Organic Field-Effect Transistors and Electronics

Professor Jerzy Kanicki, Patrick B. Shea, and Hojin Lee
Organic & Molecular Electronics
Solid-State Electronics Laboratory
University of Michigan - Ann Arbor
http://www.eecs.umich.edu/omelab

Contributions from:

MERCK
I. McCulloch

COVION Avecia
J. Veres

MITSUBISHI CHEMICAL
S. Aramaki

MOCIE ADRC
J. Jang

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H. Sirringhaus

UCSB
A. Heeger, P. Petroff, L. Kinder, and J. Swensen

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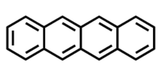
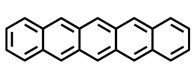
Content

Introduction: Small Molecule Organic Semiconductors

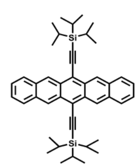
- **Polycrystalline films, crystals on micrometer scale.**
- **Charge densities confined to either a single molecule, or a group of molecules.**
- **Charge transport characterized by phonon-assisted hopping/tunneling.**
- **Examples:**



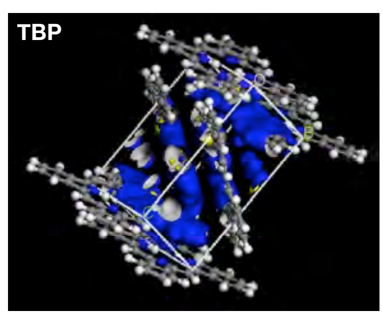
Tetracene

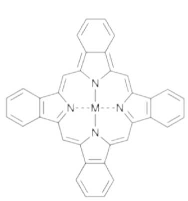


Pentacene



TIPS Pentacene



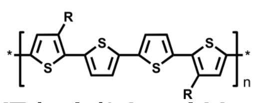


Metallotetrabenzoporphyrin (MTBP)

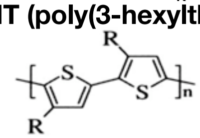
Introduction: Polymer Organic Semiconductors

- Amorphous films, or polycrystalline on a submicrometer scale.
- Charge densities confined to either a single polymer, or a group of polymers chains.
- Charge transport characterized by phonon-assisted hopping/tunneling.
- Examples:

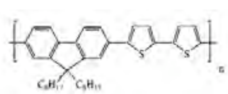
PQT-12 (poly(3,3"-dialkylquarterthiophene)

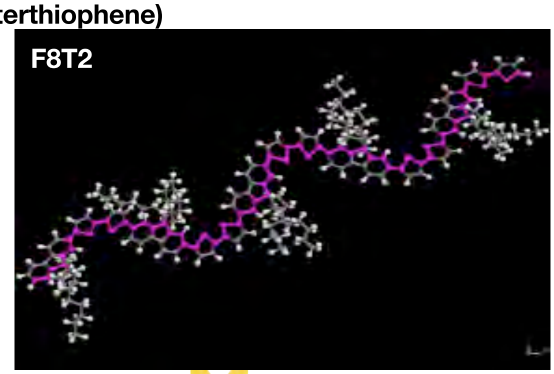


P3HT (poly(3-hexylthiophene)



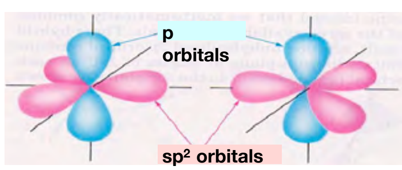
F8T2 – (dioctylfluorene co-bithiophene)



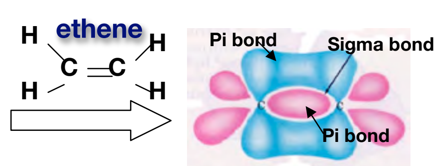


Introduction: Why Conjugated Molecules Can Be Semiconductors

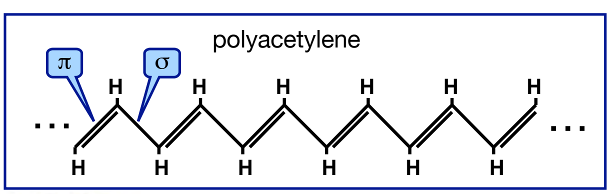
- Atomic orbitals (s, p_x and p_y) hybridize to form hybrid orbitals (sp^2) and p_z.
- Overlap of atomic p_z orbitals form a π–electron system…delocalized along molecule.
- Molecular orbitals interact via weak van der Waal forces to form narrow transport bands at the Highest Occupied and Lowest Unoccupied Molecular Orbital energy levels as well as a HOMO-LUMO energy gap.

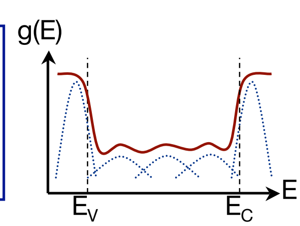


sp^2 carbon + sp^2 carbon



C-C double bond/π-bond



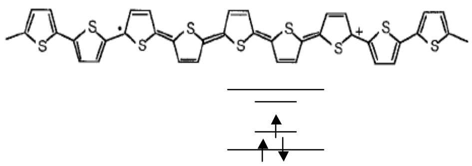


Introduction: Charge Transport In Organic Molecules

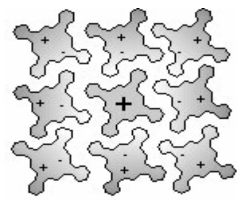
Polarons

- Carrier lowers energy by distorting lattice
- Strong charge-lattice interaction leads to self-localization
- Polarons, which appear as midgap states, decrease mobility
  - Levels have been demonstrated by UV-vis spectroscopy

p-type polaron in polythiophene



Energy band



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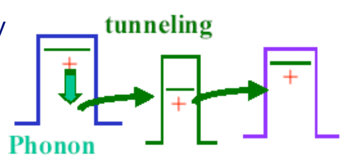
Introduction: Charge Transport In Organic Molecules

Phonon-Assisted Tunneling/ Hopping Transport

- Charge transport occurs through a hopping mechanism
  - –Phonons help e⁻'s hop, therefore increasing mobility
  - –μ ↓ as T ↑ for low temp crystals
  - –μ ↑ as T ↑ for RT crystals and disordered systems
  - –Boundary between 0.1 and 1cm²/V-s



$$W_{ij} = \nu_0 \exp(-2\Gamma R_{ij}) \begin{cases} \exp\left(-\dfrac{\varepsilon_i - \varepsilon_j}{k_B T}\right) & \varepsilon_i > \varepsilon_j \\ 1 & \varepsilon_i < \varepsilon_j \end{cases}$$

Tunneling

Phonon frequency

Boltzman factor (phonon absorption)

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Introduction: Organic Semiconductor Band Picture

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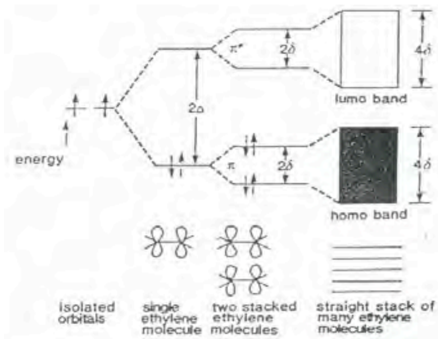

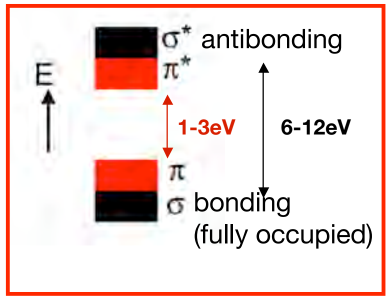

- π electrons are:
  - Delocalized and most easily excited
- π - π* transitions equivalent to energy bandgap
- π-bond interactions (p_z orbital overlap) between molecules are critical in organic solid-state electronic devices.

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Introduction: Example Organic Energy Band Diagram

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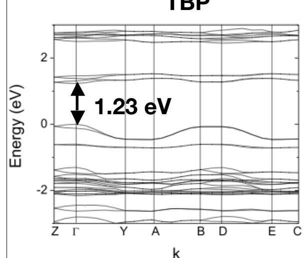
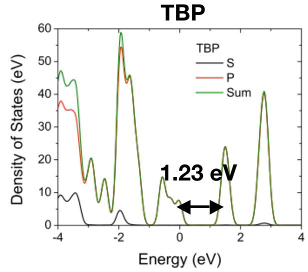
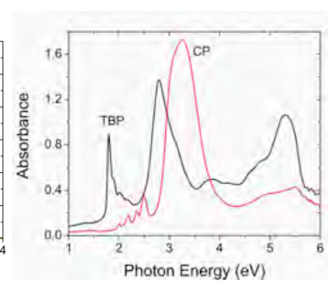
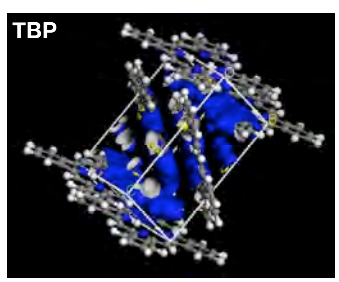






- Flat bandstructure
- Gaussian-shaped bands with narrow bandwidth
- Narrow absorption spectra



- TBP: Tetrabenzoporphyrin

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Thin-Film Transistor Structures

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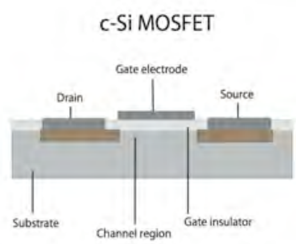
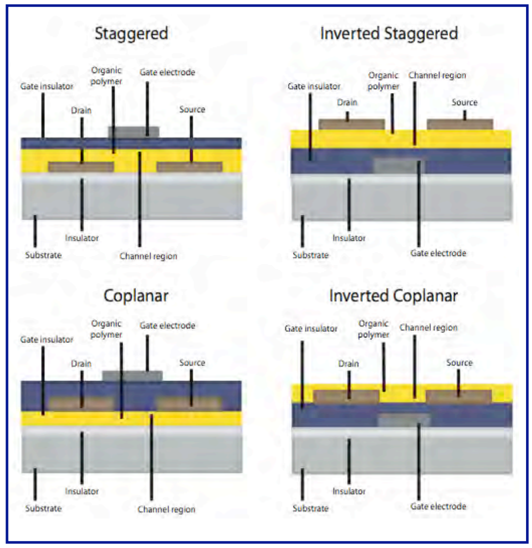
TFT = FET with a thin film as the active layer (as opposed to device built from bulk).

Fabrication advantages:
- deposited active layer
- wide range of substrates

Various TFT structures



vs.



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Example Device Structure

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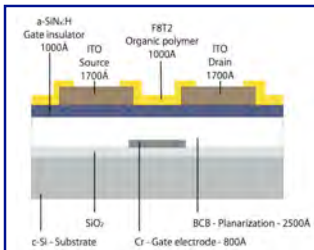
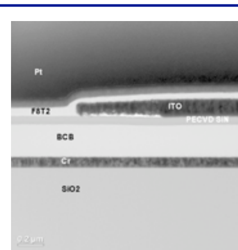
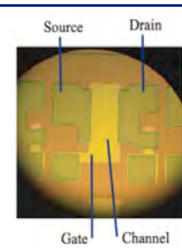
- **Patterned gate electrode (Cr) on Si/SiO_2 carrier substrate.**
- **Benzocyclobutene (BCB, organic) gate planarization/insulator layer.**
- **Amorphous, hydrogenated silicon nitride (a-SiN_x:H) gate insulator.**
- **Indium tin oxide (ITO) source and drain electrodes.**
- **F8T2 active layer (solution deposited, unpatterned).**
- **Typically, 56µm < W < 116µm and 6µm < L <56µm.**







* S. Martin, J. Y. Nahm and J. Kanicki, "Gate-planarized organic polymer thin-film transistors," *Journal of Electronic Materials*, vol. **31**, pp. 512-519, 2002.

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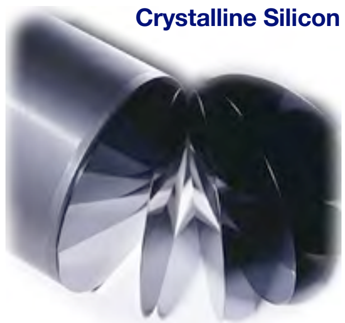
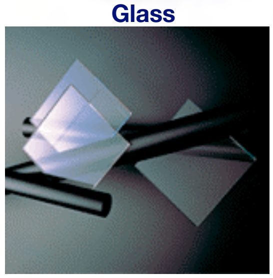
Examples of Rigid and Flexible Substrates

Crystalline Silicon



Glass



	Appear™	Teonex®	OPS
Thermal Properties			
Tg	330°C	121°C	330°C
Tm	360°C	269°C	330°C
CTE	74		
Optical Properties			
Transmission	91.6%	82.0%	93%
Haze		14.0%	0.40%
Refractive Index	1.52	1.76	1.47
Retardation (100μm-thick film)	< 10nm		< 10nm

- Appear™ by *Ferrania Imaging Technologies*
- Teonex® by *Dupont Teijin film*
- OPS by *Tosoh Corp*

Appear™ substrate appears to be suitable for organic electronics.

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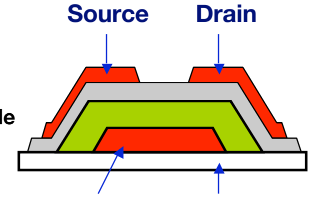
Source, Drain, and Gate Electrodes

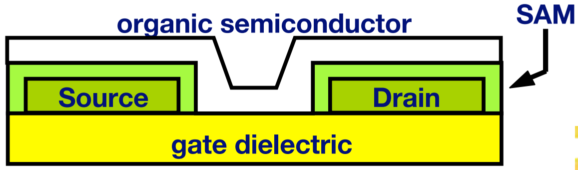
Metals:
- Au, Al, Ag, Cr, and heavily doped Si

Metal Conductive Oxides:
- Indium Tin Oxide (ITO), Aluminum-doped Zinc Oxide (AZO)

Conductive Organic Molecules:
- Polyaniline (PANI), Polyaniline/Nanotube (PANI/NT), poly(3,4-ethylenedioxythiophene)-poly(stryenesulfonate) (PEDOT-PSS)

To be considered:
- Work function matching with organic semiconductor
- Resistance to oxidation
- Processing compatibility and adhesion
- S/D modification by self-assembled monolayer (SAM)
- High conductivity





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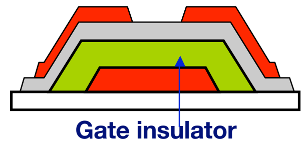
Gate Insulator Dielectrics



Inorganic
- SiO_2 — ϵ=3.9
- Al_2O_3 — 11.5
- SiN_x — 7
- TaO_5 — 11.6
- TiO_2 — 41
- $Ba_{0.7}Sr_{0.3}TiO_3$ — 16

C. Dimitrakopoulos *et al*., *Adv. Mater*., 11, 1372, 1999.

Organic

Polyimides (PI)	ϵ=3.4	Kato, *et al*., *Appl. Phys. Lett*. 2004, *84*, 3789
Poly(4-vinyl phenyl) (PVP)	4.5	Veres *et al*, *Chem. Mat.*2004, *16,* 4543
Poly(vinyl alcohol) (PVA)	7	
Polymethyl Methacrylate (PMMA)	3.5	Veres, *et al*, *Chem. Mat.*2004, *16,* 4543
Polypropylene	1.5	Veres, *et al*., *Chem. Mat.*2004, *16,* 4543
Silsesquioxane polymers		Z. Bao *et al*., *Adv. Func. Mat.* 2002, *12*, 526
Ferroelectric Polymers		Schroeder *et al., Adv. Mater*. 2004, *16*, 633.
Benzocyclobutene (BCB)		Unni *et al*., *Appl. Phys. Lett*. 2004, *85*, 1823.
Merck TCI-01		

Organic/Inorganic Composites

To be considered:
- Processing compatibility and adhesion
- Different devices must be compared with normalized gate capacitance.
- Low cost processing
- Electrical properties

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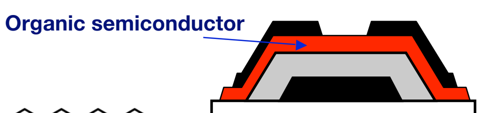
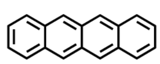
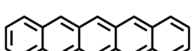
Organic Semiconductors

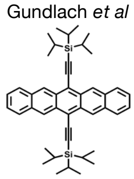




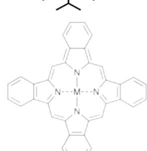
Tetracene: μ= 0.1 cm^2/Vs; ON/OFF: 10^6; V_t= -3V to -5V
Gundlach *et al Appl. Phys. Lett*. **2002**, *80*, 2925.



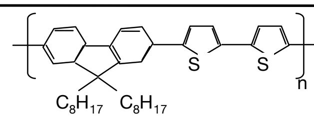
Pentacene: μ= 1.2 cm^2/Vs; ON/OFF: >10^8; V_t=~-5V
Gundlach *et al IEEE Elec. Dev. Lett.* **1997** *18,* 87



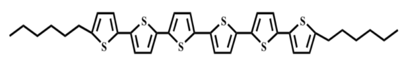
TIPS Pentacene:
μ= 0.4 cm^2/Vs; on/off: 10^6
Sheraw et al, *Adv. Mat.* **2003** *15,* 2009



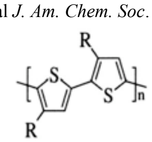
Metallotetrabenzoporphyrin:
μ> 0.1 cm^2/Vs; on/off: 10^5 ; V_T~0 V
Aramaki *et al., Appl. Phys. Lett*., **2004** *84*, 2085.



F8T2: μ= 4x10^{-3} cm^2/Vs; on/off: 10^5
S. Martin, *et al., J. of SID,* **11**, 543 (2003).



Sexithiophene: μ= 0.05 cm^2/V-s
Garnier et al *J. Am. Chem. Soc*. **1993**, *115*, 8716



P3HT*:* μ= 0.1 cm^2/Vs; on/off: 10^5
Z. Bao, et al, Appl. Phys. Lett. 69, *4108 (1996).*

F8T2: poly(9,9-dioctylfluorene-co-bithiophene)
P3HT: poly(3-hexylthiophene)

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Future Organic Semiconductors

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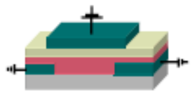
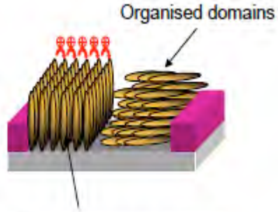
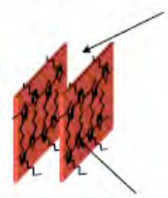


-High field-effect mobility
-Low threshold voltage and subthreshold slope
-High ON/OFF ratio and low OFF-current
-Free of charge traps and other defects
-Environmental, electrical and thermal stability
-Low cost processing

Strategies to increase charge carrier mobility

Control of Morphology





Crystalline organic semiconductors with well-defined structure, morphology, and chemical composition are desired!

Control of Chemical Structure and Impurities

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Gate Insulator Surface Treatment: SiO_2 and Organics

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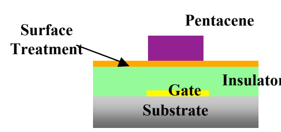
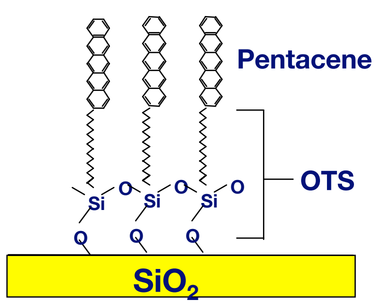
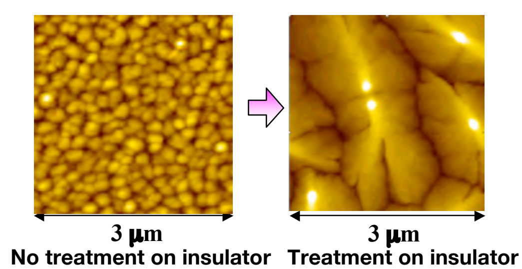
- Self assembling monolayers widely used
  - Promote adhesion
  - Improve uniformity of films
  - Improve device performance, e.g, mobility.
  - Increase grain size



- Examples
  - Hexamethyldisilazane (HMDS)
  - Octadecyltrichloro-silane (OTS) Gundlach et al, *SPIE,* **2001**, *4466,* 54
  - 7-octenyltrichlorosilane (VTS) Salleo et al, *Appl. Phys. Lett.,* **2002**, *81,* 4383
  - Benzyltrichlorosilane (BTS) Salleo et al, *Appl. Phys. Lett.,* **2002**, *81,* 4383
  - Alkanephosphonic acid Kelley et al, *J. Phys. Chem. B*, **2003**, *107,* 5877
  - Cinnamic acid Swiggers et al, *Appl. Phys. Lett.,* **2001**, *79,* 1300





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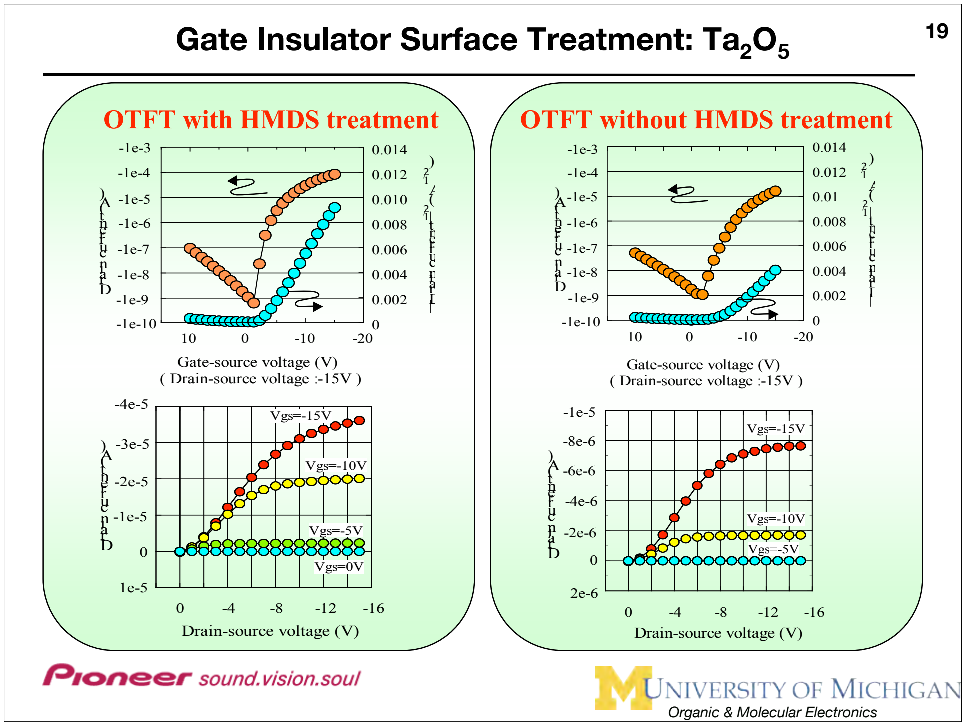
Gate Insulator Surface Treatment: Ta2O5
19
OTFT with HMDS treatment
OTFT without HMDS treatment
Gate-source voltage (V)
(Drain-source voltage :-15V)
Drain-source voltage (V)
Vgs=-15V
Vgs=-10V
Vgs=-5V
Vgs=0V
Pioneer sound.vision.soul
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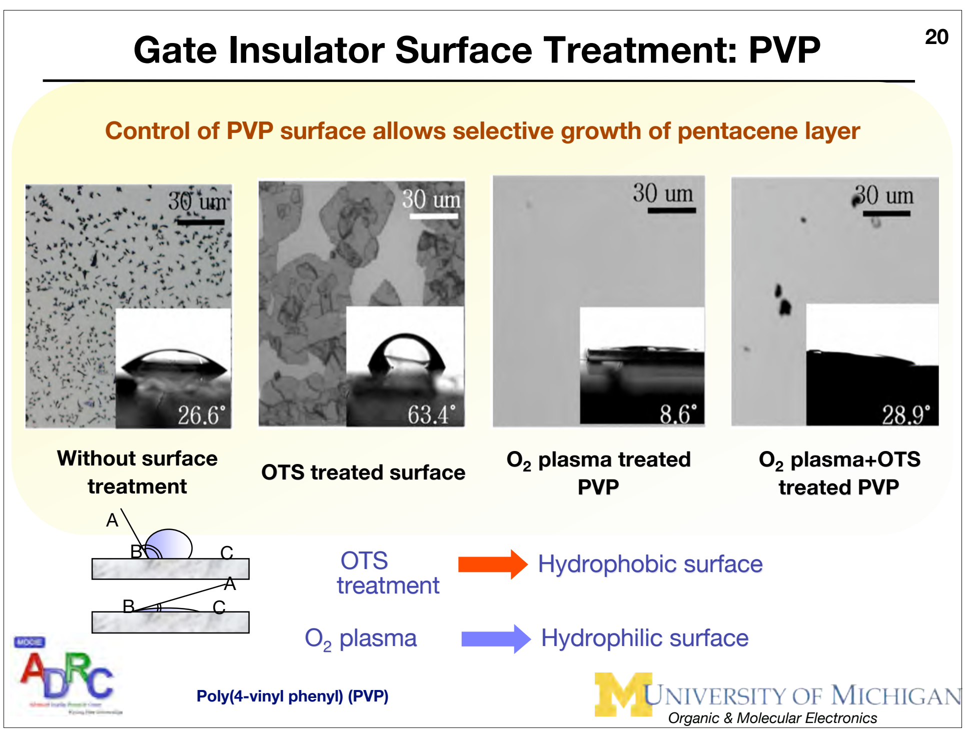
Gate Insulator Surface Treatment: PVP
20
Control of PVP surface allows selective growth of pentacene layer
30 um
26.6°
63.4°
8.6°
28.9°
Without surface treatment
OTS treated surface
O2 plasma treated PVP
O2 plasma+OTS treated PVP
OTS treatment
Hydrophobic surface
O2 plasma
Hydrophilic surface
Poly(4-vinyl phenyl) (PVP)
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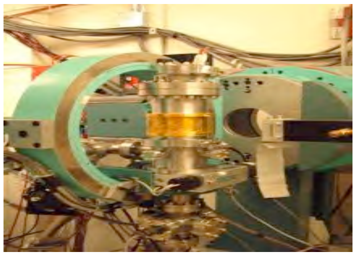
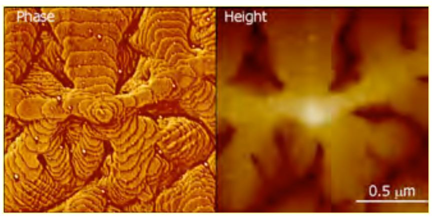
Semiconductor Deposition Methods - Vacuum Evaporation

21





- **- Vacuum evaporation from a solid**
  - Solid, usually powder, form is heated under vacuum to evaporate or sublimate, and then condenses onto a target substrate.
- **Advantages**
  - Highly crystalline films
  - Precise control on film thickness
  - Allows for In Situ study of film growth
- **Drawbacks**
  - Relatively expensive for large-area films, and requires a vacuum chamber.
  - Slow growth rate typically required to produce large crystals.

Important Issues
  - Chemical stability
  - Impurities
  - Island definition
  - High resistivity

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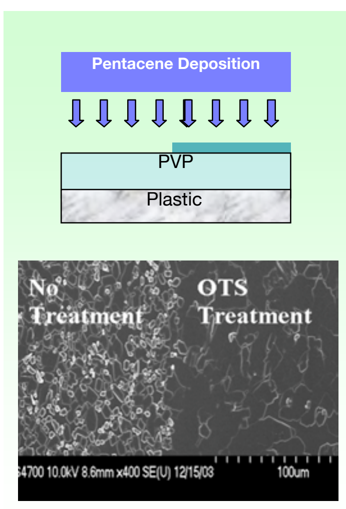
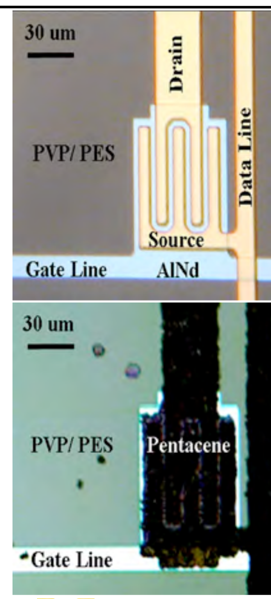
Semiconductor Deposition Method - Selective Growth

22





ADRC

J. Jang *et al*., *Adv. Mat.*, 2004.

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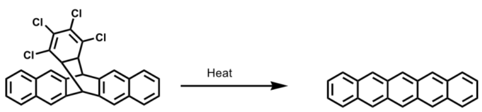
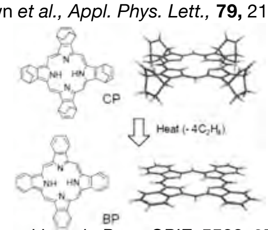
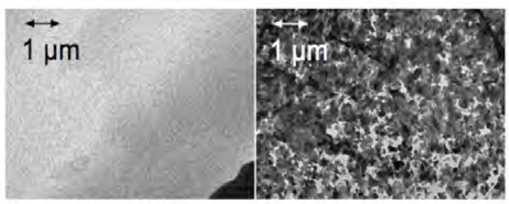
Semiconductor Deposition Methods - Precursor Solutions



A.R. Brown *et al., Appl. Phys. Lett.,* **79,** 2136-2138.



S. Aramaki *et al., Proc. SPIE,* **5522,** 27-35.



Amorphous CP Polycrystalline TBP

- Functionalized precursor forms of a molecule can be used to allow solution-processing.
- Application of heat in an inert atmosphere removes unstable part of molecule, and leaves polycrystalline thin-film.
- Spin-, Dip-, and Drop-casting possible.
- Printing allows for precise control of active material.

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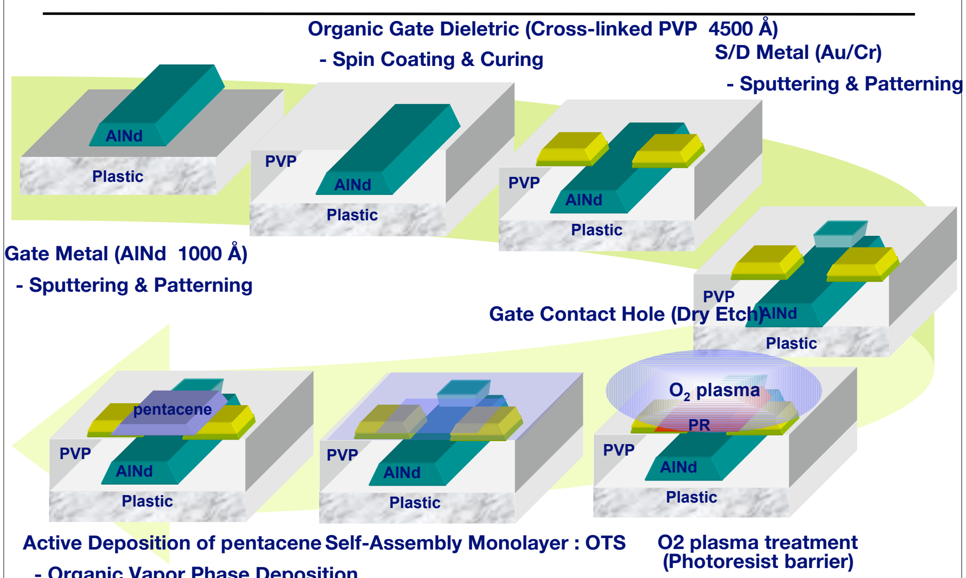
Device Fabrication: Evaporated Pentacene OFET



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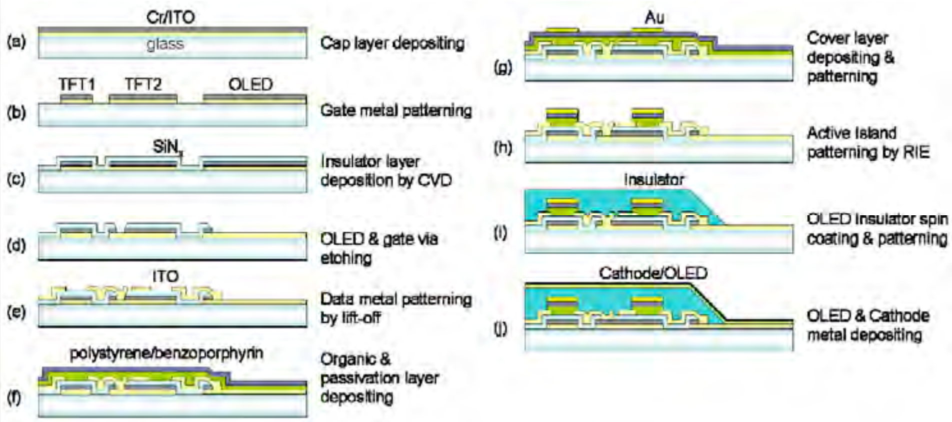
Device Fabrication: Solution-Processable OFET-based Display

25



S. Aramaki *et al., SID 2006*, L-3, 2006.

MITSUBISHI CHEMICAL

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Device Fabrication: High Resolution Patterning Methods

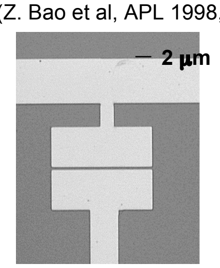
26

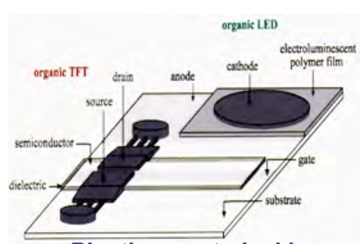
Screen printing

Z. Bao et al. *Chem. Mater.* 9, 1299 (1997)
R. Service, *Science*, 278, 383 (1997)

First all-printed plastic circuit

Soft lithography (Z. Bao et al, APL 1998, Adv. Mater. 2000, J. Mater. Chem. 1999)





Microcontact printed Au electrodes

Plastic smart pixel by molding and casting

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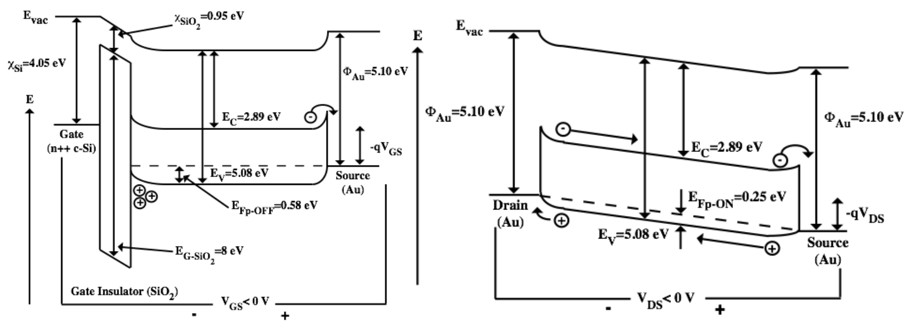
Introduction: Example OFET Bands Diagram

Gate-Source **Drain-Source**



Fermi energy level determined by measuring the thermal activation energy of I_D at varying V_{GS}.

P. B. Shea, A. R. Johnson, N. Ono, and J. Kanicki, "Electrical Properties of Staggered Electrode, Solution-Processed, Polycrystalline Tetrabenzoporphyrin Field-Effect Transistors," *IEEE Trans. Electron Devices*, vol. 52, pp. 1497-1503, 2005.

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OFET Physics - Equations

Gradual channel approximation … MOSFET square-law theory:

Linear regime ($V_{GS} > V_T$, $V_{DS} < V_{GS}$) for low V_{DS}:

$$I_D = -\mu_{FE} C_{ins} \frac{W}{L}(V_{GS} - V_T)V_{DS} \quad \begin{cases} I_D = -\mu_{0lin} C_{ins} \dfrac{W}{L}\left(V_{GS} - V_{T\,lin}\right)^{\gamma} V_{DS} \\ \mu_{FE\,lin} = \mu_{0lin}\left(V_{GS} - V_{T\,lin}\right)^{\gamma-1} \end{cases}$$

Saturation regime ($V_{GS} > V_T$, $V_{DS} = V_{GS} - V_T$):

$$I_D = -\mu_{FE} C_{ins} \frac{W}{2L}(V_{GS} - V_T)^2 \quad \begin{cases} I_D = -\mu_{0sat} C_{ins} \dfrac{W}{(\gamma+1)L}(V_{GS} - V_{T\,sat})^{\gamma+1} \\ \mu_{FE\,sat} = \mu_{0sat}\left(V_{GS} - V_{T\,sat}\right)^{\gamma-1} \end{cases}$$

Where γ is an exponent added to account for nonlinear curves.

M. C. Hamilton *et al, Chem. Mater.* **16**, 4699 (2004).

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OFET Electrical Characterization Methods

Critical issues in FET electrical characterization:

- **Ensure device reaches (quasi?) steady state (esp. at low $|V_{GS}|$)**
- **Limit aging (stress) during measurement (esp. at high $|V_{GS}|$)**
- **Limit noise (low drain currents, high gate leakage currents)**
- **Reproducibility**

Transfer characteristics (I_D-V_{GS}):

Selected procedures:
- **direction: depletion → accumulation → depletion**
- **sweep (gradually increase/decrease $|V_G|$)**

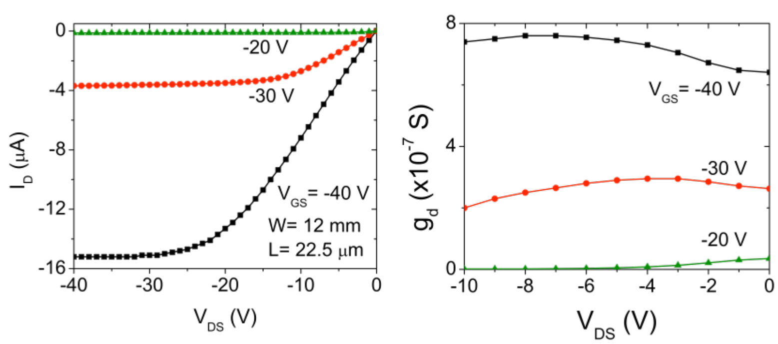
OR:
- **pulse sweep (increase/decrease $|V_G|$ in pulses that return to zero with low duty cycle (<50%))**

Output characteristics (I_D-V_{DS}):

Selected procedure:
- **direction: OFF (low $|V_{DS}|$) → ON (high $|V_{DS}|$)**
- **sweep (gradually increase $|V_{DS}|$)**

IEEE Standard 1620

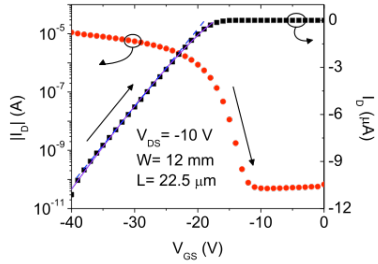
Example OFET Output Characteristics

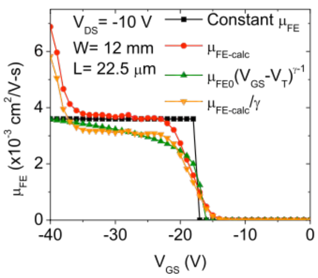


- **TBP OFETs demonstrate distinct linear and saturation regimes.**
- **Low gate leakage current as demonstrated by no offset in I_D at low V_{DS}.**
- **Conductance (dI_D/dV_{DS}) indicates small amount of current crowding.**

P. B. Shea *et al.*, *IEEE Trans. Electron Devices*, vol. 52, pp. 1497-1503, 2005.

Example OFET Transfer Characteristics - Linear Regime





$$I_{D-Linear} = -\frac{W}{L}\mu_{FE}C_i(V_{GS}-V_T)V_{DS}$$

$$\rightarrow \mu_{FE}^{Lin} = \text{constant}$$

$$\rightarrow \mu_{FE-calc}^{Lin} = \frac{dI_D}{dV_{GS}} \times \frac{L}{WC_iV_{DS}}$$

$$I_{D-Linear} = -\frac{W}{L}\mu_{FE0}^{Lin}C_i(V_{GS}-V_T)^{\gamma}V_{DS}$$

$$\rightarrow \mu_{FE}^{Lin} = \mu_{FE0}^{Lin}(V_{GS}-V_T)^{\gamma-1}$$

- **Dispersive charge transport induces a V_{GS}-dependent field-effect mobility; resulting nonlinear I_D-V_{GS} accounted for by introducing exponent to the current-voltage equations.**
- **TBP OFETs display a small nonlinearity compared to polymer OFETs:**
  - **γ=1.2, μ_{FE0}=0.002 cm$^{\gamma}$/V-s, V_T=-17.0 V.**
- **$I_{ON}/I_{OFF} > 10^5$**

P. B. Shea *et al.*, *J. Appl. Phys.*, vol. 98, 014503, 2005.

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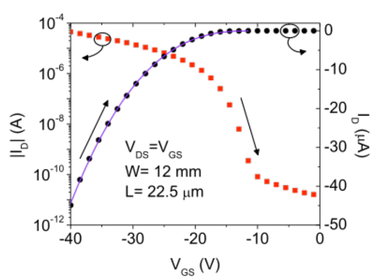
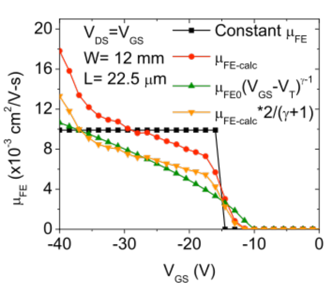
Example TBP OFET Transfer Characteristics - Saturation





$$I_{D-Saturation} = \frac{W}{2L}\mu_{FE}C_i(V_{GS}-V_T)^2$$

$$\rightarrow \text{constant}$$

$$\rightarrow \left(\frac{d\sqrt{|I_D|}}{dV_{GS}}\right)^2 \times \frac{2L}{WC_i}$$

$$I_{D-Saturation} = -\frac{W}{(\gamma+1)L}\mu_{FE0}^{Sat}C_i(V_{GS}-V_T)^{\gamma+1}$$

$$\rightarrow \mu_{FE}^{Sat} = \mu_{FE0}^{Sat}(V_{GS}-V_T)^{\gamma-1}$$

- **Dispersive charge transport induces a V_{GS}-dependent field-effect mobility; resulting nonlinear I_D-V_{GS} accounted for by introducing exponent to the current-voltage equations.**
- **TBP OFETs display a small nonlinearity compared to polymer OFETs:**
  - **γ=1.7, μ_{FE0}=0.0011 cm$^{\gamma}$/V-s, V_T=-10.8 V.**

P. B. Shea *et al.*, *J. Appl. Phys.*, vol. 98, 014503, 2005.

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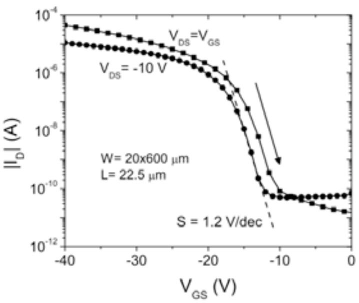
Example Subthreshold Behavior and Trap Densities



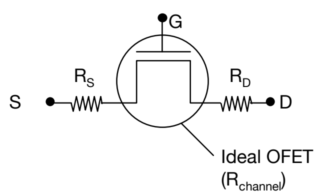
$$S = \frac{kT}{q\log(e)}\left[1 + C_i(\sqrt{\varepsilon_s N_{bs}} + qN_{ss}\right]$$

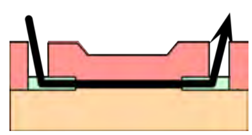
$$\sigma_t = \frac{C_i V_T^{Lin}}{q}$$

- **Best S=1.2 V/decade in the linear regime.**
- **V_T between -20 V and 0 V depending on sweep direction.**
- **Measured ε_s=3.76 (by ellipsometry)**
- **$N_{ss\text{-}max}$=2.9x10^{12} cm^{-2}eV^{-1}, $N_{bs\text{-}max}$=4.10x10^{18} cm^{-3}eV^{-1}.**
- **For V_T=-17 V, σ_t=2.6x10^{12} cm^{-2}. For a 120-nm thick film, N_t=2.2x10^{17} cm^{-3}.**
- **Assuming mid-gap trap states, $N_{ss\text{-}max}$xE_T/2≈ σ_t.**
- **Trap densities moderate compared to other organic semiconductors, and constant with energy.**

P. B. Shea *et al.*, *J. Appl. Phys.*, vol. 98, 014503, 2005.

OFET Source Drain Contact Issues



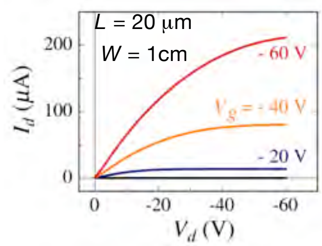


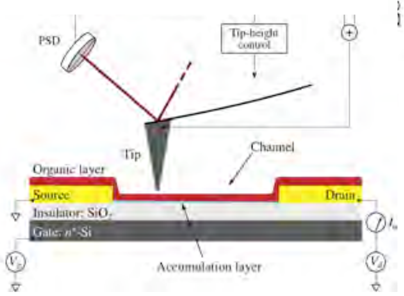
- **Measured (apparent) device field-effect mobility $\mu_{FE\ app}$:**
  - **Conduction channel (intrinsic) field-effect mobility $\mu_{FE\ int}$**
  - **Source / drain series resistances (contacts)**
- **Conduction channel resistance ($R_{channel}$) ∝ channel length (L)**
- **S/D series resistances channel length independent**

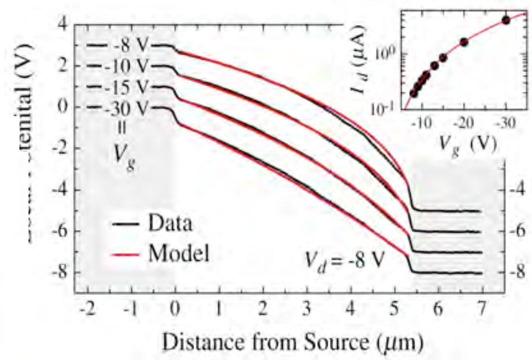
- **Series of OFETs with same characteristics but different L (Transverse Line Method) is measured.**

OFET Source Drain Contact - Potentiometry

35







Potential profiles in good agreement with those predicted by standard inorganic MOS theory.

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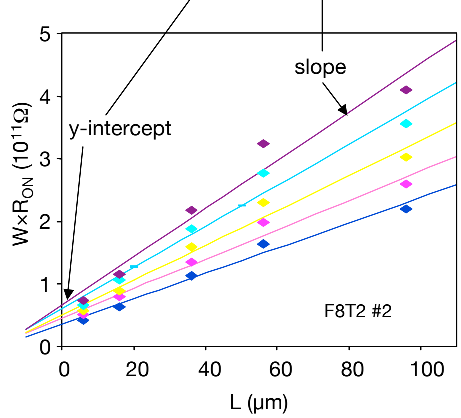
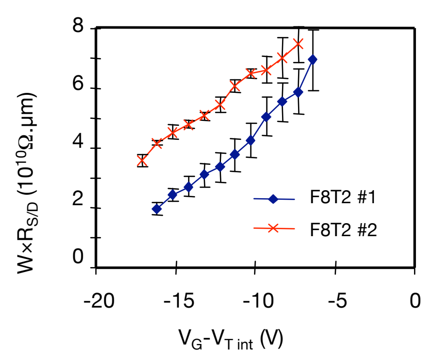
OFET Source Drain Contacts

36

Transverse Line Method (TLM)

$$WR_{ON} = \frac{V_{DS}}{I_{DS}} = WR_{S/D} + WR_{cond\ channel}$$





$R_{S/D}$~10^9Ω for $|V_{GT}|$~10V
(a-Si:H $R_{S/D}$~10^6Ω for $|V_{GT}|$~10V)

S. Martin *et al*, *Mat. Res. Soc. Sym. Proc.* **771**, 163, (2003).

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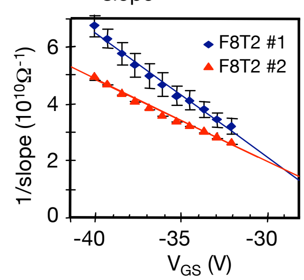
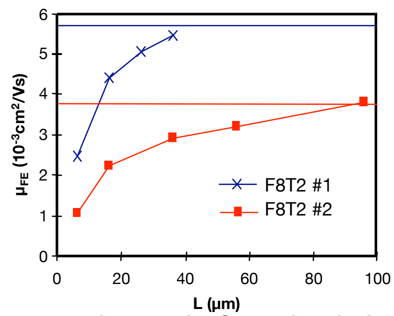
OFET Intrinsic Properties

37

$$WR_{ON} = \frac{V_{DS}}{I_{DS}} = WR_{S/D} + \frac{1}{\mu_{FE\,int} C_{ins} (V_G - V_{T\,int})} \times L$$

slope





	$\mu_{FE\,int}$ (cm²/Vs)	$V_{T\,int}$ (V)
F8T2 #1	5.6×10^{-3}	-24
F8T2 #2	3.8×10^{-3}	-23

- **For many polymers, the OFET electrical performance is limited by the channel conductivity, NOT the series resistances: no channel length dependence of μ_{FE}.**
- **Effect of R_{SD} is expected to become noticeable for high-performance OFETs, i.e. devices with high μ_{FE} or short L.**

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Effect of Gate Insulator Dielectrics

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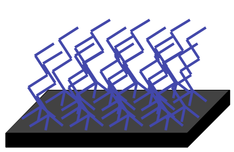
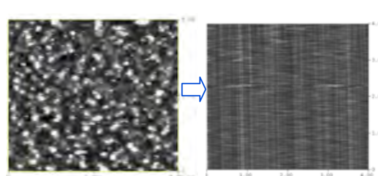
Organic Semiconductor-Insulator interface

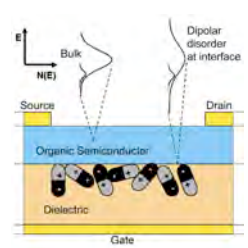
- **Key interface for performance (μ_{FE}, V_T, etc.) and stability (hysteresis)**
- **Improve semiconductor morphology at interface**
- **Reduce dipole disorder at inferface**
- **Methods:**
  - Chemical treatment (SAMs of HMDS, OTS, etc.)
  - Mechanical treatment (rubbing, patterning)
  - Low-k (organic) insulators (PI, PMMA, PVP, PVA, etc.)



SAMs



PI before and after rubbing



Interfacial dipoles

L. Kinder, et al, Proc. SPIE 5217, 35 (2003).
J. Veres, et al, Chem. Mater. 16, 4543 (2004).

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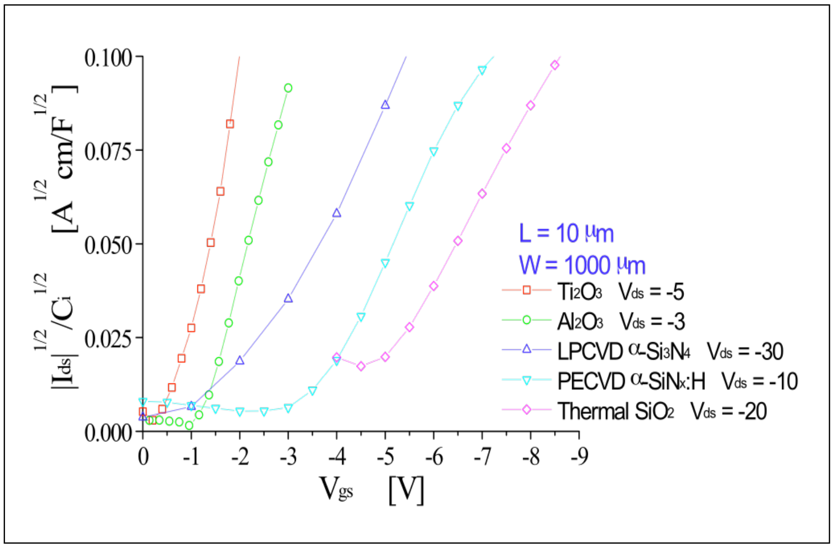
Effect of Gate Insulator on F8T2 OFET Performance

39



J. Swensen *et al*., *Proc. SPIE*, **5217**, 159-166 (2003).

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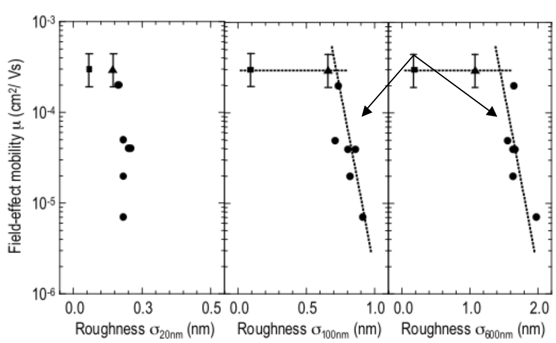
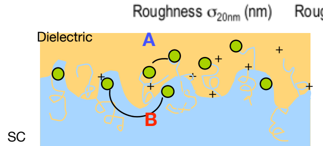
Influence of Interface Roughness

40





- **Clear correlation between mobility and roughness on a 100nm length scale (>> hopping length scale)**
- **Possible explanation: Lateral variations in charge density when roughness comparable to thickness of accumulation layer**

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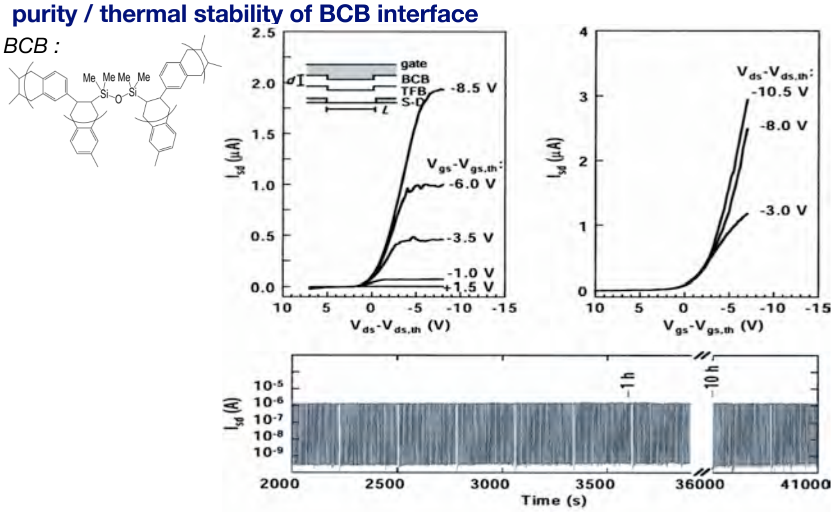
Ultrathin Organic Gate Insulator Dielectric

Leakage current < 10^{-6} A/cm^2 at field of 3MV/cm

Good bias stress stability at elevated temperatures (120˚C) – High purity / thermal stability of BCB interface

BCB :



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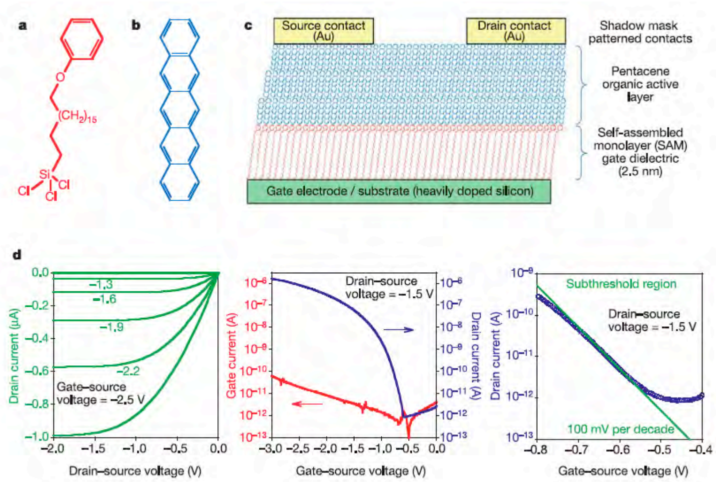
Example Electrical Performance of Pentacene



W/L= 170/130
μ= 1 cm^2/V-s
V_T= -1.3 V
ON/OFF = 10^6

M. Halik *et al., Nature,* **431**, 963-966 (2004).

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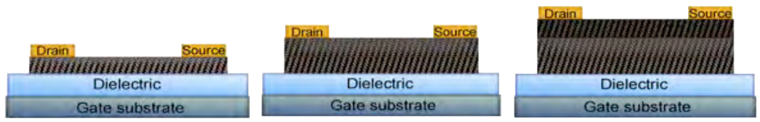
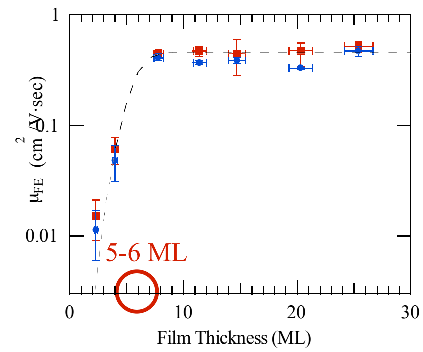
Thickness Dependence of Field-Effect Mobility

43





$$\mu_{FE} = \mu_{sat}\left(1 - Exp\left[-\left(\frac{\theta}{\theta_0}\right)^{\alpha}\right]\right)$$

Also in sexithiophene: F. Dinelli et al., Phys. Rev. Lett. 92, 116802 (2004).
Theory: G. Horowitz, J. Mat. Res. July 2004

Cornell University

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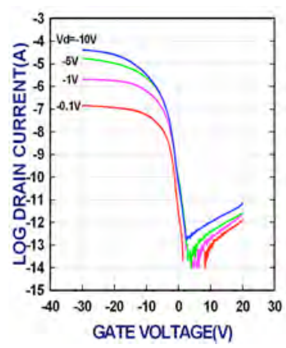
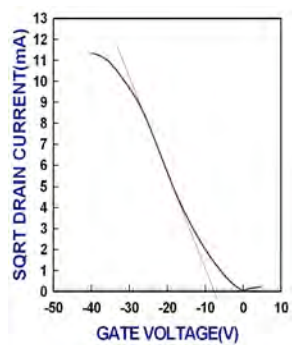
Example Electrical Performance of Selectively Grown Pentacene

44





W / L = 200 µm / 6 µm
μ_{FE} = 1.8 cm²/Vs
V_{th} = - 7.5 V
S = 0.9 V/dec
I_{on} / I_{off} > 10^8

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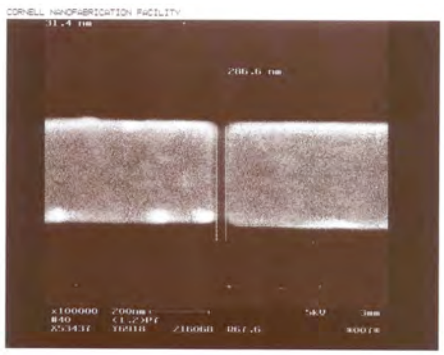
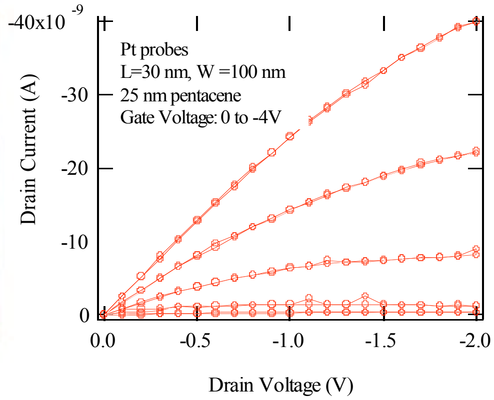
Nanoscale Pentacene OFETs

45





μ=0.01 cm²/V·sec

CNF Cornell Nanofabrication Facility

Cornell University

Only low field-effect mobility was achieved.
Y. Zhang *et. al.*, *Adv. Mater.* 15, 1632 (2003).

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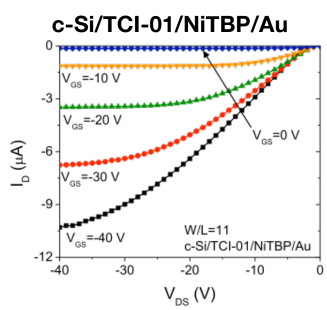
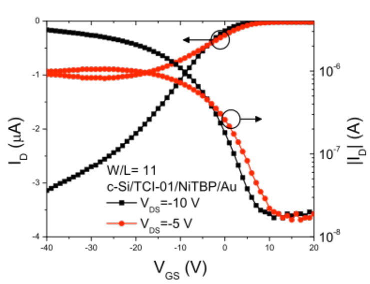
Example NiTBP OFET on TCI-01

46





- **Threshold voltages around 0 V.**
- **I_{OFF} ~ 10 nA.**
- **Large NiTBP crystals form in TCI-01 and PVP.**
- **T_{max}= 165 °C.**
- **μ_{FE}=0.6 cm²/V-s, V_T=0 V, S=7 V/dec, I_{ON}/I_{OFF}=10².**

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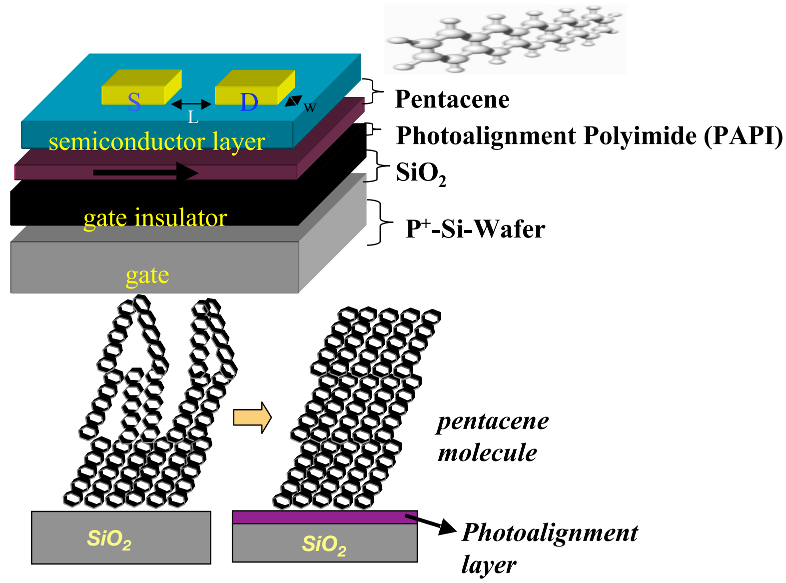
Alignment of Pentacene Molecules Within Channel

47



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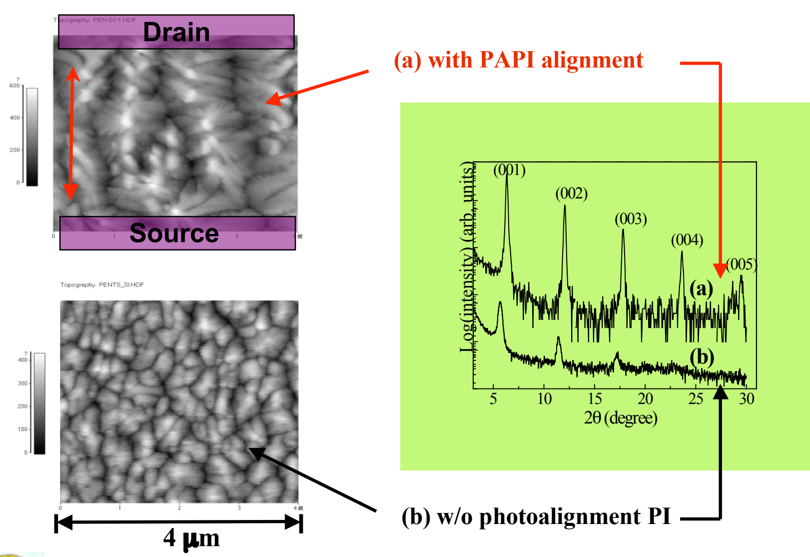
Alignment of Pentacene Molecules Within Channel

48



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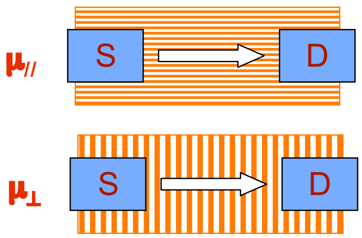
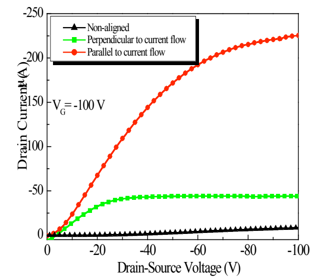
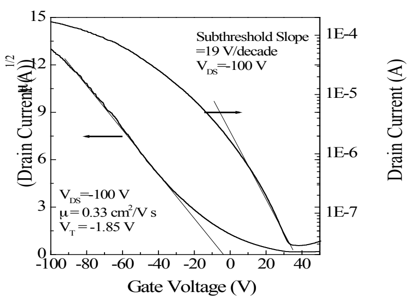
Allignment of Pentacene Molecules Within Channel

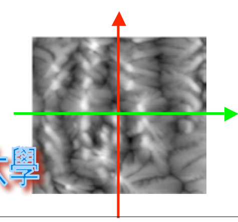




- Anisotropic field effect mobility
  $\mu_{//} / \mu_{\perp} \sim$ 2.7 - 8.3: dichroic effect

(Carriers transport parallel and perpendicular to the alignment direction)





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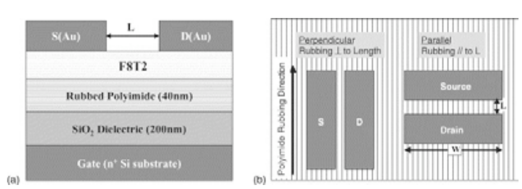
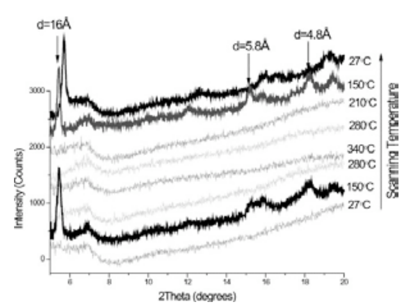
Structural Alignment of F8T2 Films

- Polyimide gate dielectric rubbed preceding F8T2 spin-casting.
- F8T2 films heated above melting temperature, then cooled.
- XRD shows polymer chains align preferentially in direction of rubbing.





L. Kinder *et al., Synth. Met.*, vol. 146, pp. 181-185, 2004.

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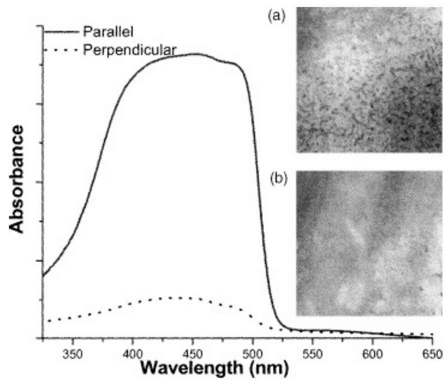
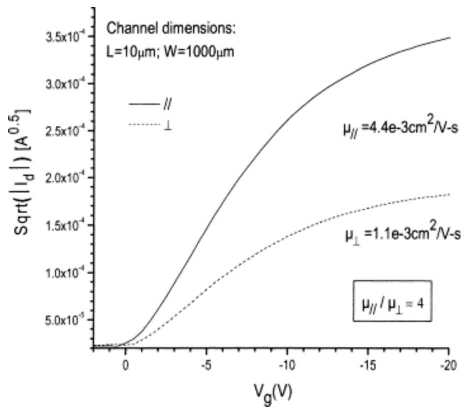
Structural Alignment of F8T2 Films

51

- Optical absorption measurements indicate polarization anisotropy.
- OFET measurements also indicate field-effect mobility anisotropy.





L. Kinder *et al., Synth. Met.*, vol. 146, pp. 181-185, 2004.

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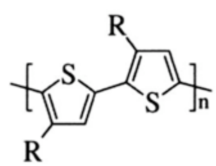
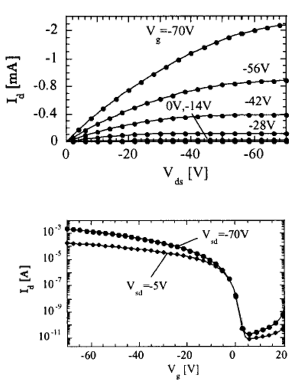
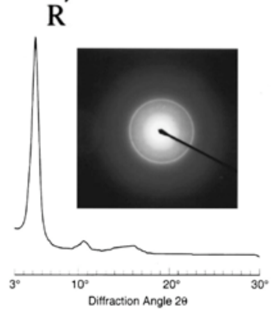
Example Electrical Performance of Polymers

52

P3HT (poly-3-hexylthiophene)/SiO_2







μ=0.1 cm^2/V-s
V_T= ~-5 V
ON/OFF > 10^6

Z. Bao, et al, Appl. Phys. Lett. 69, ***4108 (1996).***
H. Sirringhaus, et al, Synth. Met. 102, ***857 (1999).***

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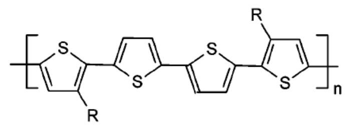
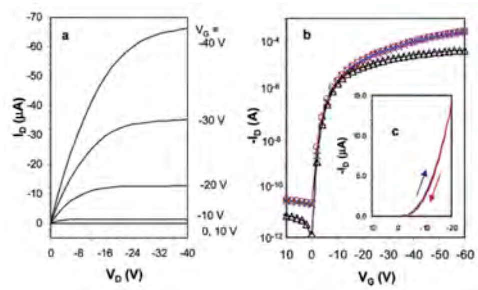
Example Electrical Performance of Polymers

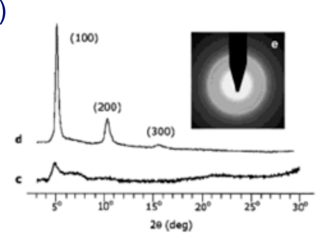
53

PQT-12 (poly-3,3-dialkyl-quaterthiophene)



Crystalline - liquid crystalline and liquid crystalline - isotropic phase changes have been observed (~120° and 140°C respectively)





μ= 0.1 cm^2/Vs
V_T= -5 V
ON/OFF =10^6

B. S. Ong, et al, J. Am. Chem. Soc. ***126****, 3378 (2004).*

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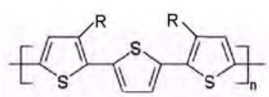
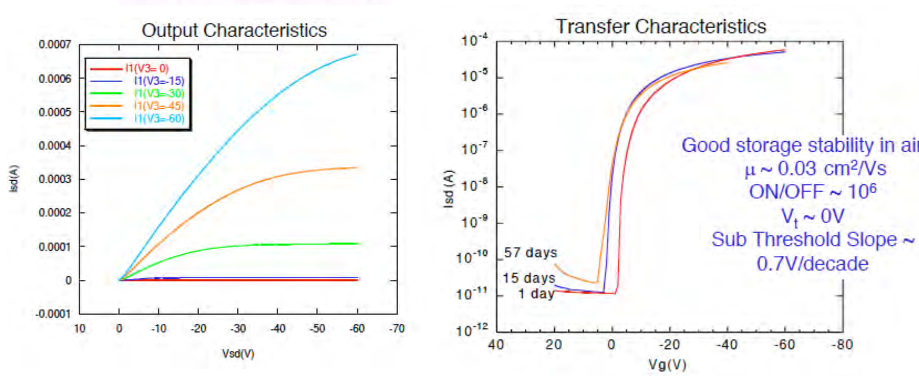
Example Liquid Crystal Polymers

54



Thienothiophene Terthiophene



Good storage stability in air
$\mu \sim 0.03\ cm^2/Vs$
ON/OFF ~ 10^6
$V_t \sim 0V$
Sub Threshold Slope ~ 0.7V/decade

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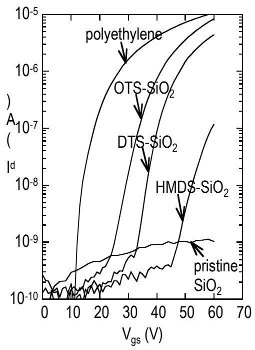
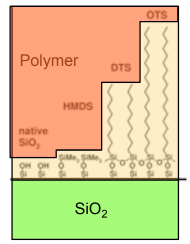
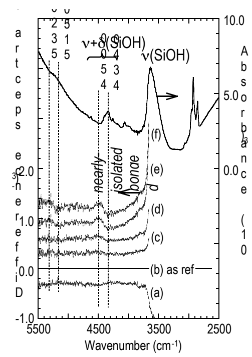
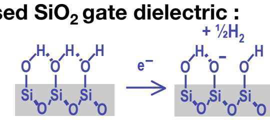
Why has electron transport been so elusive previously ?







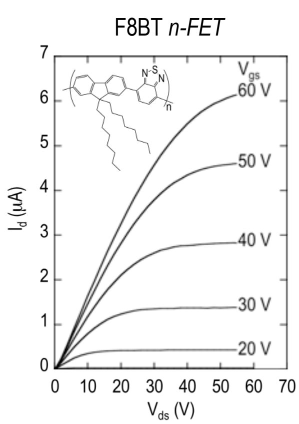
Charge trapping by electron accepting surface groups, such as silanol groups in the case of commonly used SiO_2 gate dielectric :

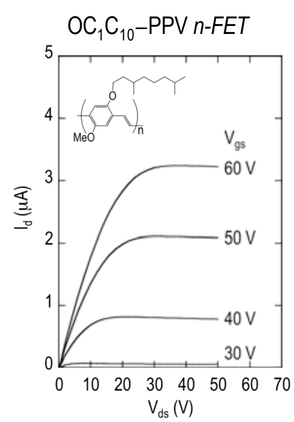


$SiOH + 1e^- \rightarrow SiO^- + ½ H_2$

Interfaces are key, but our understanding of their electronic properties is still rudimentary!

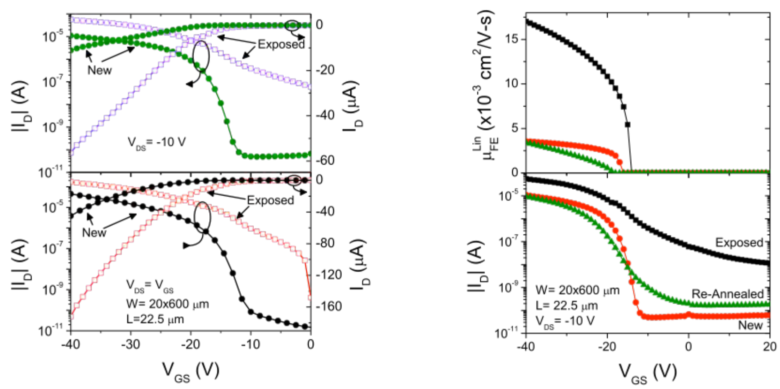
Example n-Type Polymers





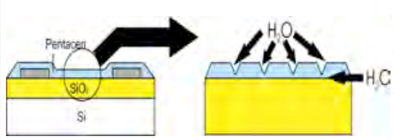
μ_{FE}= 5·10^-3^cm²/Vs **μ_{FE}=2·10^-3^cm²/Vs**

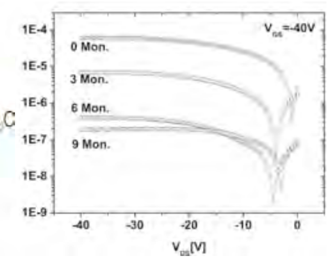
Example TBP OFET Storage Stability



- **Storage in ambient atmosphere leads to significant changes:**
  - **Increase in overall conductivity**
  - **Lower ON/OFF ratio**
  - **Larger subthreshold swing**
- **Thermal annealing in N_2 or vacuum regains most of original performance.**

Example Pentacene OFET Environmental Stability





μ
2.0×10^{-3} cm²/Vs → 1.2×10^{-5} cm²/Vs

V_{th}
4.8V → -8V

$I_{ds\text{-}max}$
-60.9μA → -187nA

Water-damp is incorporated in an electrical field driven reaction:

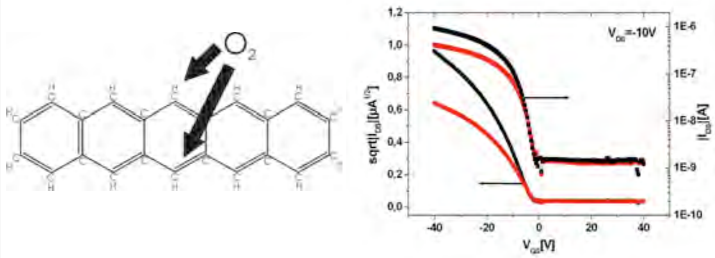
- **At the dielectric interface**
- **At the numerous grain boundaries**

Produces trapping states and polarized pentacene molecules.

J.E. Northrup, M.L. Chabinyc, *Phys. Rev. B*, **68**, 041202 (2003).

Example Pentacene OFET Environmental Stability

59



on/off ratio
~1000 → ~500

V_{th}
-0.7V → 2.2V

$I_{ds\text{-}max}$
-9.3μA → -4.1μA

Oxygen is incorporated to produce:

- **Acceptor-states for electrons**
- **Scattering centers for charge carriers**
- **Disturbance of the conjugation of the double-bonds.**

O.D. Jurchescu *et al*, *Appl. Phys. Lett.*, **84**, pp. 3061-3063 (2004).

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Die Universität der Informationsgesellschaft

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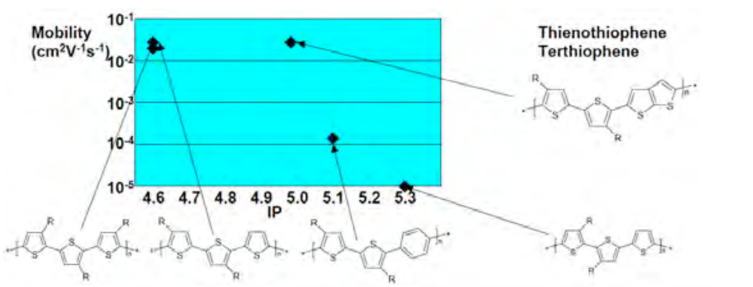
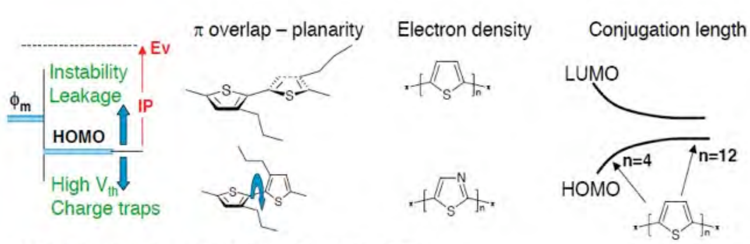
Reduction/Oxidation Stability in Organic Molecules

60





D.M. deLeeuw, et. al, Synth. Metals., 87, 53-59, (1997)

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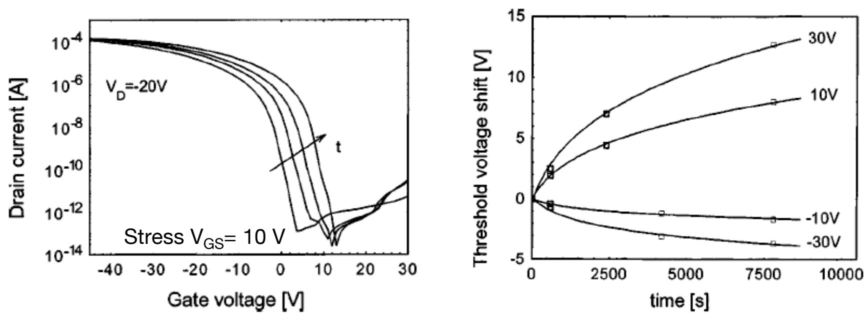
Example Pentacene OFET Electrical Stability

61

- Continuous operation (stressing) of small-molecule devices produces noticeable changes in device performance.
- Stressing pentacene devices with a gate bias for 0, 10, 30, and 90 minutes reveals significant shift in OFET threshold voltage.



D. Knipp *et al., J. Appl. Phys.*, **93,** 347-355.

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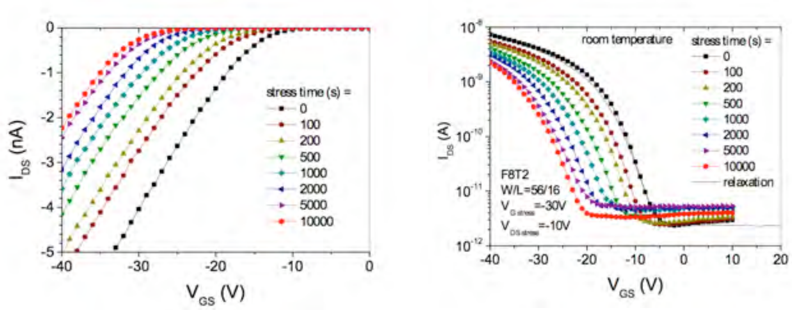
Example F8T2 OFET Electrical Stability

62

Electrical Stability (Instability)

- **Significant threshold voltage shift observed after bias stress (both positive and negative).**
  - Charge carrier trapping in states near organic semiconductor-gate insulator interface.
- **Must be accounted for in display driving circuitry**
  - Design circuits with inherent robustness against threshold voltage shifts.
  - Active-matrix pixel driving schemes set-up to allow recovery of device during down time (when not being addressed).



S. Martin *et al, Proc. of SPIE* **5217**, 7 (2003).

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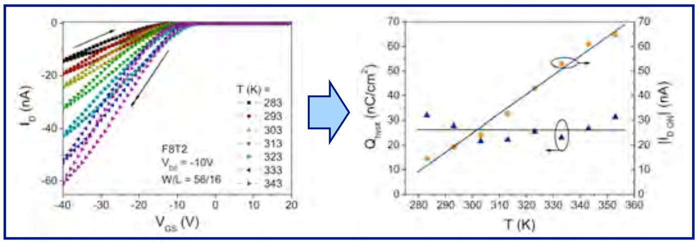
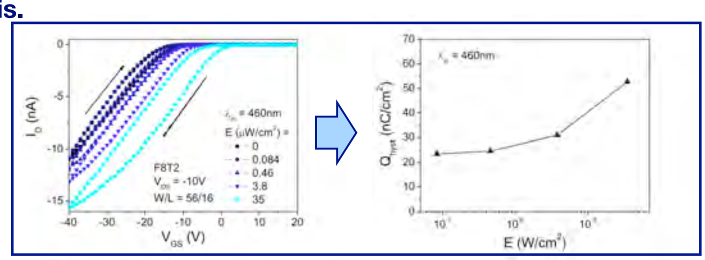
F8T2 OFET Hysteresis

Effect of temperature ➡ increase of carrier mobility ($I_{D\ ON}$) , but not hysteresis.



Effect of monochromatic illumination ➡ increases carrier density & hysteresis.

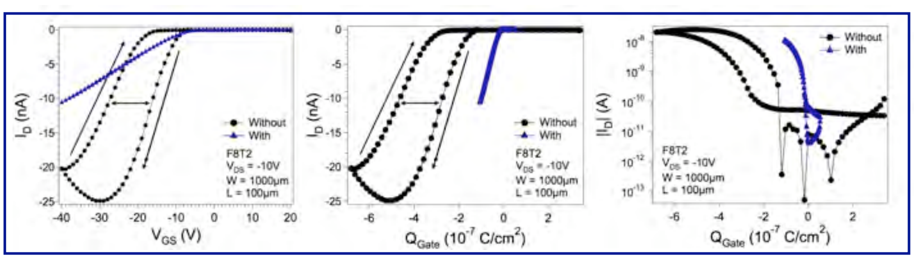


F8T2 OFET Hysteresis

Reduction of hysteresis can be achieved by using an organic insulator.

Device structures used here (fabricated at the same time, same F8T2):

- Unpatterned, heavily-doped Si wafer as gate electrode.
- SiO_2 (without) and SiO_2 + thermally cross-linkable organic insulator (with).
- F8T2 (spin-deposited from solution and cured as usual).
- Au (evaporated through shadow mask).



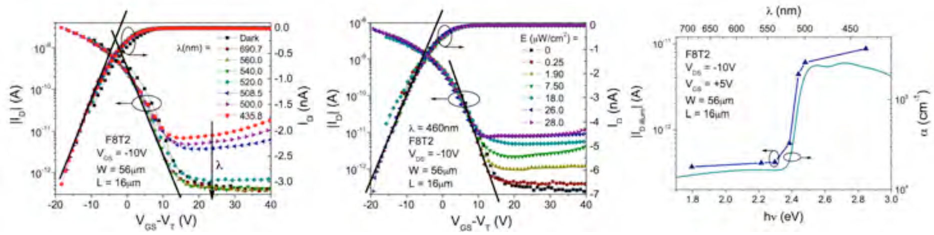
"Significant" gate-leakage current for both, but effect of organic insulator is obvious.

- When normalized for charge (i.e. with capacitance), mobility is same but threshold charge is much smaller, subthreshold slope is much sharper and hysteresis is removed completely.
- Evidence for improved interface (i.e. reduced interface states).

Effects of Illumination: Monochromatic

Monochromatic illumination at different wavelengths

- constant optical flux ~ 1.3×10^{14} photons/cm^2s.
- different irradiances at λ = 460nm.



Minimal response to sub-optical gap illumination (λ > 520nm).

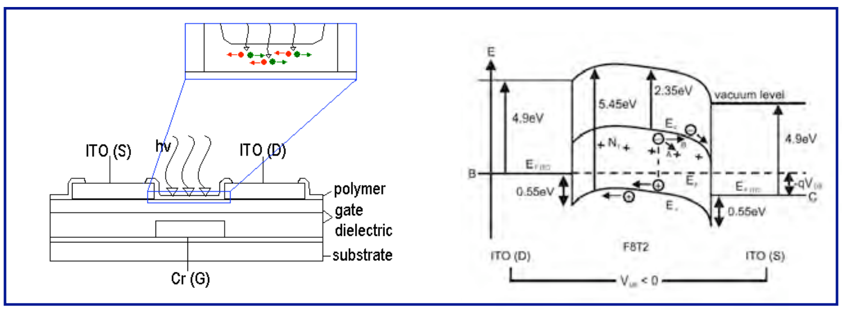
Maximum response to strongly absorbed illumination (peak at ~460nm).

Major effect (again) decrease of V_T, no significant changes in μ_{FE} or S.

Can we describe how I_D depends on irradiance?

* M. C. Hamilton, S. Martin, and J. Kanicki, “Organic Polymer Thin-film Transistor Photosensors,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. **10**, pp. 840-848, 2004.

Effects of Illumination: Physical Mechanisms



Photoconductive device ⇒ photo-carrier generation due to absorption of photons in polymer channel of device.

Proposed physical mechanism:

> photon absorption …exciton formation … diffusion … dissociation into free carriers … trapping of e’s … transport and collection of h’s

Explains: V_T reduction, I_D increase, no change in μ_{FE} or S with illumination

Next step ⇒ monochromatic illumination to get more detailed results.

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OFET Operating Temperature Range?

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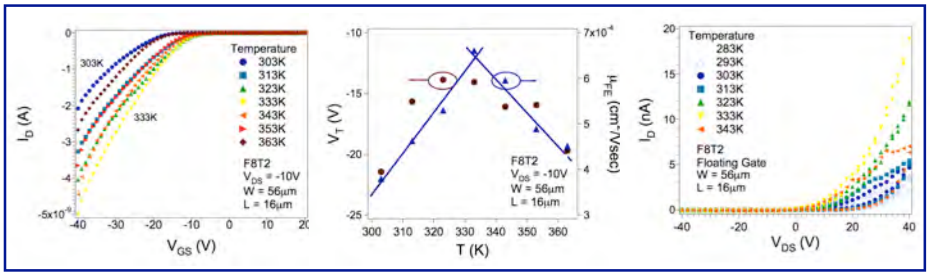
Evidence that there may be a (relatively low) operating temperature at which the device performance is optimal.

Possible relation to change in morphology and/or conformation of polymer chains with temperature (i.e. as temperature is increased, distance between chains increases, resulting in a decrease in inter-chain carrier mobility).



No apparent gate-bias dependence and no evidence from XRD or DSC.

Observations are consistent with (unexplained) experimental results published by other groups…reduction of mobility at elevated temperatures (near 340K).

Implications for applications based on organic devices.

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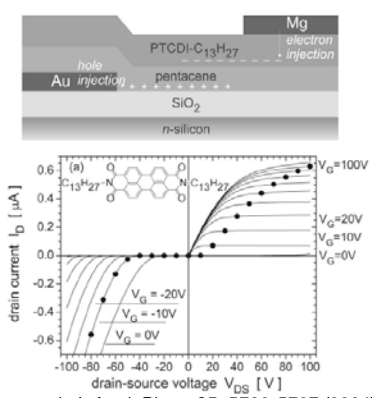
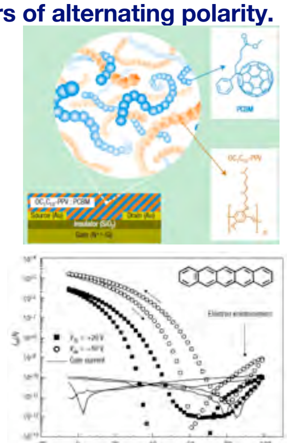
Ambipolar Organic Transistors

68

Ambipolar OFETs have been prepared using blends of organic semiconductors, or multiple layers of alternating polarity.



C. Rost *et al.*, *J. Appl. Phys.*, **95,** 5782-5787 (2004).



E. Meijer *et al.*, *Nature Mat.*, **2**, 678-682 (2003).

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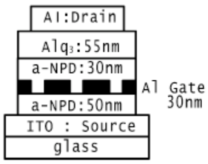
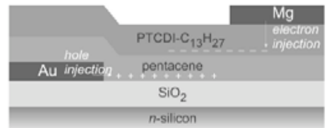
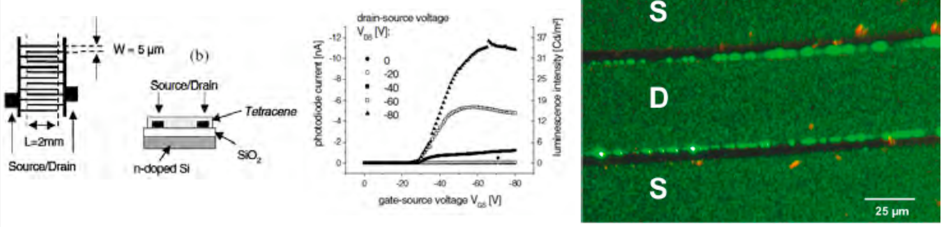
Light-Emitting Organic Transistors



K. Kudo *et al., Thin Solid Films,* **438-439,** 330-333.



C. Rost *et al., Syn. Met.,* **146,** 237-241.



A. Hepp *et al., Phys. Rev. Lett.,* **91,** 157406.

- **Devices exhibit drain and gate-bias-dependent behavior.**
- **Gated OLEDs?**

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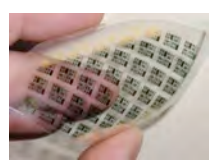
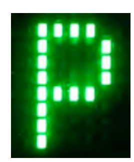
Possible OFET Applications

OFET Driven AM-EPD (Phillips)

OFET Paper Substrate (Infineon)

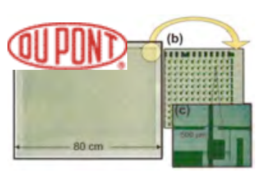


RFID (3M)



OFET Driven OLED(Pioneer)

OFET AM-LCD (Penn State Univ.)



OFET Backplane (DuPont)

OFET Backplane (Lucent/e-ink)

OFET Backplane (PlasticLogic)

DUPONT *The miracles of science*™

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Example of OFET-based Active-Matrix Displays

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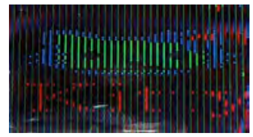
- 2000 Lucent/E-Ink 16×16 E-Paper display
- 2001 Sarnoff/Penn State/Kent State 16×16 TFT LCD
- 2002 Philips 64×64 TFT LCD
- 2003 Plastic Logic 80×60 TFT LCD
- 2003 PARC 128×128 ink-jetted TFT LCD
- 2006 Samsung SDI 4" 120×192 OTFT based AMOLED
- 2006 Plastic Logic/E-Ink 800×600 SVGA ink-jetted OTFT E-paper display



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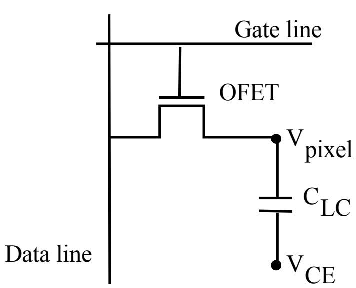
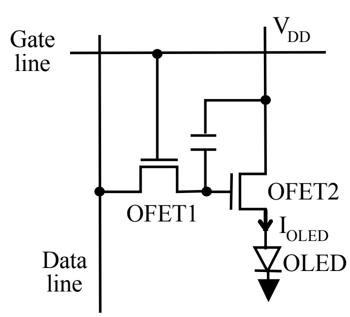
Examples of OFET Active-Matrix Addressing

72

AM-LCD typical pixel electrode driving circuit
- One TFT



AM-OLED typical pixel electrode driving circuit
–2 TFTs minimum



- More complex pixel electrode circuits are required to accomdate for OFETs electrical stability.

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Requirements for Active-Matrix Addressing

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	AM-LCD	AM-PDLC	AM-OLED
I_{OFF} (A)	$< 2\times10^{-13}$	$< 2\times10^{-13}$	$< 10^{-12}$
I_{ON} (A)	$> 2\times10^{-7}$	$> 2\times10^{-7}$	$> 10^{-6}$
I_{ON}/I_{OFF}	$> 10^{6}$	$> 10^{6}$	$> 10^{6}$
V_T (V)	< 2	< 5 V	< 2 V
S (V/dec)	< 0.5	< 1.5	< 1.0
τ (switching)		> 3 ms	> 200 ns

F. Libsch, *TFTs in Active-Matrix Liquid Crystal Displays.*
S. Martin *et al.*, *J. SID,* **11/3**, 2003.
M.L. Chabinyc and A. Salleo, *Chem. Mater.*, **2004**.

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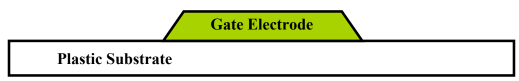
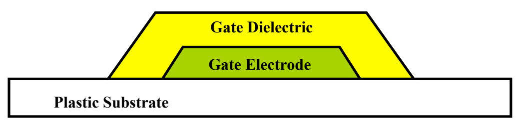
Example of OFET Active-Matrix Process (1)

74

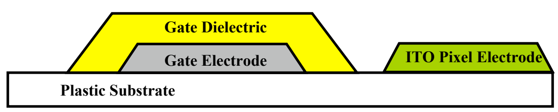
Deposit and pattern gate



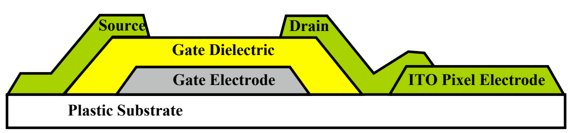
Deposit and pattern gate dielectric



Deposit and pattern ITO pixel electrode



Deposit and pattern source/drain contacts



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Example of OFET Active-Matrix Process (2)

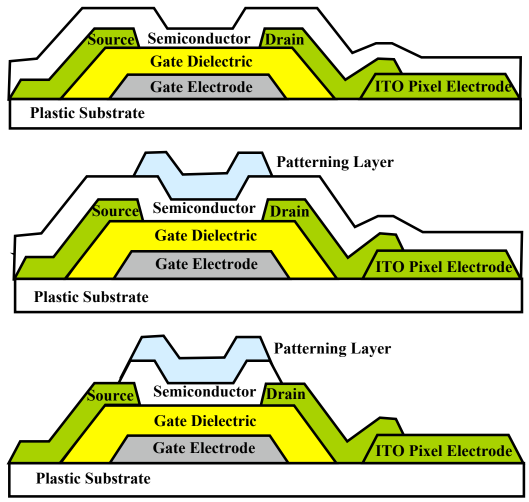
75

- Minimize leakage current between transistors.
- Deposit patterning layer. e.g.: Parylene polyninyl alcohol (PVA), Si_3N_4

Deposit semiconductor

Define patterning layer

Etch semiconductor



Encapsulation or passivation layers are needed.

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Example of Reflective AM-PDLCD Backplane

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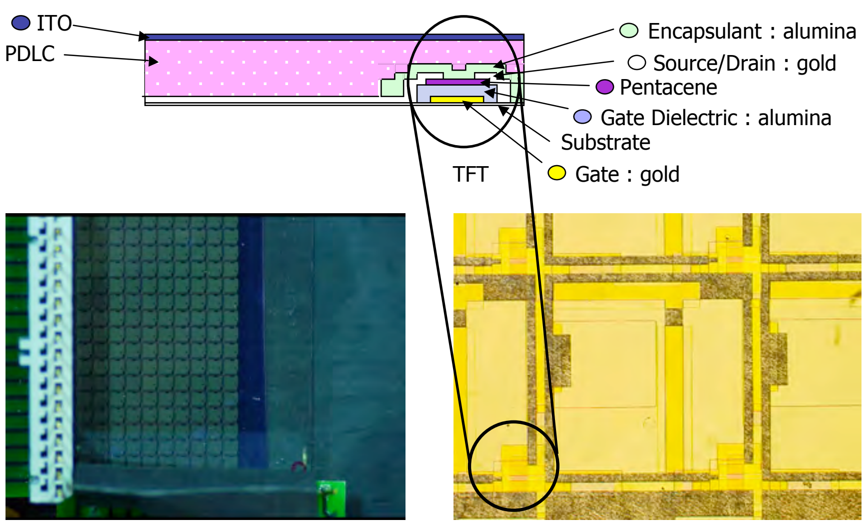

3M

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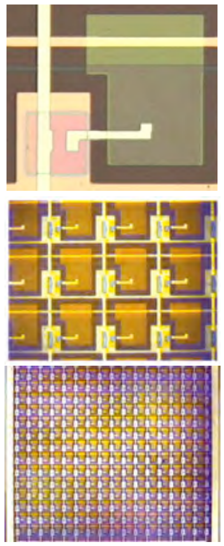
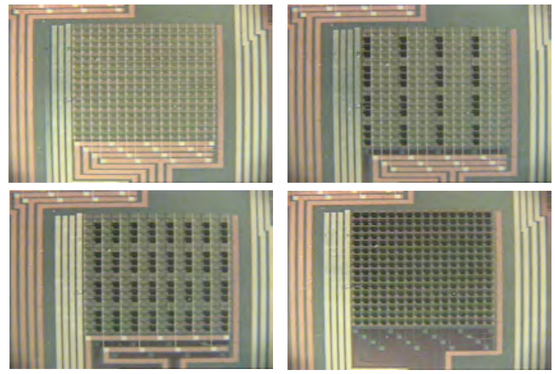
Example of Reflective AM-PDLCD on Plastic

77





Sarnoff-Penn State-Kent State Rensselaer OFET AMLCD

Reflective 16x16 Pixel Array
Driven with 1/4 VGA Video
Display Waveforms (60 Hz refresh rate, 69 μsec line time)

M. Kane *et al.*, SID 2001.

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Example of Refective AM-PDLC Display

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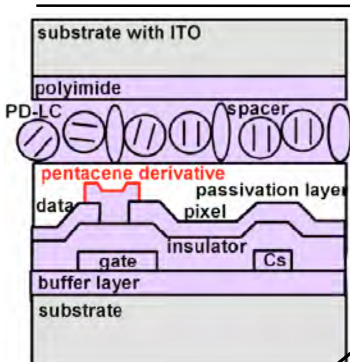
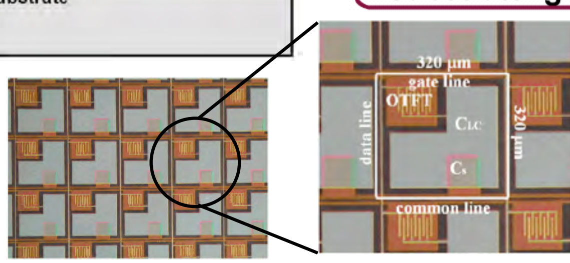
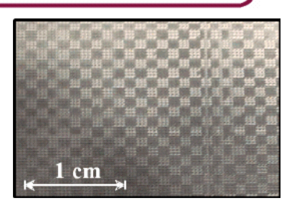


- display size: 2.5 inch
- resolution: 79 dpi, QQVGA
- aperture ratio: 73 %
- frame rate: 60 Hz
- display mode: normally white
- electrode & wire: organo-Ag
- insulator: PVP-OTS
- semiconductor: pentacene
- substrate: glass





Monochromatic image of AM-PDLCD

SONY

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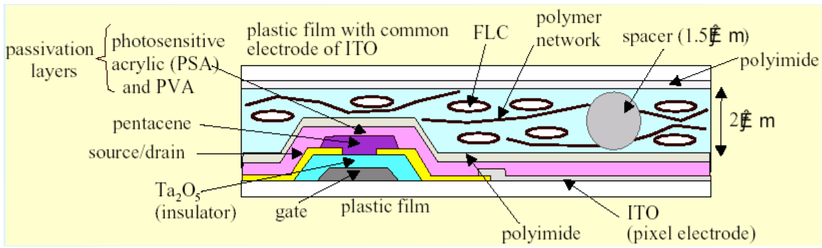
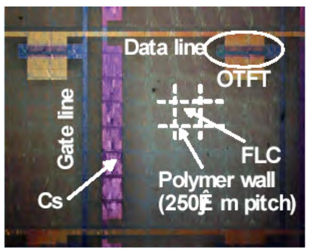
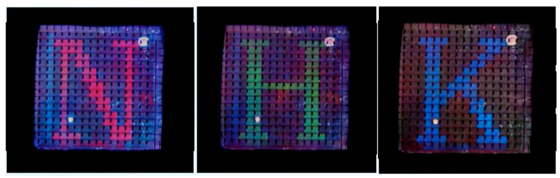
Example of AM-FLC Display



Film LCD : Ferroelectric LC (FLC) stabilized by polymer walls and networks





Data scan frequency : 360Hz×16

Gate voletage : 14Vpp

Data voltage : 13Vpp

Y. Fujisaki *et al., SID 2006*, pp. 119-122, 2006.

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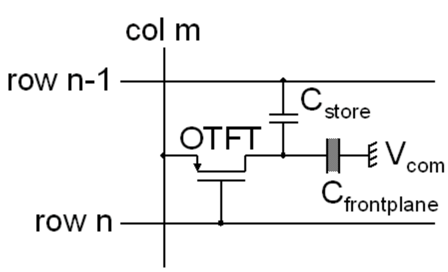
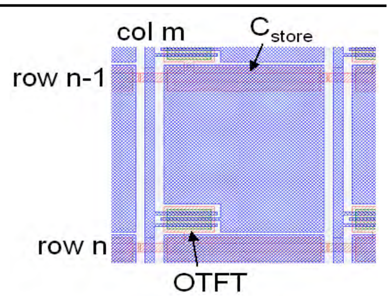
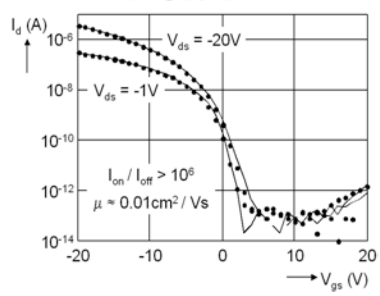
OFET Active-Matrix Addressing of E Ink Display





- ✓ **Pentacene OTFTs with Au S/D contacts are used.**
- ✓ **L/W = 5/140**
- ✓ **Pixel size: 300 µm x 300 µm**



For all rows:

1. **Select row n: $V_{row\ n}$ = 25V → $V_{row\ n}$ = -25V**
2. **Apply V_{data} (-15V ... 15V) to columns**
3. **Deselect row n: $V_{row\ n}$ = -25V → $V_{row\ n}$ = 25V**

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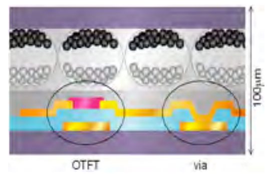
Roll-up OFETs Active-Matrix E Ink Display

Main properties:

- 4.7” diagonal, 7.5mm roll radius
- 240 rows x 320 columns / 300 µm square pixel (85 dpi)
- 50 Hz refresh rate, 4 gray levels
- Contrast > 10
- Display type: electrophoretic (E Ink)
- Working organic shift resisters
  : Up to 233 stages & 11 kHz

Key benefits of roll-up e-paper:

- Very flexible: rollable
- Unbreakable
- Light weight & Low power
- Integrated drivers – standard driver connection technologies cannot be used easily.



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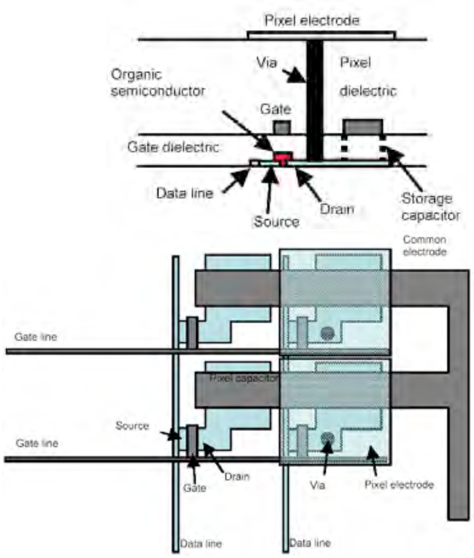
Example of OFET Active-Matrix Flexible E Ink Display



- Resolution: SVGA (800×600) 100ppi
- Display size: 10”
- Backplane: PET substrate (Dupont)
- Pixel electrode: PEDOT/PSS

S. E. Burns *et al., SID 2006*, pp. 74-76, 2006.

E·INK Plastic Logic

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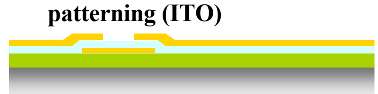
Example of Flexible OFET Active Matrix Processing

(a) Fix the plastic on the carrier

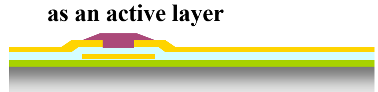
(b) ITO deposition and patterning as a gate electrode

(c) Coating organic insulator

(d) Source and drain electrodes patterning (ITO)



(e) Pentacene thermal deposition as an active layer



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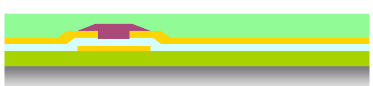
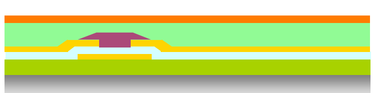
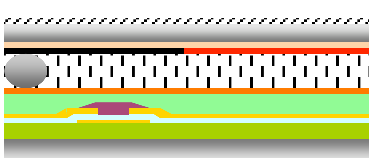
Example of Flexible OFET Active Matrix TN LCD Processing



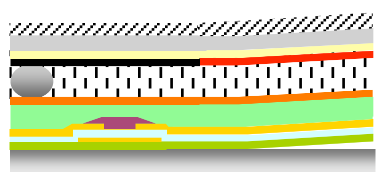
(a) Polymer passivation layer coating



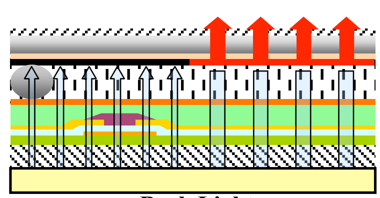
(b) PI layer coating for TNLC alignment



(c) TNLC injection and sealing



(d) Release plastic from carrier



Back Light

(e) The panel assembled with the back light

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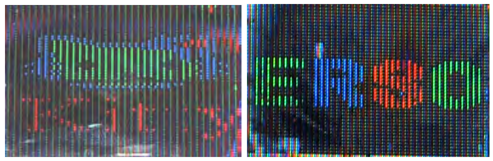
Example of Flexible OFET AM-TN LCDs

Color OTFT-LCD on Glass



Display: 3" OTFT-TNLCD
Resolution: 64 x 43 x 3 pixels
Pitch: 500 µm x 1500 µm
Device: 1T1C PMOS

Monochrome OTFT-LCD on Plastic

Display: 3" OTFT-TNLCD
Resolution: 64 x128 pixels
Pitch: 500 µm x 500 µm
Device: 1T1C PMOS

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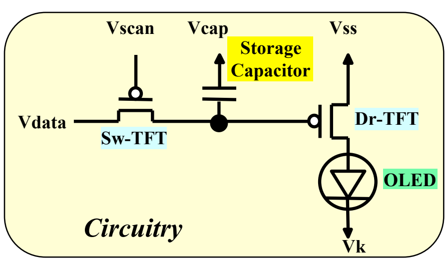
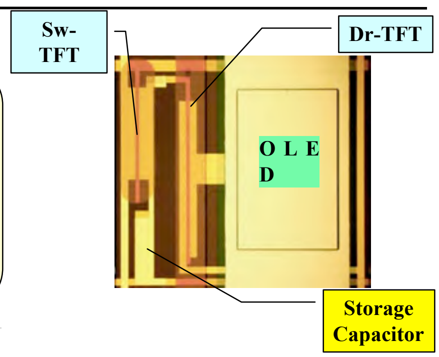
Active-Matrix OLED: Pixel Configuration

Schematic pixel circuit





pixel number	8 x 8
pixel pitch	1mm
aperture ratio	27%
TFT channel length	10µm
TFT channel width	Dr-TFT:680µm Sw-TFT:400µm

mobility	0.2 $cm^2V^{-1}S^{-1}$
threshold voltage	-3 V
on/off ratio	10^5
off-current	10^{-9} A

* With HMDS treatment of gate dielectric. (Ta_2O_5)

Pioneer sound.vision.soul

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Active Matrix OLED: Cross-Section of OFET and OLED

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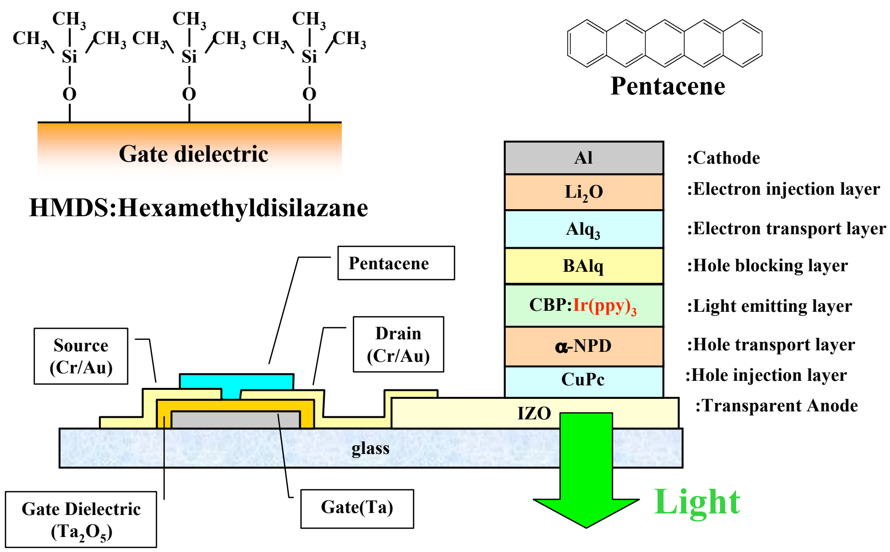

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Example of OFET Active-Matrix - OLED

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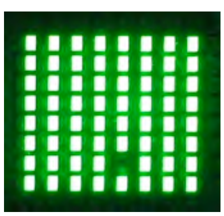
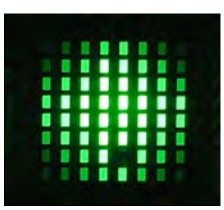


(a) Whole lighting



(b) 16 gray scales

Specification of AM OLED panel	
Pixel number	8 x 8
Pixel pitch	1 mm
Emission color	Green
Aperture ratio	27%
Maximum lumanance	400 cd/m^2
I_{EL} per 1 pixel at L_{max}	22 μA
Frame frequency	60 Hz
Scan duty	1/60
Gray scale method	Analog 16 gray scale

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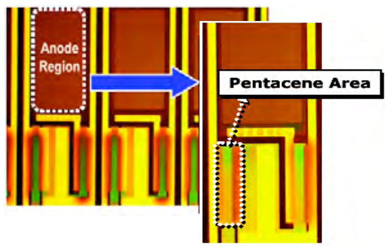
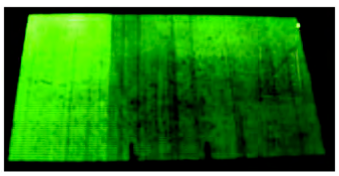
Example of OFET Active-Matrix - OLED

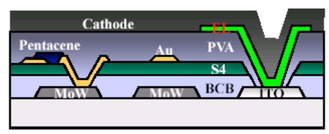


(a) Pixel Layout



(b) Display after optimization

Items		Specification
Layout	Panel size	4"
	Outer size	5" (107200um x 64225um)
	Number of pixels	64 x 3 x 120 (64x360)
	Sub-Pixel size	750 μm x 250 μm (34ppi)
	Aperture ratio	30 %
	Storage cap	1.2 pF
Circuit	Gray	Black / White
	Pixel element	2Tr_1Cap
	TFT size	SW: 200um/20um DR: 200um/20um
Optical Performance	Display color	Green mono (bottom emission)
	Full white luminance	50 cd/m²



SAMSUNG
SAMSUNG SDI

M.-C. Suh *et al., SID 2006*, pp. 116-118, 2006.

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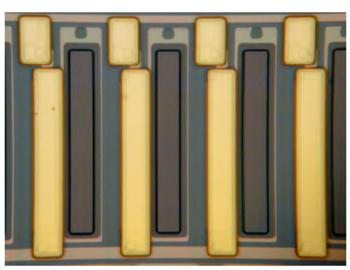
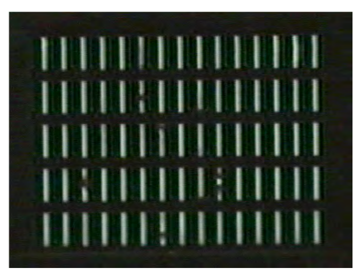
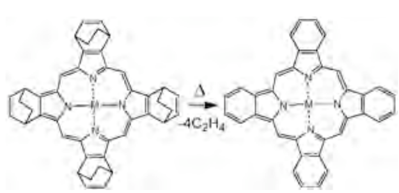
Example of OFET Active-Matrix - OLED



(a) Pixel Layout



(b) Emission of Pixel Array



(c) Tetrabenzpporphyrin Molecule

Specification of AM OLED panel	
Pixel number	5 x 15
Pixel pitch	300μm × 100 μm

MITSUBISHI CHEMICAL

S. Aramaki *et al., SID 2006*, L-3, 2006.

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OFET-based Circuits - Inverters

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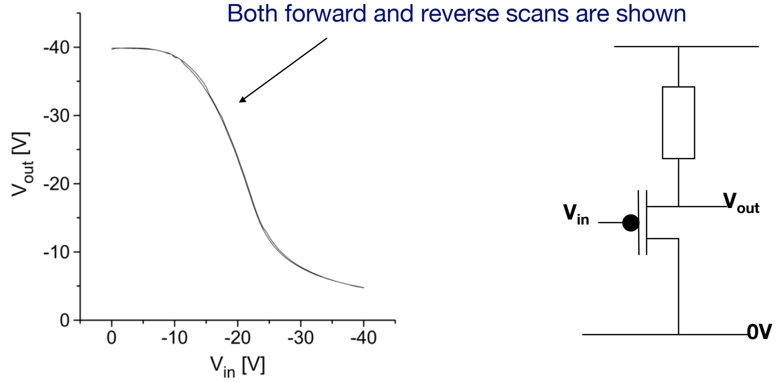

2nd generation PAA with low k dielectric

covion Avecia

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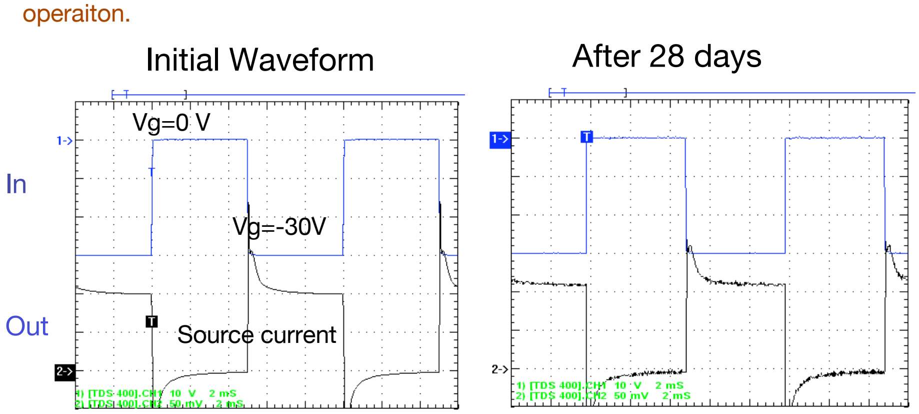
OFET-based Circuits - Inverters (2)

92

Inverter circuits can be environmentally stable after prolonged exposure and operaiton.



- 100 Hz signal 0 to -30V signal applied to the gate
- Source current is monitored with a current feedback amplifier
- Turn-on time is comparable to accumulation time for a 130 μm channel

covion Avecia

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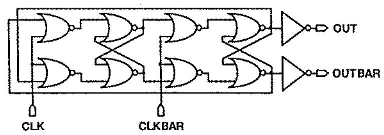
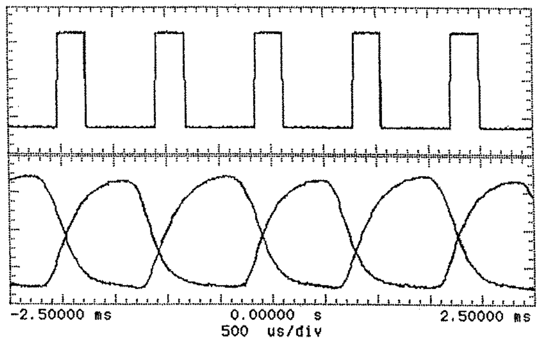
OFET-based Circuits - Frequency Divider





Input

Complementary Outputs

M. Kane *et al.*, *IEEE EDL*, **21**, 534-536 (2000).

- **48 transistors**
- **Operation at 1.1 kHz**
- **65% functional yield**

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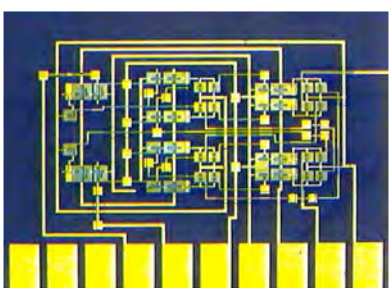
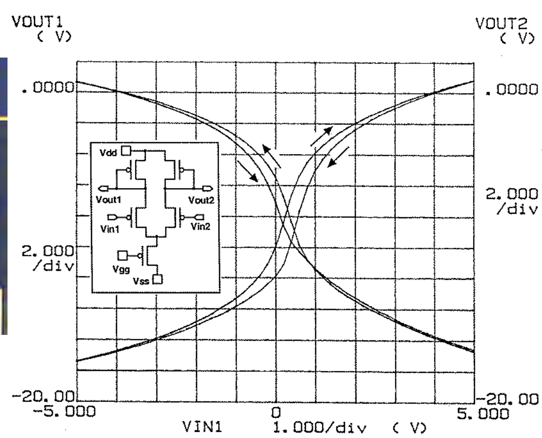
OFET-based Circuits - Differential Amplifier

- **Voltage gain = -5 to -10**
- **Offset voltage = -1V to +1V**





Kane *et al.*, *IEEE EDL*, **21**, 534-536 (2000).

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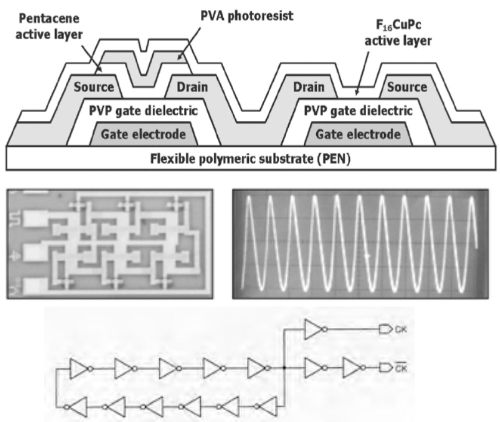
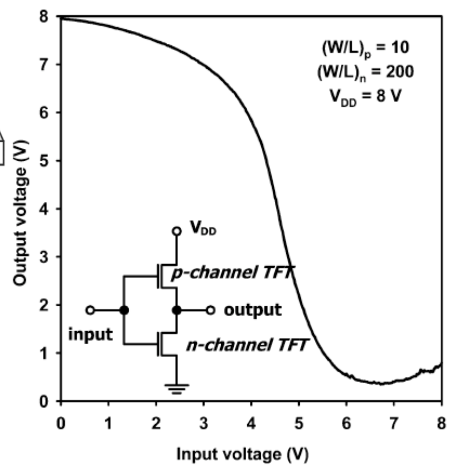
OFET-based Circuits - Ring Oscillators



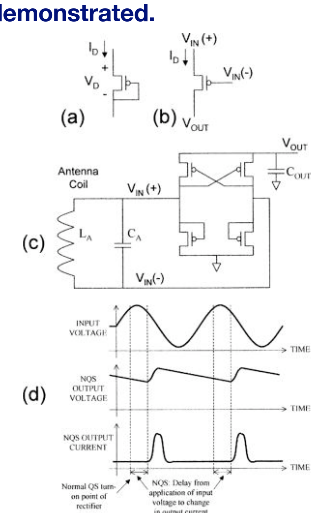


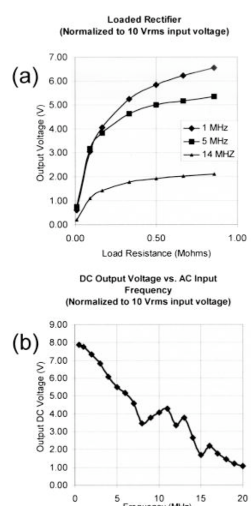
Requires both P- and N-type OFETs.

H. Klauk *et al., IEEE T-ED,* **52**, 618-622 (2005).

OFET-based Circuits - RF-ID Tags

- **Circuits oscillating at radio frequency (13.67 MHz) have been demonstrated.**





R. Rotzroll *et al., Appl. Phys. Lett.*, **88,** 123502 (2006).

Organic Electronics

Topics relevant, but not covered, in this presentation:
- OLEDs / PLEDs
- Solar cells
- Chemical sensors
- Image sensors
- Lasers
- Memory and storage
- X-ray and gamma ray sensors
- Advanced pixel electrode circuits for AM-OLEDs
- Driving electronics

Conclusions

- Organic thin-film field-effect transistors (OFETs) can be fabricated using:
  - Many different device structures
  - By solid- or solution-processing
  - With a wide variety of materials suitable for various applications.
- Many aspects of OFET physics are not well understood, but are close to being solved.
- In other respects, OFETs behave much like c-Si MOSFETs.
- OFETs have been shown to be suitable for:
  - Large-area, full-color displays
  - RF-ID circuits
  - Logic circuits
  - Chemical sensors
  - Light-emitters and detectors

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Conclusions (2)

- **Problems to be addressed:**
  - Electrical stability
  - Processing stability
  - Low-cost fabrication
  - Packaging
  - Etching
  - Impurities
  - Etc.
- **It may take several years for practical products to be brought to market.**
- **Potential payoff could be very large…billions?**

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