West Lafayette, Nous Voila

Birck Nanotechnology Center Distinguished Lecture, Purdue University, West Lafayette, IN, Dec. 3, 2018

Organic Photonics and Electronics: The Endless Frontier

Bernard Kippelen

Georgia Tech

Center for Organic Photonics and Electronics

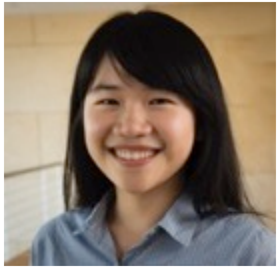
Atlanta: A Fast Growing Technology Hub

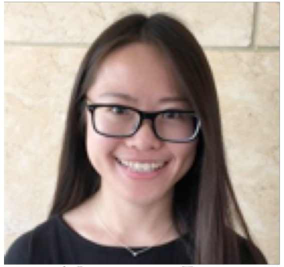
Kippelen Research Group


Canek Fuentes
Principal Research Scientist

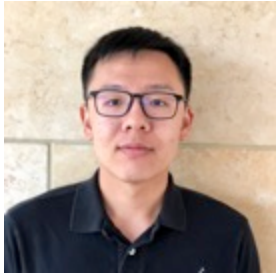

Xiaoqing Zhang

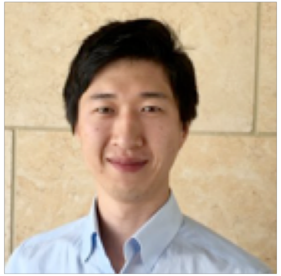

Silja Abraham


Wen-Fang Chou


Xiaojia Jia

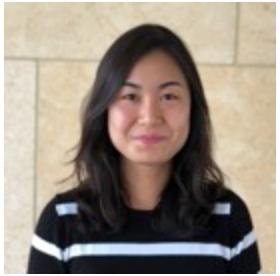

Felipe Larrain


Yi-Chien Chang


Youngrak Park


Victor Rodriguez


Oliver Moreno


Gunhee Kim

NNSA National Nuclear Security Administration
CAOP Center for Advanced Organic Photovoltaics
ONR Science & Technology
SAMSUNG
MITSUBISHI CHEMICAL
Domtar

Outline

- Motivation and external drivers
- Recent advances:
    - Electrode engineering
    - Organic light-emitting diodes
    - Thin-film transistors

Global Macro Trends

Increasing **population**: 7.6 Billion today, 8.5 Billion by 2030

Increasing **energy** demand:
16 TW in 2007 (0.5 ZJ), 28 TW by 2050 (0.9 ZJ)

Population shift from rural to urban areas
Aging population
Increasing economic disparity

An Economy in Flux

2018 — amazon — Alphabet

(1,091)

2008 — ExxonMobil — PetroChina — GAZPROM

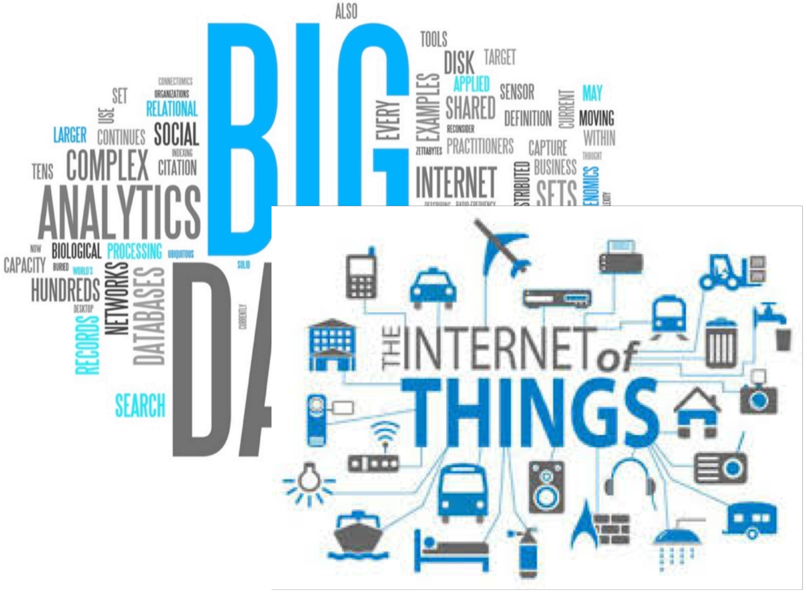
1996 — Coca-Cola — NTT

(136)

Source: Financial Times Global 500 rankings; Based on market capitalization

Technology Trends

- Artificial Intelligence
- Internet of Things
- Cybersecurity
- Blockchain
- Quantum computing
- Immersive experience
- CRISPR:Cas9
- **<u>Smart materials</u>**



What is the Next Big Thing?

What's Next: Fourth Industrial Revolution*

Source: www.transconflict.com

Physical

Digital

Biological

An accelerated convergence

(*) Coined by Klaus Schwab, Founder of the World Economic Forum

Grand Challenges and Opportunities

Improve the quality of life through *sustainable development*:

- ***P**rofit (economics)*
- ***P**eople (societal)*
- ***P**lanet (environment)*

From "Digital" to "Deep Tech"

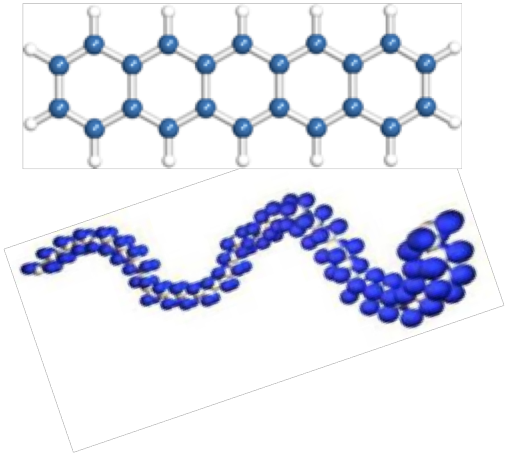
Katsushika Hokusai's *The Great Wave off Kanagawa*

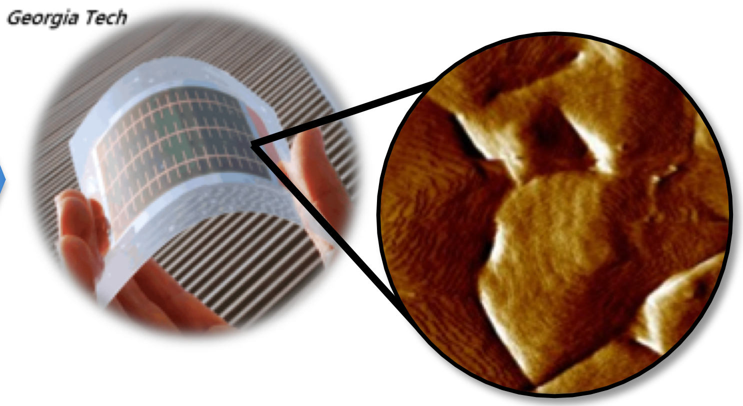
[1] "From Tech to Deep Tech," Boston Consulting Group and Hello Tomorrow report.
[2] The 4th Industrial Revolution, Klaus Schwab, Crown Publishing Group 2016.

Digital innovation wave:
wider dissemination enabled by hyper-connected world

Next Deep Tech wave:
disruptive solutions built around unique, protected technological or scientific advances

Organic Molecules and Polymers

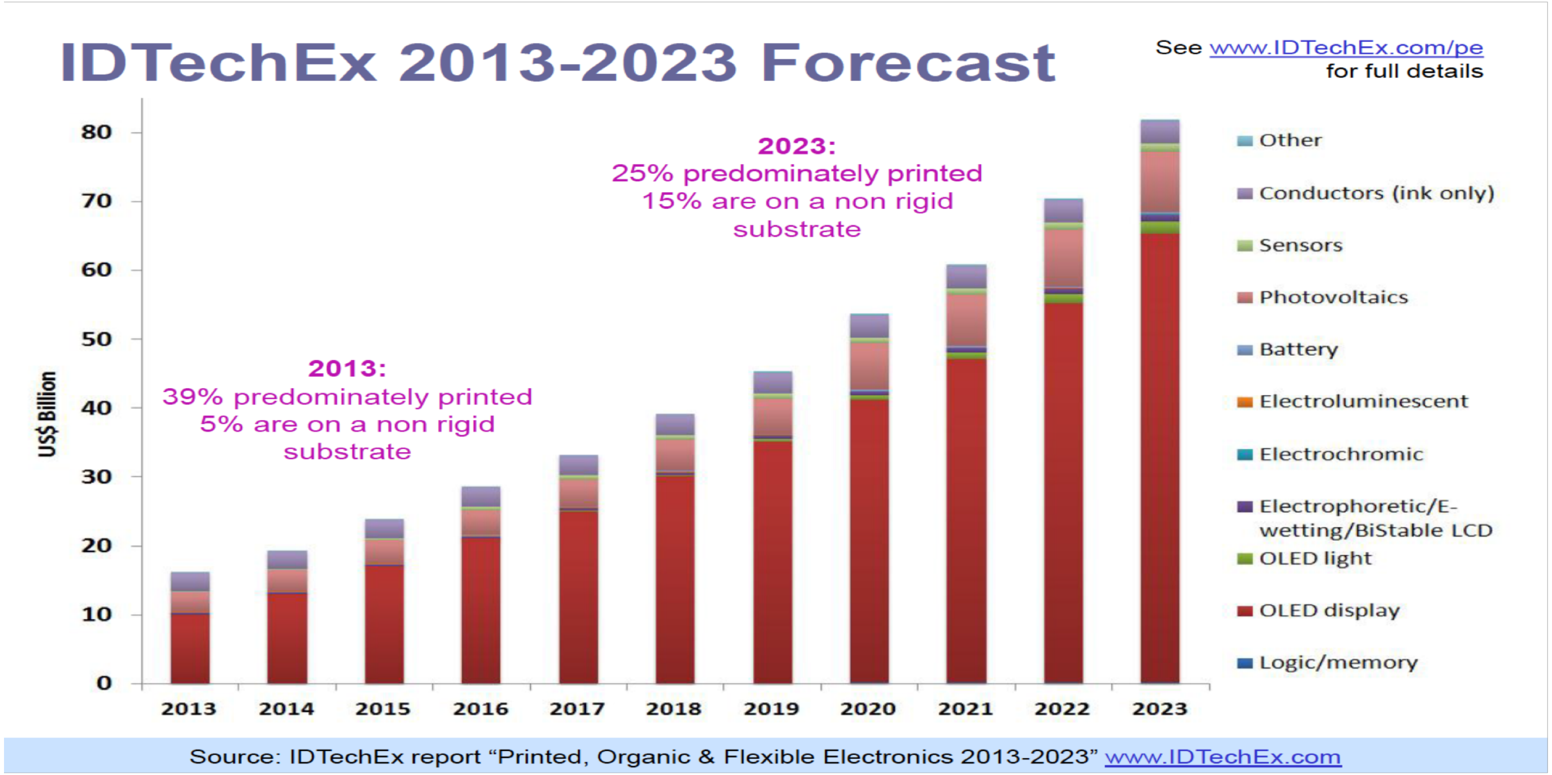




Carbon-based compounds with tailored optical, electrical and mechanical properties

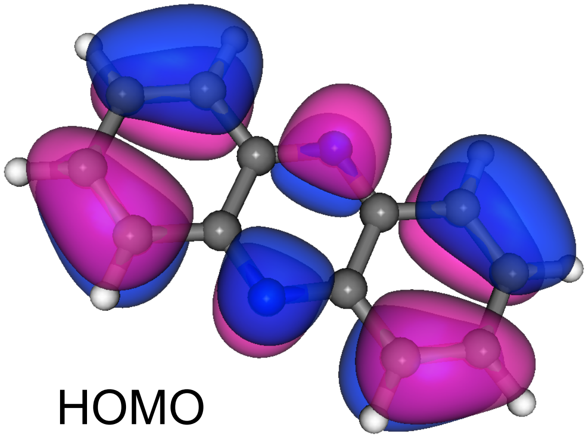
Semiconductor films processed at room temperature from vacuum or solution.

Printed Electronics Market Forecast

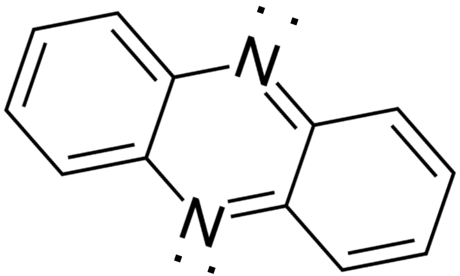


Organic Semiconductors: Conjugated Molecules and Polymers

π orbital

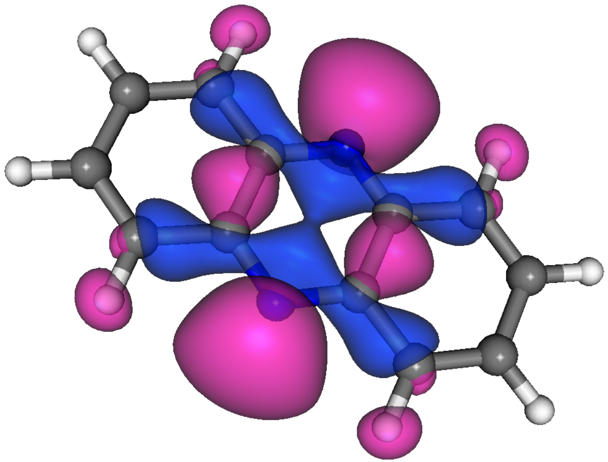


HOMO



Phenazine

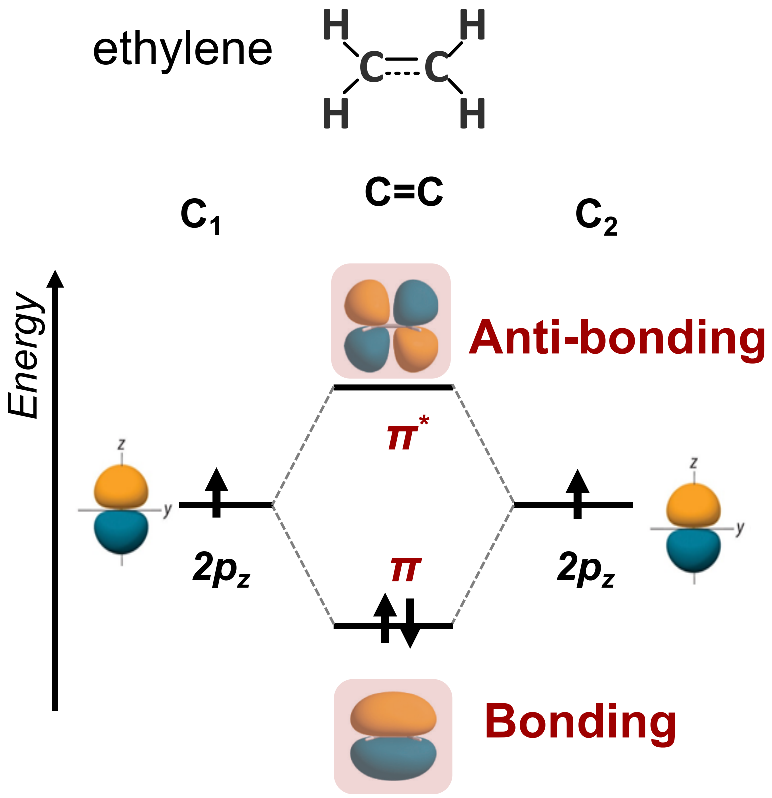
n orbital

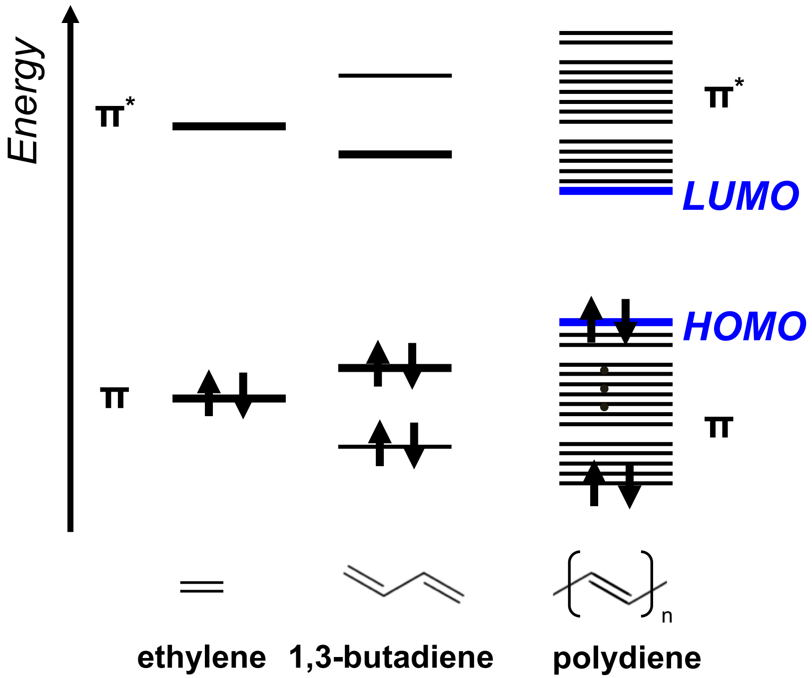


HOMO-1

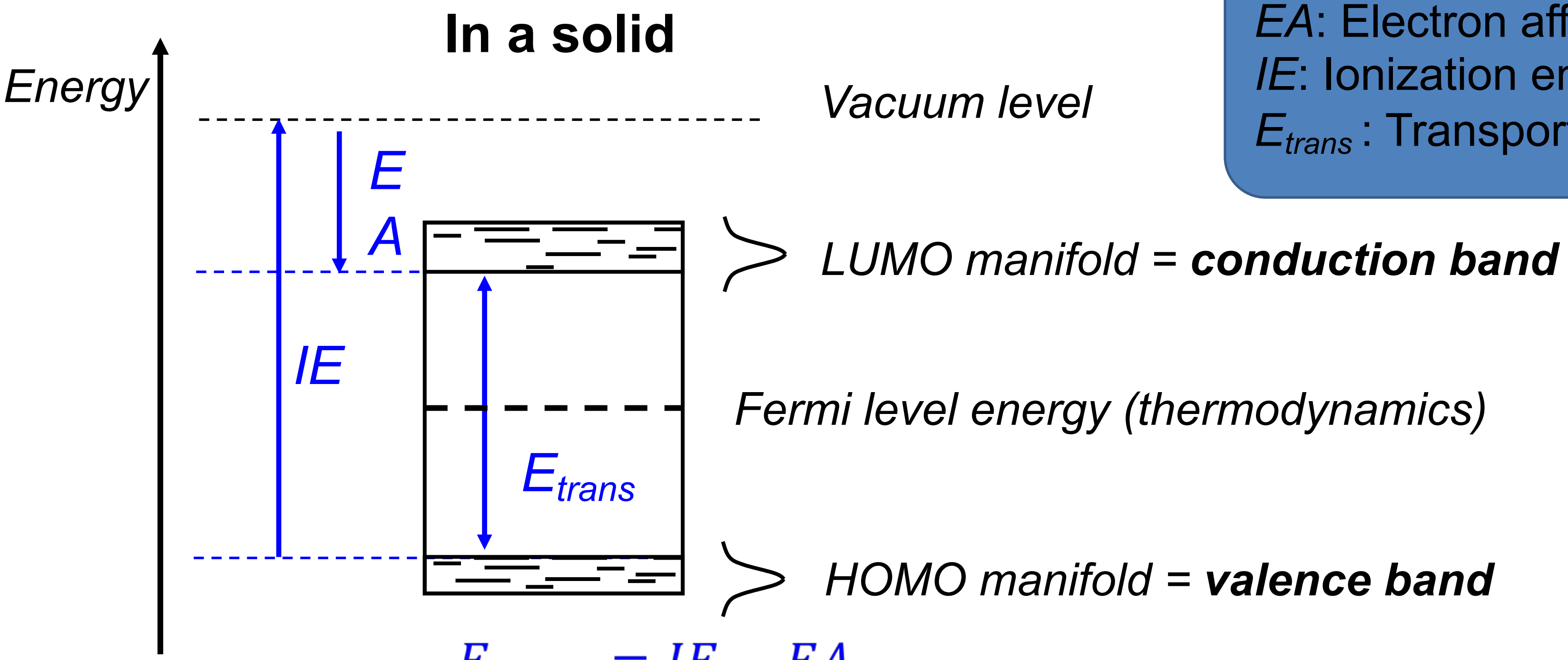
Drawings: courtesy of Wolfram Ratzke, Lupton Group, Univ. of Regensburg

Frontier Molecular Orbitals





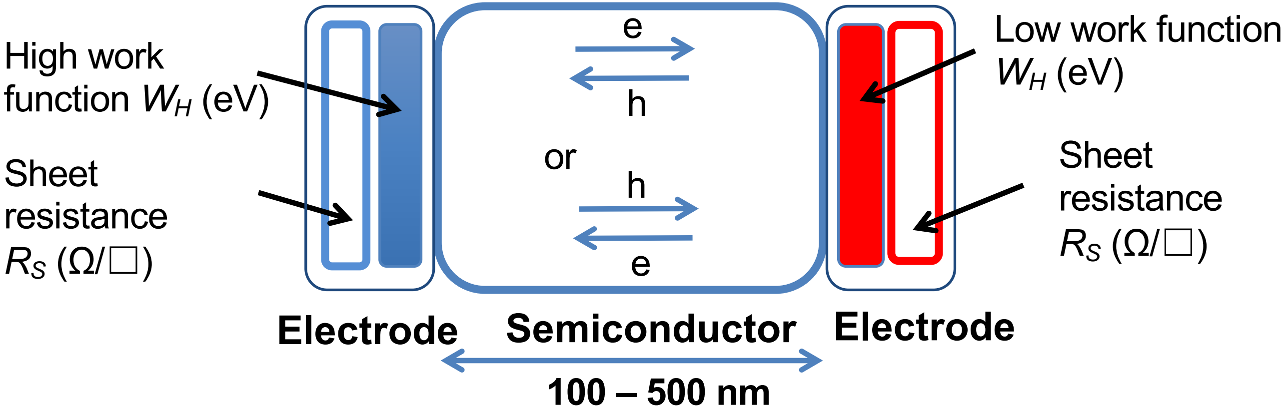
Organic Semiconductors: Transport Bands

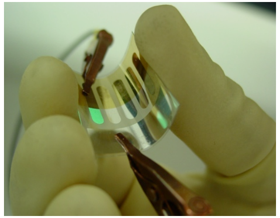


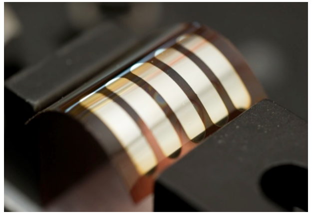
$$E_{trans} = IE - EA$$

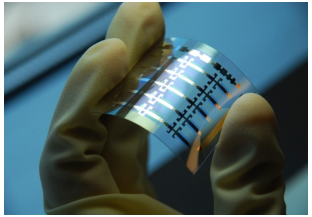
EA: Electron affinity
IE: Ionization energy
E_{trans} : Transport gap

Solid-state Organic Optoelectronic Devices









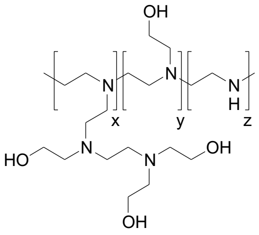
Electrodes for charge injection (OLED, OFET) or charge collection (OPV) are essential device-enabling building blocks

Outline

- Motivation and external drivers

- Recent advances:
  - Electrode engineering
  - Organic light-emitting diodes
  - Thin-film transistors

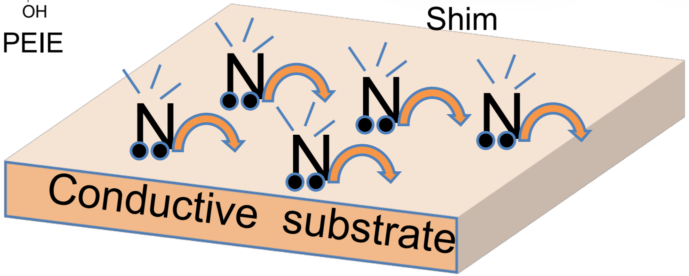
Simple Method to Produce Stable Low Work Function Electrodes (Electron Collection)

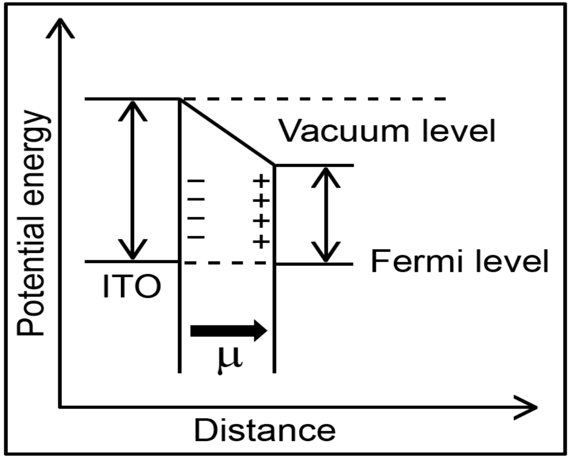


PEIE

Jaewon Shim

Yinhua Zhou



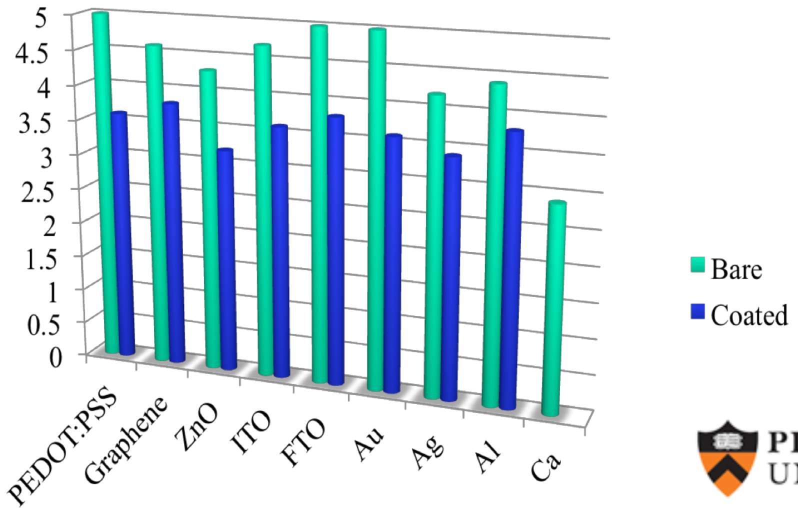


Y. Zhou, J. Shim, S.R. Marder, J.L. Bredas, S. Graham, A. Kahn, B. Kippelen et al. Science, 336, 327 April 20 (2012).

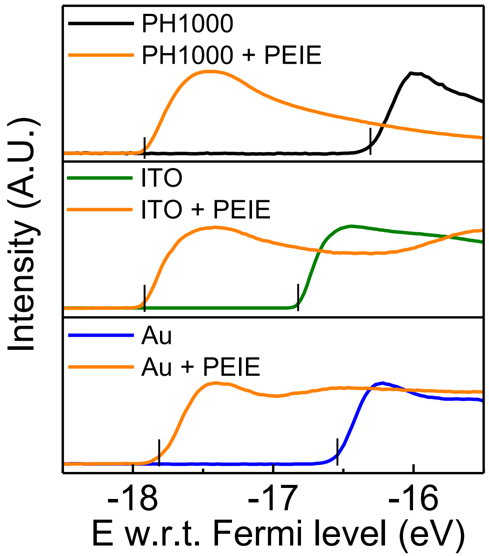
A Universal Method

UPS measurements: Kahn group

Secondary photoelectron cutoffs

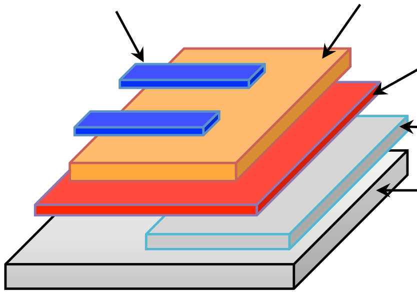


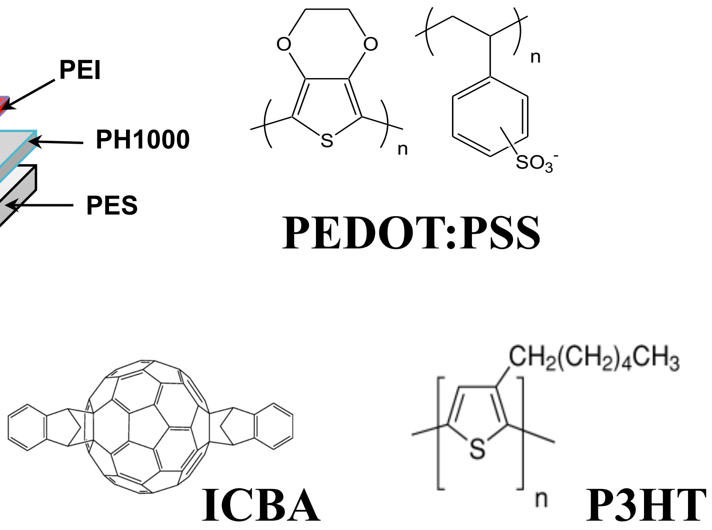
PRINCETON UNIVERSITY

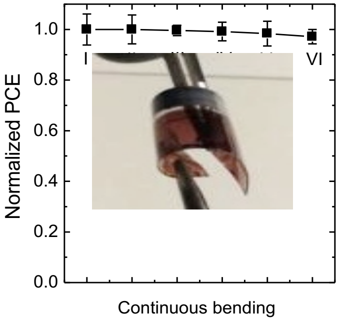


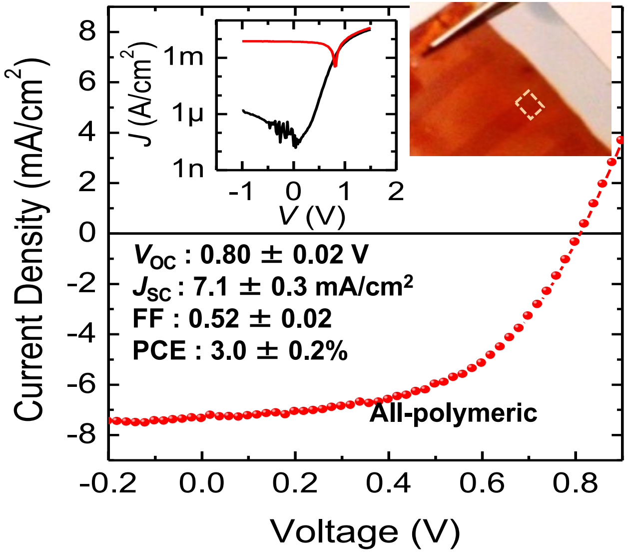
Reduction in work function up to 1.5 eV

All-organic Solar Cell









Y. Zhou, J. Shim, S.R. Marder, J.L. Bredas, S. Graham, A. Kahn, B. Kippelen et al. Science, 336, 327 April 20 (2012).

All-organic Solar Cells in the News

Forbes / Tech

APR 25, 2012 @ 04:04 AM 16,404 VIEWS

New Technique Creates First Plastic Solar Cell

Jennifer Hicks
CONTRIBUTOR

I write about science, robotics & innovative technologies in Europe.

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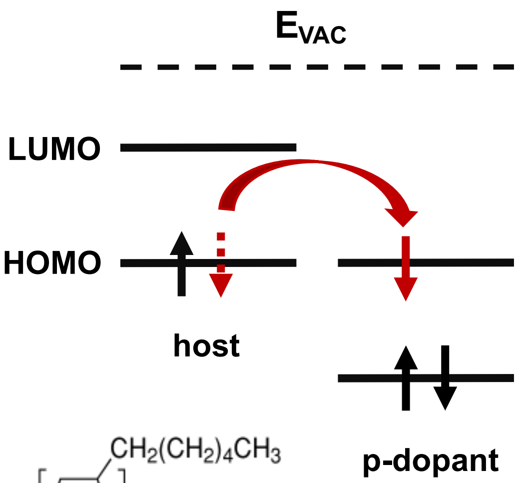
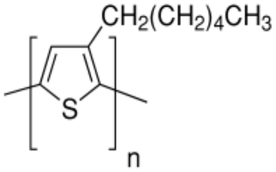
Georgia Tech's Bernard Kippelen and his team developed the first completely plastic solar cell. Courtesy: Virginie Drujon-Kippelen

The growth of the solar industry has been limited by the supply of the polysilicon material used to make solar panels. In 2006, more than half of the world's supply of polysilicon was used for production of renewable electricity. In 2008, only twelve factories produced solar-grade polysilicon. In 2011, the industry produced an excess of polysilicon. And now, another shift – the creation of a plastic solar cell.

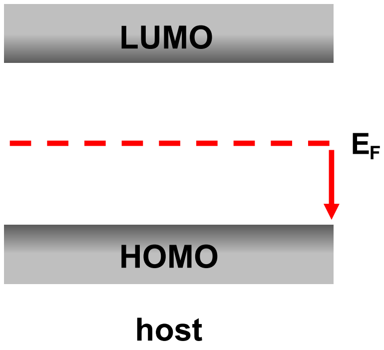
Y. Zhou, S.R. Marder, J.L. Bredas, S. Graham, A. Kahn, B. Kippelen et al. Science, 336, 327 April 20 (2012).

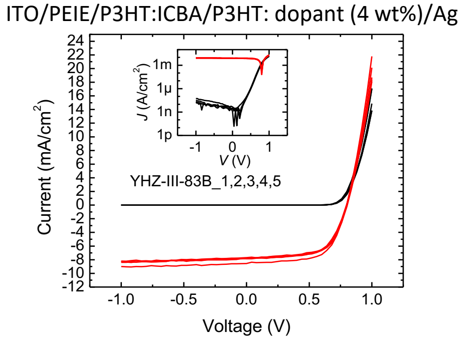
Electrical Doping of Organic Semiconductors

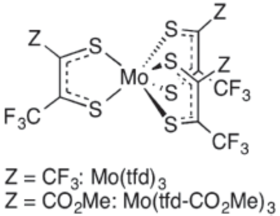


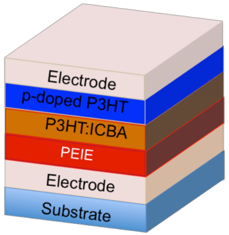


p-type doping



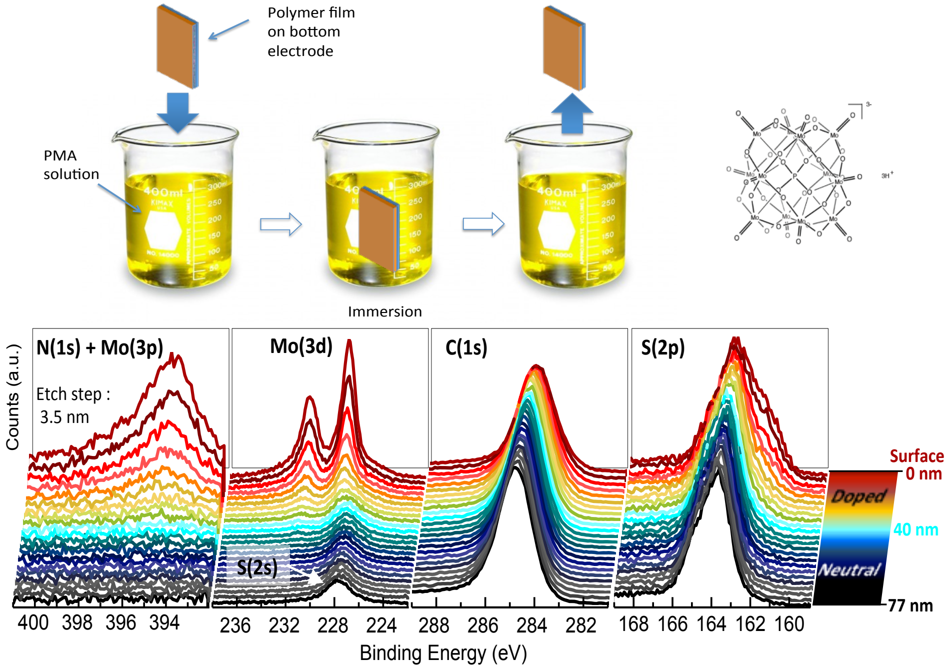


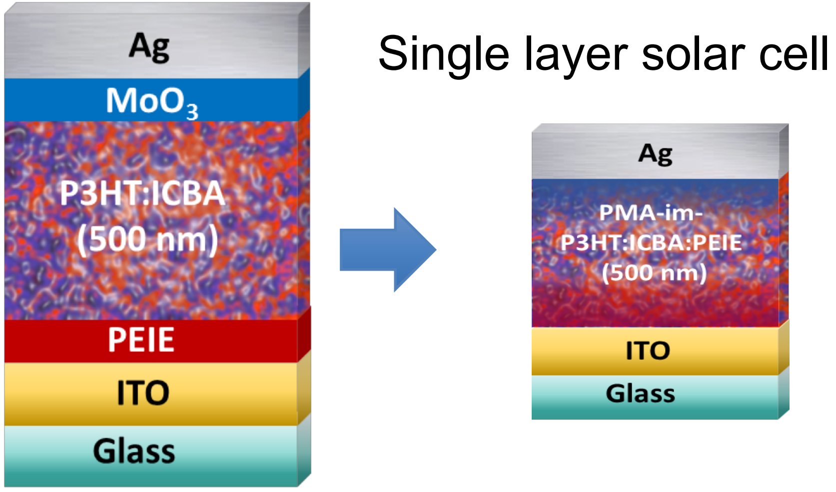




Dai, A., et al. *Adv. Funct. Mater.* **24**, 2197-2204, (2014).

Simple Method for Electrical Doping





V.A. Kolesov et al., *Nature Materials* 16, 474, April 2017. Doi: 10.1038/nmat4818

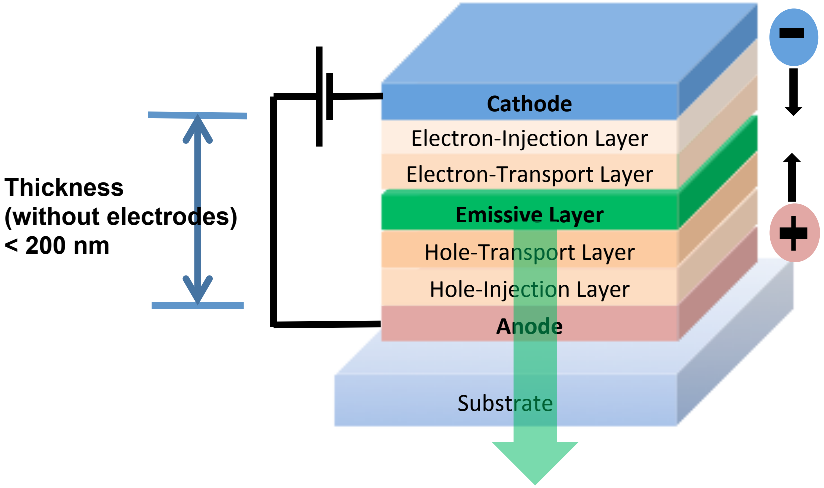
Outline

- Motivation and external drivers
- Recent advances:
  - Electrode engineering
  - Organic light-emitting diodes
  - Thin-film transistors

OLEDs: Light Sources of the Future

Diffuse light, UV free, large area, ultra-thin, flexible, transparent

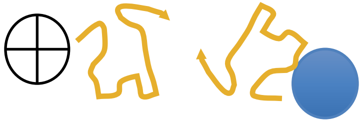
OLED Science and Technology



- Materials
- Device architecture
- Manufacturing technology
- Integration: packaging and bonding (interconnects with backplane, barrier coatings, functional films)

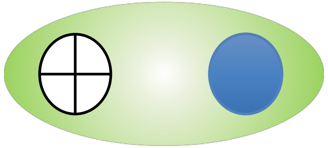
Electroluminescence for Beginners

Step 1:



Charge injection and transport

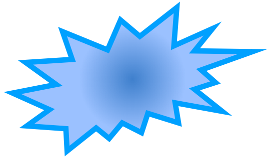
Step 2:



Easy

Excited state formation

Step 3:

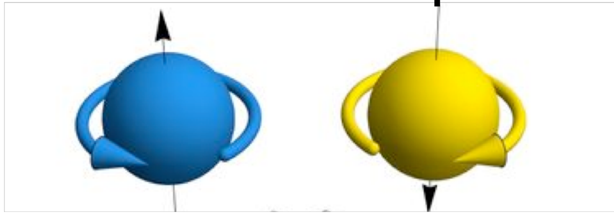


Complex

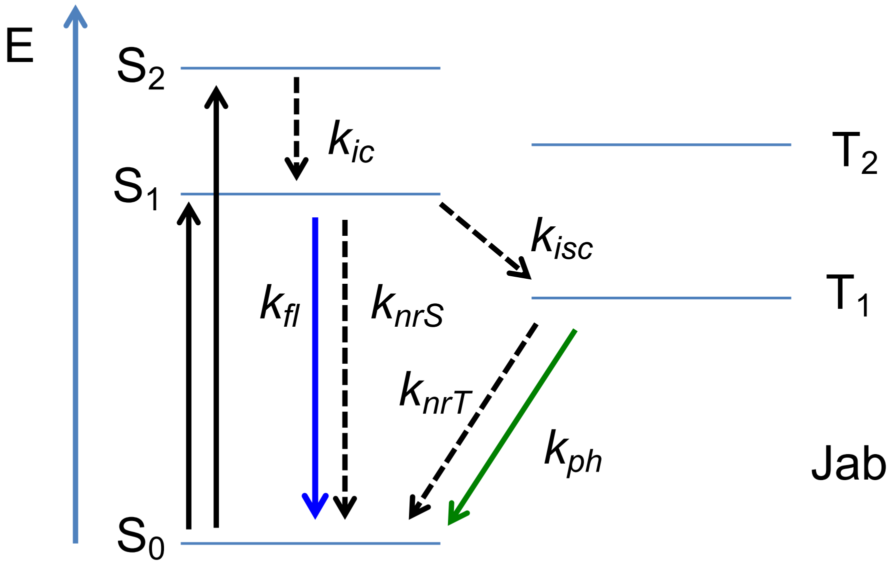
Light emission

Bohr, Heisenberg, Pauli

Electron spin



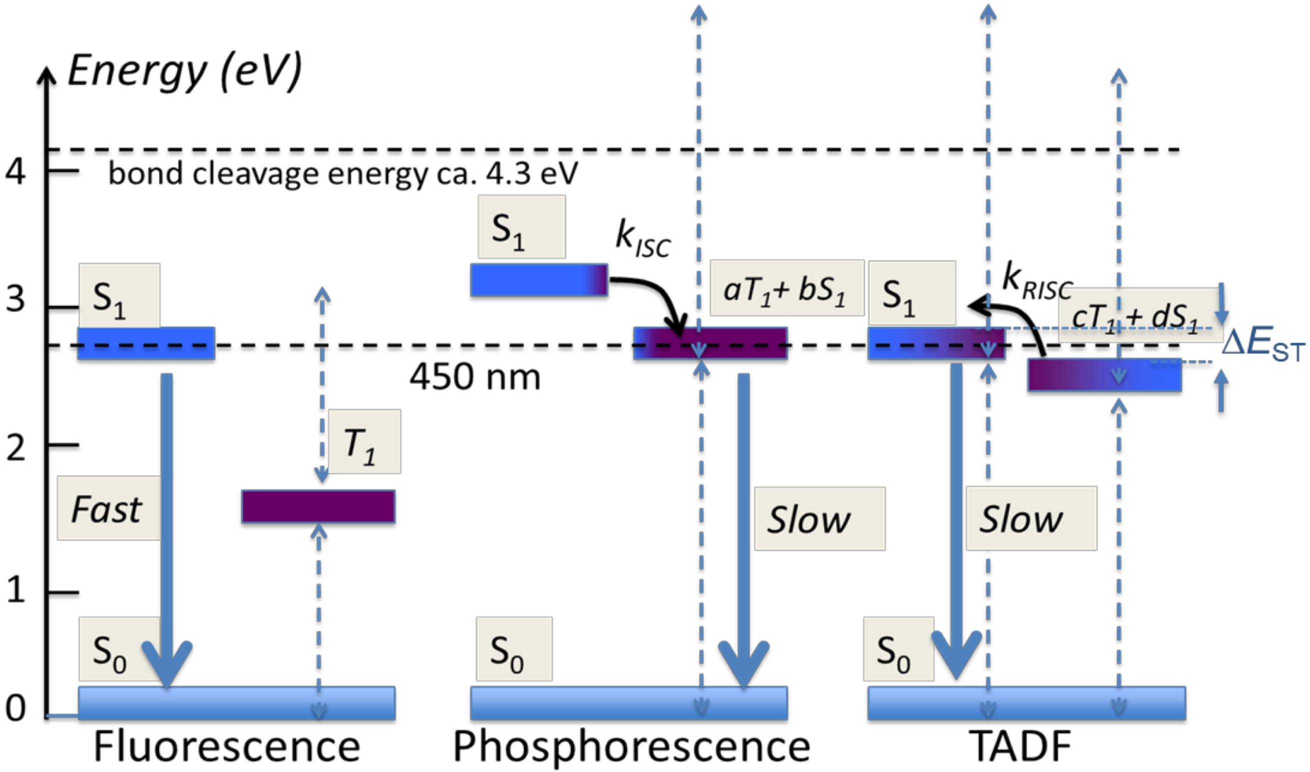
Photophysics of Organic Molecules



Jablonski Diagram

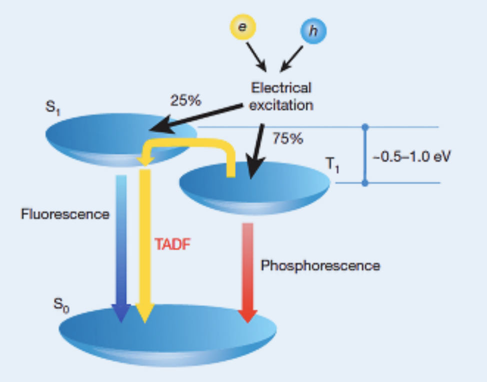
Simplified electronic state diagrams for planar all-carbon conjugated compounds: neglects non-bonding orbitals and charge-transfer states

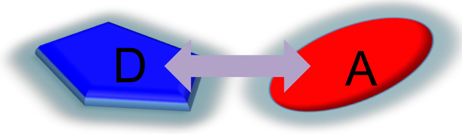
Light Emission in Organic Molecules



Thermally Activated Delayed Fluorescence

All-organic compounds that do not contain precious heavy metals, an alternative to phosphorescence



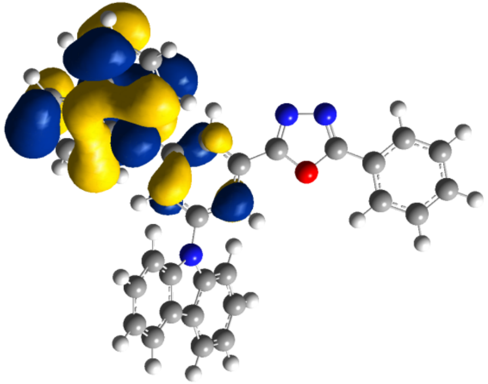


Design criteria based on engineering a weak coupling between donor and acceptor-like moieties.

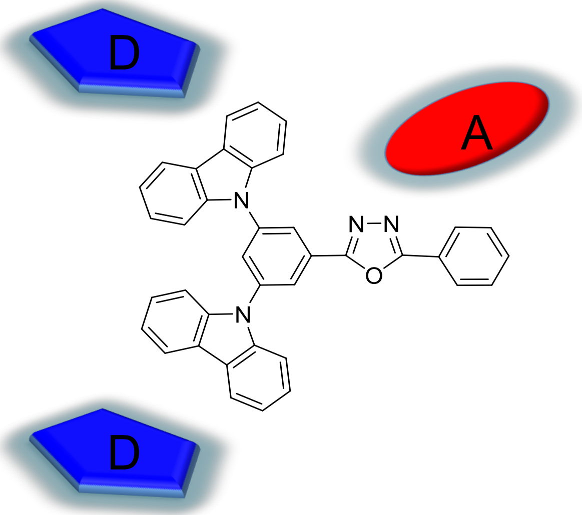
$$\boldsymbol{k}_{\mathbf{RISC}} = \boldsymbol{A}\ \exp(-\Delta \boldsymbol{E}_{\boldsymbol{ST}} / k_B T)$$

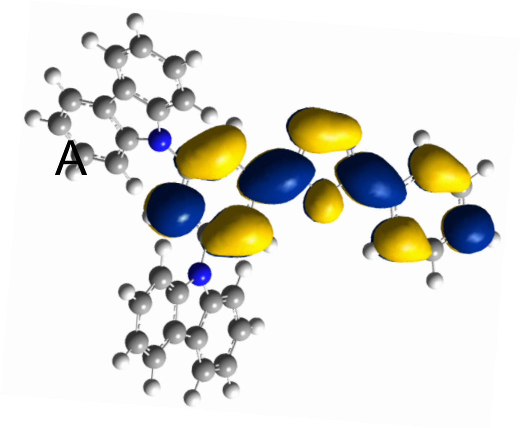
Uoyama, H., Goushi, K., Shizu, K., Nomura, H., Adachi, C. *Nature*. 492, 234 (2012).
Nakanotani, H., Masui, K., Nishide, J., Shibata, T., Adachi, C., *Scientific Reports*. 4, 2127 (2013).

Material Design Strategy



HOMO: carbazole-like





LUMO: oxadiazole-like

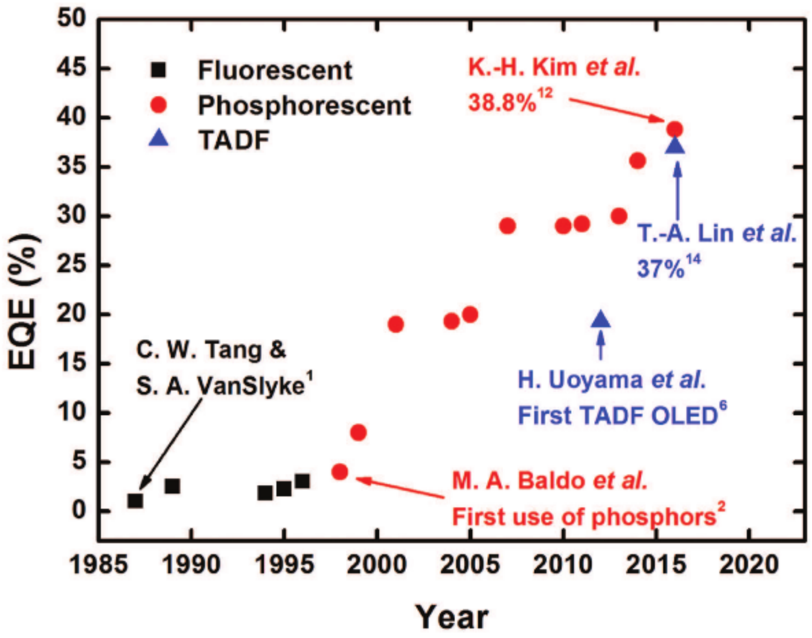
SOLVAY

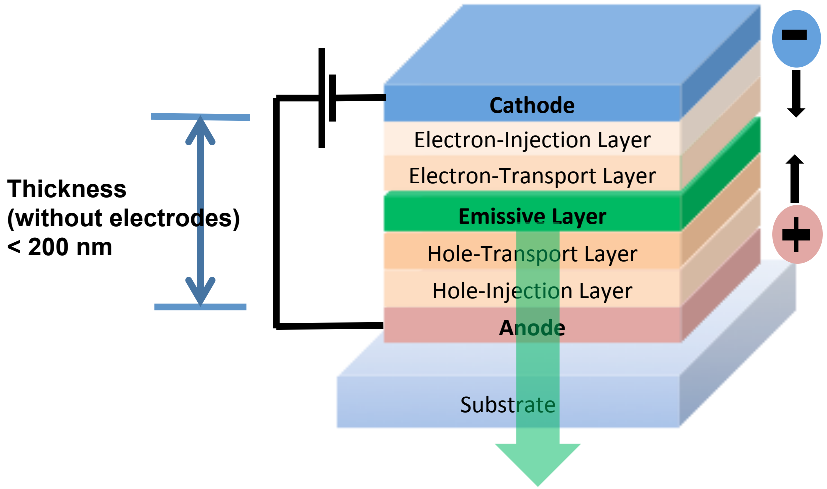
US 9,133,177 B2 issued Sep. 15, 2015

Collaboration with Bredas Group, Georgia Tech

Computed at the DFT B3LYP/6-31 G** level

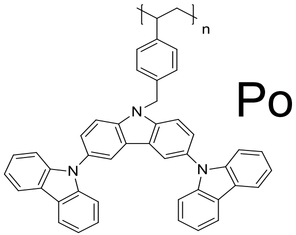
TADF: Organic Light-emitting Diodes



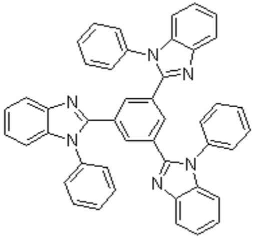


Kim, Kwon-Hyeon & Jang-Joo Kim, Advanced Materials (2018)

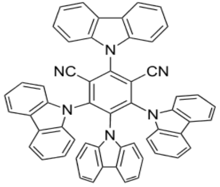
TADF Devices with Carbazole/Sulfone Host



Poly-TriCZ

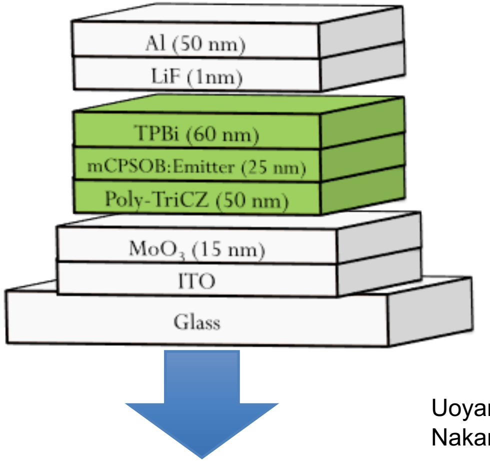


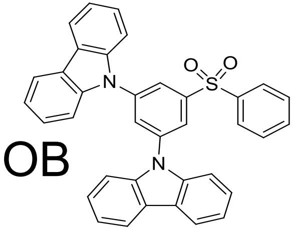
TPBi



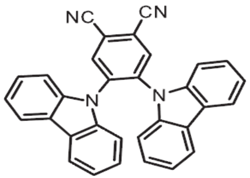
4CzIPN

Bottom emission, top cathode





mCPSOB

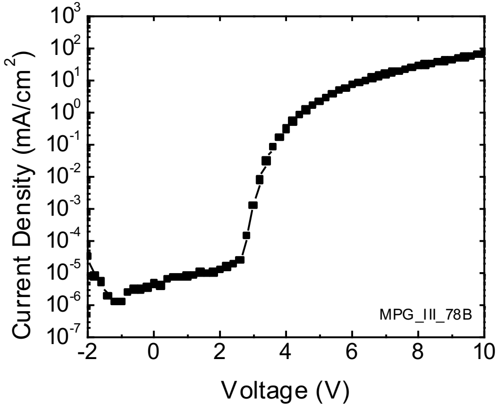


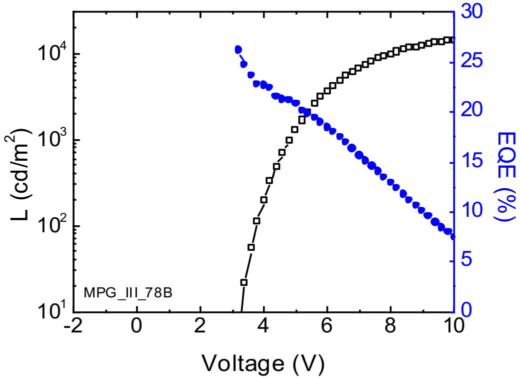
2CzPN

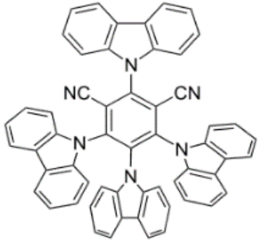
Collaboration with the Marder Group

Uoyama, H., Goushi, K., Shizu, K., Nomura, H., Adachi, C. *Nature*. 492, 234 (2012).
Nakanotani, H., Masui, K., Nishide, J., Shibata, T., Adachi, C., *Scientific Reports*. 4, 2127 (2013).

Green-emitting TADF OLEDs







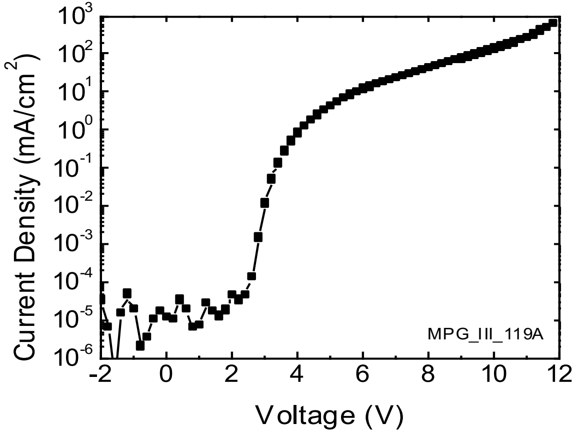
4CzIPN

ΔE_{ST} = 83 meV

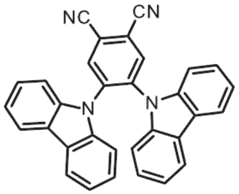
Device	Luminance (cd/m²)	Volt (V)	EQE (%)	cd/A	Lm/W	mA/cm²
4CzIPN	6	3.2	26.2	79.5	78.1	0.01
	110	3.8	22.3	69.2	57.2	0.16
	965	4.8	21.1	64.2	42.0	1.50
	10365	8.2	12.3	37.4	14.3	27.7

M. Gaj, B. Kippelen et al. Org. Electron. 16, 109-112 Jan. (2015)

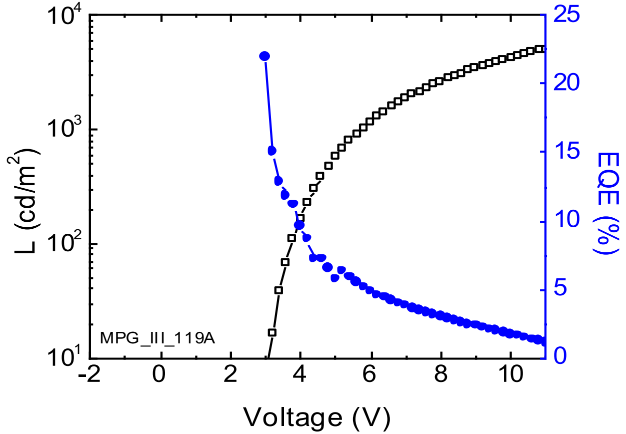
Blue-emitting TADF OLEDs



Blue Emitter

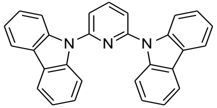


2CzPN

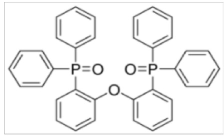


Device	Luminance (cd/m²)	Volt (V)	EQE (%)	cd/A	Lm/W	mA/cm²
2CzPN	6	3.0	22.0	53.8	56.4	0.01
	111	3.8	11.1	27.2	22.5	0.41
	1040	5.8	5.1	12.5	6.8	8.30
	5070	11.0	1.2	2.7	0.8	185.1

High-efficiency Blue-emitting OLEDs

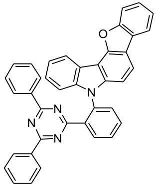


YZ-I-10 (PYD2)
ΔE_{ST}=0.61 eV



DPEPO
HOMO: -6.1 eV
LUMO: -2.0 eV
E_T = 3.3 eV

Host

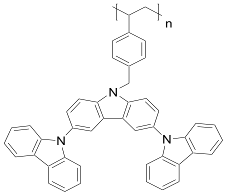


oBFCzTrz (YZ-XI-49)
ΔE_{ST}= -0.14 eV

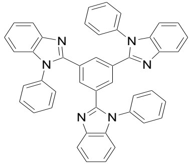
Emitter

Al/Ag (50 /100 nm)
LiF (1 nm)
TPBi (50 nm)
TP3PO (4 nm)
Host : emitter (25 nm, X %)
Poly-TriCZ (80 nm)
MoO_3(15 nm)
ITO
Glass

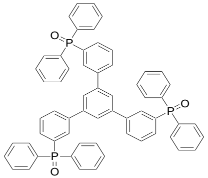
Transport materials



HTL
Poly-TriCZ



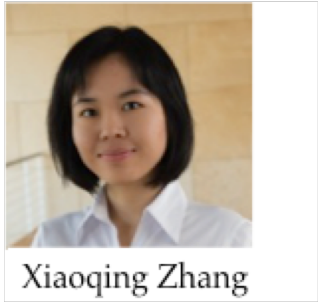
ETL
TPBi

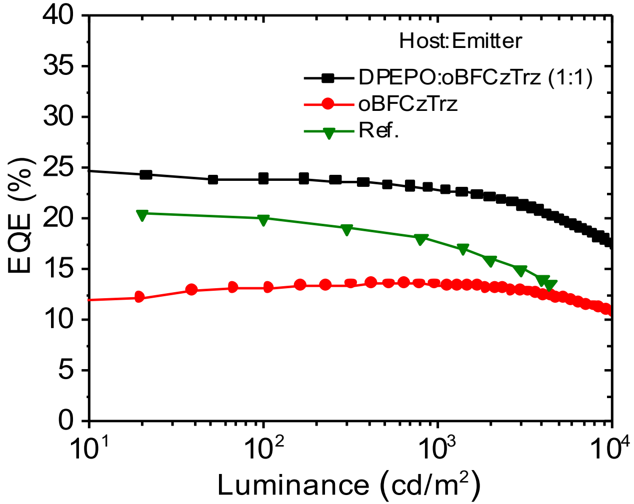


HBL
TP3PO

Ref. [1] Dong Ryun Lee, et.al., ACS Appl. Mater. Interfaces 2016, 8, 23190−23196

Optimized Performance





- **Blends EML:**
  Higher EQE & smaller roll-off

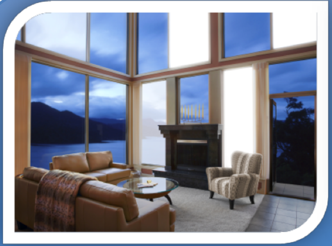
- **Pure material EML:**
  Roll-off is negligible

Emissive layer	EQE(%) Max, @ 10 / 100 /1000 /10000 cd/m²	Von (V) @10 cd/m²	η_C (cd/A) @ 1000 cd/m²	η_P (lm/W) @ 1000 cd/m²
DPEPO: oBFCzTrz (1:1)	25.5, 25.5/24.2/22.8/16.4	3.3	57.9	35.0
oBFCzTrz	13.5, 12.1/ 13.2/ 13.5/ 10.8	4.2	36.3	17.8

Ref. [1] Dong Ryun Lee, et.al., ACS Appl. Mater. Interfaces 2016, 8, 23190−23196

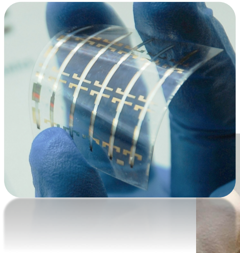
Towards Adaptive Lighting

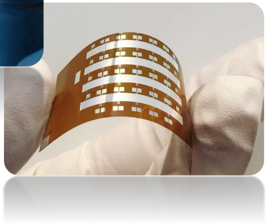
Lighting technology



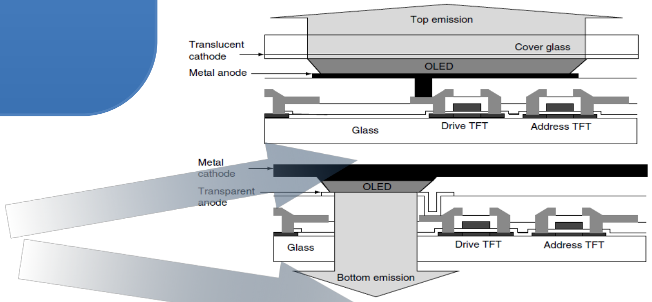
Display technology

Convergence of functionalities





Organic thin-film transistors

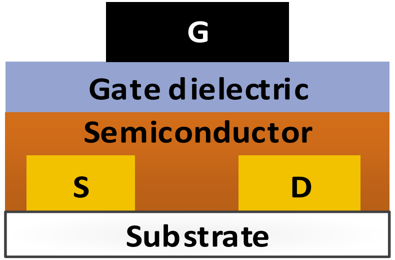


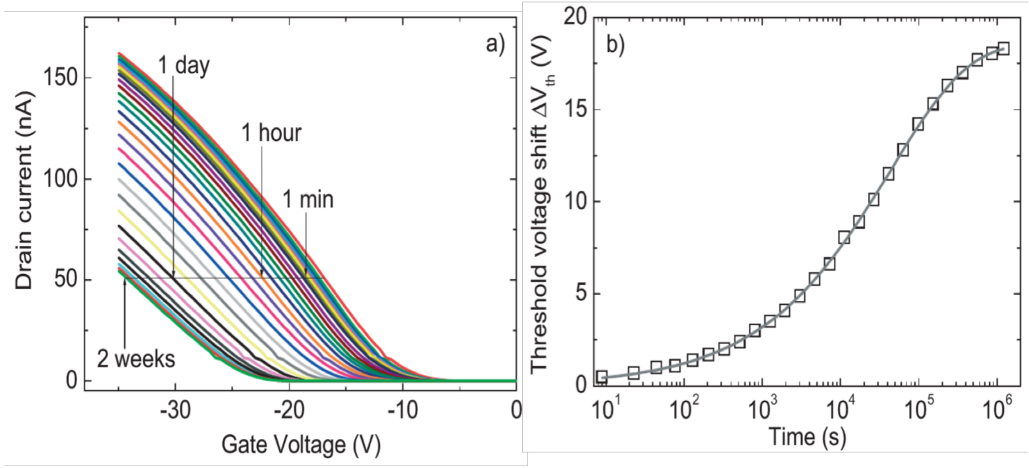
W. D. Bower, *Active Matrix Liquid Crystal Displays,* 1st ed. Burlington: Newnes, 2005.

Outline

- Motivation and external drivers
- Recent advances:
  - Electrode engineering
  - Organic light-emitting diodes
  - Thin-film transistors

Organic Field-Effect Transistors: The Problem

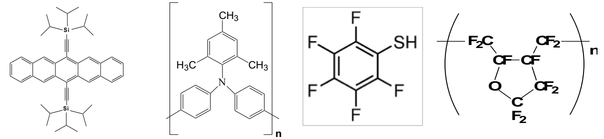




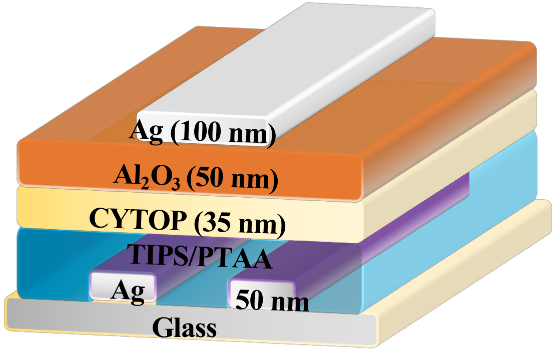
Stability challenge: charge trapping leads to shifts in threshold voltage

$$\Delta V_{TH}(t) = \Delta V_{TH,1\infty} \cdot \left\{1 - \exp\left[-\left(\frac{t}{\tau_1}\right)^{\beta_1}\right]\right\}$$

OFETs with Bilayer Gate Dielectric

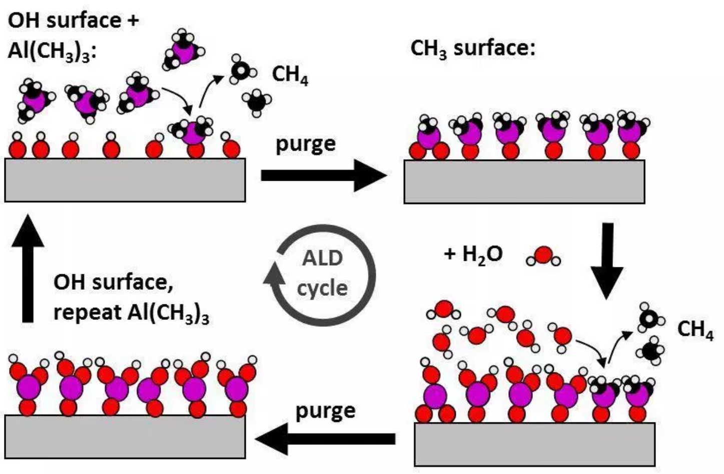


Bi-layer gate dielectric



- US Patent # 9,368,737 B2, issued Jun. 14, 2016.
- D. K. Hwang et al., Advanced Materials 2011, 23, 1293.

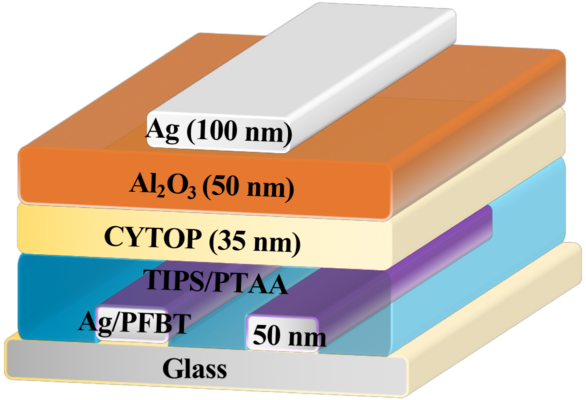
Atomic Layer Deposition (ALD) of



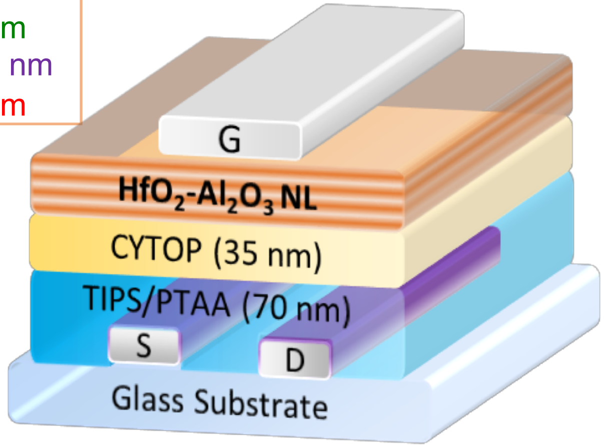
Pioneered the use ALD in OFETs.

- X.-H. Zhang et al., Organic Electronics 2007, 8, 718.

Architecture for Stability Optimization



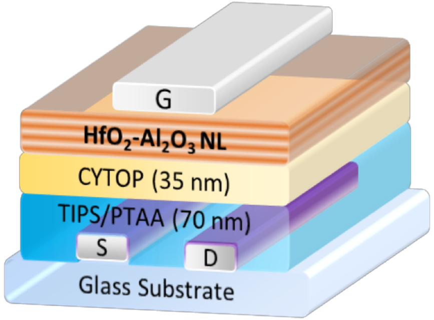
Group A:
A_33: 33 nm
A_27: 27.5 nm
A_22: 22 nm



Oxide layer: Al_2O_3 (grown by ALD)
Problem: corrosion in humid environment and high temperature

Oxide layer: HfO_2/Al_2O_3 nanolaminate (grown by ALD) with different thickness

Compensation Effect in OFET with Bilayer Gate Geometry

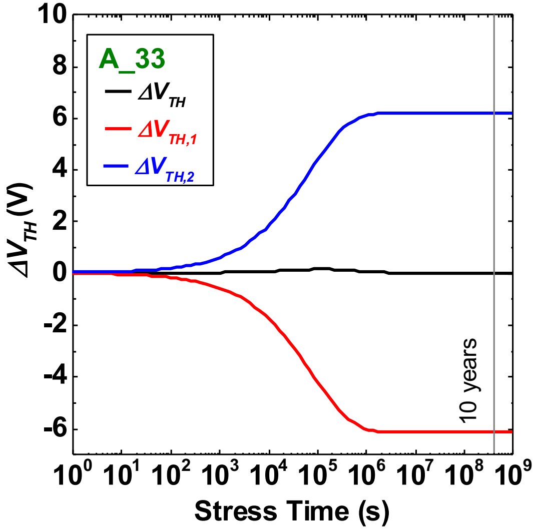


$$\Delta V_{TH}(t) = \Delta V_{TH,1\infty} \cdot \left\{1 - \exp\left[-\left(\frac{t}{\tau_1}\right)^{\beta_1}\right]\right\}$$

charge-trapping effect (decrease)

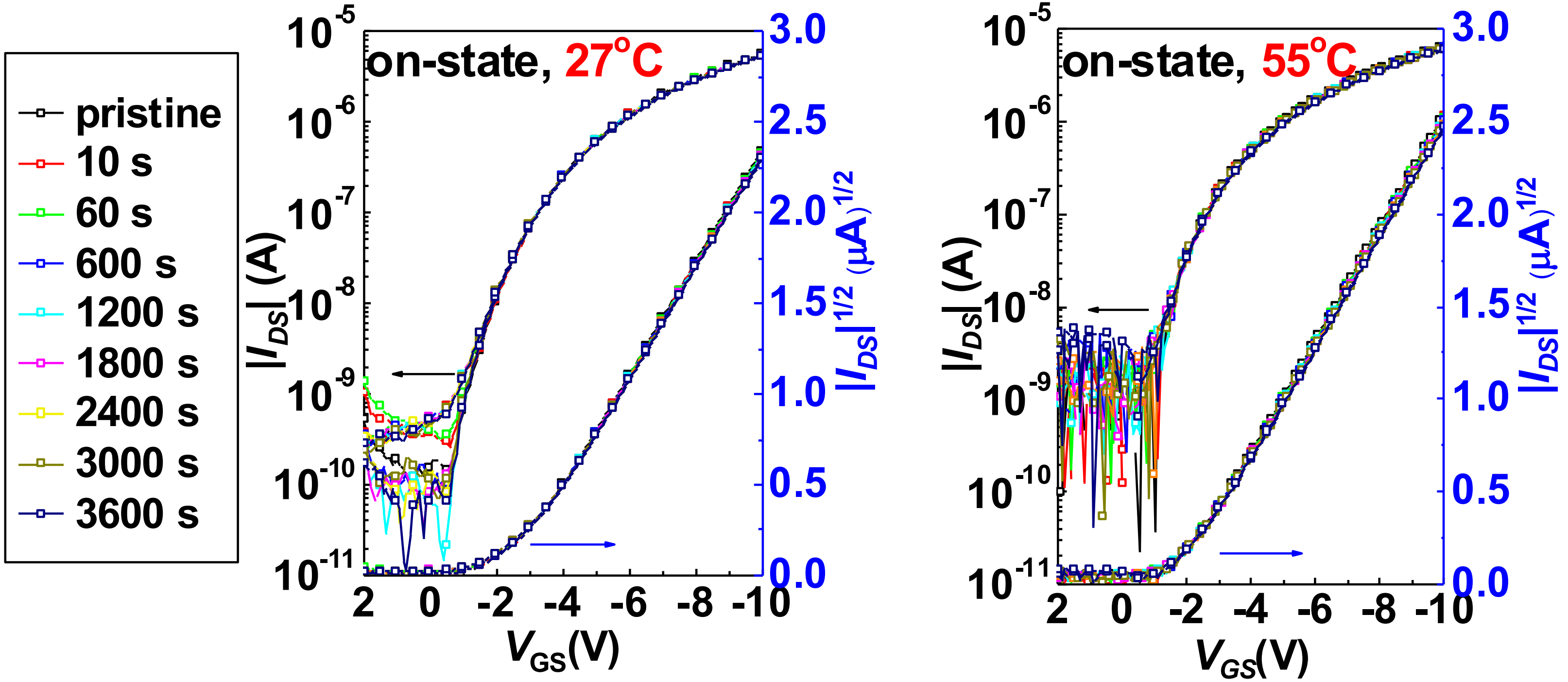
$$+\Delta V_{TH,2\infty} \cdot \left\{1 - \exp\left[-\left(\frac{t}{\tau_2}\right)^{\beta_2}\right]\right\}$$

(increase)



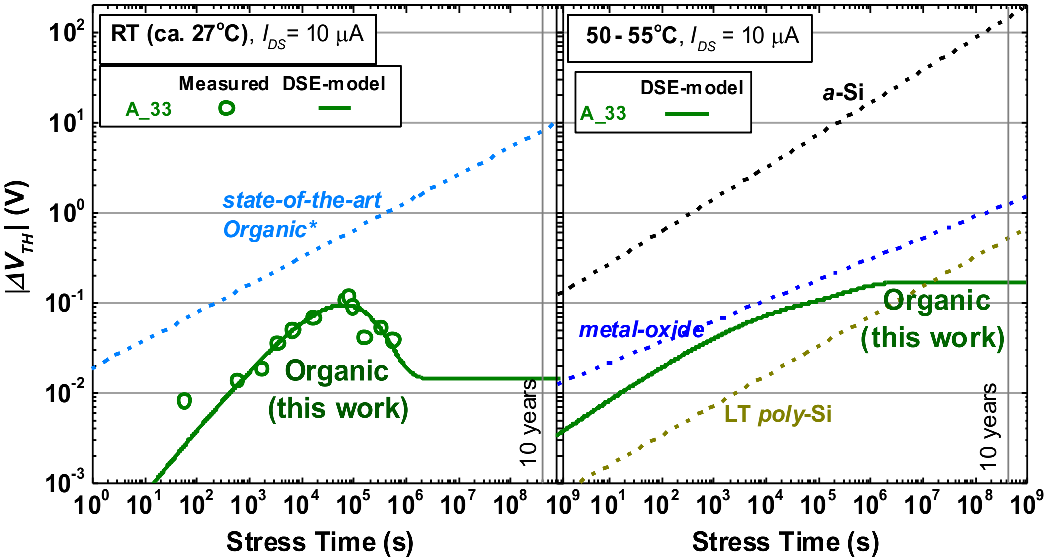
Compensation due to two mechanisms with opposite effect

Bias Stress Tests @ Higher Temperature



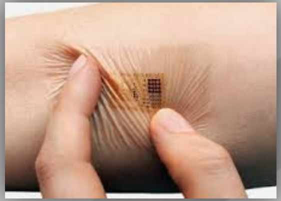
On-state (A_33) ($V_{DS} = V_{GS} = -10$ V)

Stability of Thin-film Transistors

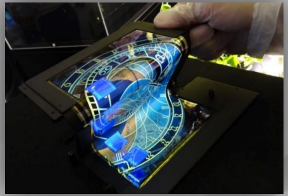


X. Jia, C. Fuentes-Hernandez, C.-Y. Wang, Y. Park, B. Kippelen, Science Advances 2018, 4, aao1705.

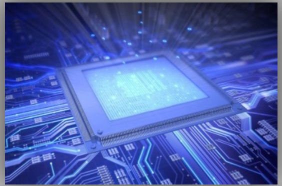
Technology Roadmap



Implantable, in vivo electronics - **Biocompatible**



Conformal, stretchable and wearable - **Soft**



All additive direct writing and 3D printing - **Flexible**

Photolithography and etching - **Rigid**

Georgia Tech | Center for Organic Photonics and Electronics

2005 2015 2025

Synopsis: Lessons Learned

- Science is your friend, keep exploring
- When you go in the lab be prepared for the unexpected
- Do not disregard outliers in your data sets
- Challenge the conventional wisdom and push the frontiers

Louis Pasteur

Thank you