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Transparent amorphous oxide semiconductors and their TFT applications

Hideo Hosono

Tokyo Institute of Technology, Japan

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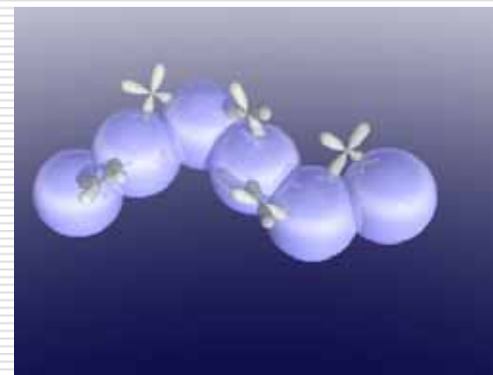
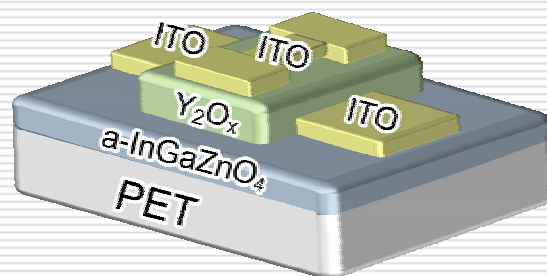
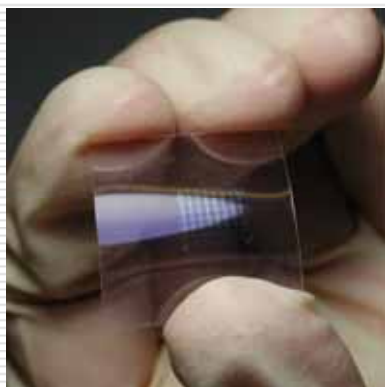
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Transparent Amorphous Oxide Semiconductors and Their TFT Application



Hideo HOSONO

Frontier Collaborative Research Center
& Materials and Structures Laboratory,
Tokyo Institute of Technology, Yokohama, JAPAN
& ERATO-SORST, Japan Science and Technology Agency



Thin Film Transistor : Switching device in display

present : TFT on glass

Semiconductor: a-Si:H



future : TFT on plastic

?



<http://www.pioneer.co.jp/>

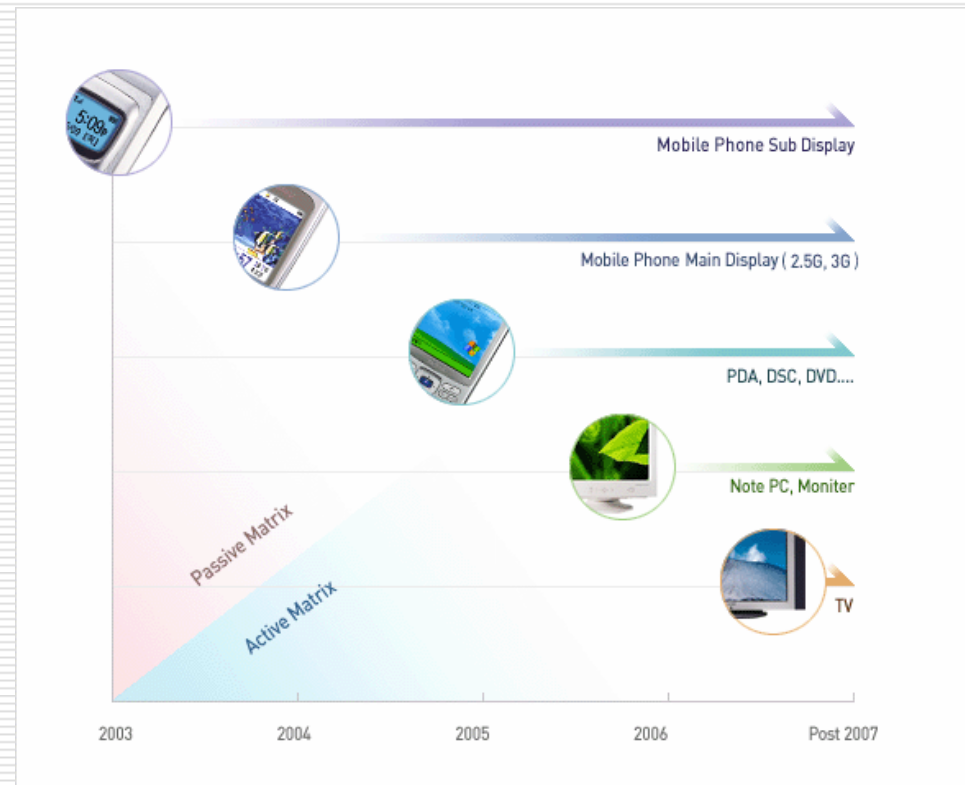
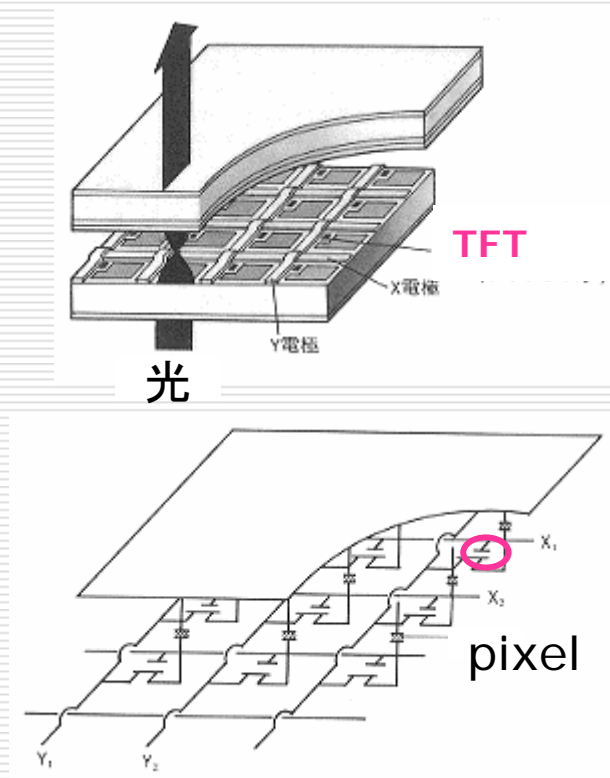
Electronics everywhere

a display that pulls out from a roll

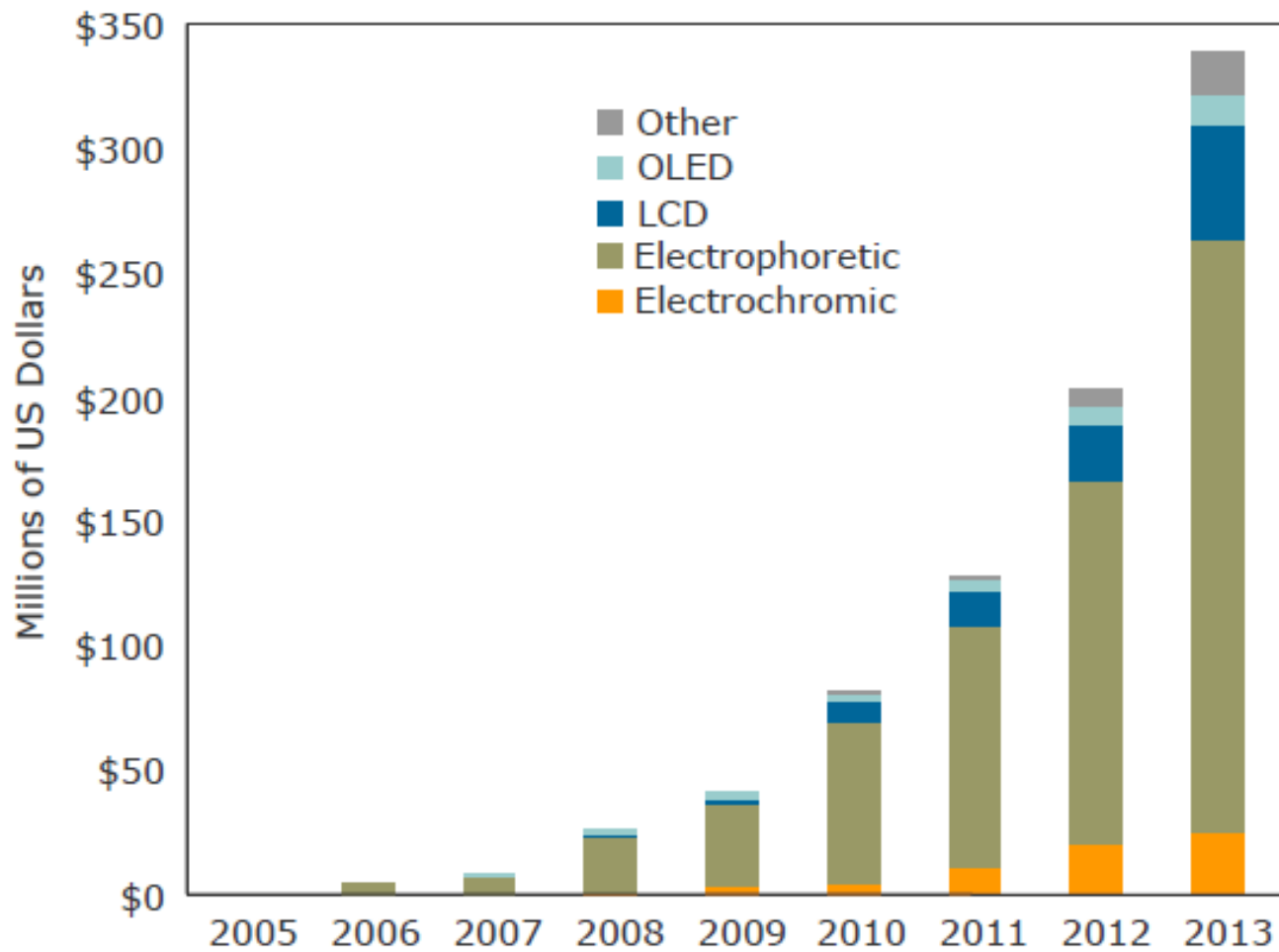
PHILIPS

Giant-microelectronics → flexible electronics,

TFT: Active Matrix Display



Market Forecast of Flexible Display



Sources :iSuppli

Examples of Flexible TFT

a-Si on SUS foil

LG. Philips LCD

Heavy

Expensive (Passivation)



LG Philips

poly-Si (Transfer Technique)

SEIKO EPSON

Difficulty in large area fabrication

Expensive



SEIKO EPSON

Organic TFT

Philips & Polymer Vision

Plastic Logic

Low mobility

Poor stability



Plastic Logic

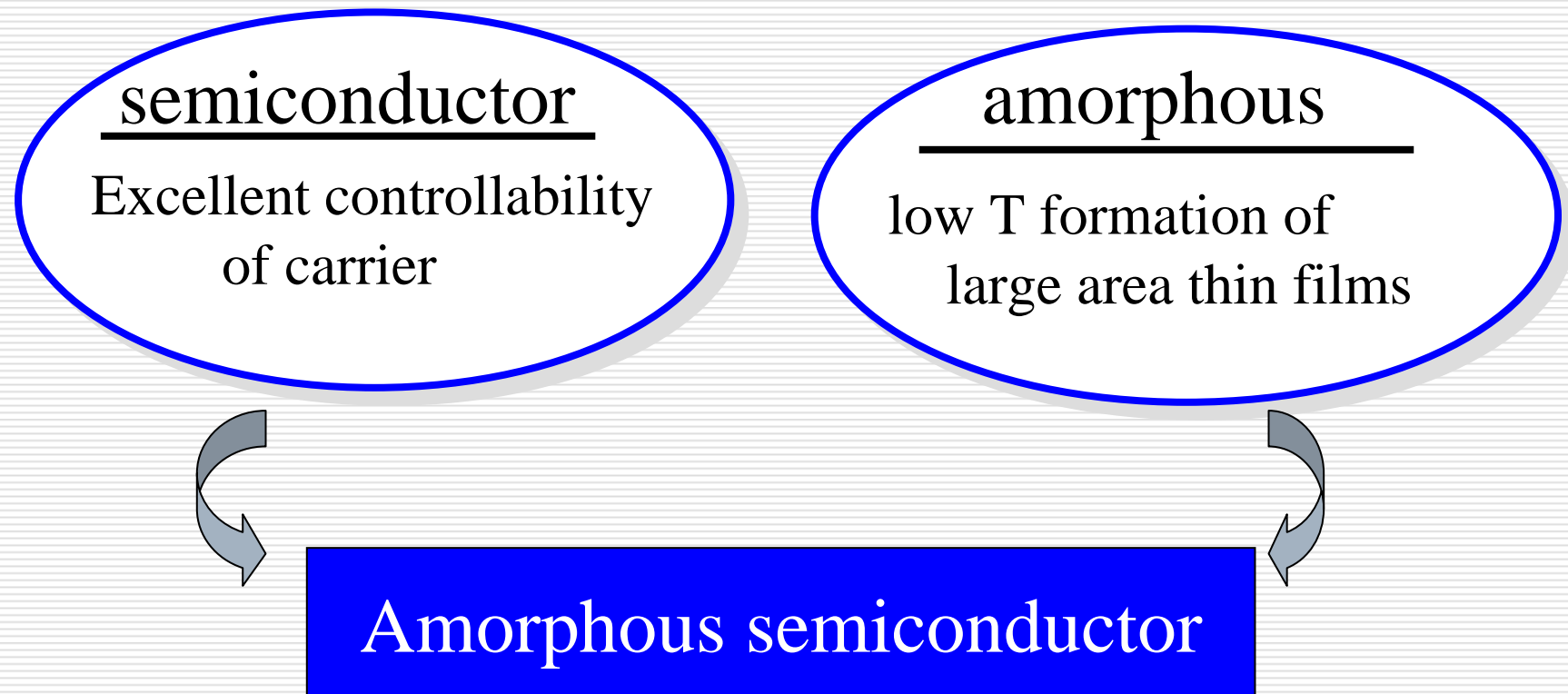
Novel Material

Low process temperature

Long-term stability

High mobility

Why amorphous semiconductor



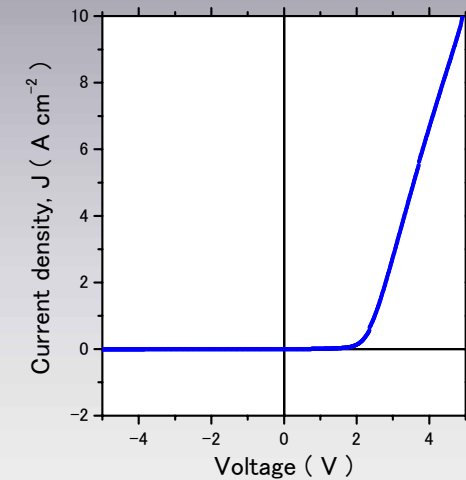
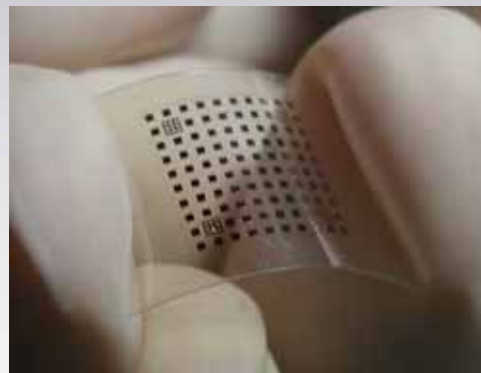
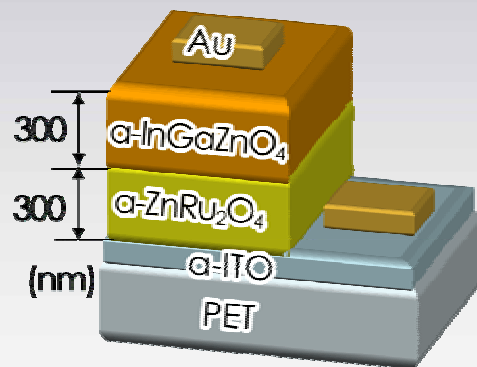
Why Amorphous oxide semiconductor (AOS)?

- Wide controllability of carrier concentration.
- High optical transparency in invisible region.
- Room temperature and large area deposition.
- Unique carrier transport properties



→ Transparent & Flexible electronics

AOSs based flexible *pn* diodes



■ A rectifying ratio : $>10^3$

■ V_{th} : $\sim 2V$

Adv. Mater. **15**,1409 (2003)

History of amorphous semiconductor

1950.

1960.

1970.

1980.

1990.

2000

Photoconductivity in a-Se(Xerography)

Glassy semicond.(V₂O₅ based oxide)

Chalcogenide glass→ DVD)

Switching and memory effect in a-chal. film

a-Si:H→'Giant-Microelectronics'



**Flexible electronics
(novel a-sc)**

Proposal of materials design concept for a-TAOS with large mobility



ELSEVIER

Proc. of ICAMS-16

Journal of Non-Crystalline Solids 198–200 (1996) 165–169

JOURNAL OF
NON-CRYSTALLINE SOLIDS

Working hypothesis to explore novel wide band gap electrically conducting amorphous oxides and examples

Hideo Hosono^{a,b,*}, Naoto Kikuchi^a, Naoyuki Ueda^b, Hiroshi Kawazoe^a

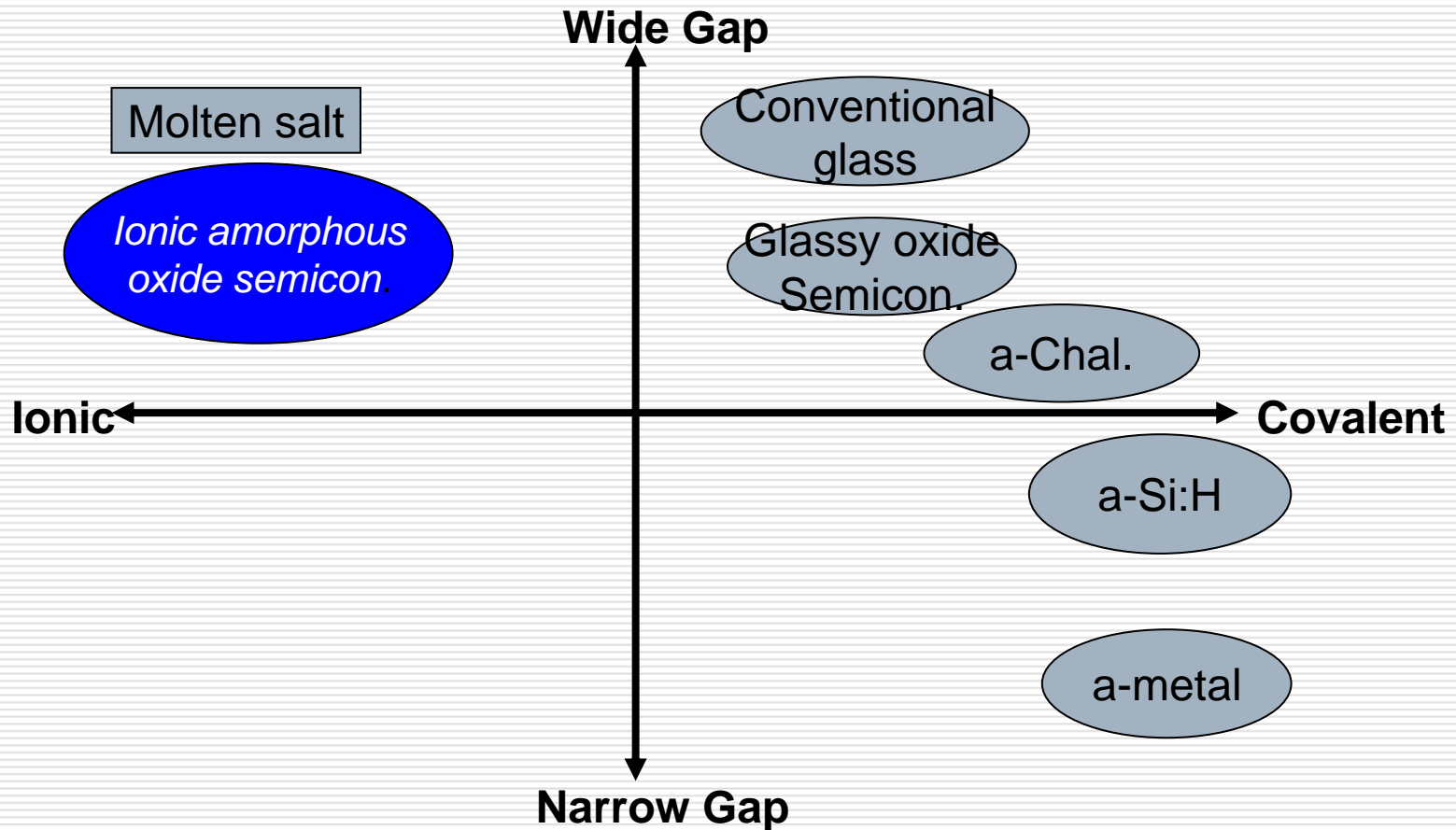
^a Tokyo Institute of Technology, Research Laboratory of Engineering Materials, Nagatsuta, Midori-ku, Yokohama 226, Japan

^b Institute for Molecular Science, Myodaiji, Okazaki 444, Japan

Abstract

A working hypothesis for exploring optically transparent and electrically conducting amorphous oxides is proposed on the basis of simple considerations concerning chemical bonding. The hypothesis predicts that amorphous oxides composed of heavy metal cations with an electronic configuration of $(n-1)d^{10}ns^0$ may be converted into transparent conducting amorphous oxides when doped by Li ion implantation or heating at temperatures below crystallization. Three new materials, amorphous Cd_2GeO_4 , $AgSbO_3$ and Cd_2PbO_4 , have been prepared as examples.

Ionic Amorphous Oxide Semiconductor : novel class of a-Semicon.



Material design concept (electron pathway)

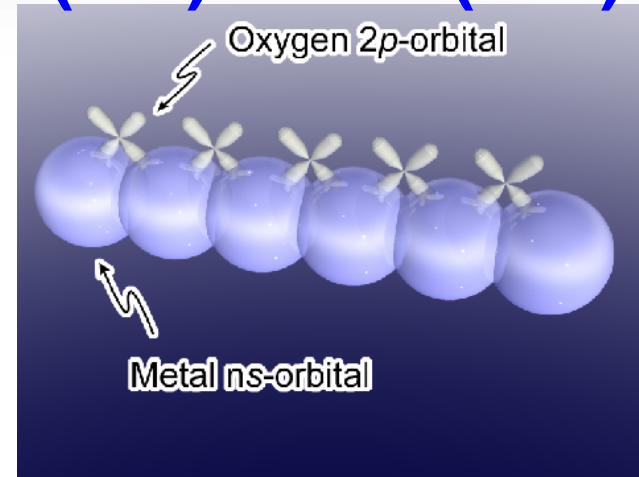
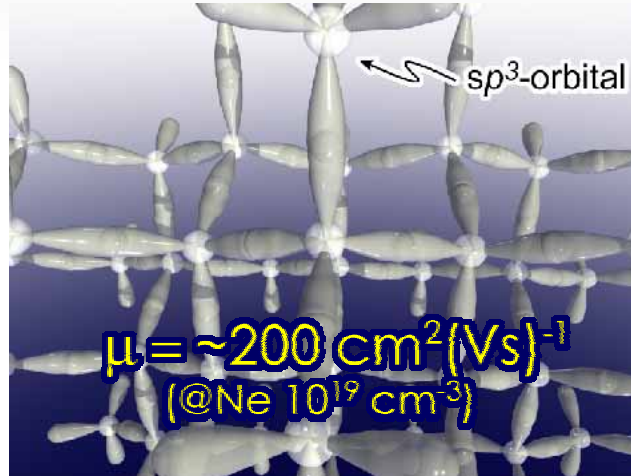


covalent semicon.

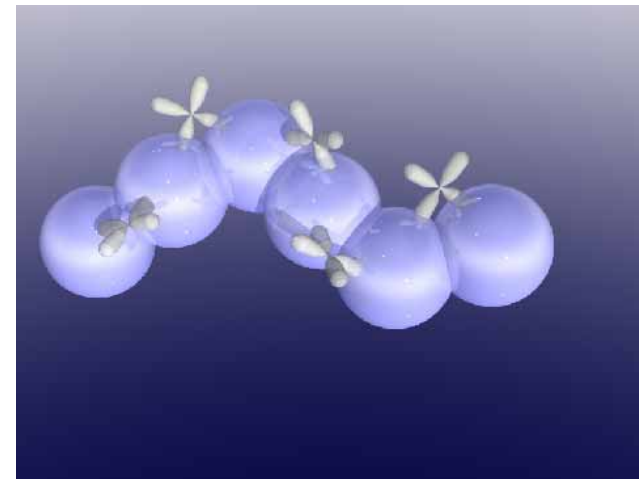
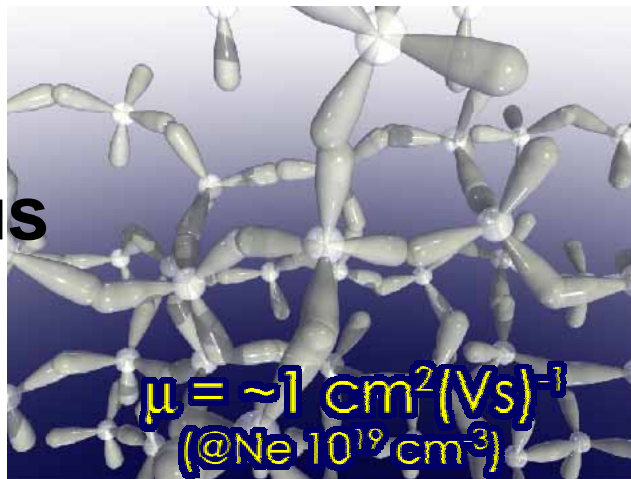
ionic oxide semicon.

$M:(n-1)d^{10}ns^0$ ($n \geq 4$)

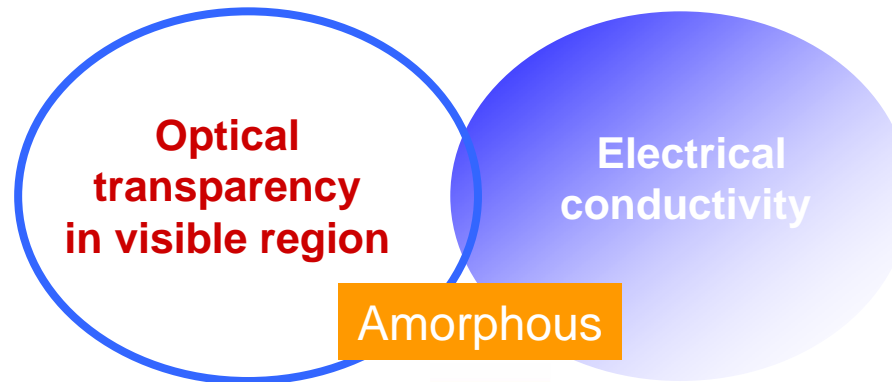
crystal



amorphous



Ionic amorphous oxide semiconductors (N-type)



Transparent amorphous oxide semiconductors

e.g. $a\text{-}2\text{CdO}\cdot\text{GeO}_2$, $a\text{-}\text{CdO}\cdot\text{PbO}_x$, $a\text{-}\text{AgSbO}_3$, $a\text{-}\text{InGaO}_3(\text{ZnO})_m$

(found in 1995-2001)

$a\text{-}\text{In}_2\text{O}_3\text{:Sn}$

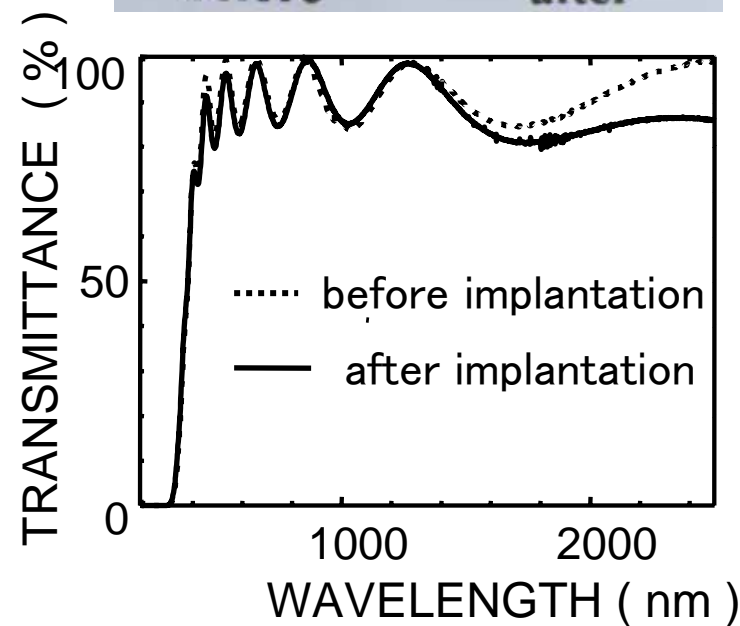
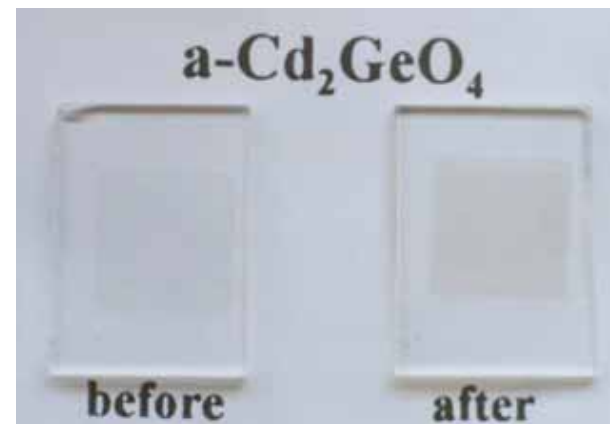
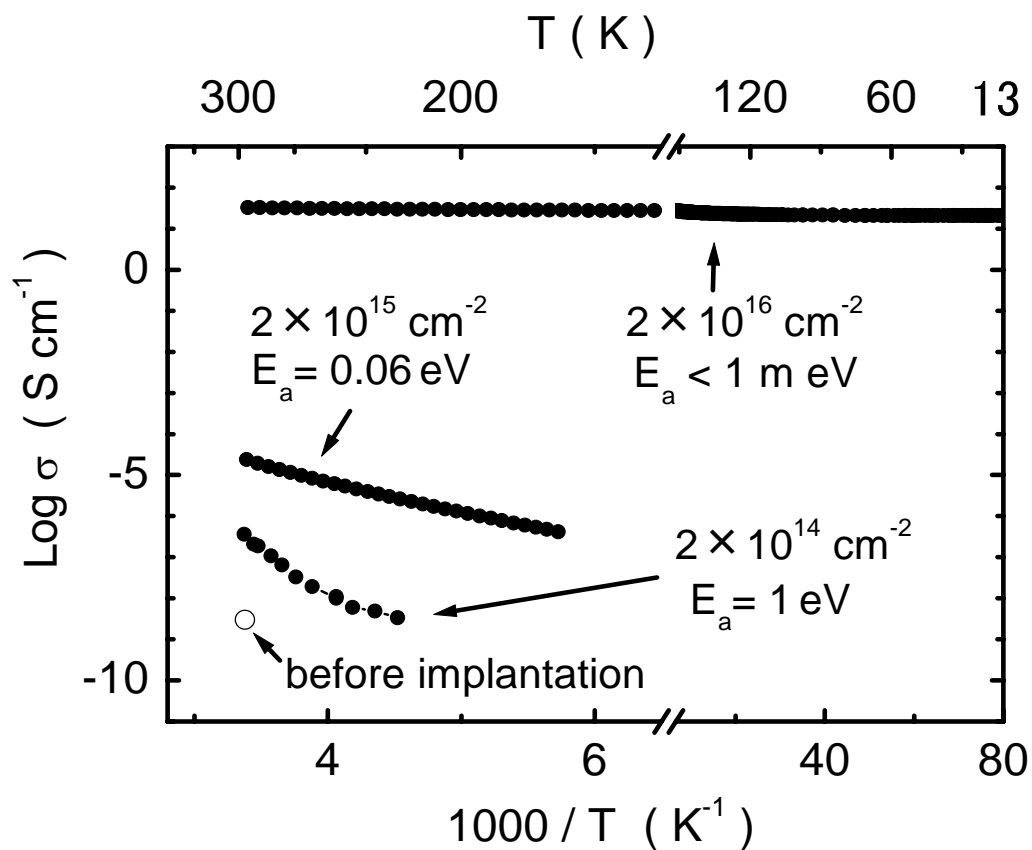
Advantages

- Low temperature deposition \Rightarrow flexible electronic device
- No long range ordering \Rightarrow reduction of severe requirements for PN-junction
- Large electron mobility compared to the conventional a-semiconductors.

Conductivity change upon H⁺- implantation

H⁺:40kV+70kV

Sample: sputtered thin film(300nm^t)

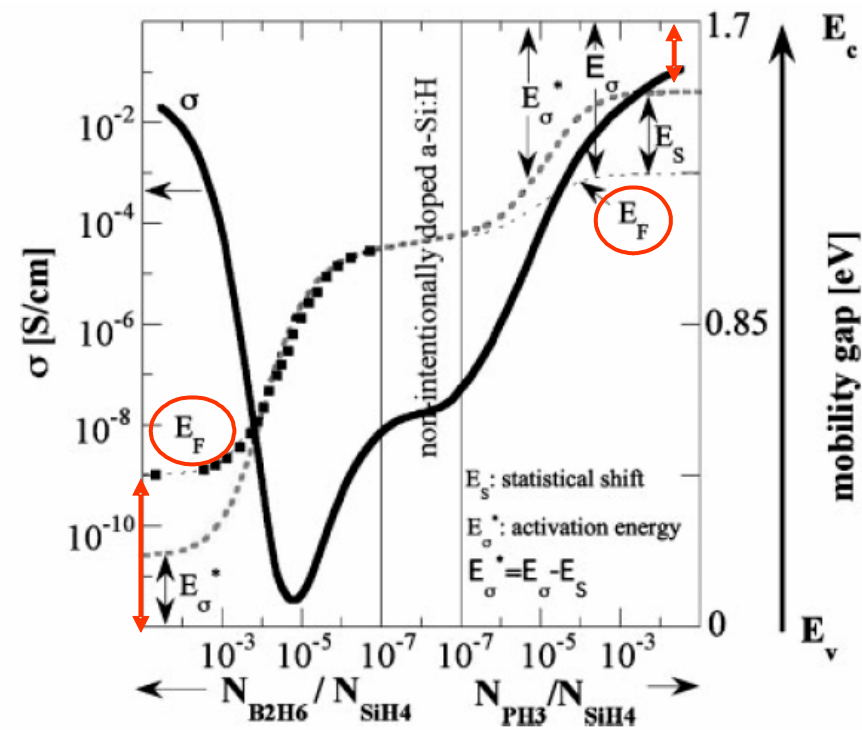


E_F is continuously controllable from $\sim E_g/2$ to above mobility gap

APL(1995)

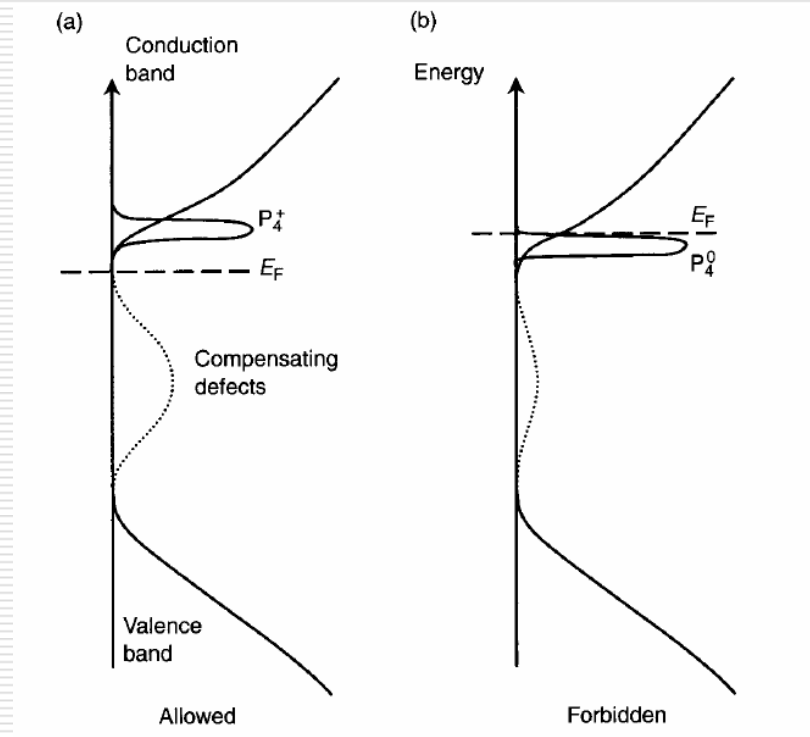
Mobility amorphous 15 cm²(Vs)⁻¹ cf. crystal 20cm²(Vs)⁻¹

a-Si:H doping limit



E_F cannot exceed mobility gap

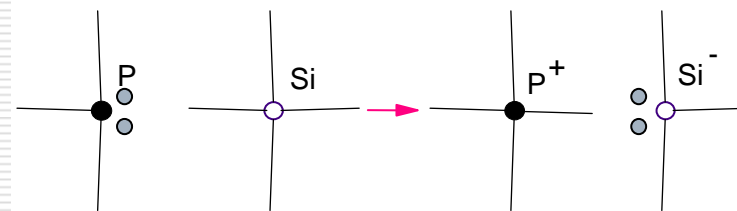
Why doping is inefficient for a-Si:H ?



E_F never enters conduction band extended states by doping



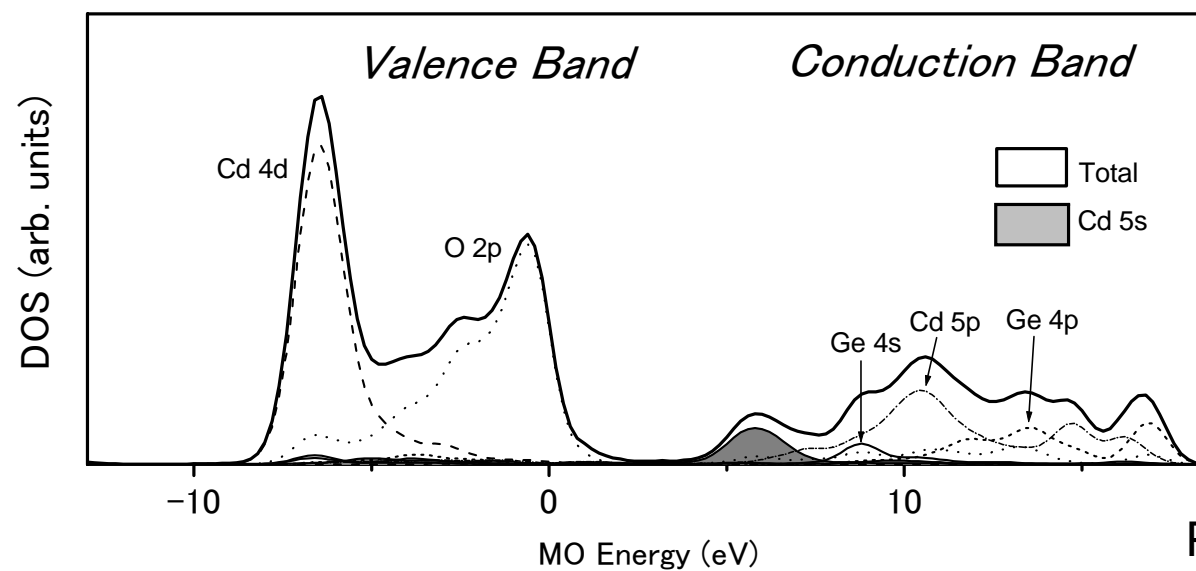
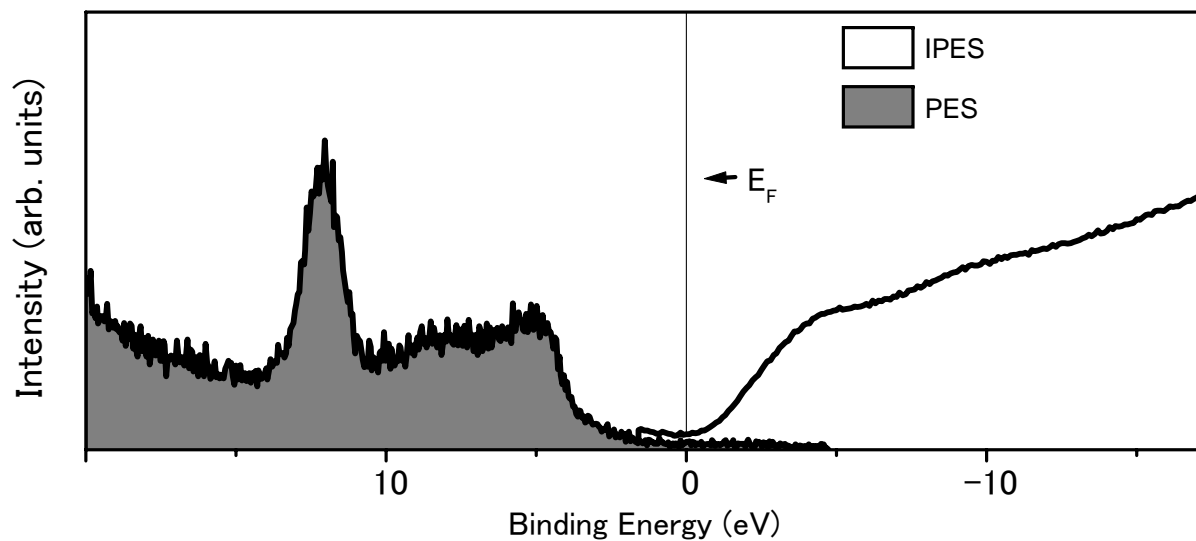
Doping creates D^- state



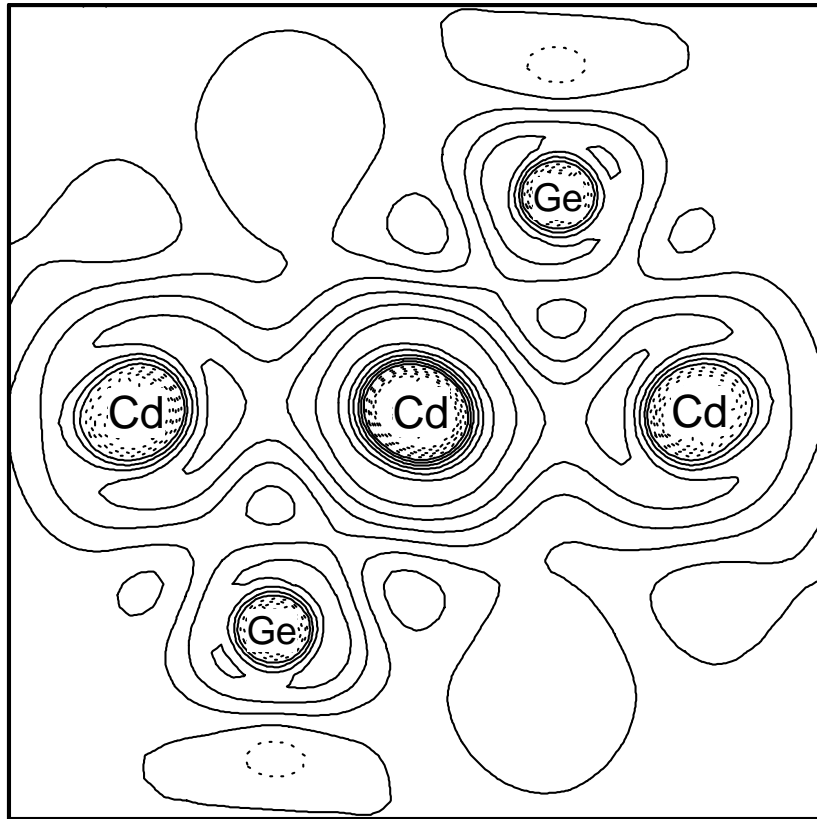
Carriers are NOT generated

Mott-Street model

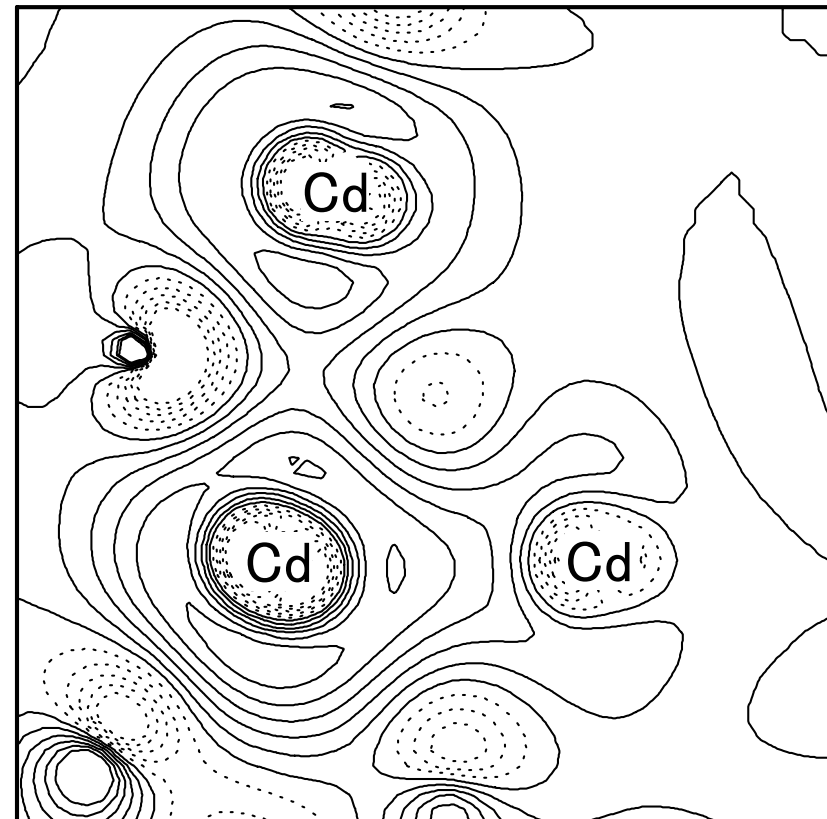
Observed and calculated DOS



Contour map of wave function @ conduction band bottom



(a) crystalline

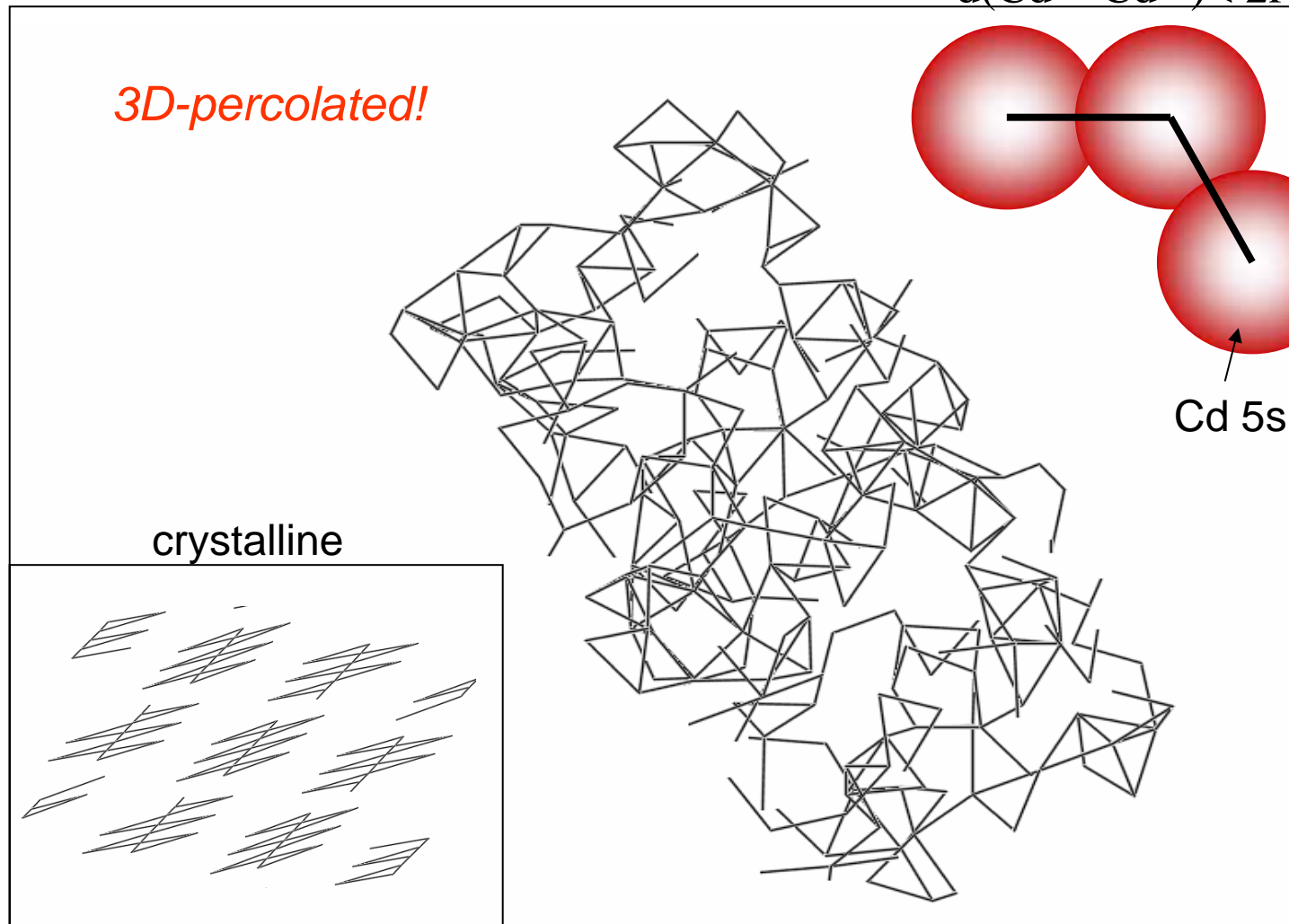


(b) amorphous

Cd-Cd correlations in RMC-fitted model

$$d(\text{Cd}^{2+}-\text{Cd}^{2+}) < 2r(\text{Cd } 5s)$$

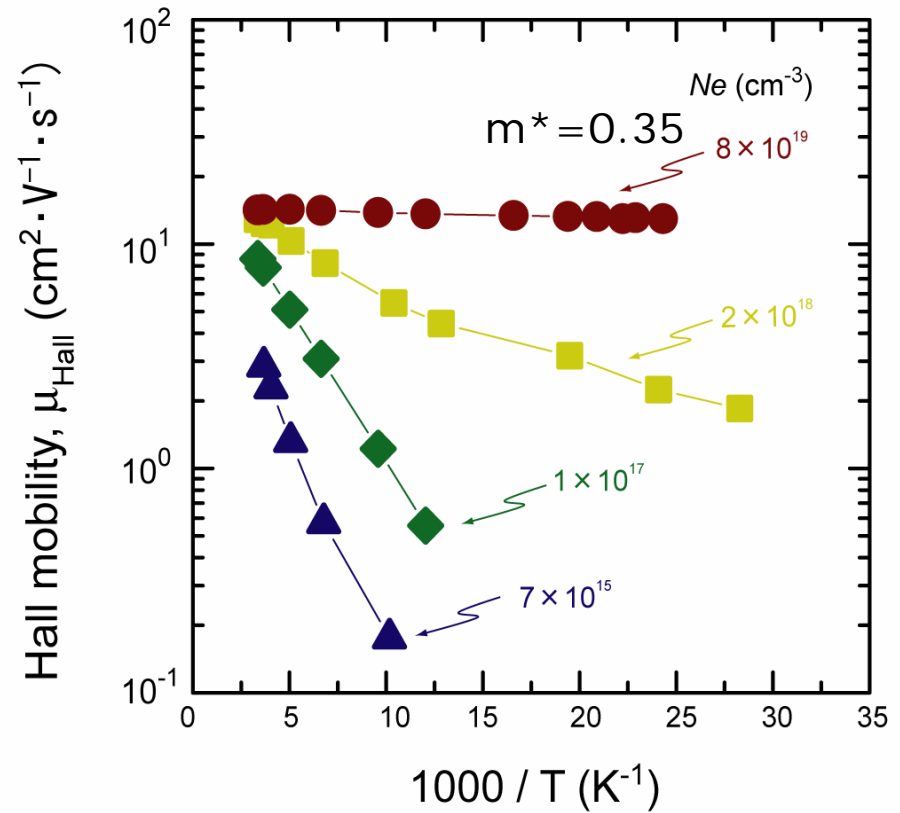
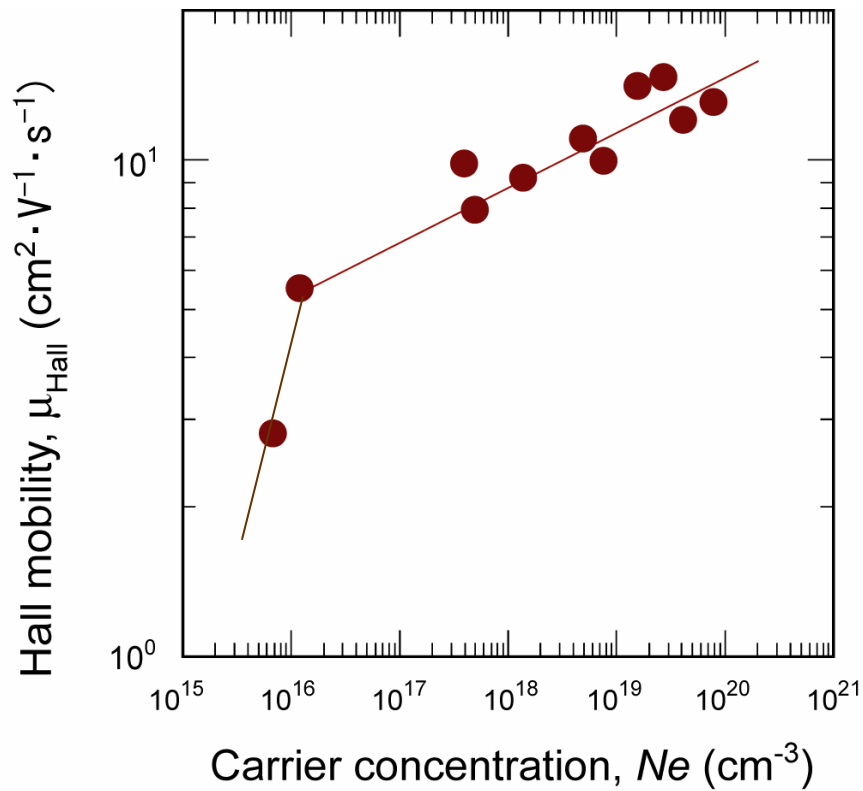
3D-percolated!



Cd 5s

PRB(2002)

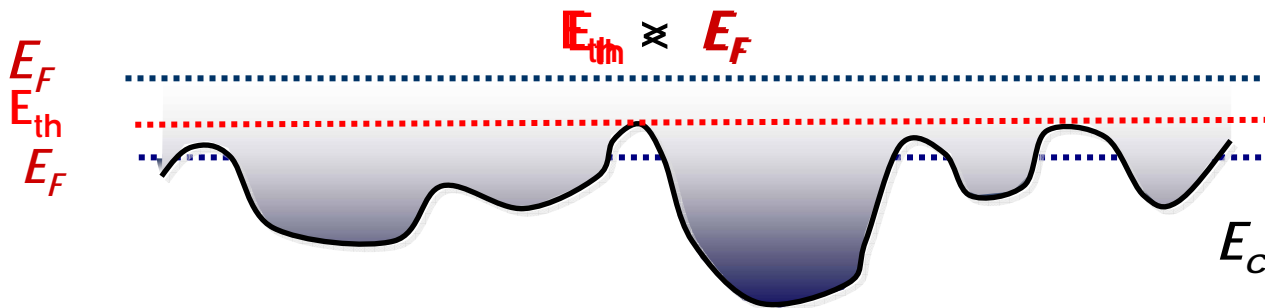
Electron Transport in a-IGZO



APL(2004)

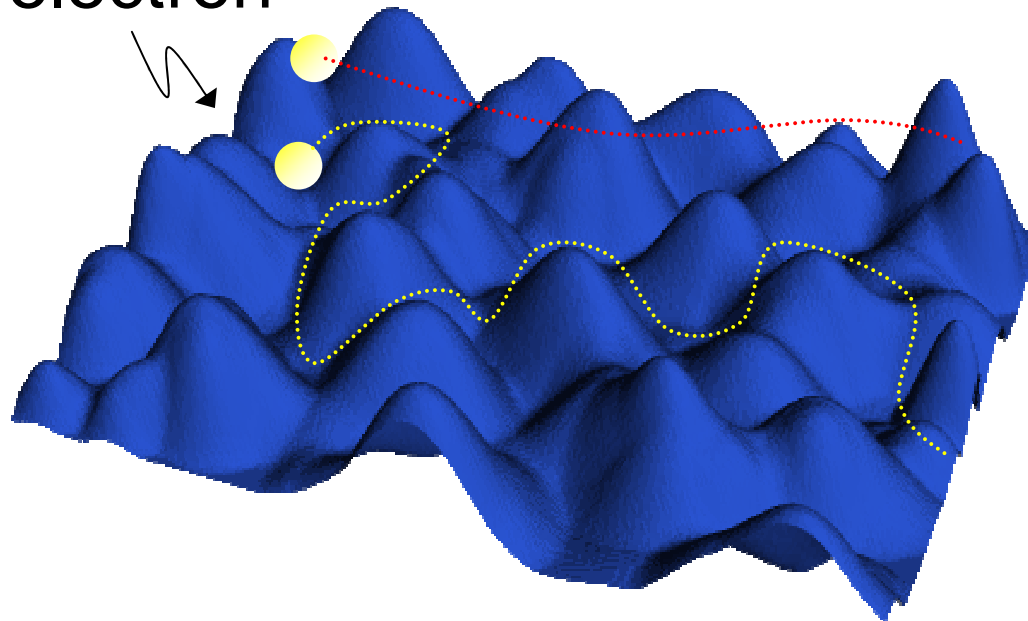
Carrier Concentration and conduction

$$N_e > 10^{18} \text{ cm}^{-3}$$



electron

$$\mu_{Hall} > 10 \text{ cm}^2(\text{Vs})^{-1}$$



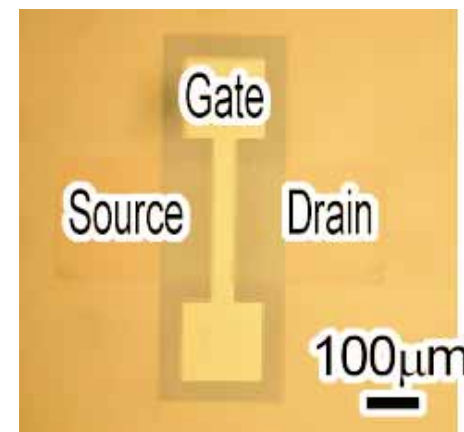
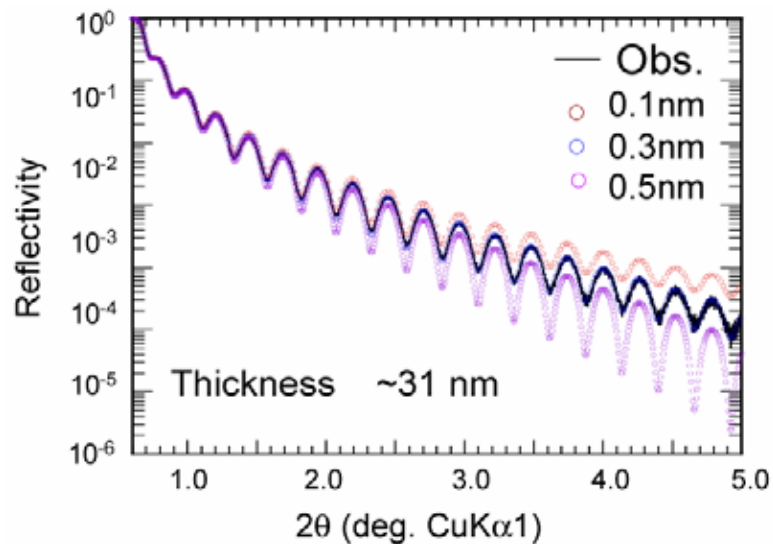
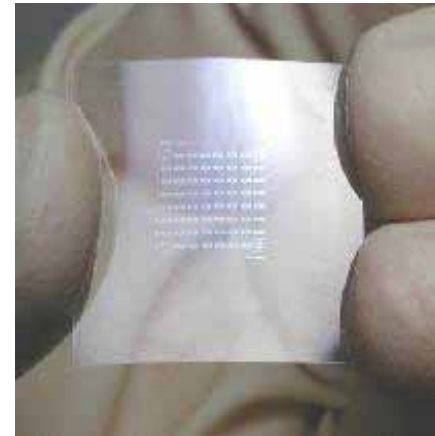
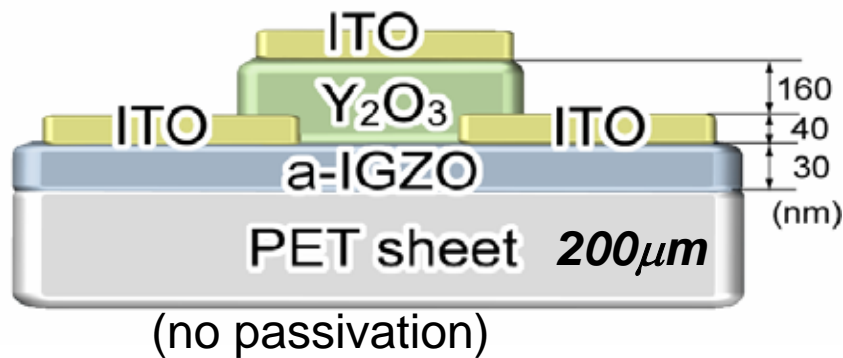
APL(2004),TSF(2005).

Ionic Amorphous Oxide Semicon.

Material system	Chemical bond	Mechanism	Hall effect	Mobility (cm ² /(Vs))	Example
Tetrahedral	covalent	hopping	abnormal	~1	Si:H
Chalcogenide	covalent	hopping	abnormal	< 10 ⁻³	Tl ₂ Se- As ₂ Se ₃
Oxides (glass semiconductors)	covalent + Ionic	hopping		~10 ⁻⁴	V ₂ O ₅ -P ₂ O ₅
(Ionic amorphous oxide semiconductors)	Ionic	Band conduction	normal	10~60	In-Ga-Zn-O

Transparent FET on plastic

Device structure

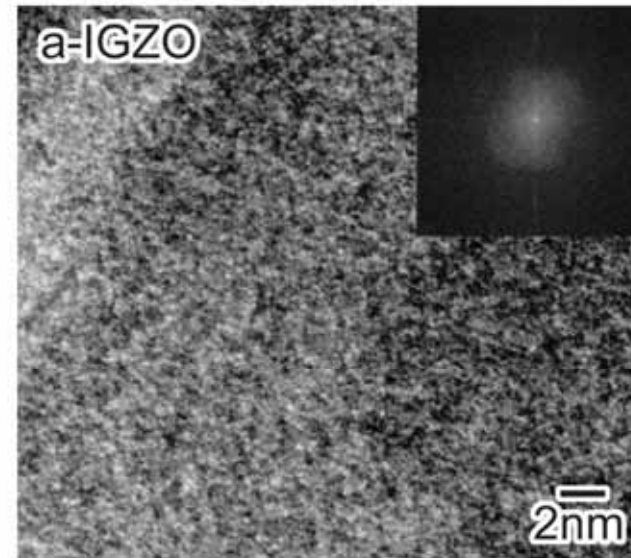
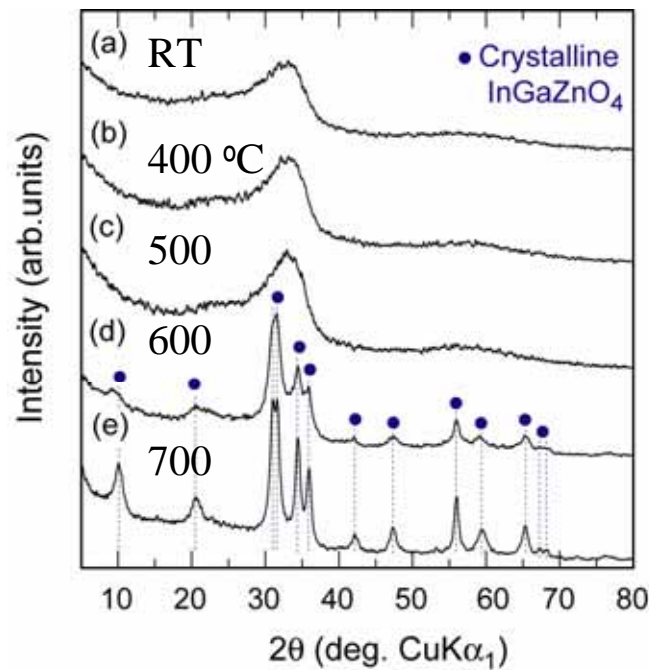


W / L : 200 / 50 (μm)

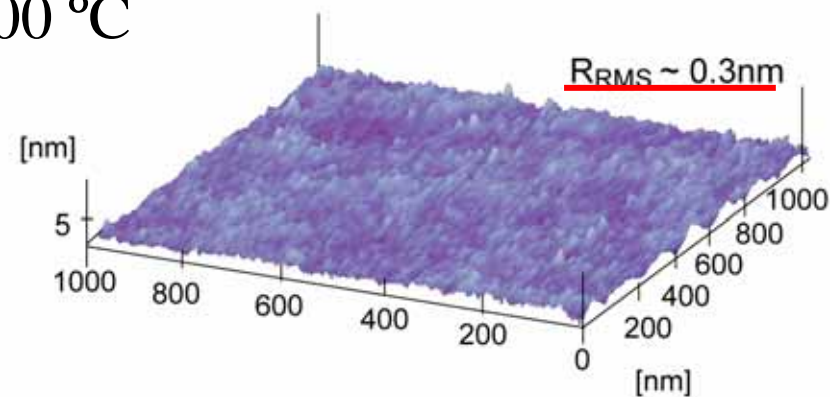
Amorphous InGaZnO₄ Thin Films

t=200nm thick

Pulsed Laser deposition @ RT



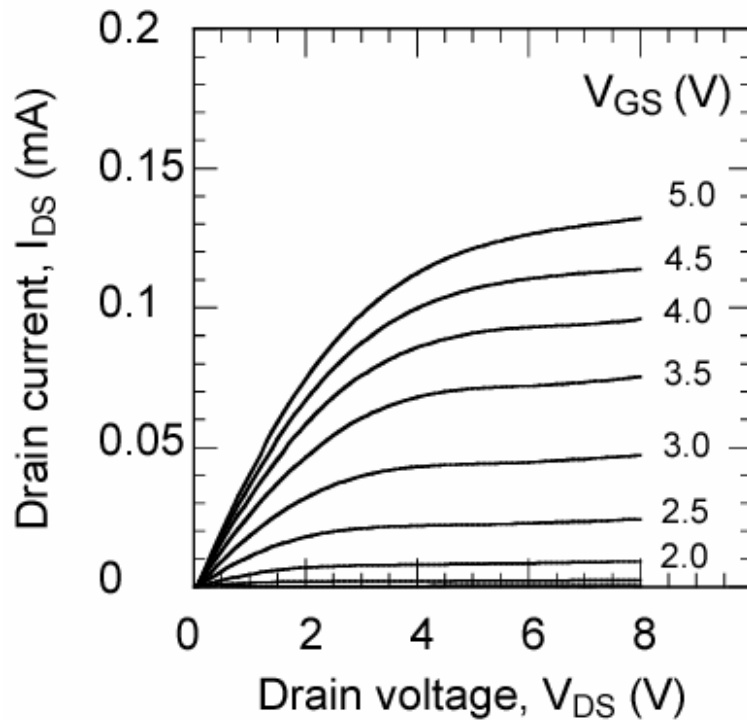
Stable up to ~500 °C



Transistor Performance

output

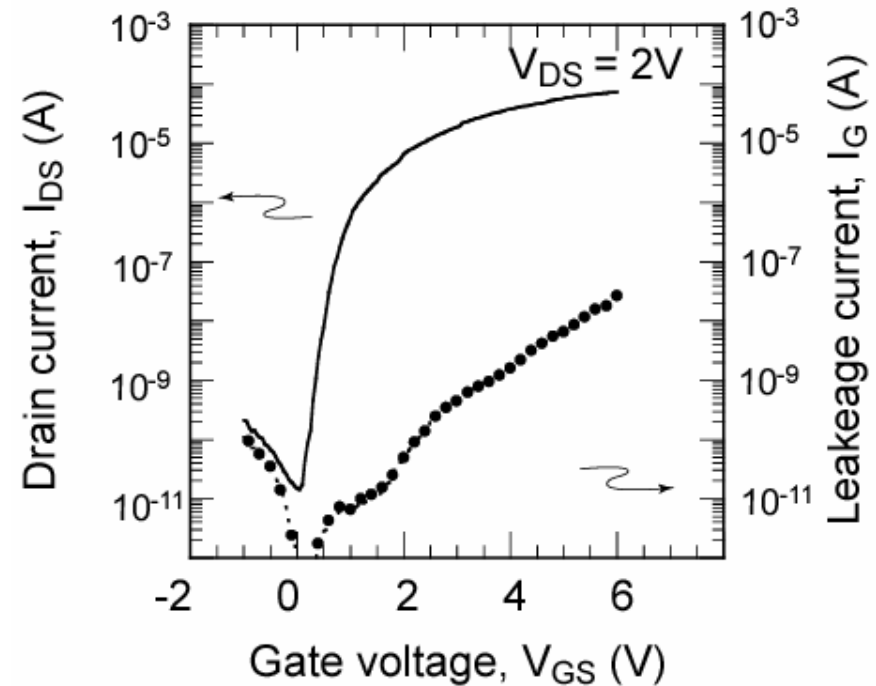
$$\mu_{\text{sat}} = 12 \text{ cm}^2(\text{Vs})^{-1}$$



$W / L : 200 / 10 (\mu\text{m})$

transfer

$$\text{ON/OFF ratio} = 10^6$$



Nature(2004)

High performance transparent FET was fabricated on PET substrate

□ Material exploration

High mobility & carrier controllability

➔ N-type AOS, In-Ga-Zn-O (a-IGZO)

$$\mu_{\text{Hall}} > 15 \text{ cm}^2(\text{Vs})^{-1} : N_e < 10^{15} - 10^{21} \text{ cm}^{-3}$$

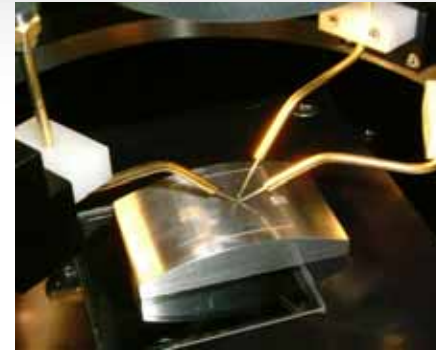
□ Carrier transport

➔ Localized to extended state

$$> 10 \text{ cm}^2(\text{Vs})^{-1} @ N_e > 10^{18} \text{ cm}^{-3}$$

□ Device fabrication

➔ Y_2O_x (high k) as gate insulator & RT



□ $\mu_{\text{sat}} \sim 12 \text{ cm}^2(\text{Vs})^{-1}$
cf. ~ 1 for a-Si:H, pentacene
c

□ f_{ON} / OFF ratio $\sim 10^6$

□ Normally-Off ($V_{\text{th}} \sim +1 \text{ V}$)

□ $S = \sim 0.2 \text{ V/dec}$

a-IGZO can be deposited on plastic by the same process as ITO

➔ ***Large process merit***

Current Status of TFT for Elexible Displays

Channel material	Pentacene	a-Si:H	Poly-ZnO	a-IGZO
Thin Film Fabrication	Vacuum Evap.	CVD	PLD	sputter
Max. Tem.()	<100	300	300	RT
Mobility(cm ² V ⁻¹ s ⁻¹)	0.5	0.5	~5	~12
Current ON/OFF (log ₁₀)	5~6	>6	~5	~8
S (V/decade)	0.2	0.4	1.3	0.2

Long Term Stability

- Spec for Large-sized OLED TV Panel

SID2006

70.1: Invited Paper: Large-Sized Full Color AMOLED TV :
Advancements and Issues

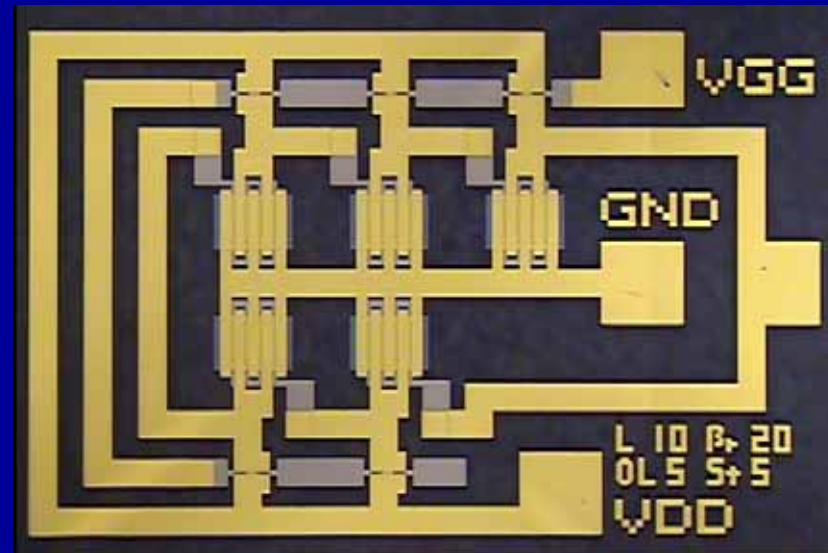
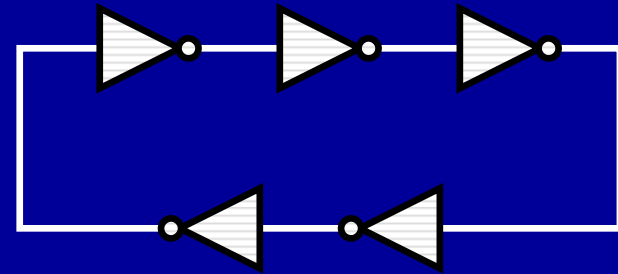
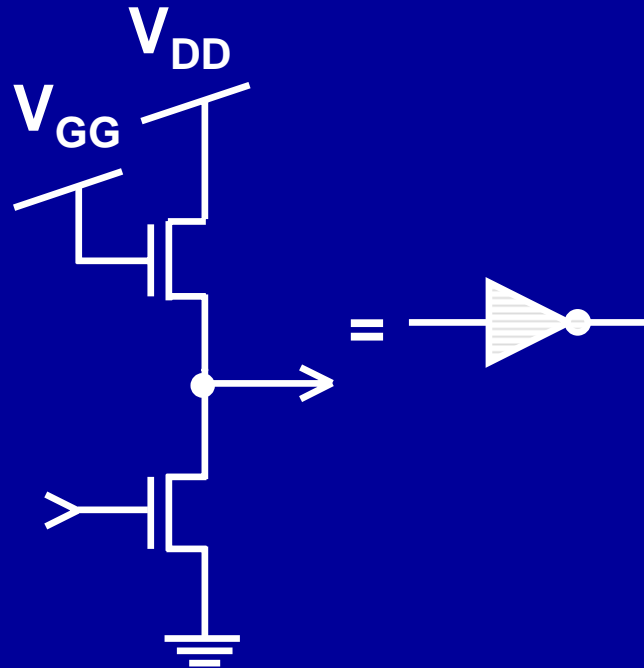
Kyuha Chung, Namdeog Kim, Joonhoo Choi, Changwoong Chu and Jong-moo Huh
OLED Development Team, LCD Business, Samsung Electronics Co., Ltd., Kyunggi-do, Korea

μ_{FE}	1-10 cm ² /Vs
ΔV_{TH}	< 1 V for 10 ⁵ hrs

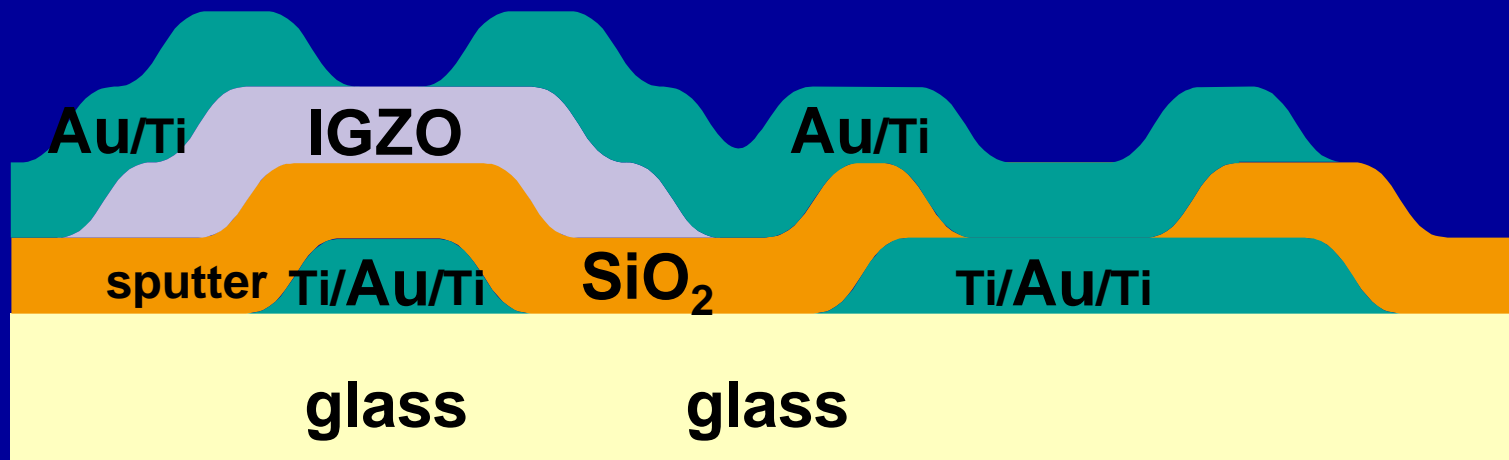
- Long Term Stability Test (SAIT) @E – MRS2006

W/L=200/4 μ m, 3 μ A/Pixel x 300hrs			
Active Layer	ZnO	IZO	IGZO
ΔV_{TH} (V)	5.0	3.0	0.2

5-stage RO



0.5 mm

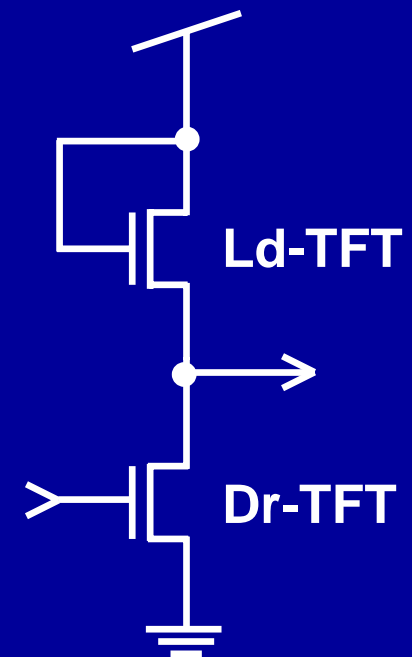


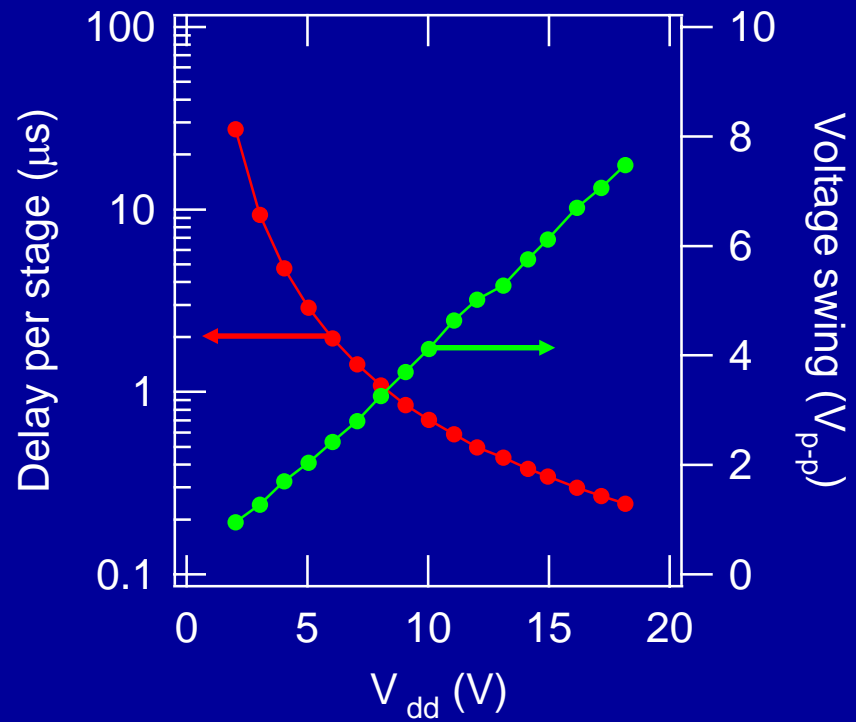
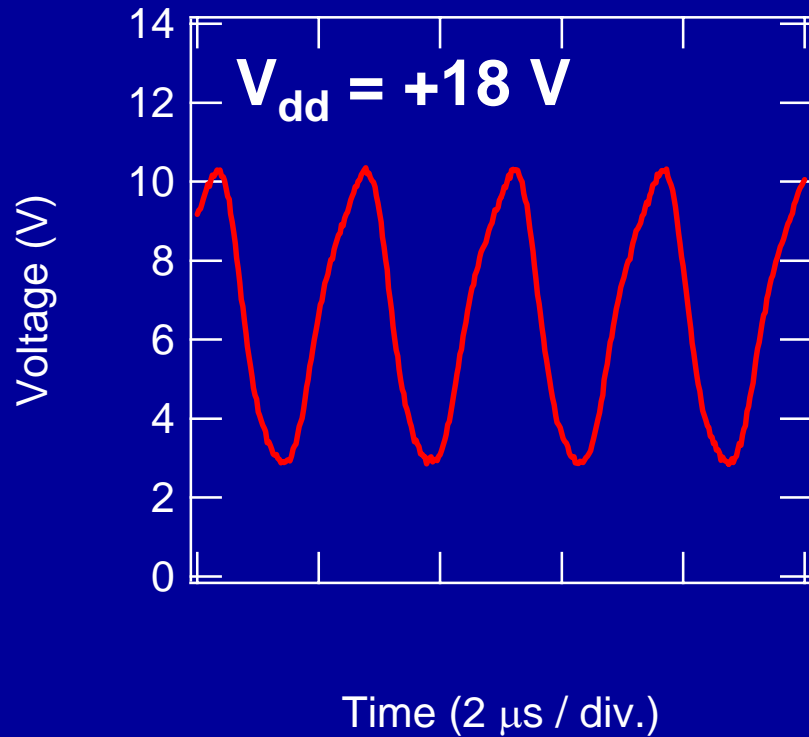
patterning

metals	lift-off
semiconductor	etching
insulator	etching

$$L_{Ld} = L_{Dr} = 10 \mu\text{m}$$

$$\beta_R = (W/L)_{Dr} / (W/L)_{Ld} = 5$$



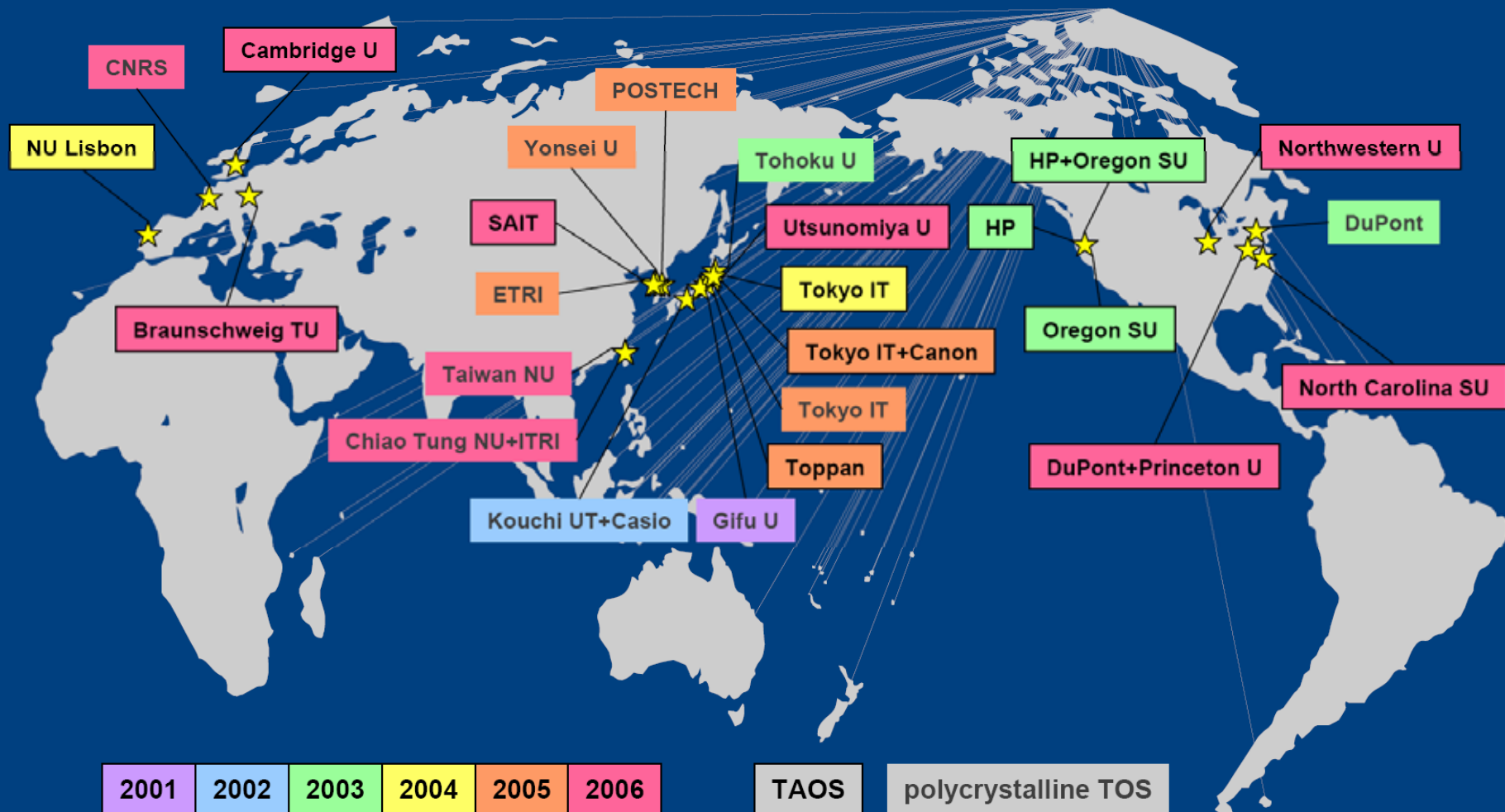


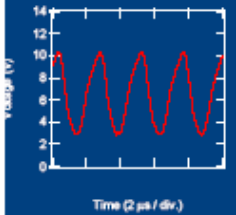
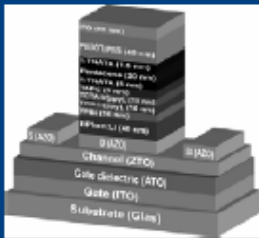

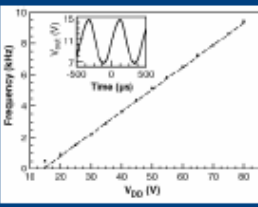
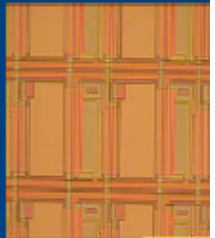

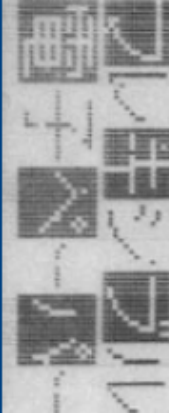
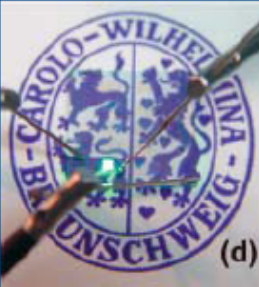

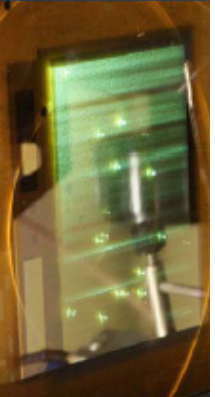
**410 kHz (0.24 μs /stage), 7.5 V_{p-p}
@ $V_{dd} = +18$ (V)**

amorphous/oxide TFT-based Ring Oscillators

	a-Si:H	Organic	Oxide	
		P3HT	IGZO	<i>a-IGZO</i>
L (μm)	5	2 – 5	60	?
V_{DD} (V)	+30	-80	+80	?
f_{osc} (kHz)	83	106	9.5	?
Δt ($\mu\text{s}/\text{stage}$)	0.54	0.68	11	?
Ref.	EDL 5, 224 (1984)	APL 81, 1735 (2002)	SSE 50, 500 (2006)	

Worldwide T(A)OS-TFT Activities



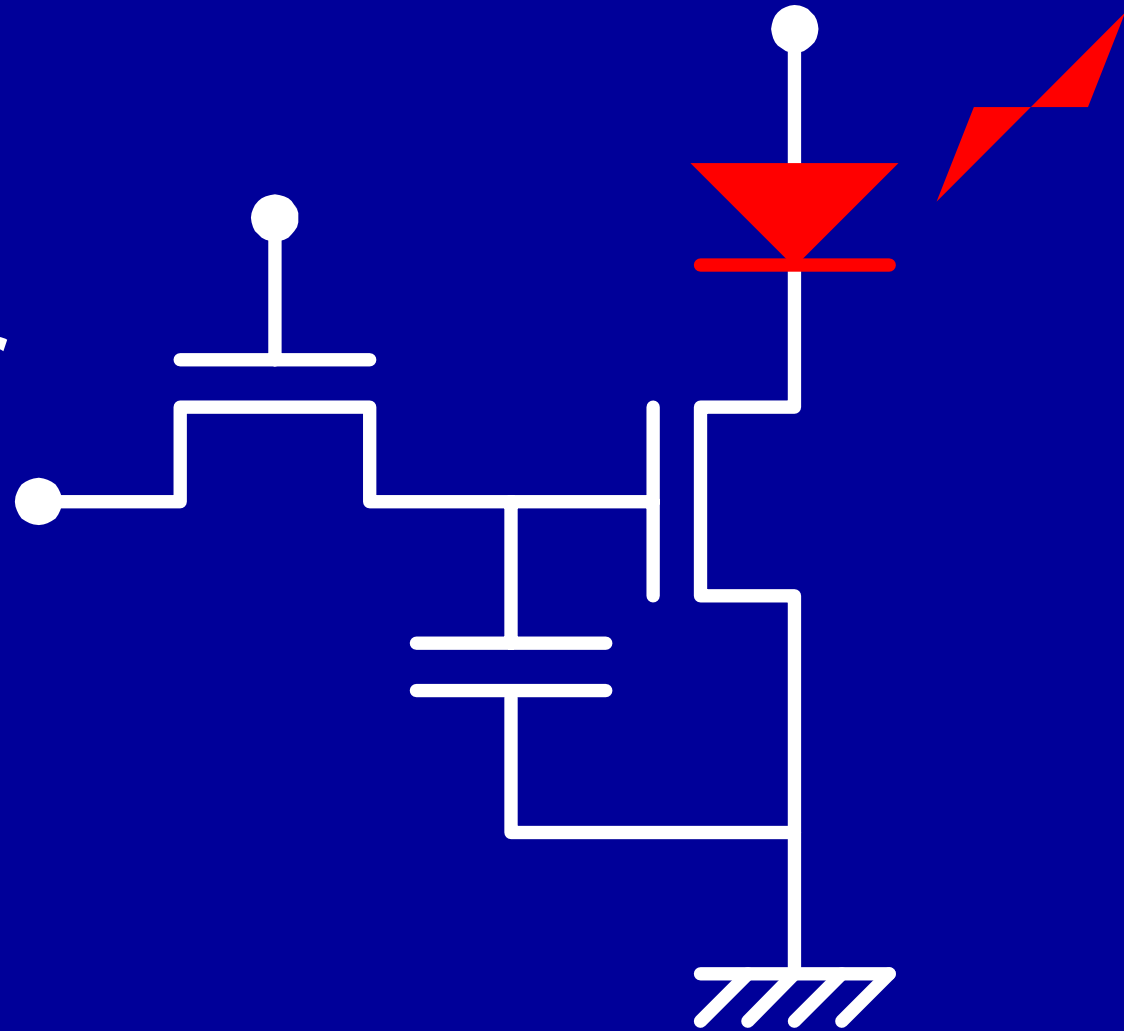
	TIT Canon	Toppan	Braunschweig TU	Kochi IT Casio	HP Oregon SU	ETRI
materials	IGZO	IGZO	ZTO	ZnO	IGO	ZnO
circuits/ devices	RO 	AM swich 1T (1C) ?	stacked OLED 	AM 	RO 	AM 
FPD application	AMOLED 	AM-ePaper 	stacked OLED 	AM-LCD 	-	AM-OLED 

OLED

monolithic

2Tr-1C

pixel driver



3.5' OLED using TAOS-FET Backplane

Table 1 Specification of OLED panel driven by IGZO TFTs

Display size	3.5 inch diagonal
Resolution	176 (x 3) x 220
Display device	Top emission OLED
TFT	IGZO (W/L=10 μm /20 μm)

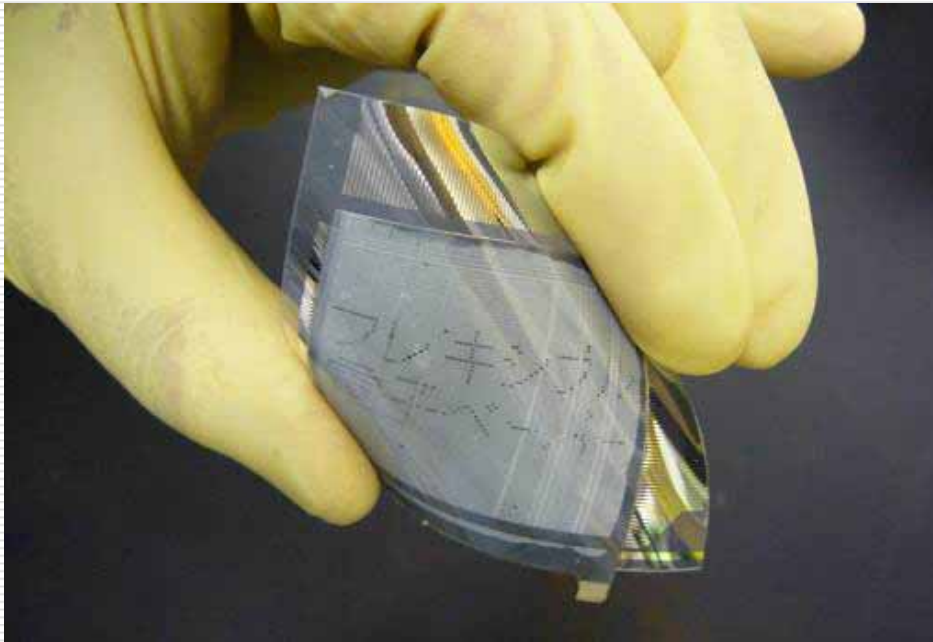


Fig. 8 Operation image of AM-OLED driven by IGZO TFTs

Gate insulator;
 Si_3N_4

LG (IDW '06)

Images of Flexible Electrophoretic Displays Driven with a-IGZO TFT Array



Thickness : 320 μm
Weight : 1.3 g



Electrophoretic imaging film supplied by  **E·INK**

Toward New Continent of Transparent Oxide Electronics



Flexible displays

