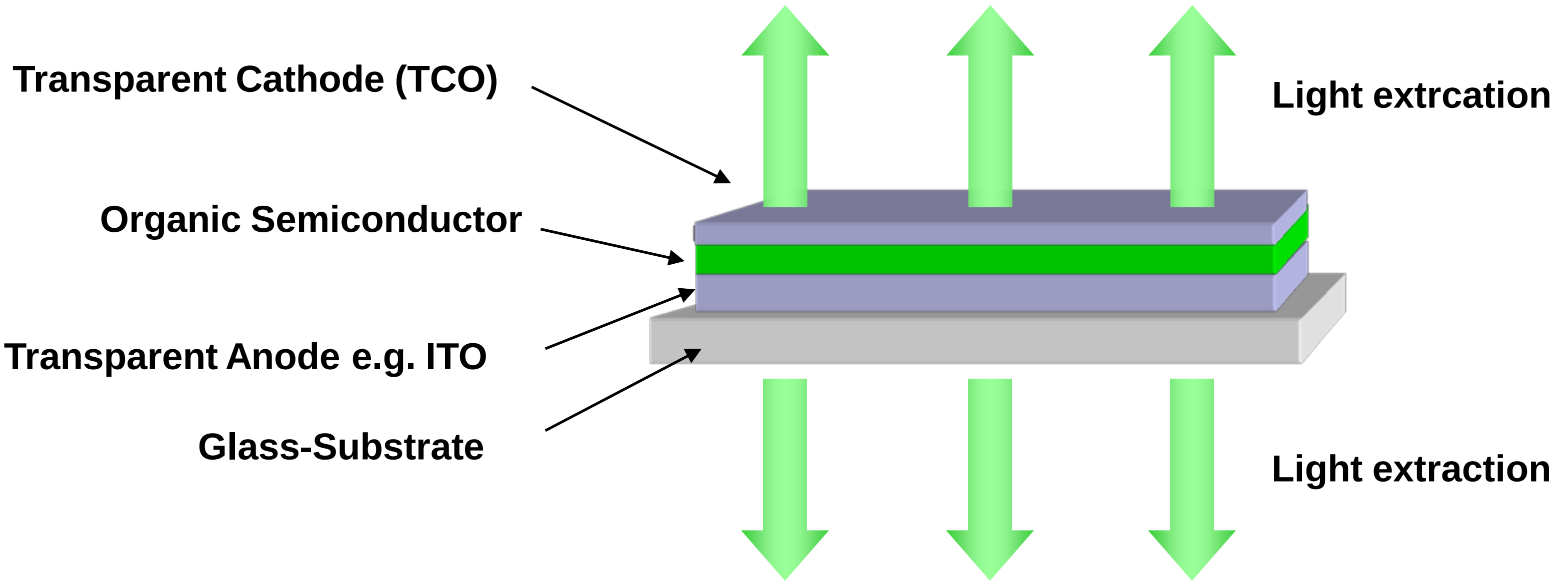
$Ir(ppy)_3$



taylored organic layers:

+ absorption in the UV (< 400 nm)
+ emission in the visible

→ large „Stokes shift“



⇒ entirely transparent OLEDs

Transparent Conducting Oxides on Top of Organics

Organic semiconductors are brittle !

→ low processing temperatures (< 80 °C)

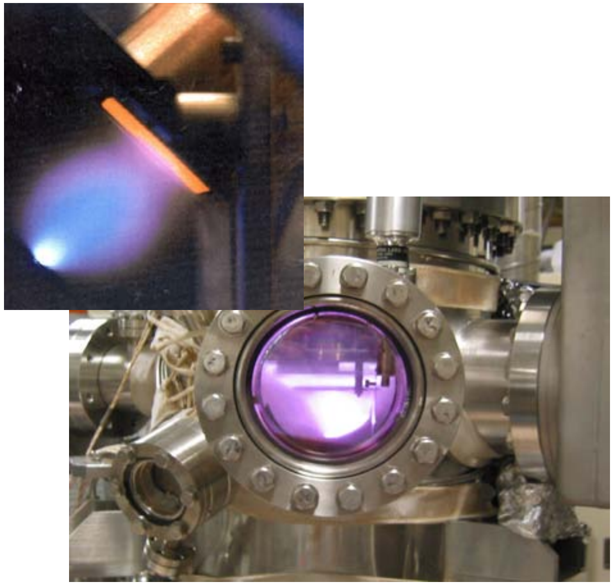
→ avoid oxygen + high-energy particles/radiation

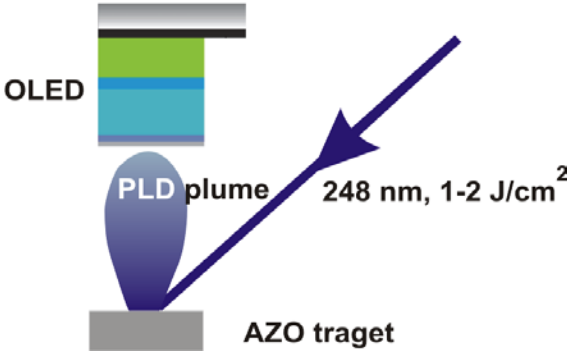
Bonding energies:
C-C (3.73 eV), C=C (6.21 eV)

Typical by-products : charge carrier traps
non-radiative defects

but:

→ transparent oxides contain oxygen
→ sputtering, pulsed laser deposition
→ particle energies ~1-100 eV ?
→ UV radiation





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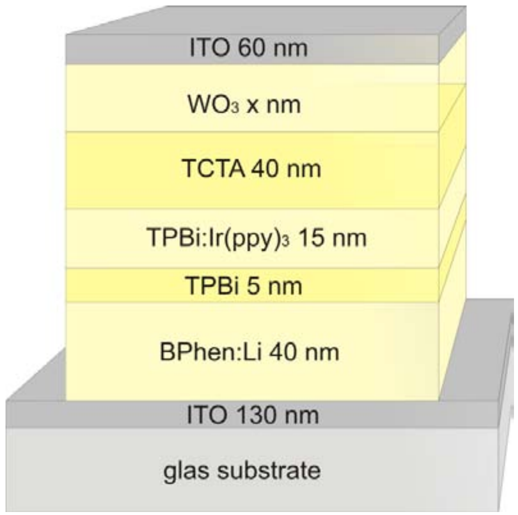
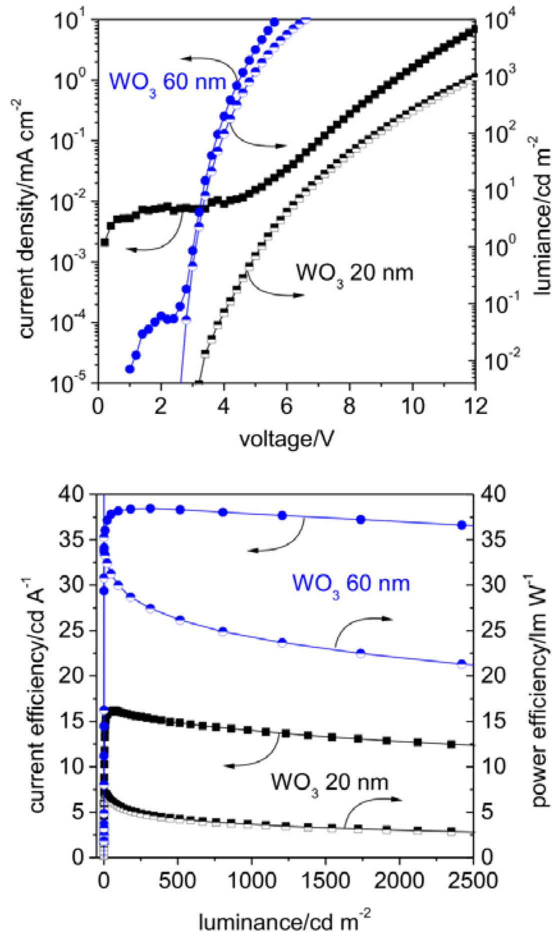
Transparent OLED Structure





→ bullet-proof vest (WO_3, MoO_3, …)

→ thermal deposition of WO_3, MoO_3, …

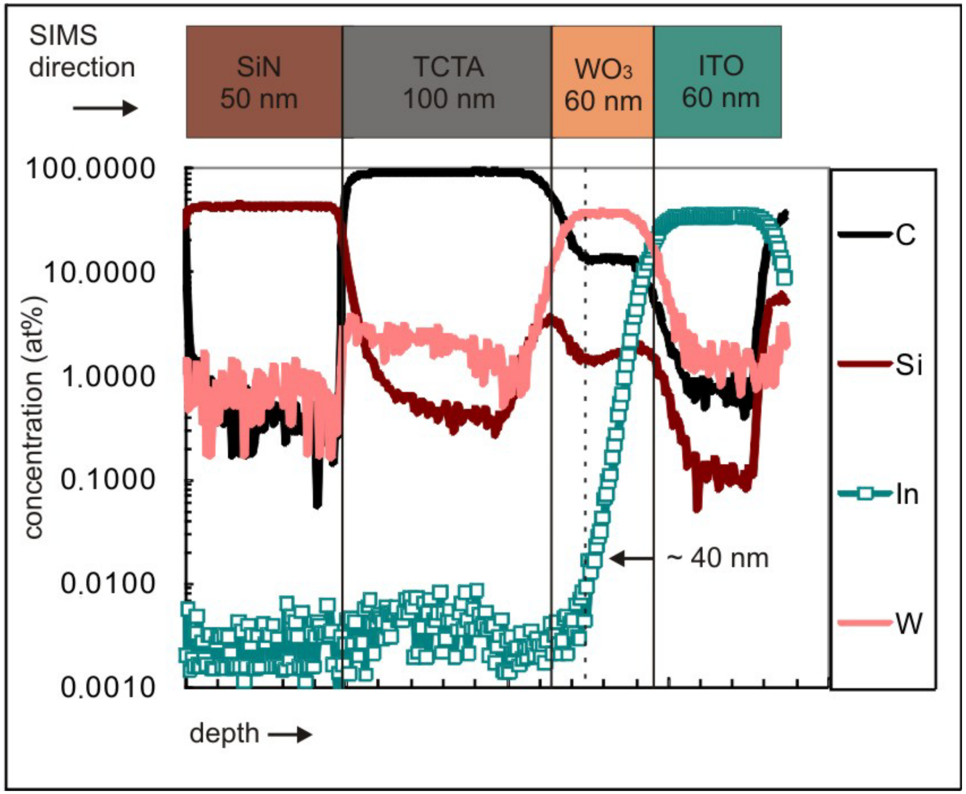
→ WO_3, MoO_3 transparent, conductive

→ record-efficiency: 30 lm/W, 38 cd/A

Adv. Mater. 20, 3839 (2008)

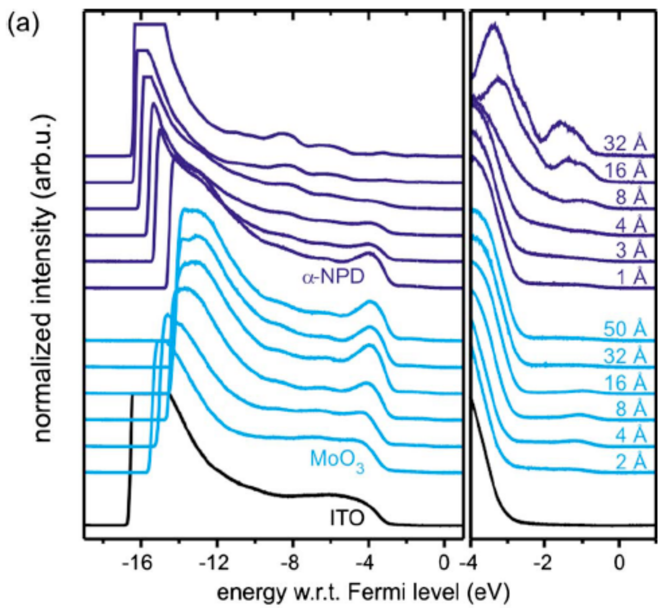
WO_3 as Sputter Protection Layer - SIMS Analysis

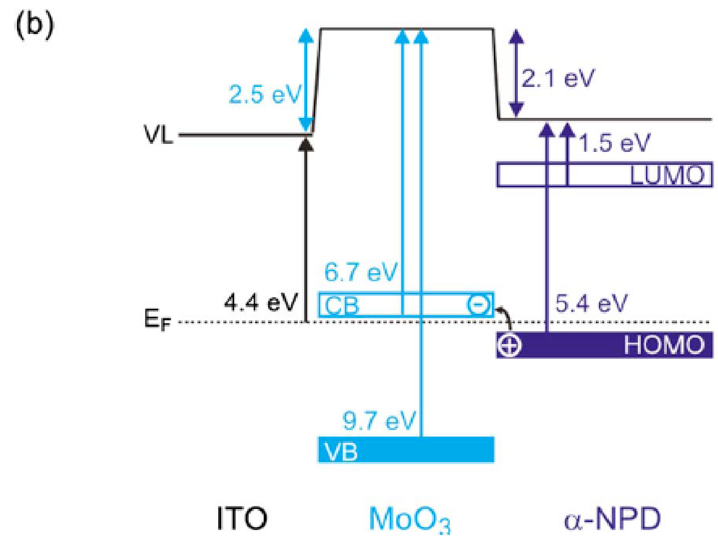
Analysis of particle penetration → secondary ion mass scectroscopy



Sputter particles penetrate WO3 layer only by 40 nm → protection for OLED

MoO_3 High-Work-Function Material





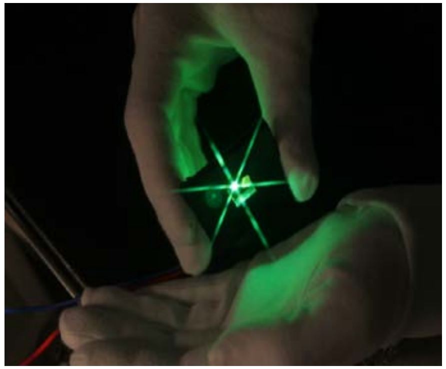
Appl. Phys. Lett. **95,** 123301 (2009)

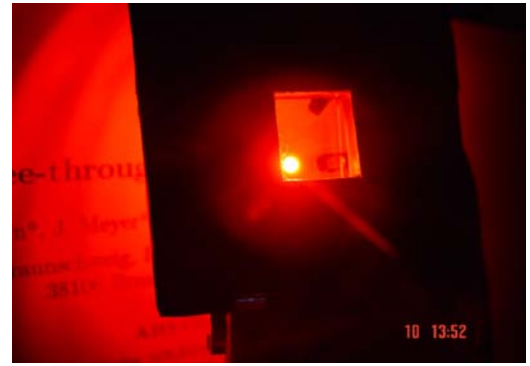
	EA (eV)	WF (eV)	IE (eV)
MoO_3	6.7	6.86	9.68
WO_3	6.27	6.47	9.66

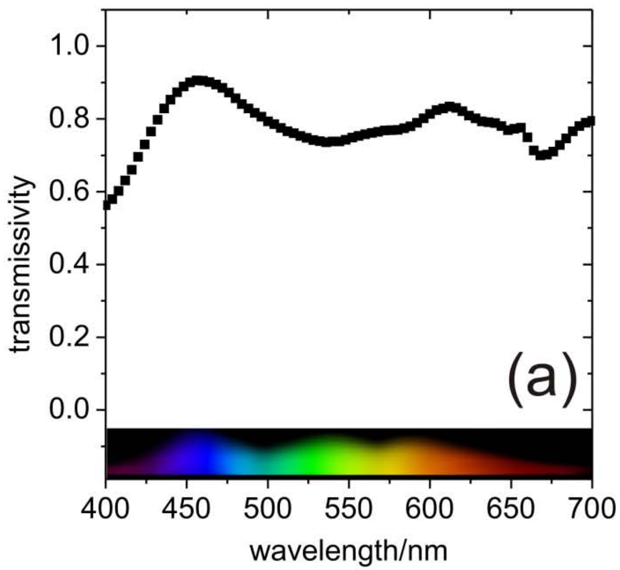
→ transition metal oxides: n-type semiconductors

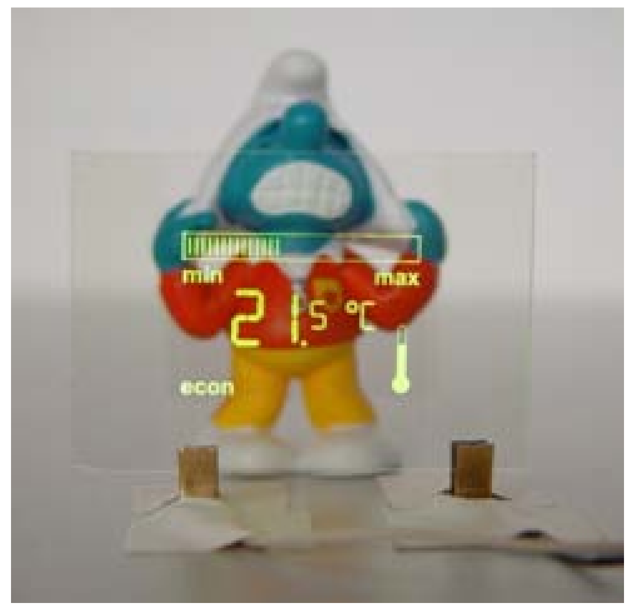
→ no electron blockers

→ high workfunction, very deep valence band



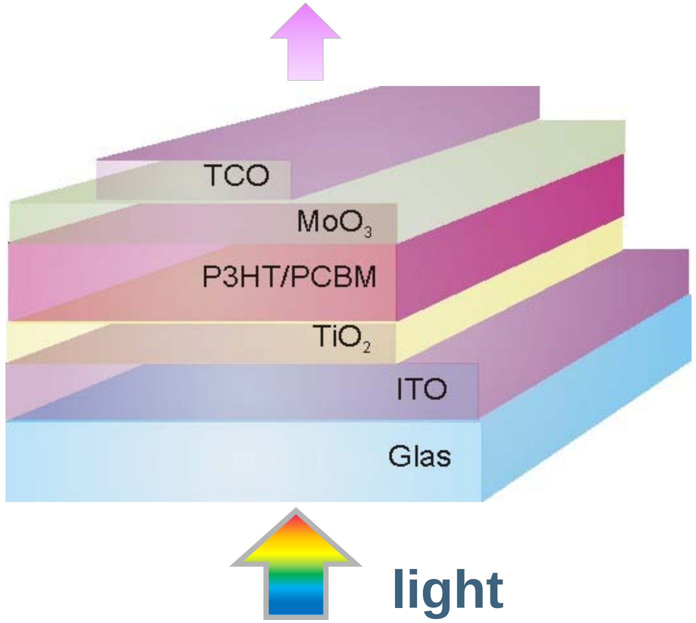

10 13:52

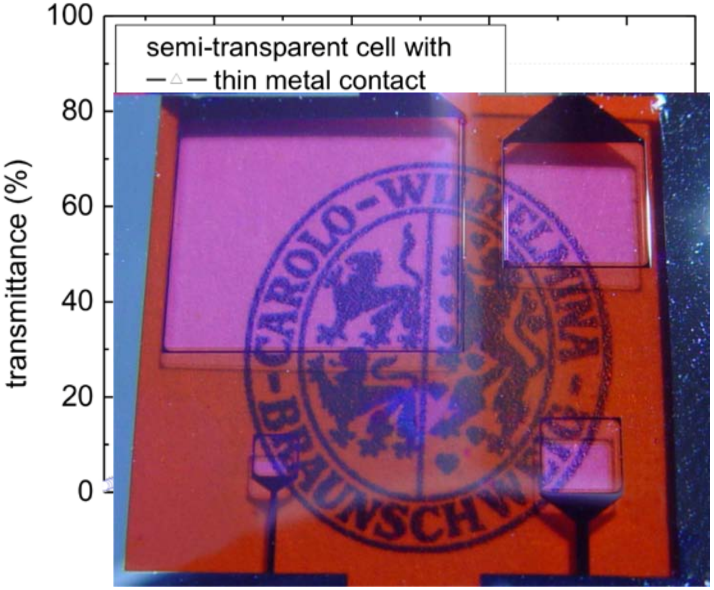

1.0
0.8
0.6
0.4
0.2
0.0
transmissivity
(a)
400
450
500
550
600
650
700
wavelength/nm


min
max
econ

Transparent electrodes → semi-transparent OPV

currently ~ 2.5 % efficiency





Appl. Phys. Lett. 94, 243302 (2009)

Terminal 2G Airport Paris Charles de Gaulle

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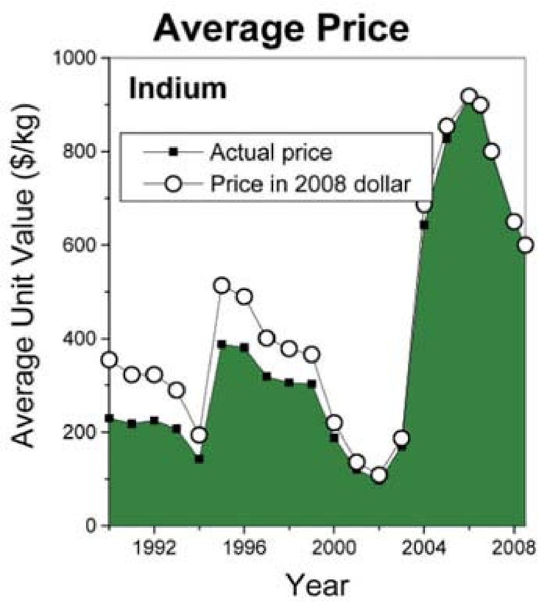
Indium-Tin-Oxide (ITO) as TCO



indium (metric tons)

			2005	2006	2007	2008	2009
sources	+	Virgin	429	497	476	518	551
		Reclaim	357	503	650	802	961
uses	−	FPD	595	774	928	1114	1281
		Other	181	188	210	245	274
		annual net*	10	38	-12	-39	-43
		cumulative**	**23**	**61**	**49**	**10**	**-33**

* annual net = sources and uses balance for that year
**cumulative = annual net plus prior year-end balance

13 *source(s): Roskill Letter of Japan, press releases, Indium Corporation and partners*

INDIUM CORPORATION

→ Indium is scarce and expensive

→ resources last for only 20 years

(US geological survey 2006)

Issues with Indium-Tin-Oxide (ITO)

ITO consumption in 2006 and 2030

Technologie	Bedarf 2006	Bedarf 2030
Dünnschicht-Photovoltaik	1	285
ITO auf Displays	230	1.580
Weiße LED	3	46
Bedarfssumme	234	1.911
Bedarf / Rohstoffproduktion 2006	0,40	3,29

Quelle: Fraunhofer Gesellschaft 2009: „ Rohstoffe für Zukunftstechnologien“

→ identify alternatives

ZnO is cheap and abundant !

- $ZnO:Al_2O_3$ (4 wt%)
- pulsed laser deposition (PLD)
- sputter deposition

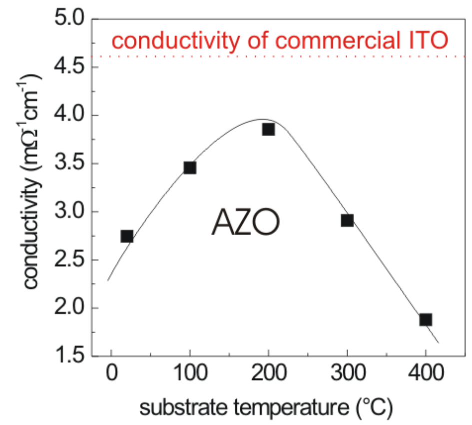
„our" AZO:

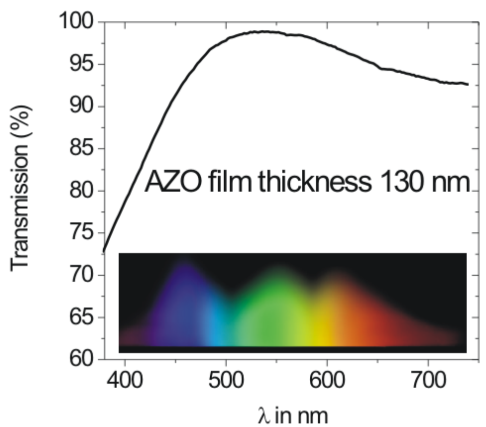
→ optimum conductivity: 4000 S/cm
(n=6x10^{20} cm^{-3}; μ_n=42 cm^2/Vs)

c.f. ITO (MERCK) 4700 S/cm

→ high transmissivity in the visible:

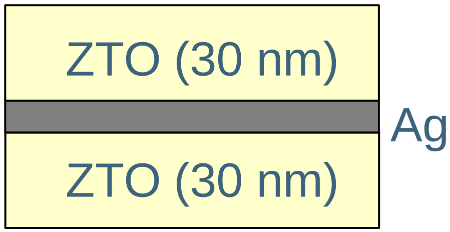
@ 550 nm: α=200 cm^{-1} → T= 98 % (1 μm film)
→ R_{sheet} = 4 Ω/sq.



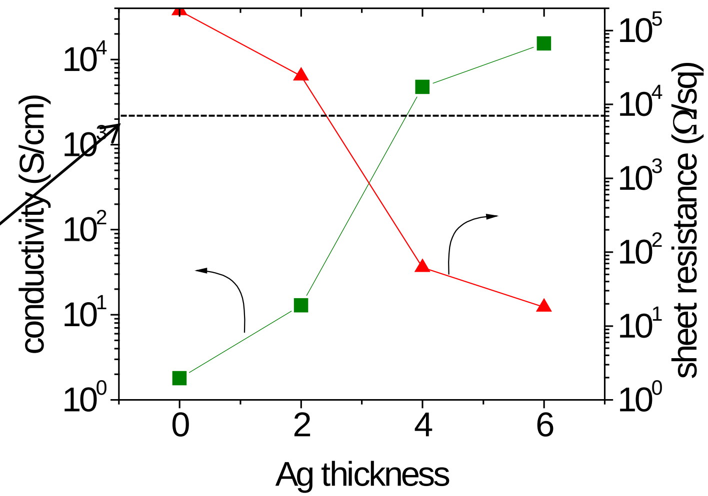


Appl. Phys. Lett. 91, 041113 (2007)
Appl. Phys. Lett. 93, 073308 (2008).

ZTO/Ag/ZTO



RT ITO



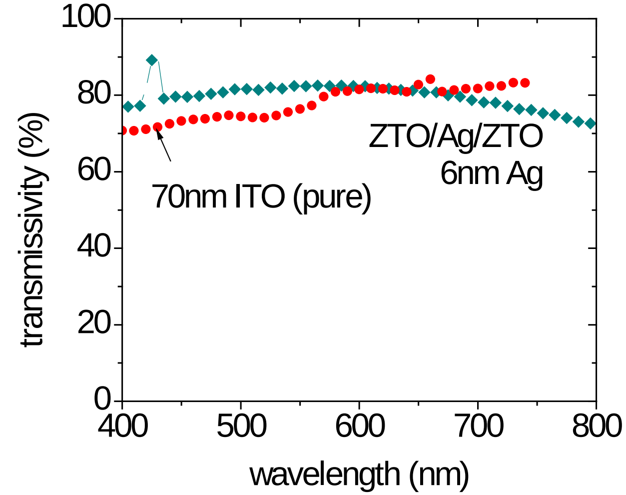
Zinc-Tin-Oxide (ZTO)

→ high carrier mobility

→ highly transparent > 80 %

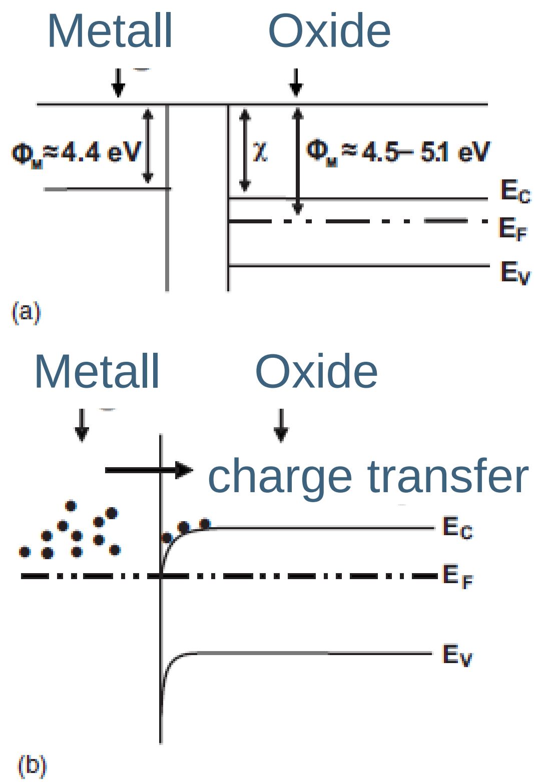
→ simple processing technology

sputter-deposition at room temperature



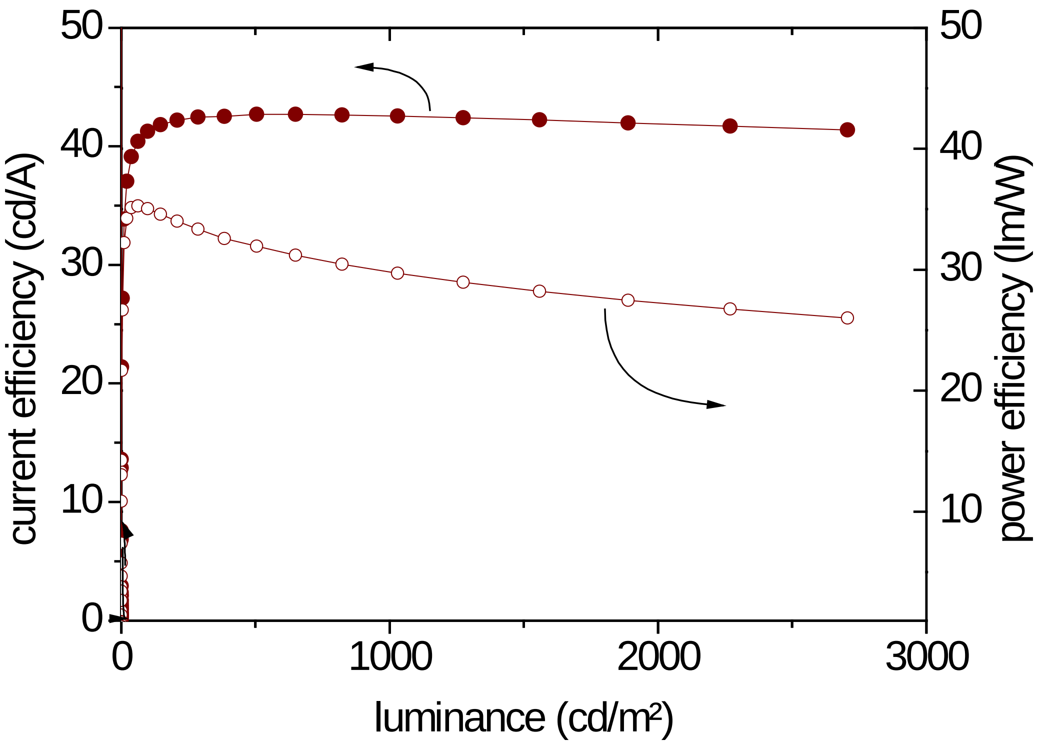
ZTO/Ag/ZTO

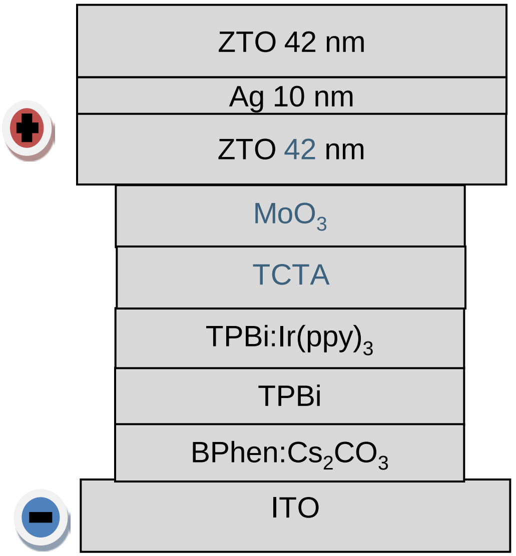
Kontakt	Leitfähigkeit (S/cm)	Schichtwiderstand (Ω/□)
ITO (91nm)	~ 2000	~ 55
ITO (30nm – 1.Prozess)		
ZAZ 8nm Ag	~ 15000	~10
ZAZ 10nm Ag	~ 40000	~ 5



Charge transfer → doping of the oxide

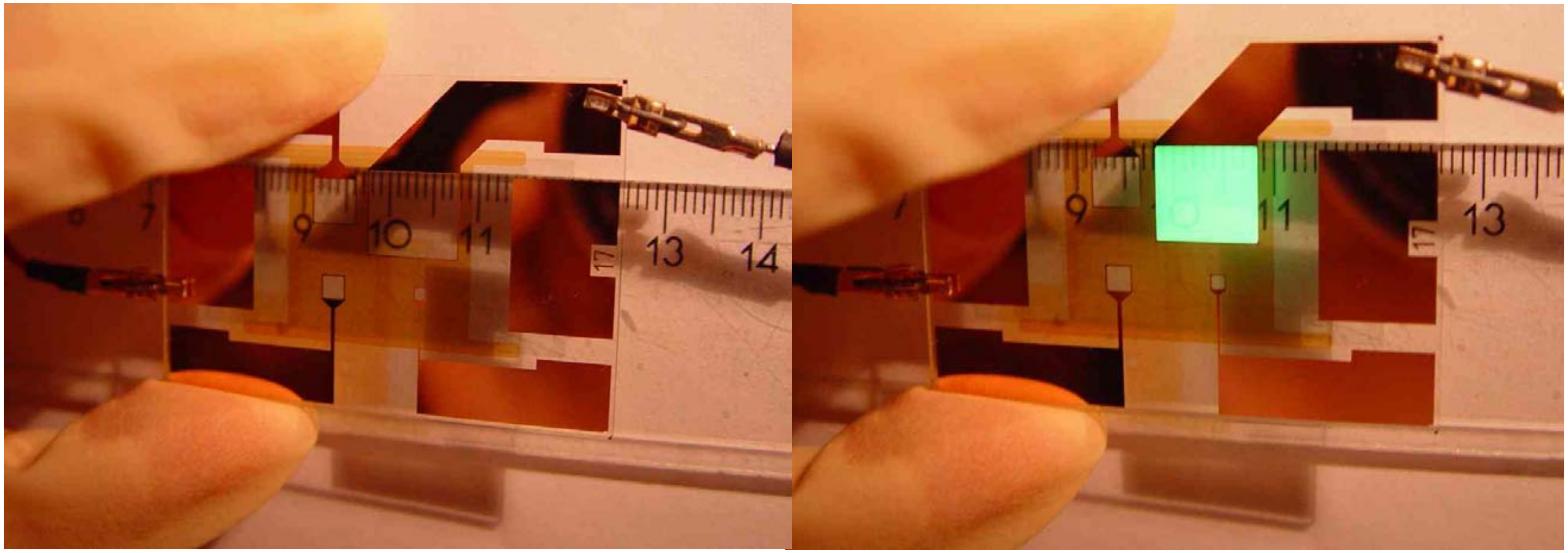
Alternative Transparent Electrodes





- η_{phot} = 43 cd/A, η_{lum} = 30 lm/W @ 1000 cd/m²

Kooperation T. Winkler, TU-BS



>80 % transmission @ 500 nm
defect free!

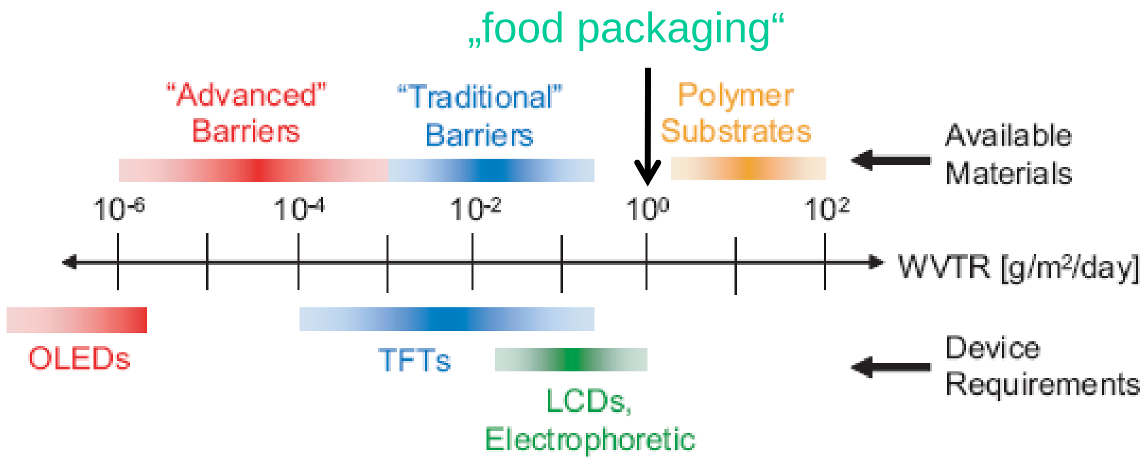
Kooperation T. Winkler, TU-BS

Metaloxides as Components of AM-Displays

→ Transparent Electrodes (OLED, OPV)

→ Thin-Film Encapsulation

→ Oxide TFTs



Conventional glass-lid encapsulation:

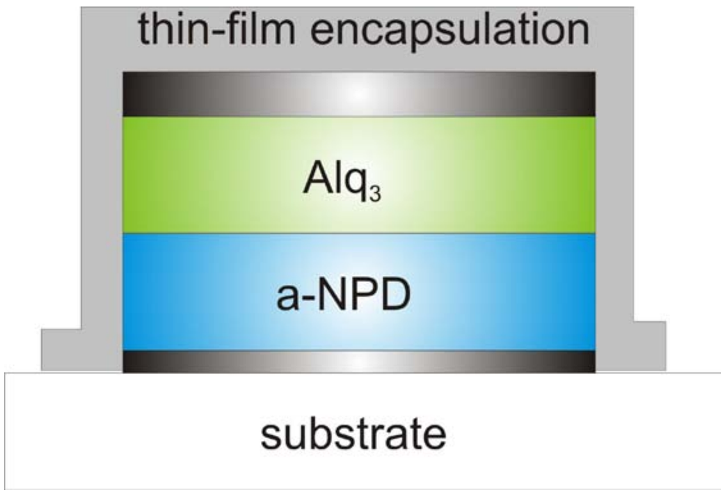
→ not flexible, heavy

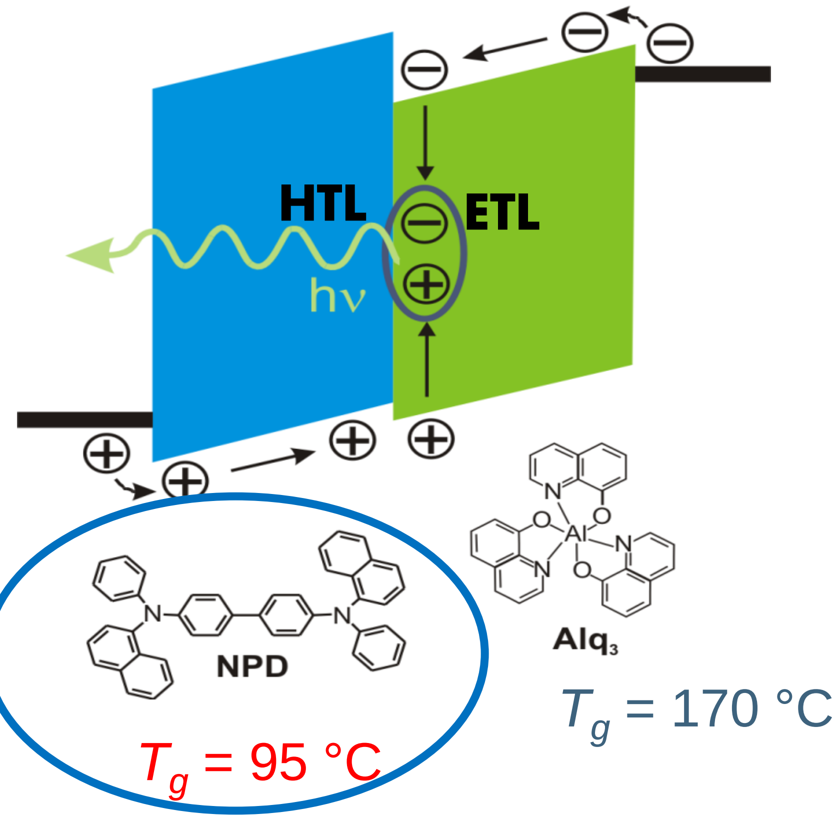
→ expensive

→ problematic for transparent OLEDs

⇒ efficient thin-film encapsulation needed

Temperature aspects

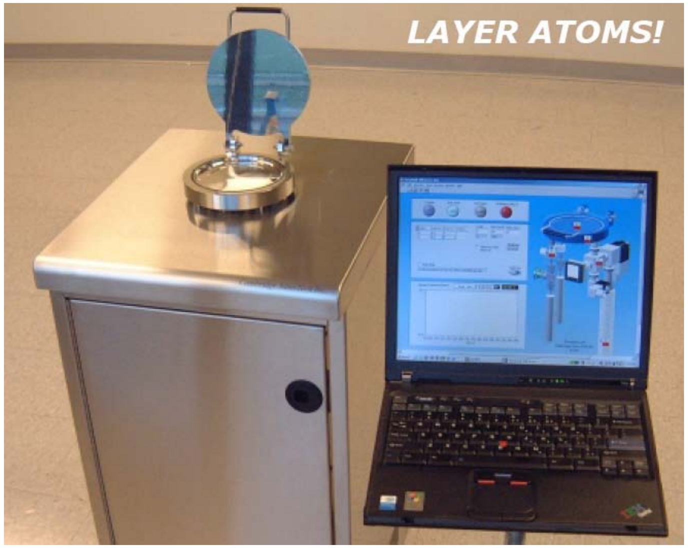


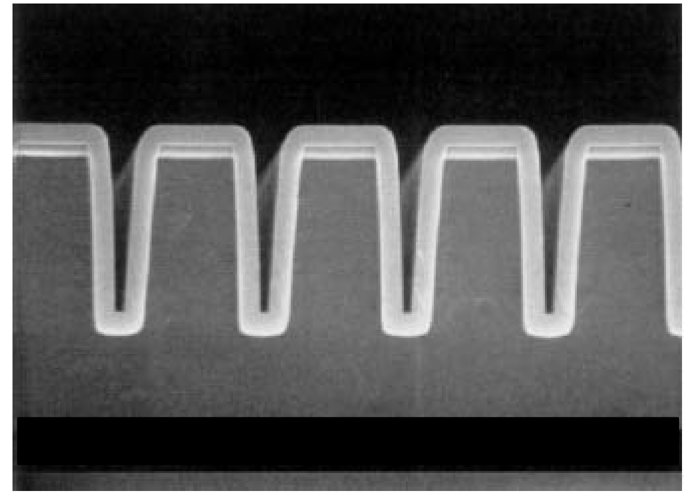


→ organic materials form glassy films: typically T_g = 50 - 200°C

→ Low-temperature (*T* < 100 °C) encapsulation process required

Atomic Layer Deposition



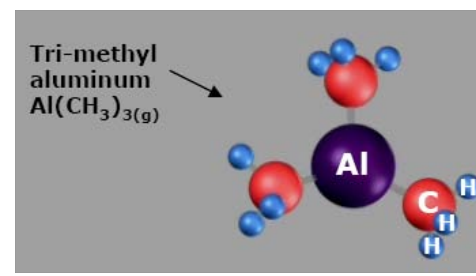


ALD: Technique for extremely dense and conformal dielectric layers

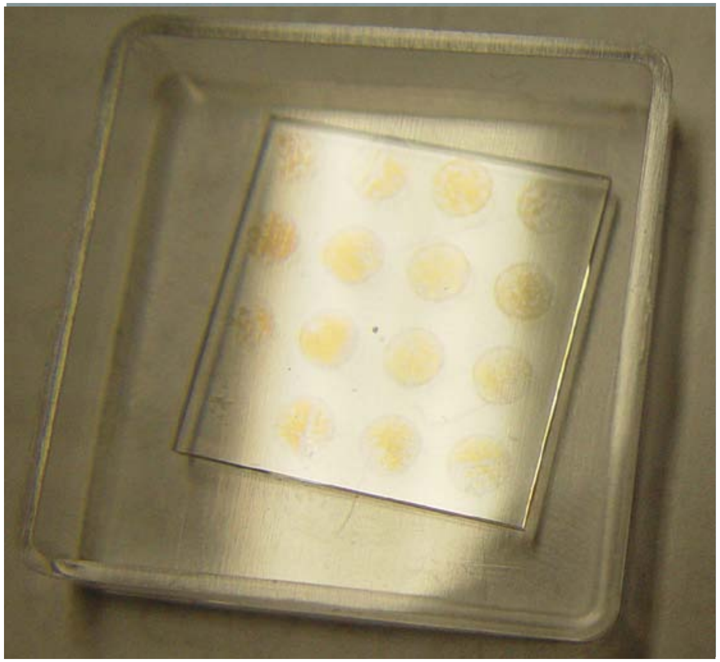
highly reactive precursors
e.g. for Al_2O_3 Trimethylaluminum (TMA) and H_2O

→ low processing temperatures (< 100°C)

→ promising for barrier layers for organic devices



Array of Ca Pads



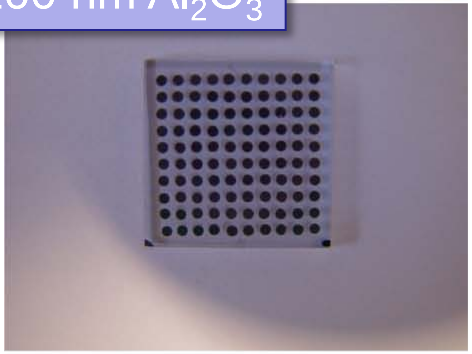
Without encap → 100 nm Calcium completely oxidized (90 s in air)

expected: with encap. (WVTR=$1x10^{-6}$ g/m^2 d) → 700 days

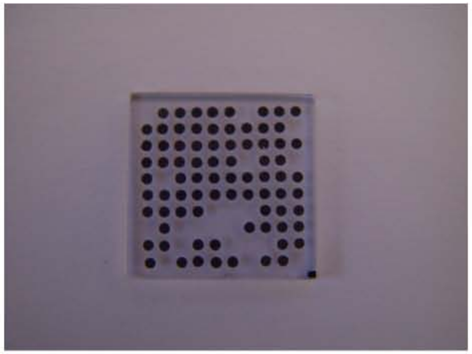
Corrosion of Al_2O_3

Large area encapsulation (80 °C, 80 % RH)

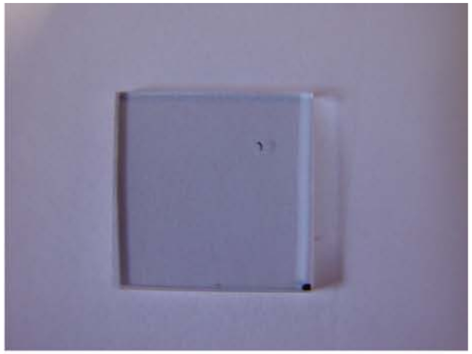
100 nm Al_2O_3



fresh

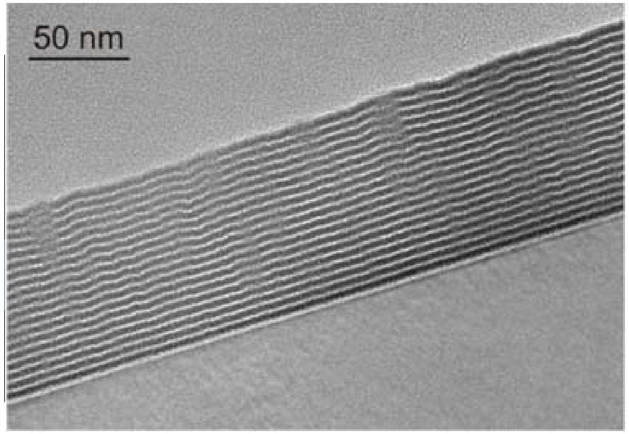


48 h



118 h

next generation thin film encapsulation → nano-laminates



cyclic deposition of Al_2O_3 and ZrO_2

20 cycles Al_2O_3 (2 nm)
20 cycles ZrO_2 (3.8 nm)

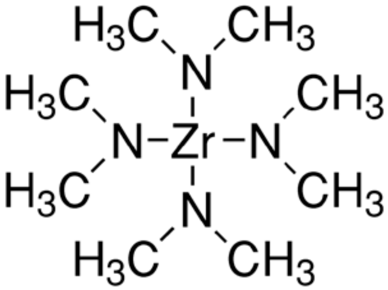
aim:

→ protection against corrosion

→ forced amorphicity
(neat ZrO_2 polycrystalline)

→ avoid permeation channels

Precursor for ZrO_2 preparation

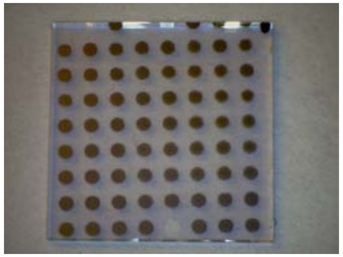


Tetrakis(dimethylamido)zirconium(IV)

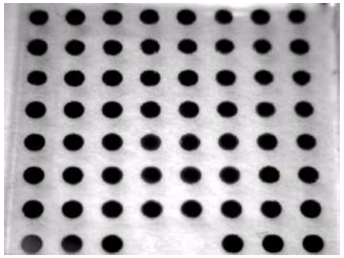
Adv. Mater. 21, 1845 (2009).

Large area encapsulation (70 °C, 70 % RH)

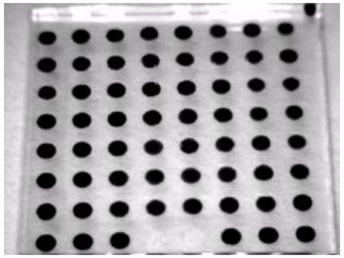
100 nm Al_2O_3 + ZrO_2 nanolaminate



20 h



60 h



160 h

Adv. Mater. 21, 1845 (2009).

Test conditions (climate cabinet): 70 °C and 70 % RH

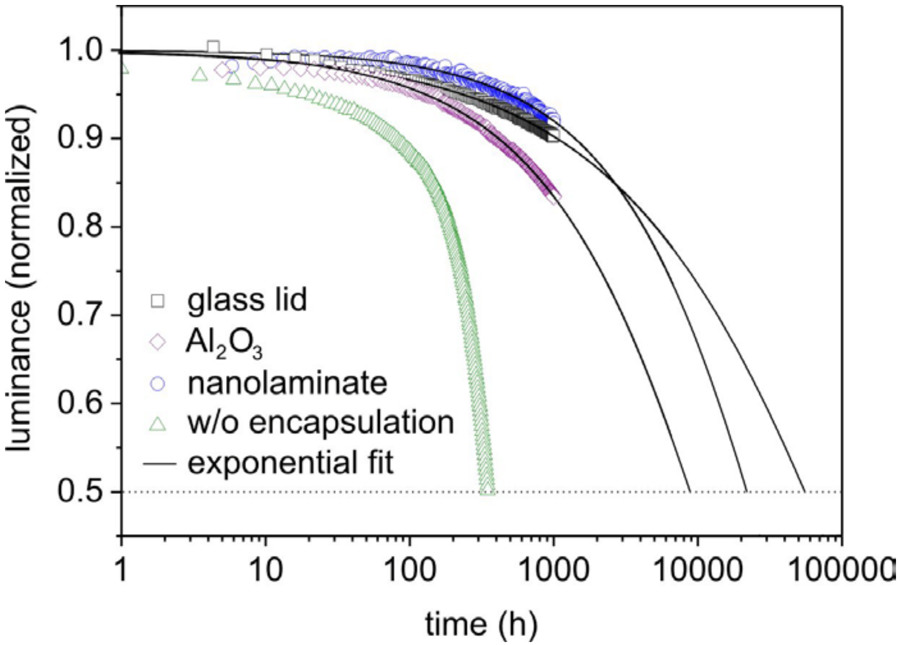
encapsulation	permeation rate for water (g/m² day)	permeation rate for oxygen (cm³/m² day)
Al_2O_3 130 nm @ 80 °C	8.8×10^{-5}	3.9×10^{-2}
Al_2O_3 & ZrO_2 130 nm @ 80 °C	4.7×10^{-5}	2.1×10^{-2}

with E_a = 92 kJ/mol → 5 $\times 10^{-7}$ (at RT)

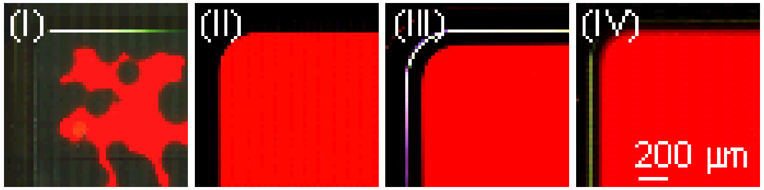
→ Low permeation rates maintained down to 40 nm thin laminates !

Adv. Mater. 21, 1845 (2009).

Starting luminance 1,000 cd/m^2, constant-current mode



w/o encap:	350 h
Al_2O_3:	8,700 h
ZrO_2/Al_2O_3 NL:	22,000 h
glass lid + getter:	56,000 h

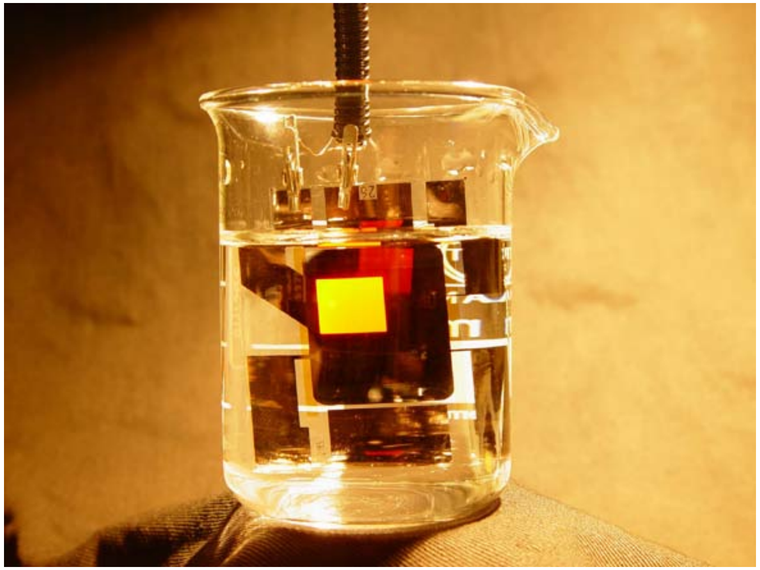


Appl. Phys. Lett. 94, 233305 (2009).

Substantially improved OLED lifetime through ALD nanolaminate

→ close to benchmark of glass lid encap

Underwater OLEDs



ALD barriers allow for wet chemical post-processing:

→ photo-lithography
→ printing

Metaloxides as Components of AM-Displays

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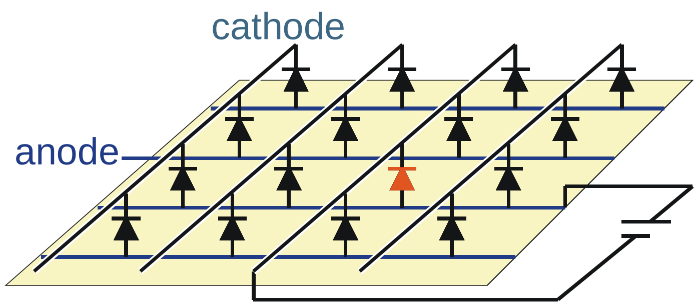
Ice Touch YP-H1 - Samsung CES 2010

Passive-Matrix OLED (PMOLED) Displays



Passive-Matrix Display:

→ row by row addressing

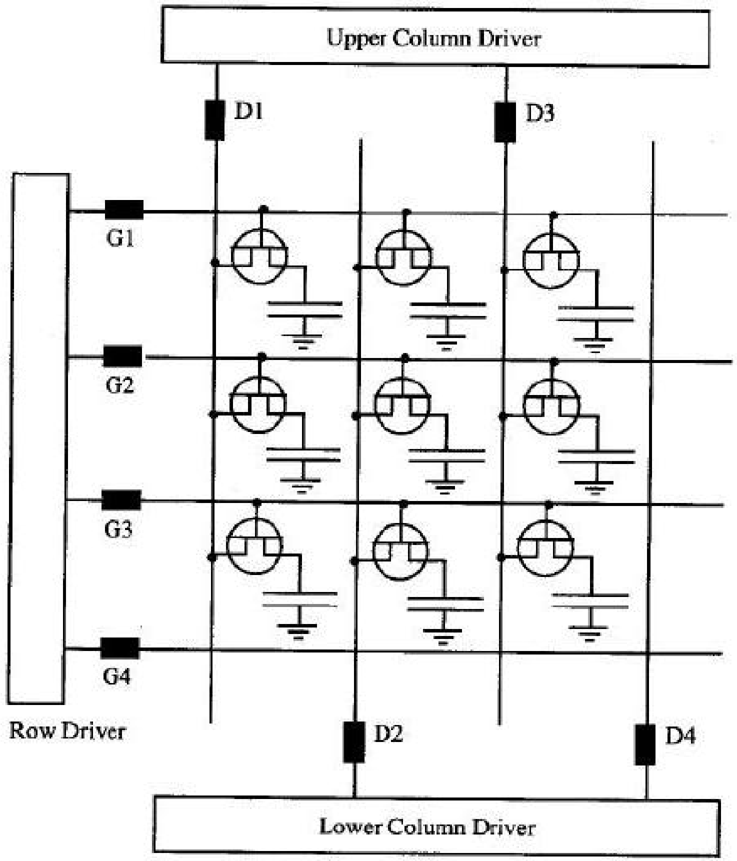
→ ok for small area/low resolution

⇒ pixel brightness >> display brightness

e.g. VGA-Display (640 x 480 pixels) 100 cd/m^2

→ required pixel brightness > **48,000 cd/m^2**
→ reduced efficiency, reduced lifetime

solution: active-matrix addressing



- •Introduce non linear device that improves the selection.
- •Storage of data values on capacitor so that pixel duty cycle is 100%
- •Improve brightness of display by a factor of N (# of rows) over passive matrix drive
- •Display element could be LC, EL, OLED, FED etc

Yeh & Gu

Bundesministerium
für Bildung
und Forschung

BMBF Project:

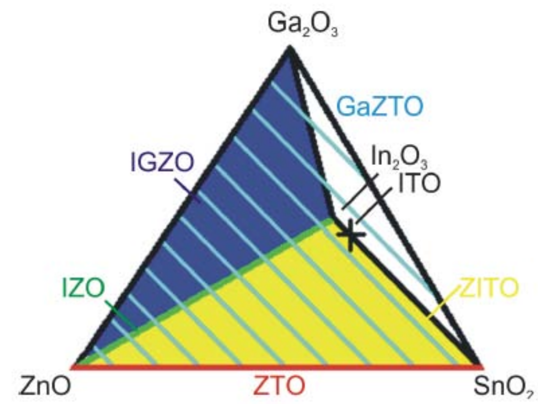
Grundlagenuntersuchungen zu Transparenten Elektronischen Bauelementen und Schaltungen

Thomas Riedl

Institute of Electronic Devices

Transparent Semiconductors

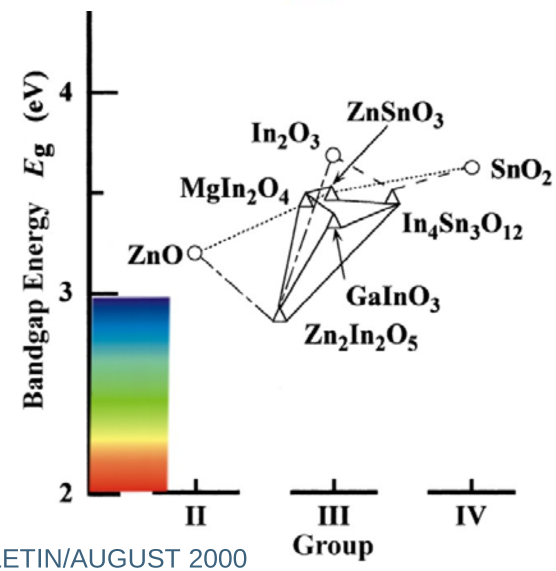
Material	Dopant or compound
SnO_2	Sb, F, As, Nb, Ta
In_2O_3	Sn, Ge, Mo, F, Ti, Zr, Hf, Nb, Ta, W, Te
ZnO	Al, Ga, B, In, Y, Sc, F, V, Si, Ge, Ti, Zr, Hf
CdO	In, Sn
$ZnO–SnO_2$	Zn_2SnO_4, $ZnSnO_3$
$ZnO–In_2O_3$	$Zn_2In_2O_5$, $Zn_3In_2O_6$
$In_2O_3–SnO_2$	$In_4Sn_3O_{12}$
$CdO–SnO_2$	Cd_2SnO_4, $CdSnO_3$
$CdO–In_2O_3$	$CdIn_2O_4$
$MgIn_2O_4$	
$GaInO_3$, $(Ga, In)_2O_3$	Sn, Ge
$CdSb_2O_6$	Y
$ZnO–In_2O_3–SnO_2$	$Zn_2In_2O_5–In_4Sn_3O_{12}$
$CdO–In_2O_3–SnO_2$	$CdIn_2O_4–Cd_2SnO_4$
$ZnO–CdO–In_2O_3–SnO_2$	



$ZnO\text{-}SnO_2$: abundant, non-toxic

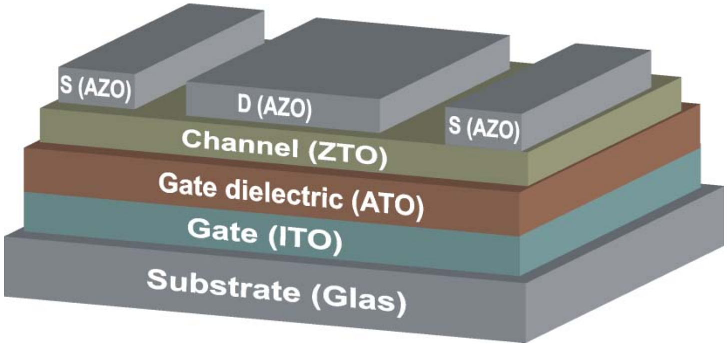
wide band gap (> 3eV) → see-through

deposition by sputtering or PLD



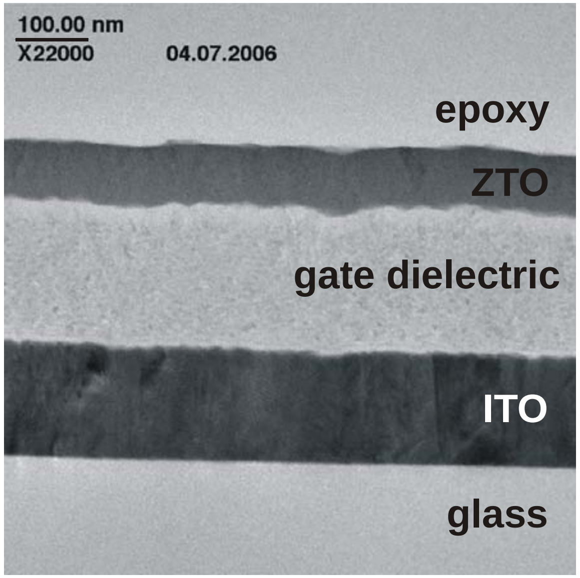
Minami, MRS BULLETIN/AUGUST 2000

Transparent TFTs on Glass



Bottom-Gate stucture

TEM cross section



channel: **$(ZnO)_x (SnO_2)_{1-x}$** (ZTO)

Drain-Source Electrodes: **ZnO:Al** (AZO)

Gate dielectric: Al_2O_3 (by atomic layer deposition)

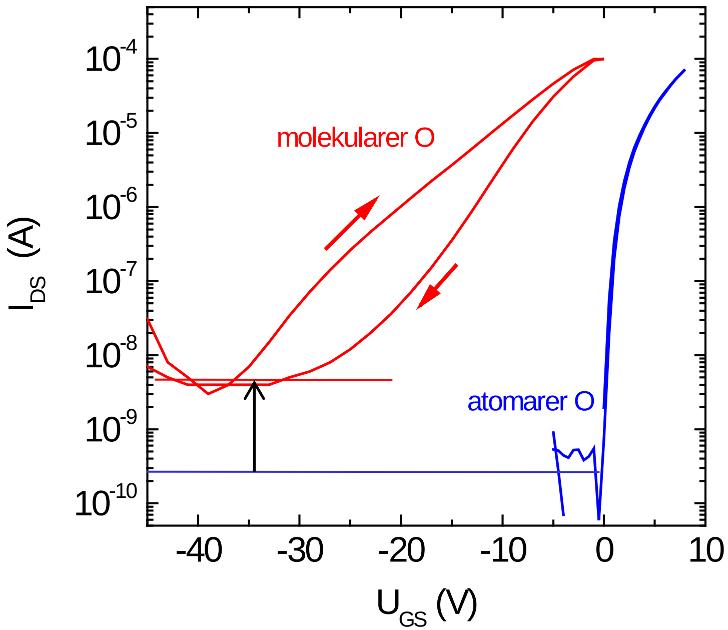
TEM images:
Dr. Thomas Weimann
Peter Hinze

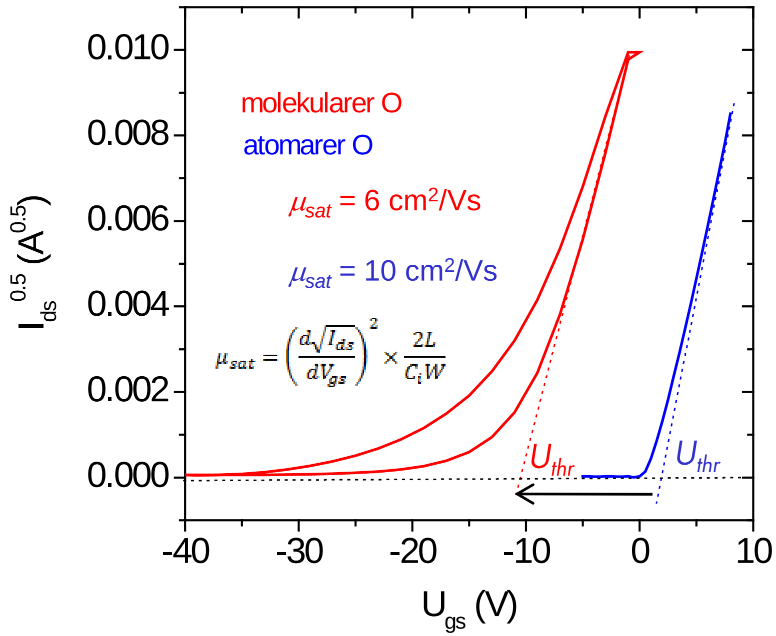
- TEM: ZTO amorphous structure
- Transmissivity > 80 %

Appl. Phys. Lett. **90**, 063502 (2007)

Plasma assisted deposition

Oxygen partial pressure: 2×10^{-4} mbar (PLD)



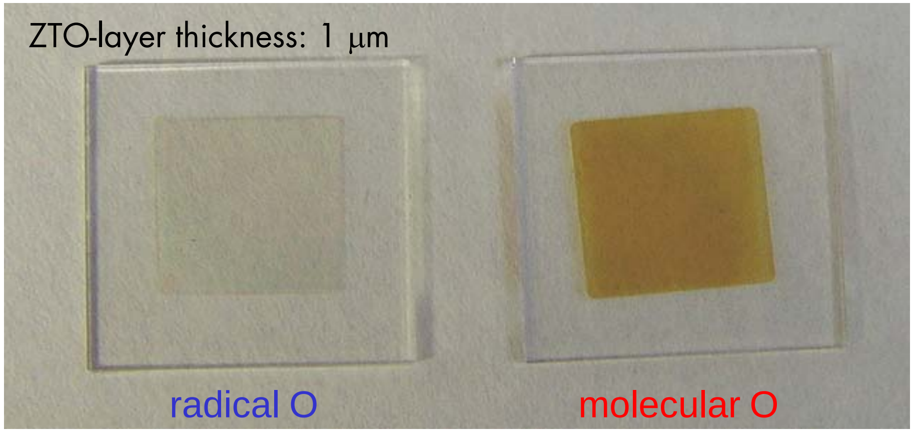


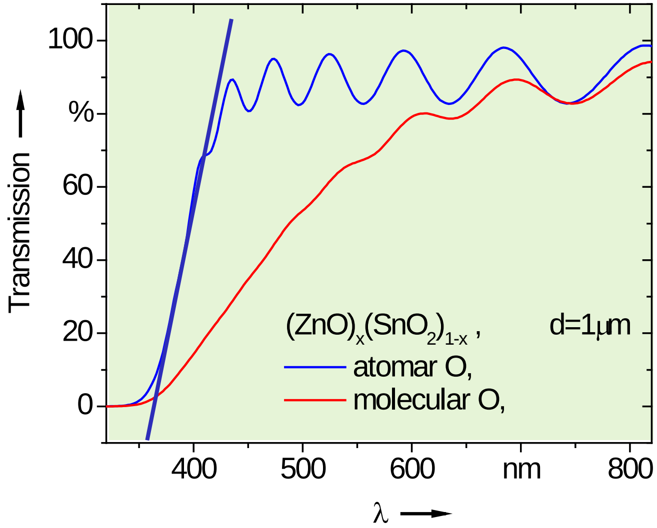
→ severe hysteresis → defect states

→ elevated off current

→ Threshold shifted towards negative U_{gs} → elevated carrier density

Appl. Phys. Lett. (in preparation)



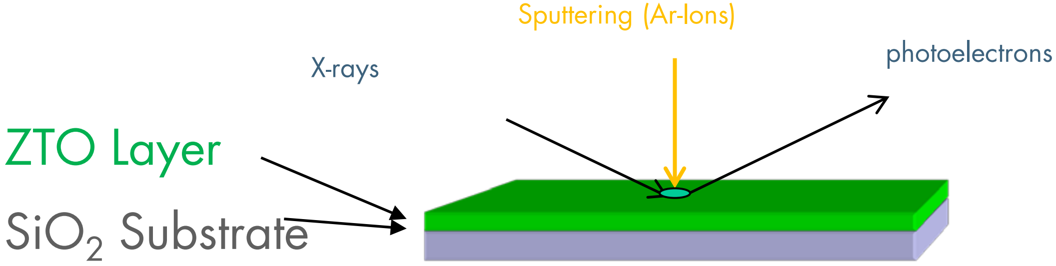


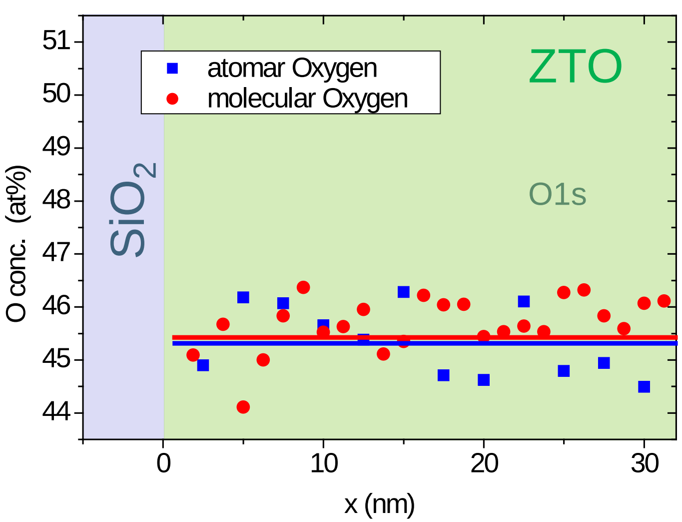
- many sub-bandgap states
- shallow donors

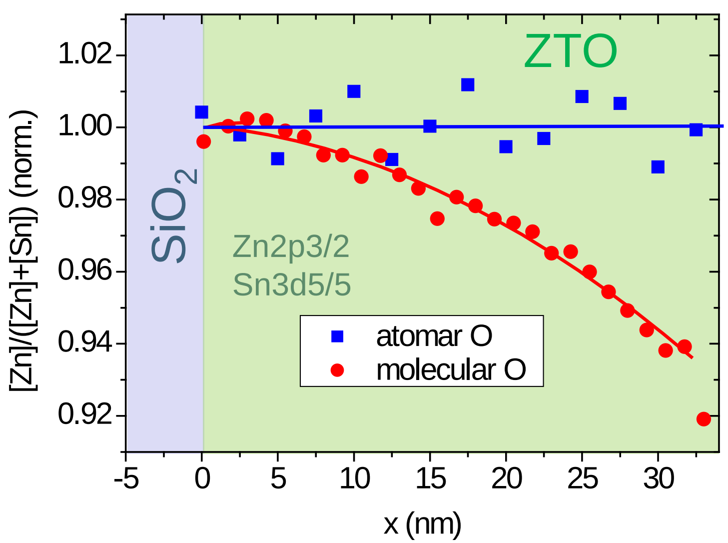
→ ZTO carrier density (Hall):

Molekular O : $n = 10^{19}\ cm^{-3}$

Radical O : $n = 2\times10^{16}\ cm^{-3}$

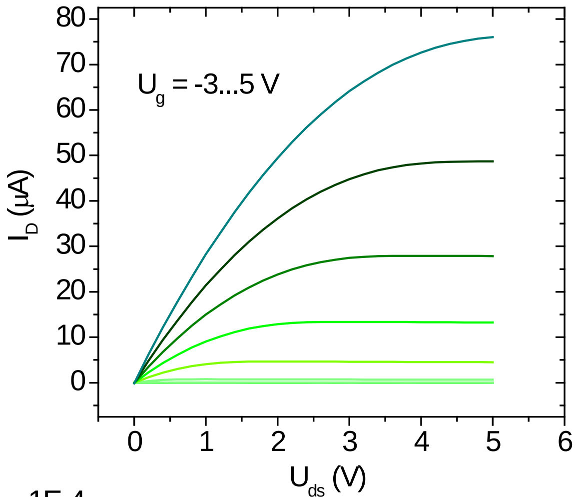


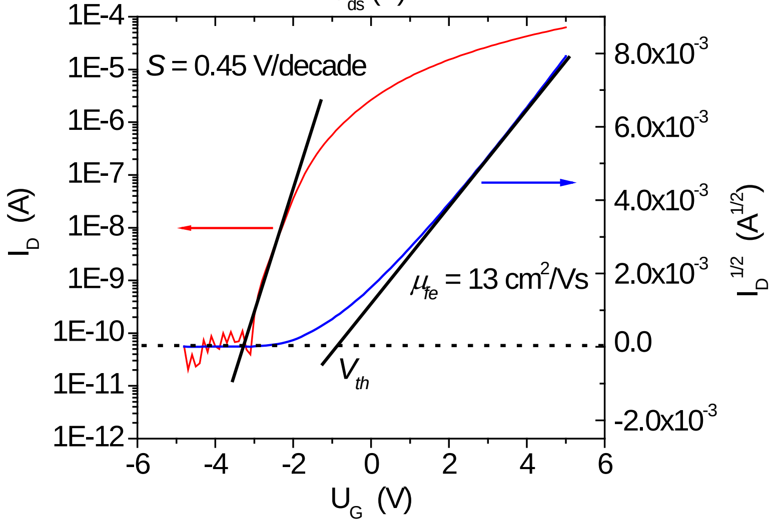




Gradient in [Zn]-content → out-diffusion of Zn_i → defects: excess zinc (Zn_i)

ZTO-TTFTs on Glass





TTFT output-characteristics

TTFT transfer-characteristics

$I_{on}/I_{off}=10^6$
$\mu_{FE,SAT}$ = 13 cm²/Vs

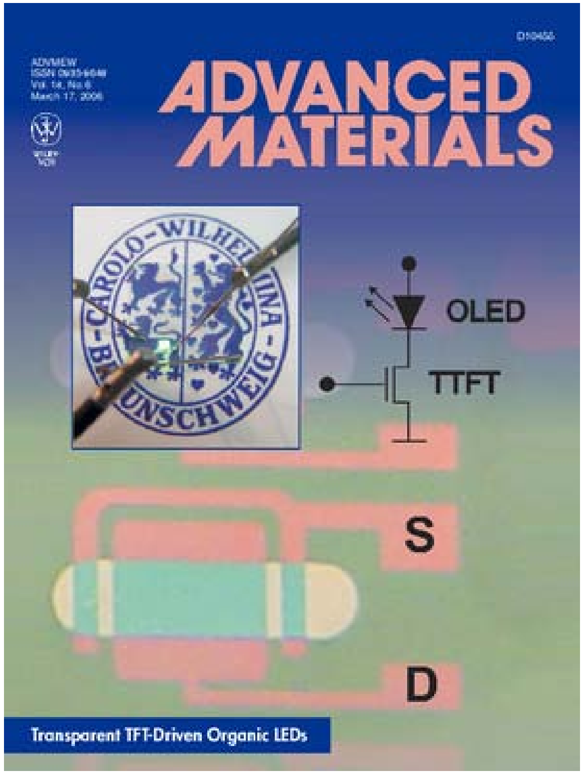
(c.f. a-Si: $\mu_{FE,SAT}$ = 1 cm²/Vs)

U_{th} = -1..1 V

→ no hysteresis measureable
→ low sensitivity towards visible light

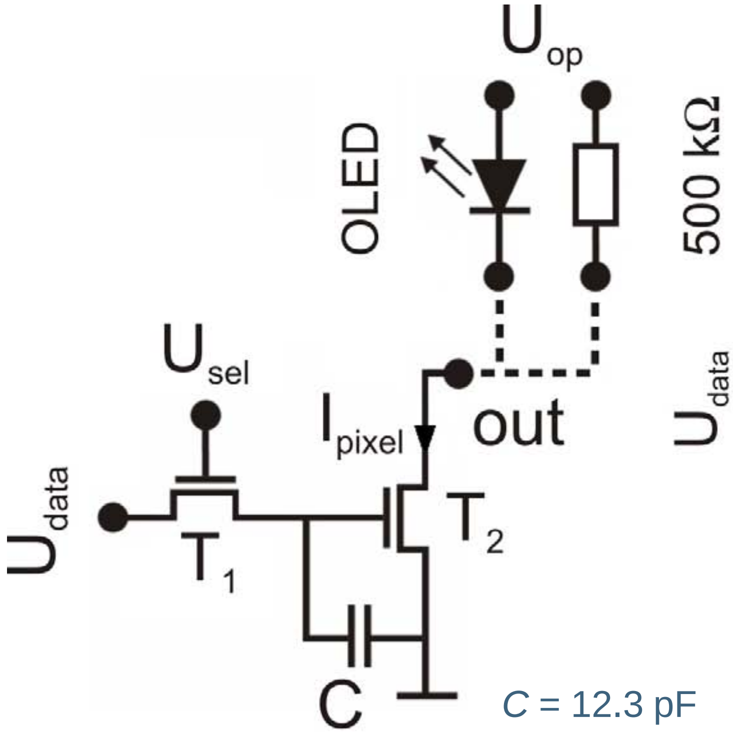
Appl. Phys. Lett. **90**, 063502 (2007)
Appl. Phys. Lett. **91**, 193504 (2007)
phys. stat. sol. (rrl) **1**, 175 (2007)

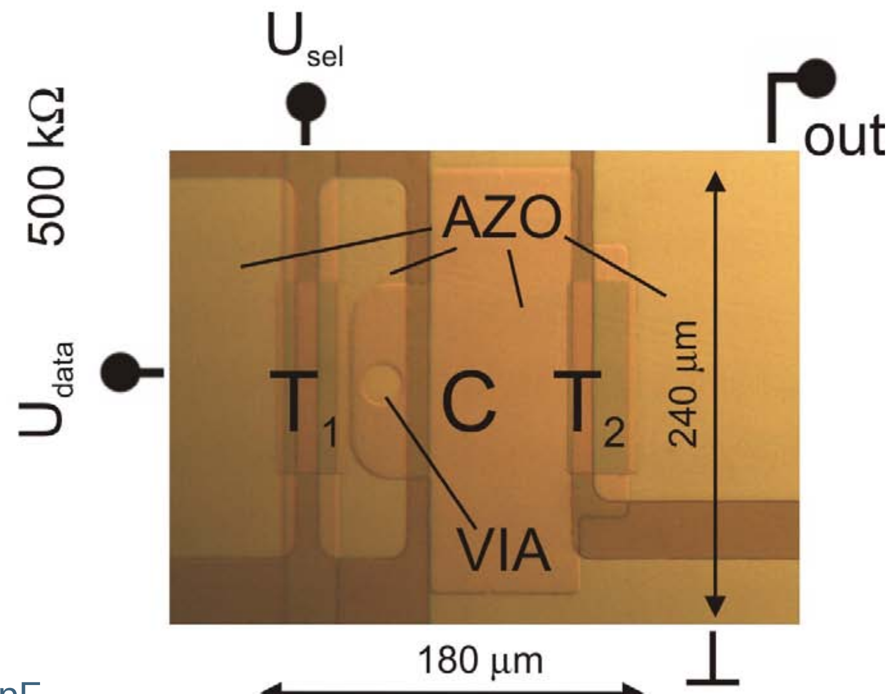
TTFTs and Transparent OLEDs



P. Görrn et al., *Adv. Mater.* **18**, 738 (2006)

building block of transparent AMOLED displays





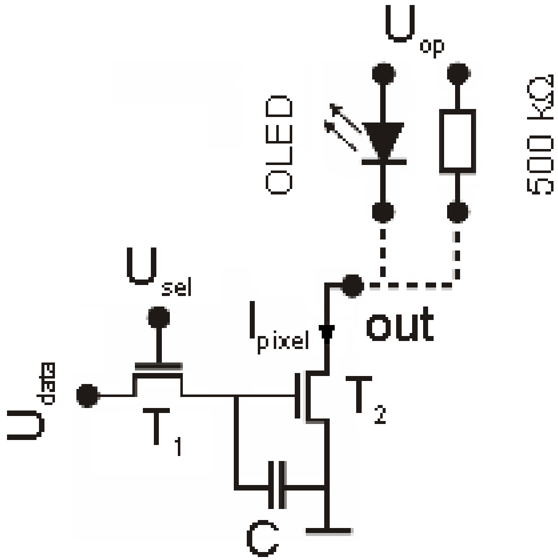
C = 12.3 pF

W/L = 100 µm/10 µm

pixel area: 180 × 240 µm^2

transmissivity 80 %

Solid State Electron. 53, 329 (2009).
IEEE/OSA J. Displ. Technol. 5, 810 (2009)



Requirement:

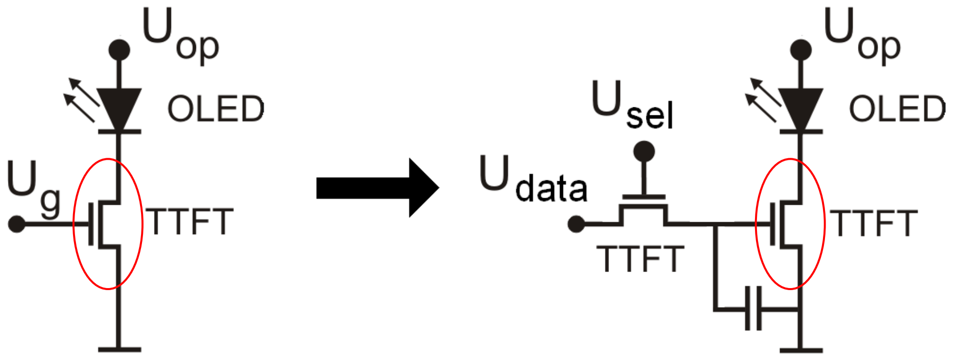
full HD (1,920x1,080 pixels) + 100 Hz refresh

frame-time 10 ms

max. pixel charging time ~10 μs

Solid State Electron. 53, 329 (2009).
IEEE/OSA J. Displ. Technol. 5, 810 (2009)

smart pixel | active pixel



stability considerations for analog driving TFT:

drift in the TFT device parameters $\Rightarrow$ drift in pixel brightness

a-Si TFT Instability – Ghost Images

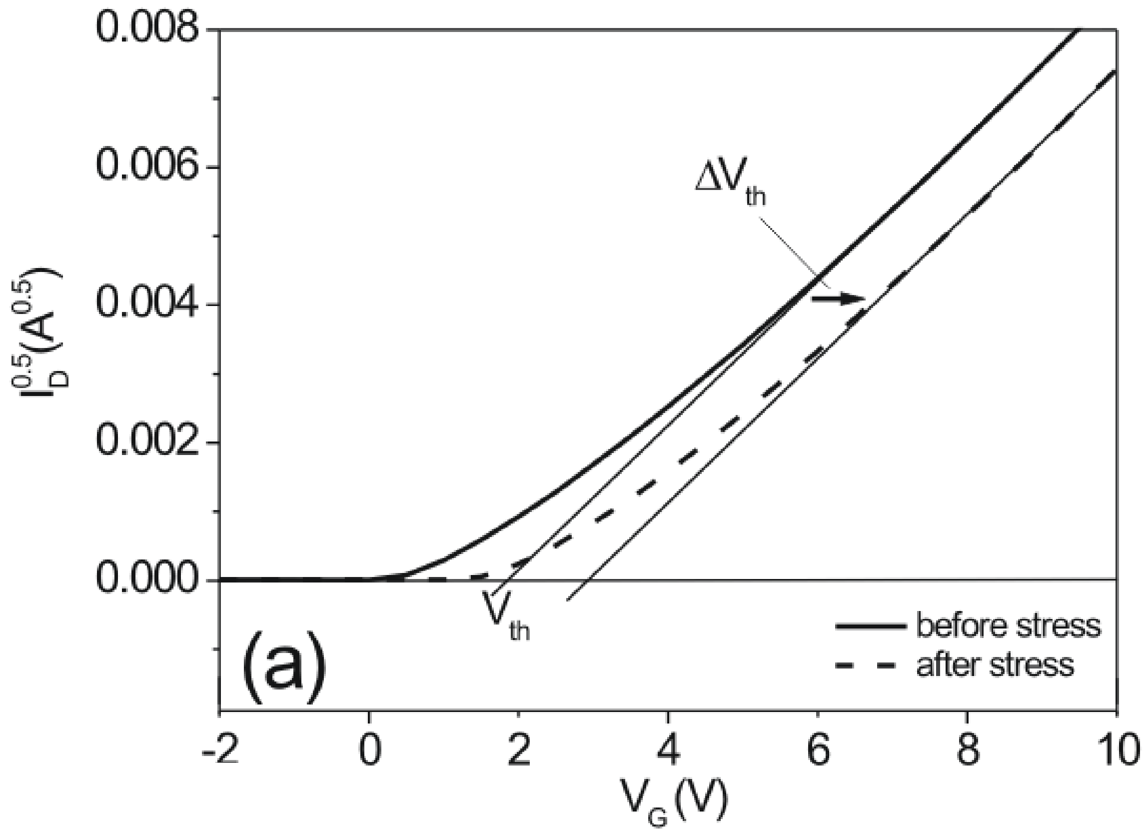
AMOLED Display with Si TFT backplane

Original image (stress for TFTs)

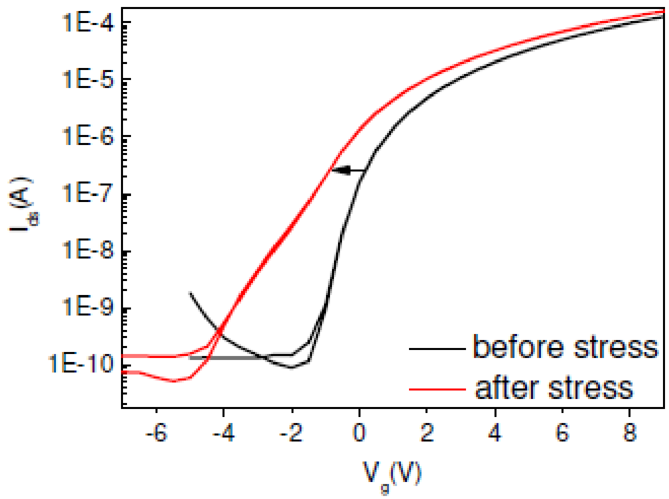
homogeneous background with *Ghost image*

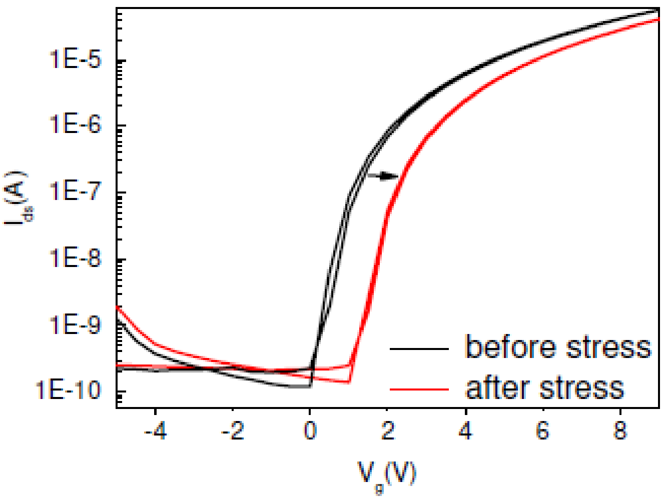
Lee *et al. IEEE* Electron Device Lett. 27, 830 (2006)

Shift of the threshold voltage after 10 h gate bias stress U_g=10 V



Stability against bias stress: V_g=10 V for 16.7 h





Depending on the composition, the threshold is ….

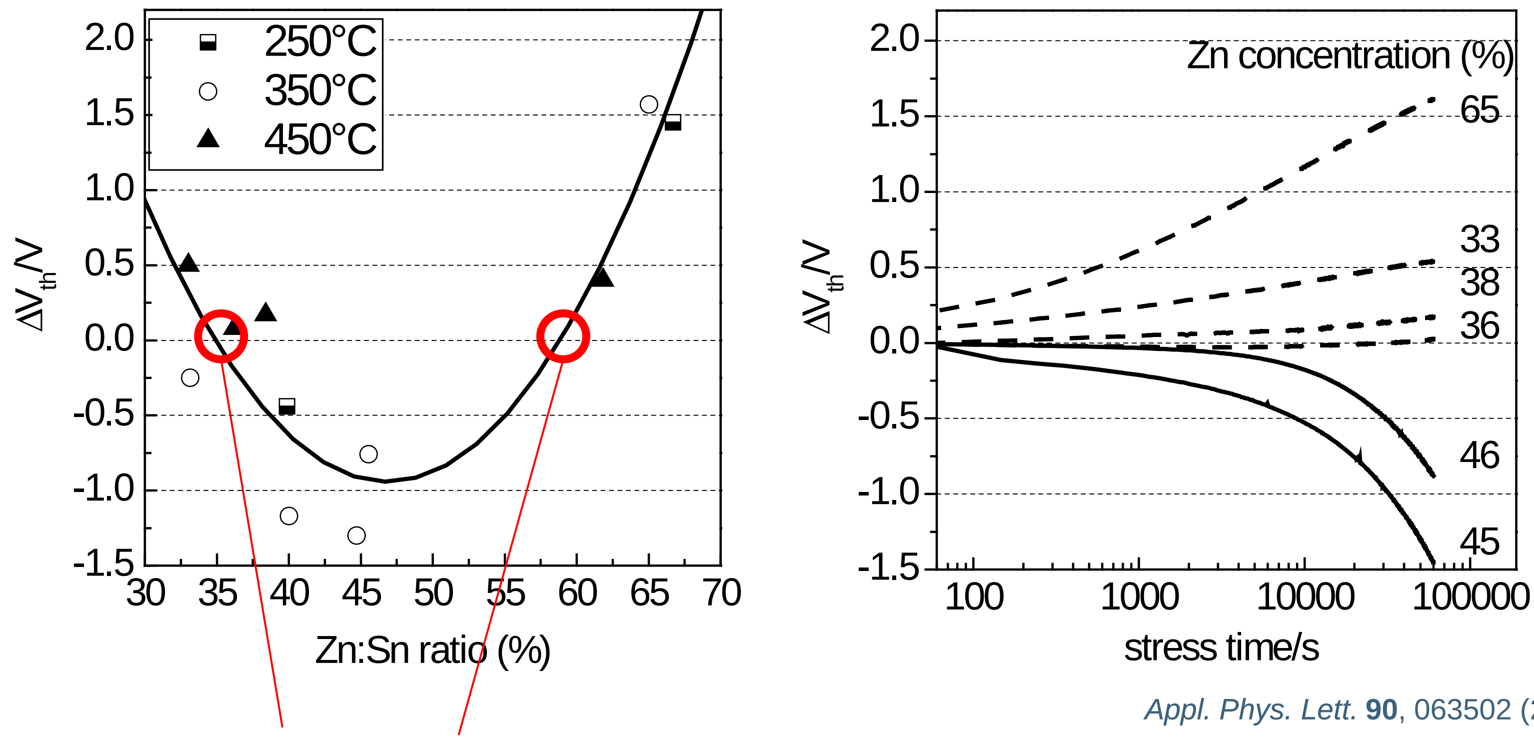
- …. increased by trapping of electrons in the dielectric
- …. lowered by deep state creation in the ZTO

P. Görrn, P. Hölzer, T. Riedl , et al. ***Appl. Phys. Lett.* 90, 063502 (2007).**

20

Our devices with varied [Zn]:[Sn] ratio

Shift of the threshold voltage after 10 h gate bias stress U_g=10 V

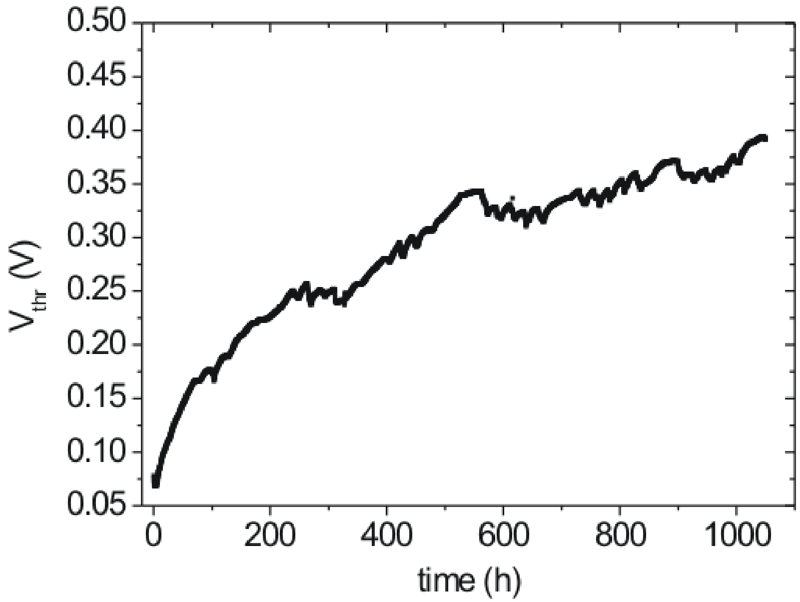


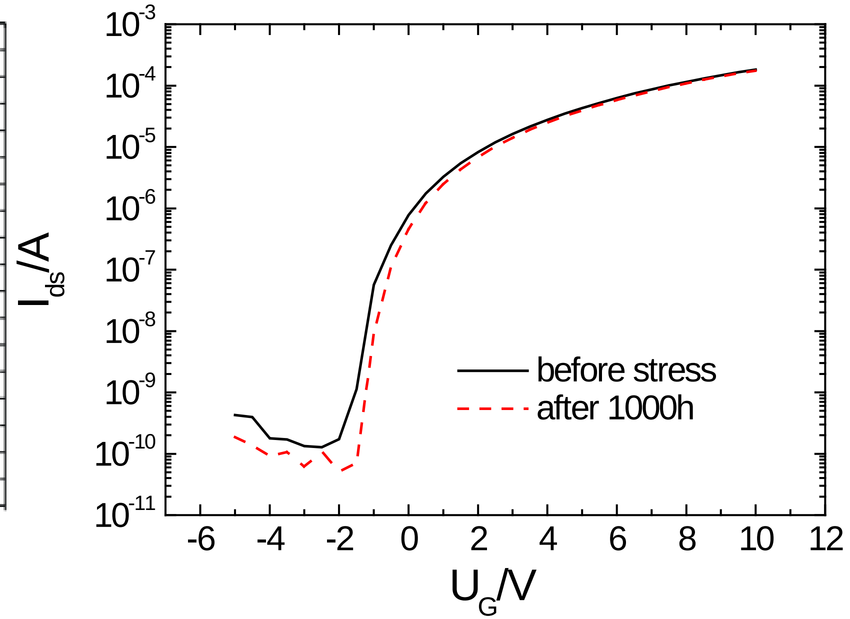
Appl. Phys. Lett. **90**, 063502 (2007)

[Zn]:[Sn] compositions for extremely high TFT stability

1,000 h Lifetime Test

DC bias stress: U_{ds} =10 V, U_{gs} =10 V, I_{ds} = 188 μA



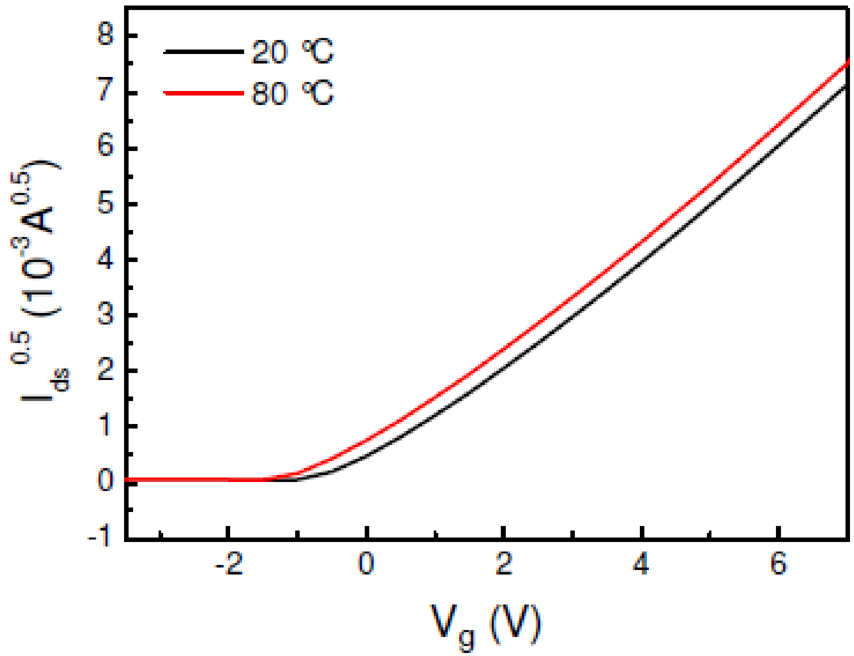


after 1,000 h: ΔV_{th} = 320 mV for DC current stress 100 × I_{OLED}

- c.f. a-Si TFT ΔV_{th} = 2 V after 5 h (A. Nathan *et al. J.Vac. Sci. Technol.* 24 , 875 (2006))
- *IGZO TFT* ΔV_{th} = 1.6 V after 10 h stress (SAMSUNG SID 2008)

⇒ ZTO unsurpassed stability for TFTs with amorphous semiconductor

phys. stat. sol. (rrl) **1**, 175 (2007)
Appl. Phys. Lett. **90**, 063502 (2007)



- Between 20 °C and 80 °C: ΔV_{th} = -370 mV
- Off current unchanged

Impact of Illumination – IGZO Case

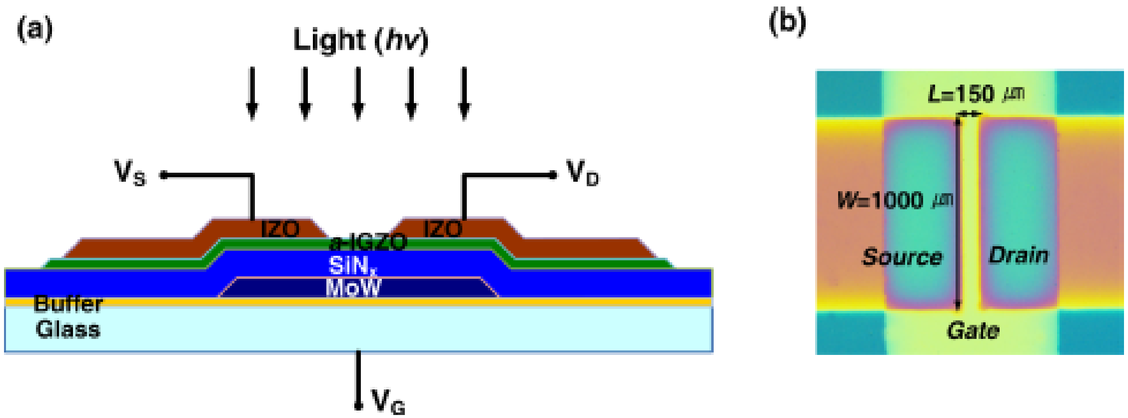


Fig. 1. (a) Cross-section of an inverted staggered-type TFT fabricated on an SiO_2-buffered glass substrate. (b) Top view of the TFT.

Journal of Information Display, Vol. 10, No. 4, December 2009

Impact of Illumination – IGZO Case

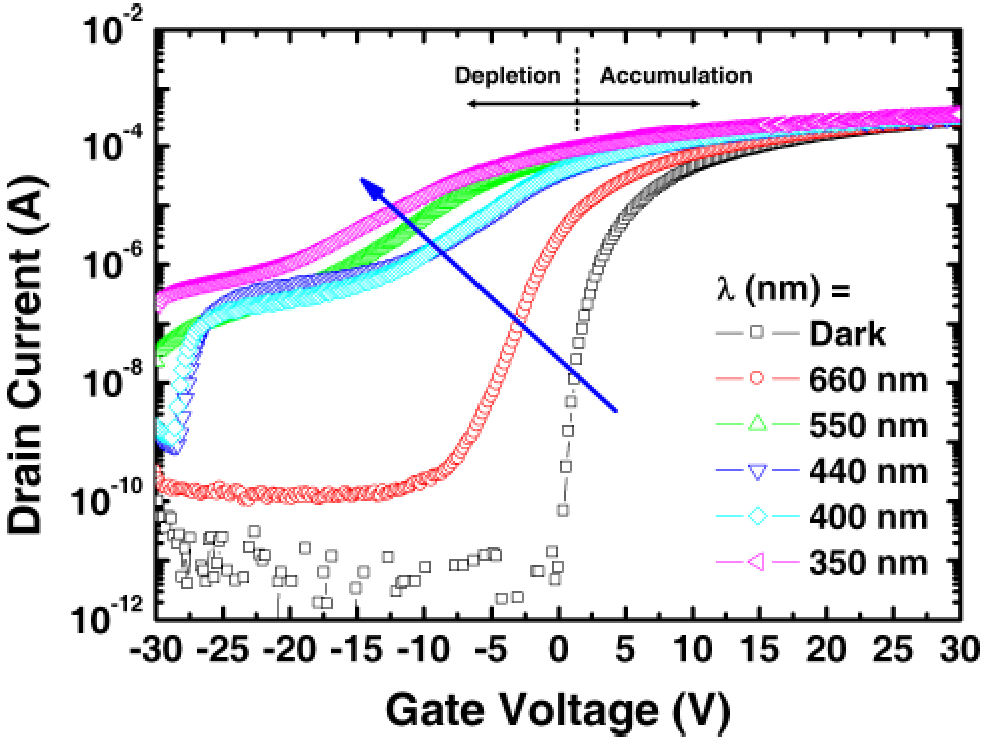
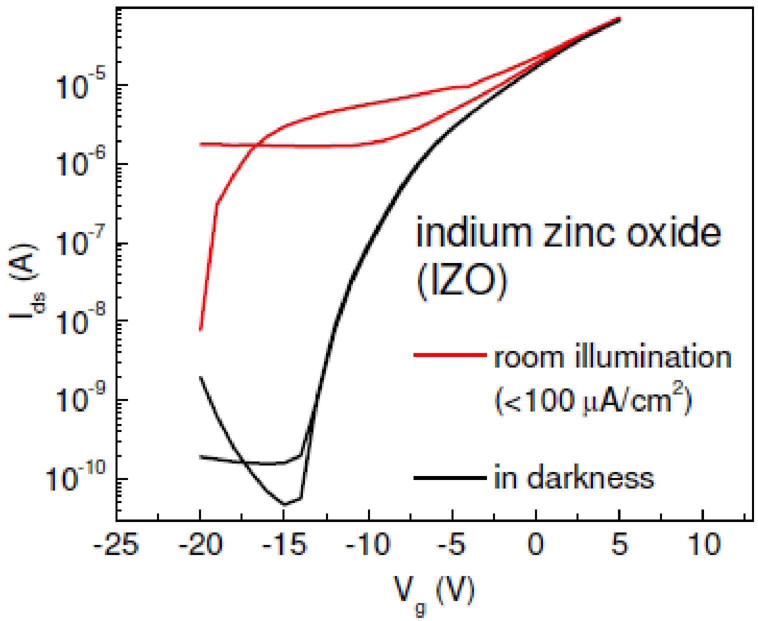


Fig. 2. Spectral response of the *a*-IGZO TFT observed in the $\log_{10} I_{DS}$-V_G curves.

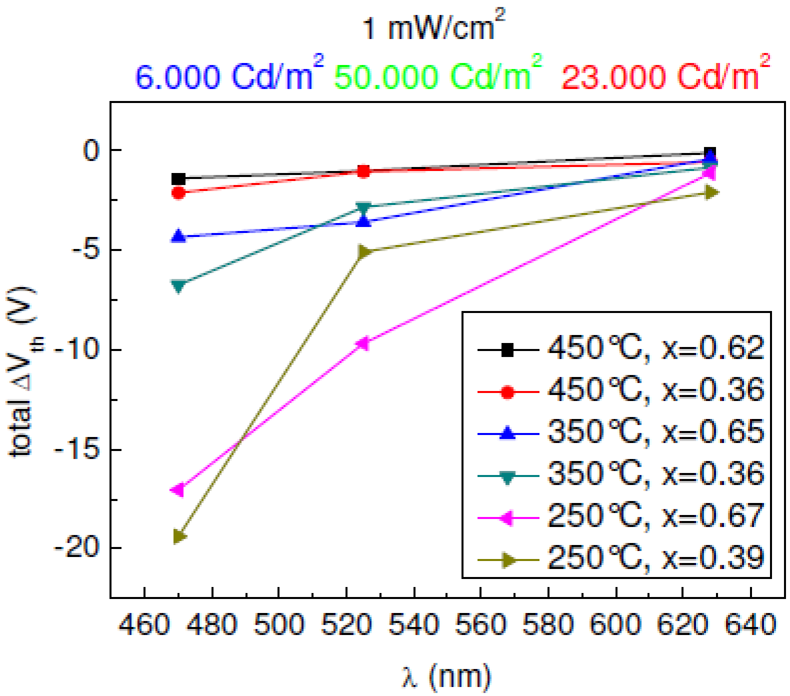
Journal of Information Display, Vol. 10, No. 4, December 2009

Illumination – Issues with Zinc Indium Oxide

Application in transparent displays → no light shielding



Transparent pixel can not be switched off → TFT not applicable



Strong influence of:

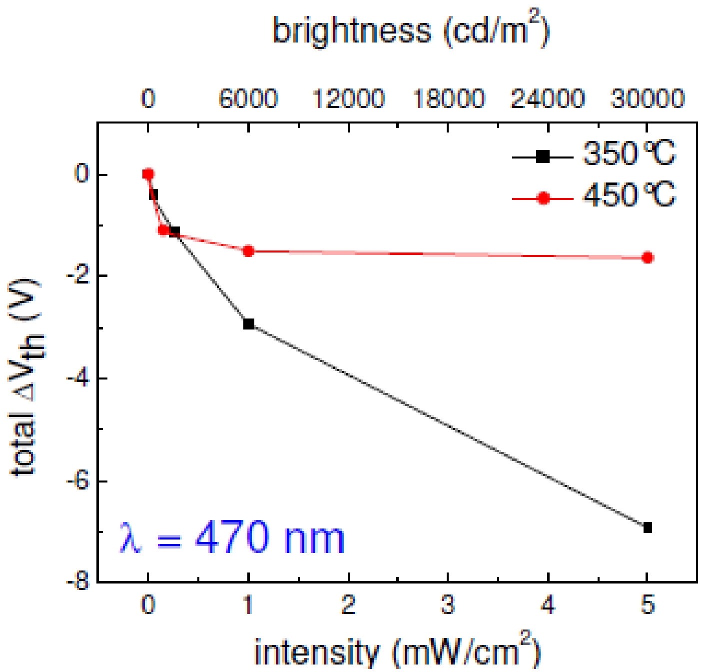
→ wavelength

→ annealing temperature

P. Görrn, M. Lehnhardt, T. Riedl, et al. ***Appl. Phys. Lett.*** **91, 193504 (2007).**

25

Saturation of the V_{th} shift for high intensity



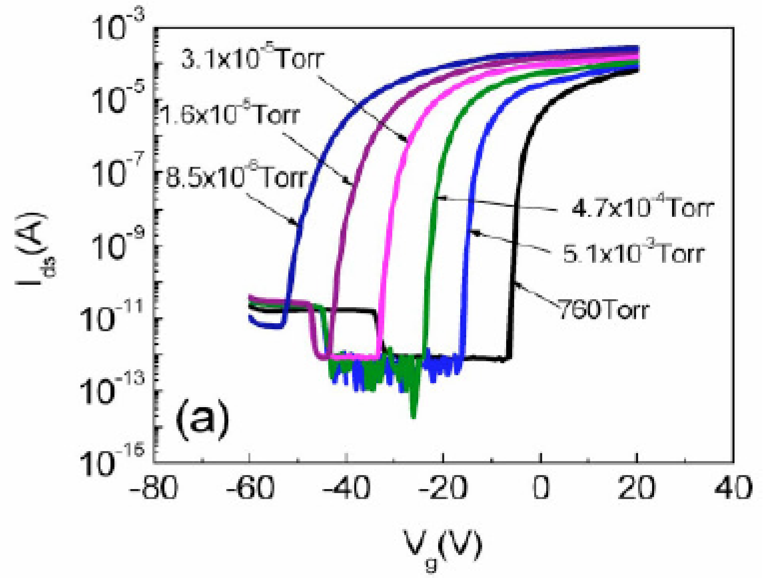
TFTs with 450°C channels in transparent displays:

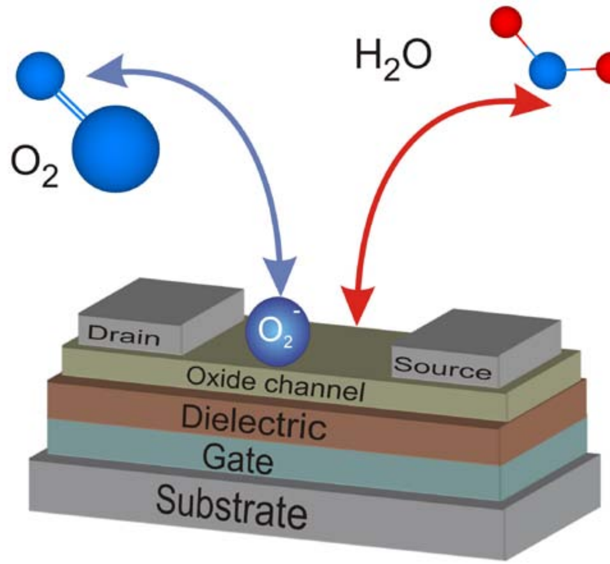
No shift > **1.7 V** expected !

Interaction with Oxygen - IGZO

Chemisorbed negatively charged adsorbates deplete the channel

IGZO

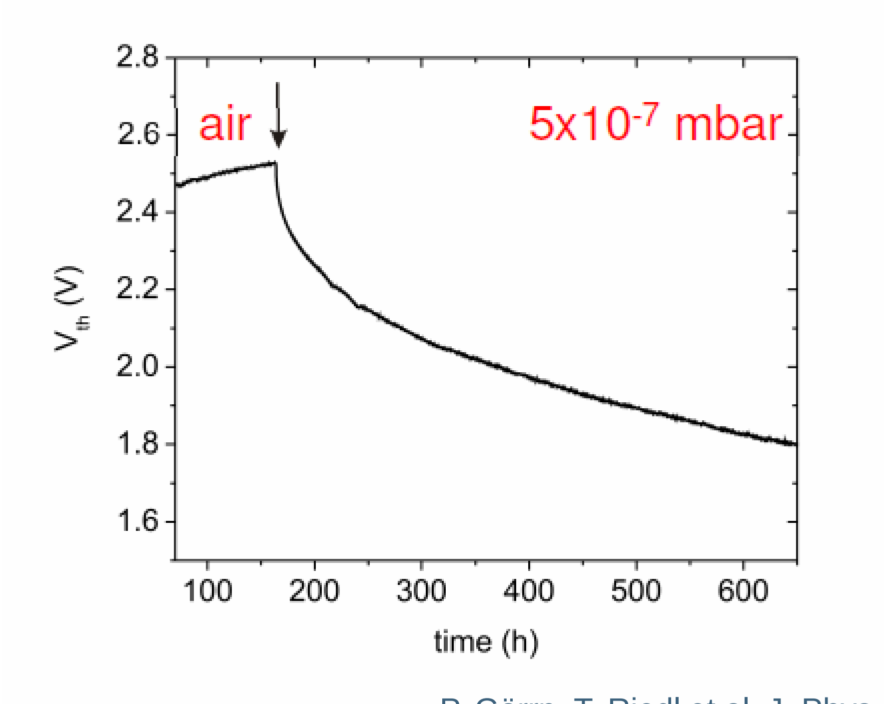


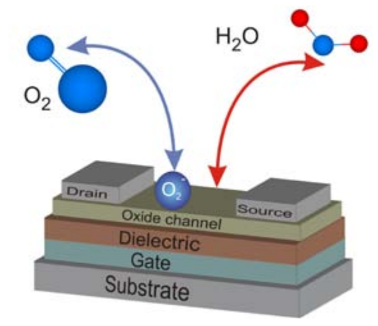


D. Kang, H. Lim, C. Kim, et al. ***Appl. Phys. Lett.* 90, 192101 (2007).**

problematic for encapsulation as required in OLED displays

Encapsulation of Oxide TFTs – Zinc Tin Oxide



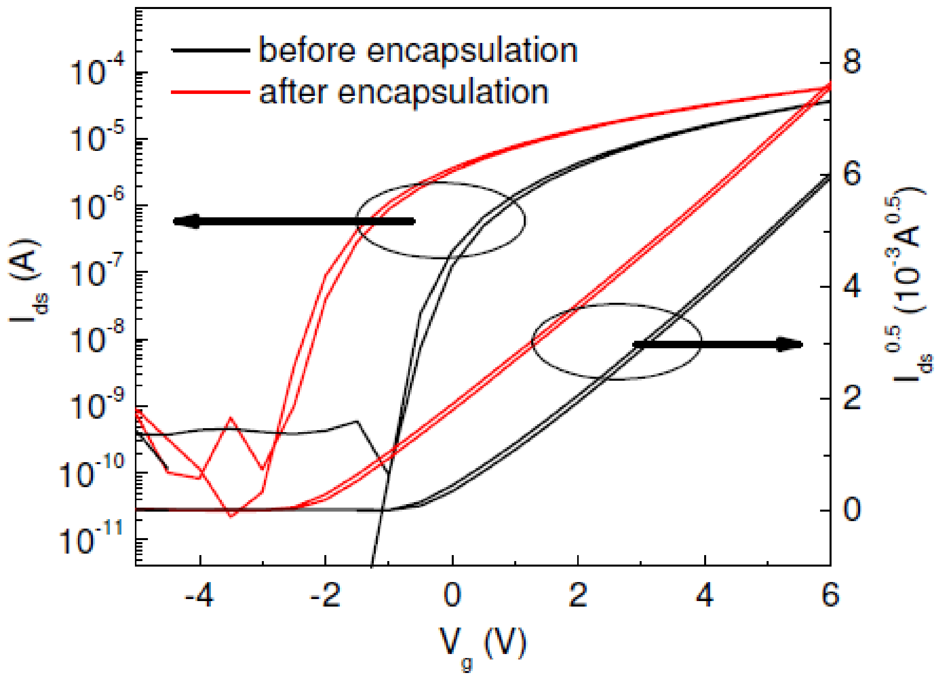


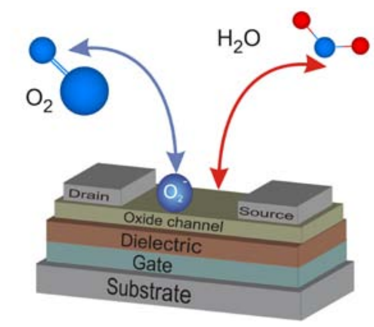
P. Görrn, T. Riedl et al. J. Phys. Chem. C 113, 11126 (2009).

Slow shift by less than 1 V → small influence of adsorbends

→ Higher binding energy of O_2^- in ZTO

Encapsulation of Oxide TFTs – Zinc Tin Oxide





small shift (<2V) after dense ALD thin film encapsulation

J. Phys. Chem. C, **2009**, *113* (25), pp 11126–11130

Encapsulation of Oxide TFTs – Zinc Tin Oxide

novel encapsulation strategy:

→ **deposit thin (1nm) encap. first**

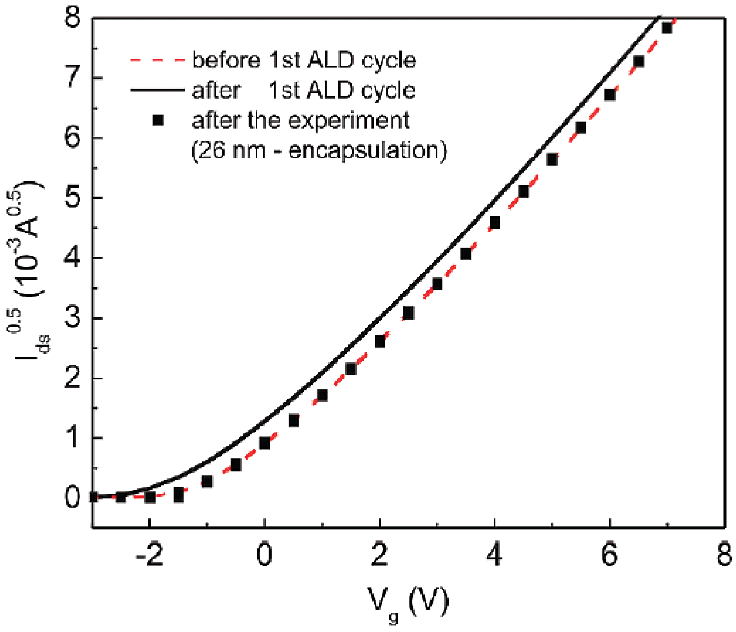
→ **re-expose to oxygen**

→ **oxygen can re-adsorb at channel**

→ **apply full encapsulation**

→ **pre-encap. clamps adsorbed Oxygen**

→ **change of threshold voltage ΔV_{th} < 1V**



J. Phys. Chem. C, **2009**, *113* (25), pp 11126–11130

Future Prospects

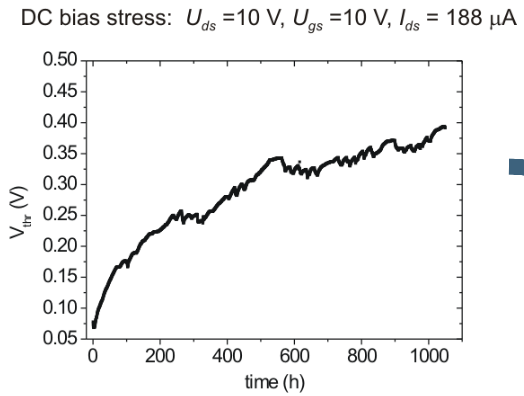
→ target 3-D Displays

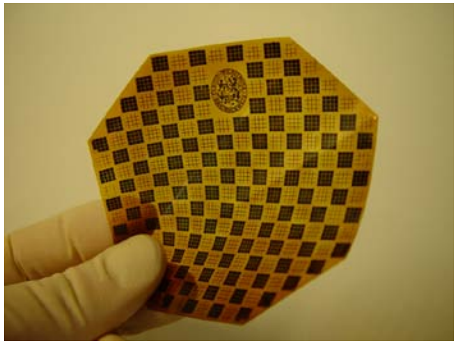
→ resolution > full HD

→ 480 Hz refresh

→ **beyond reach for a-Si electronics**

→ **metal-oxide TFTs key technology**



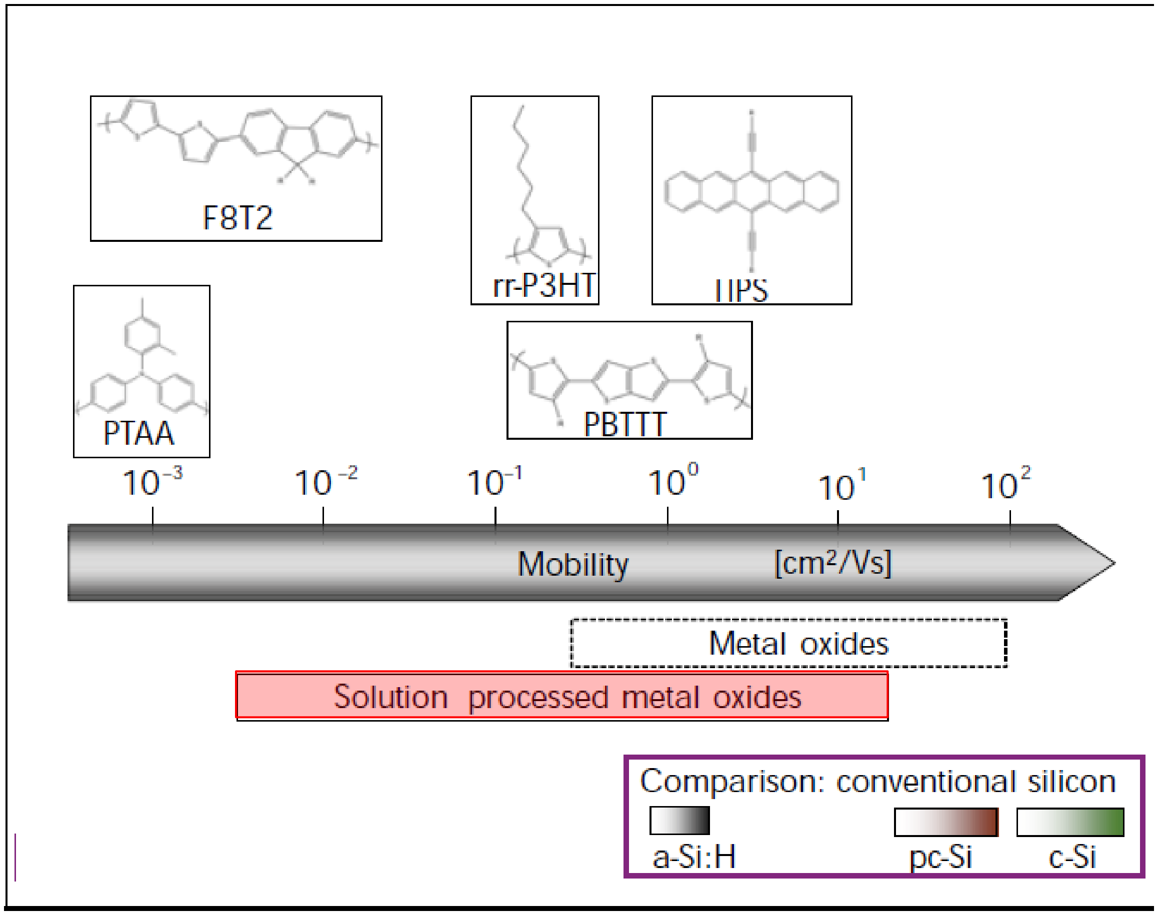


harvest benefits of both worlds:

→ stability/performance of in-organic oxide semiconductors

→ large-area, high-throughput, low-cost printing techniques (formerly domain of polymer electronics)

Printed Oxide TFTs



Vakuum in Forschung und Praxis 21 (2009) Nr. 2

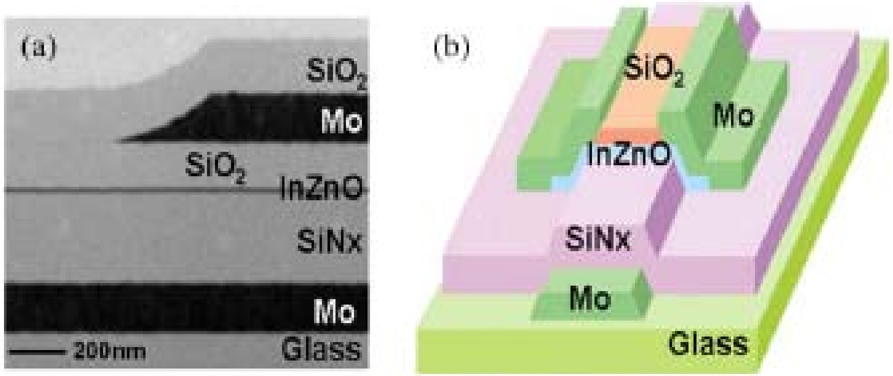
Advanced Materials, 2007. 19(15): p. 1897-1916.

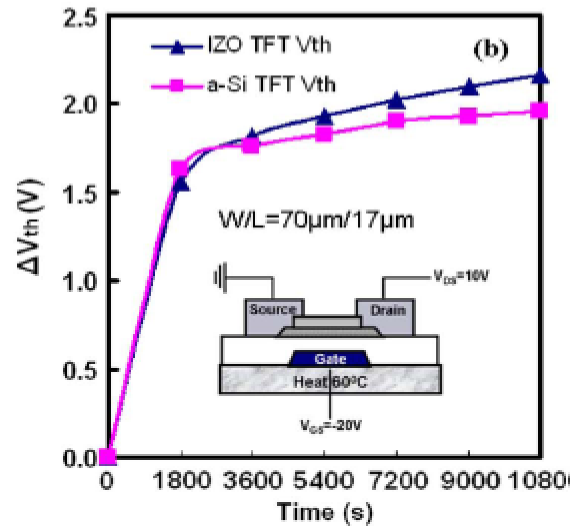
Literature reports for liquid processing of metal oxides

Metal-oxide system	Precursors used	Annealing temp
In_2O_3	(In chloride)	400 °C
Zn-In-O	(Zn chloride, In choride)	600 °C
Zn-Sn-O	(Zn acetate ,Tin acetate)	500 °C
Ga-In-O	$(Ga(NO_3)_3)$	600 °C
Ga-In-Zn-O	(ZnAc, $Ga(NO_3)_3$, $In(NO_3)_3$)	300 °C
In-Sn-O	(In chloride, Tin chloride)	250°C

....

Printed In-Zn-O TFTs





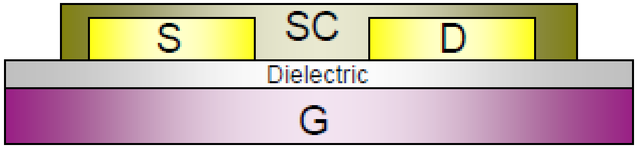
Precursors:

Indium nitrate
Zinc acetate

Process-temp.: 450 °C

$\mu_{FE,SAT}$ > 6 cm²/Vs

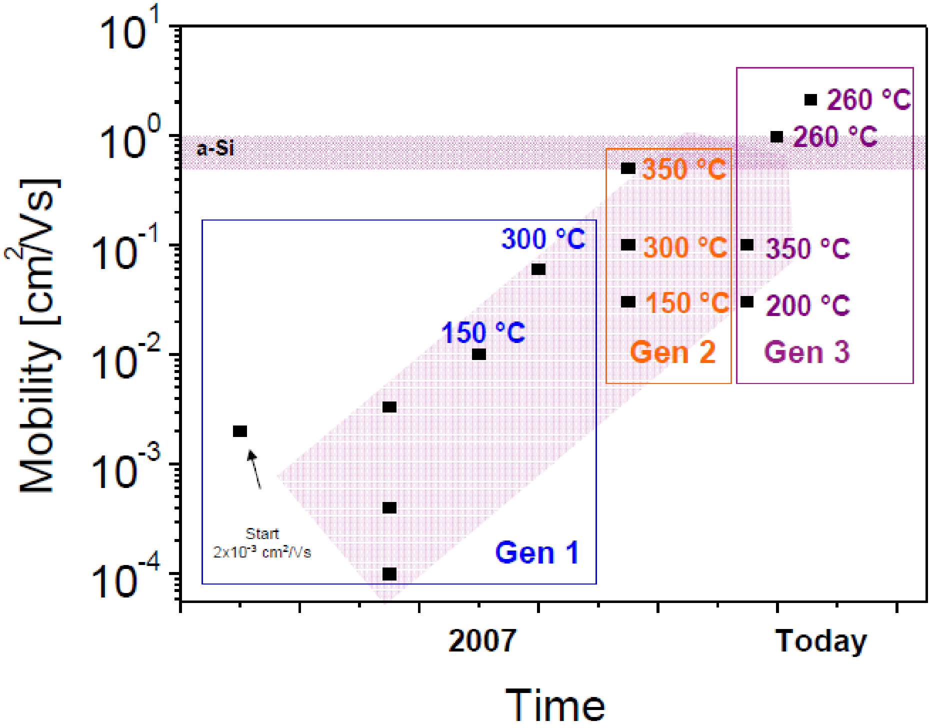
IEEE ELECTRON DEVICE LETTERS, VOL. 31, NO. 4, APRIL 2010



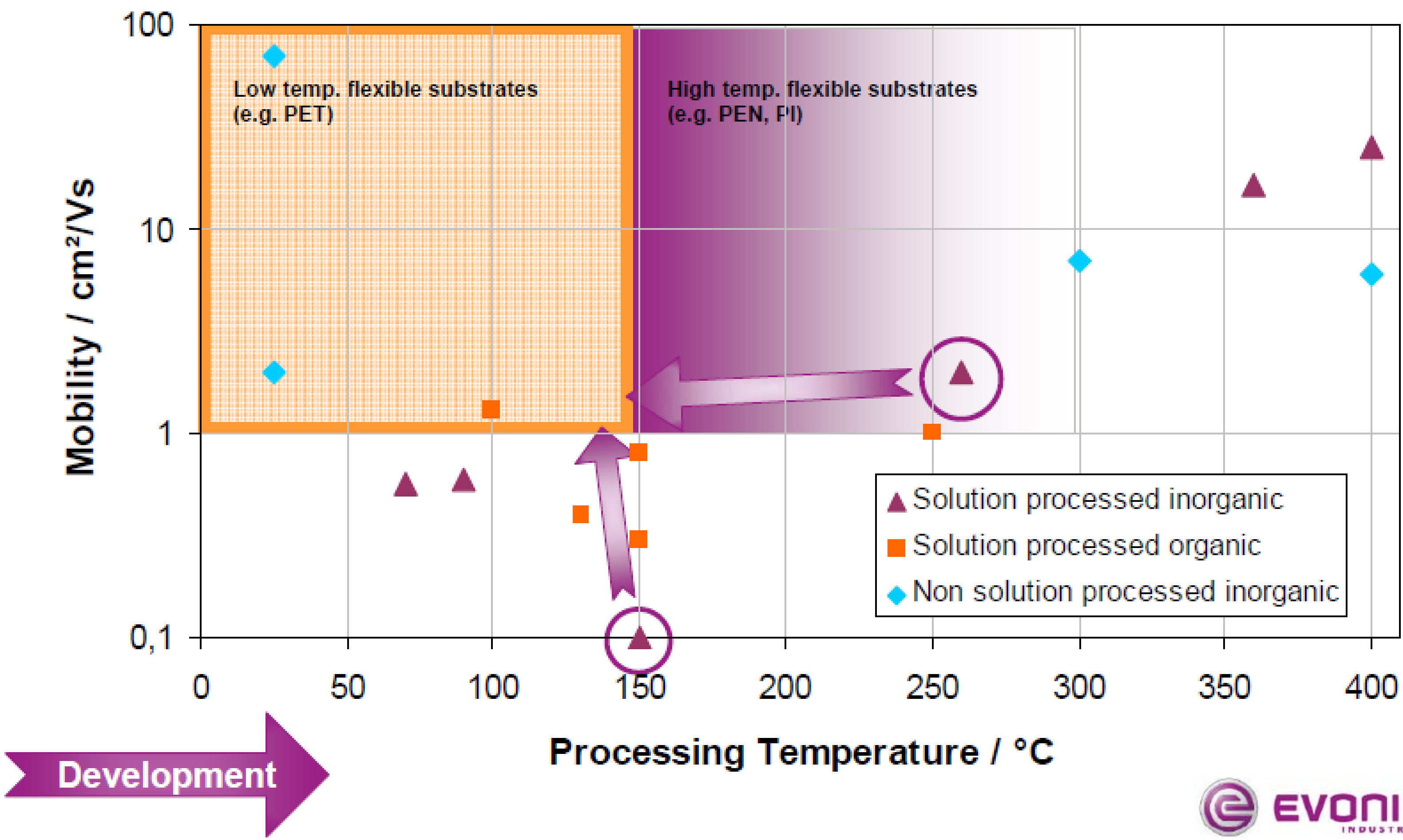
Recent data 5 cm²/Vs

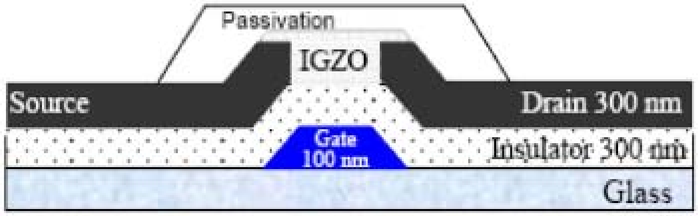
stability vs. stress ?

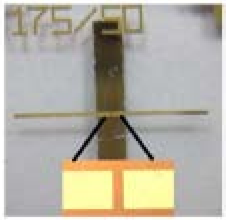
hysteresis ?



Printed Oxide TFTs





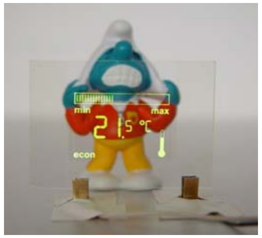


$ZnNO_3$, $Ga(NO_3)_3$, $In(NO_3)_3$ aqueous solution

Metaloxide formation at 95°C

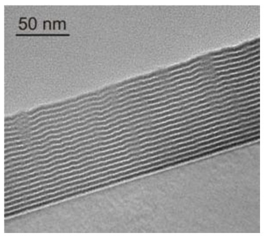
Mobility: 2.3 cm^2/Vs

Y.-H. Yang et al. IEEE ELECTRON DEVICE LETTERS, VOL. 31, NO. 4, APRIL 2010



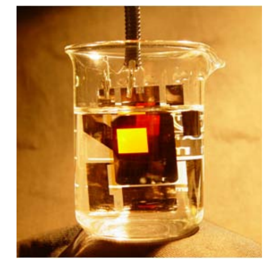
Transparent OLED technology

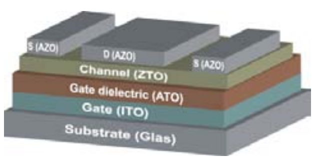
> 40 cd/A , 80 % transmissivity



ALD Thin film encapsulation

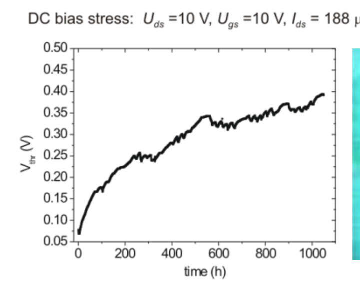
WVTR 5×10^{-7} g/(m^2day), lifetime > 20 000 h

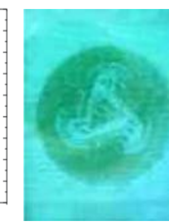


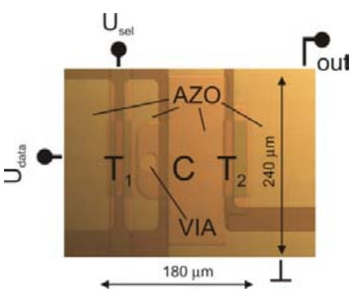


Transparent ZnO-SnO_2 TFTs

80 % transmissivity, outstanding stability

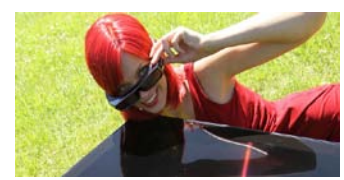






Transparent drivers electronics

100 Hz, full HD, >4,000 cd/m^2



Acknowledgement

Co-workers at :

- TU Braunschweig
- PTB
- Princeton University
- Innovation Lab Heidelberg

Funding:

Bundesministerium für Bildung und Forschung

Deutsche Forschungsgemeinschaft
German Research Foundation
DFG