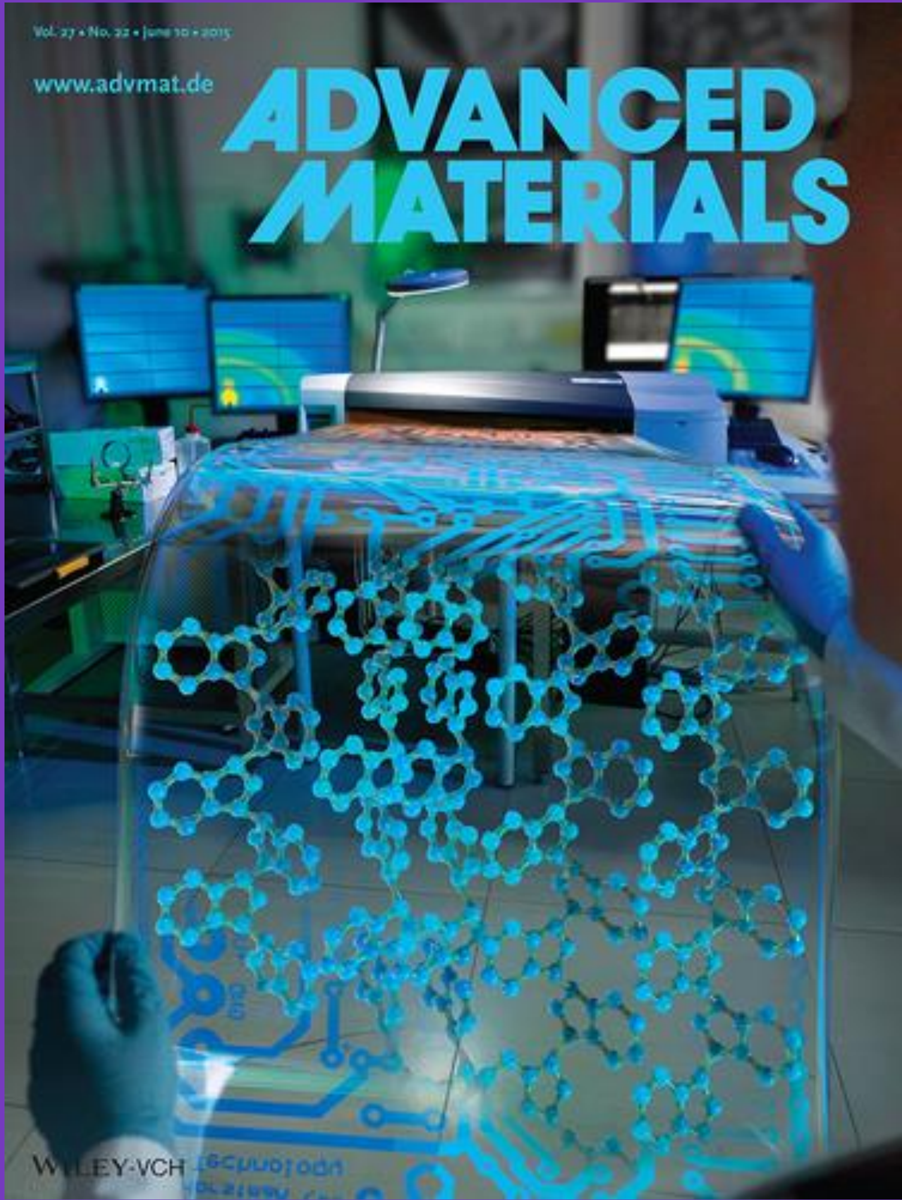
ELEC-E9210 Organic Electronics: Materials, Devices & Applications

Organic Field-Effect Transistors II

Aalto University
School of Electrical Engineering

organicelectronics.aalto.fi



Today´s Class

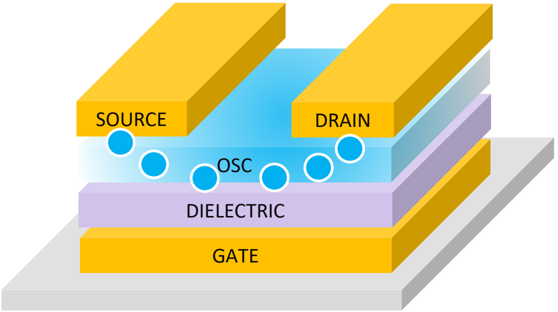
Previously

- basic ***working principle*** of organic *field-effect* ***transistor*** and main features

Today´s class

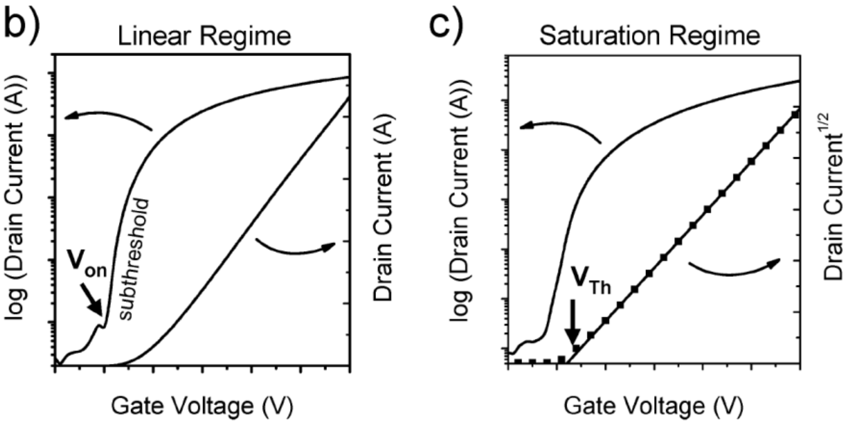
- ***building blocks*** of organic transistor and how to engineer those to improve

OFET in Brief



Field-Effect Transport (FET)

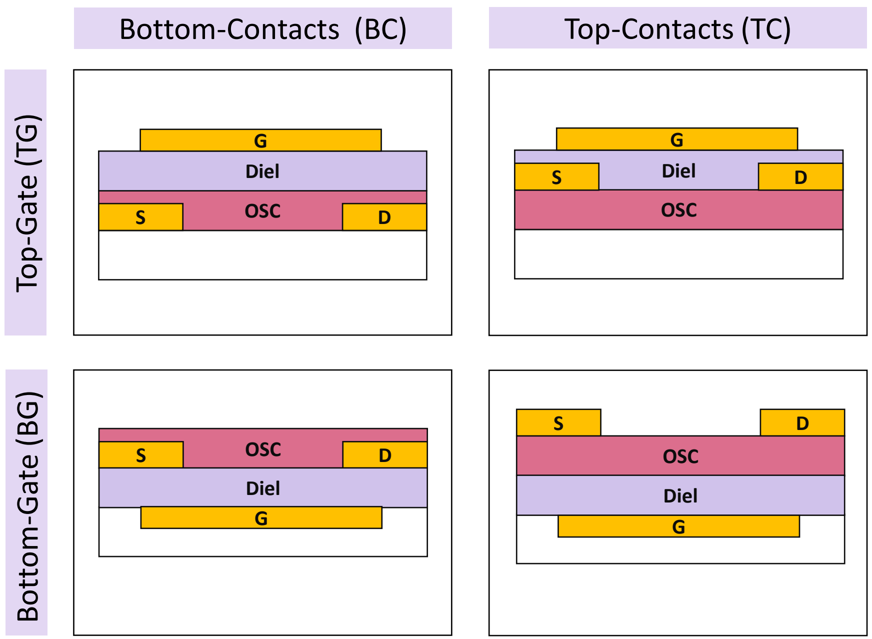
- 3 electrodes (S, D, G)
- horizontal *field-effect*



$$I_{D,lin} = \frac{W}{L}\,\mu\,C_i(V_G - V_{th})\,V_D$$

$$I_{D,sat} = \frac{W}{2L}\,\mu\,C_i(V_G - V_{th})^2$$

OFET Configuration(s)

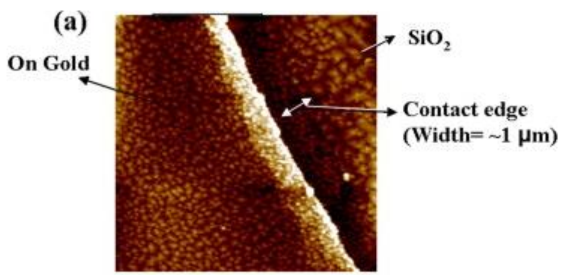


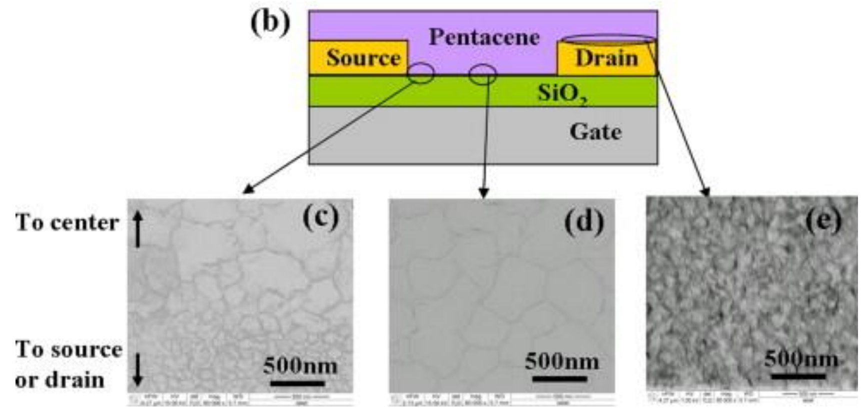
- is any fabrication process interfering/affecting OSC properties (*i.e.* electrode fabrication)?
- **OSC packing** and **film parameters** (*i.e.* mobility) depends on the underlying surface
- **interface(s) become crucial**

OFET: Top *vs.* Bottom Contacts

underlying surface/substrate

TC BC



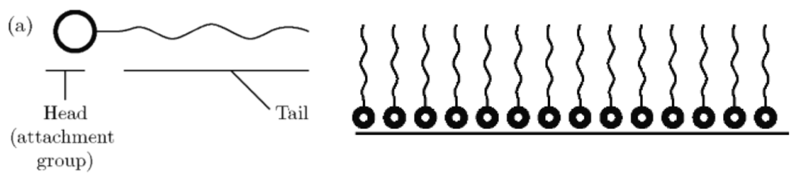


Org. El. **10**(5), 775 (2009)

Contact resistance also changes based on underlying growth surface and the electrode

OFET: Improving Contacts with SAM

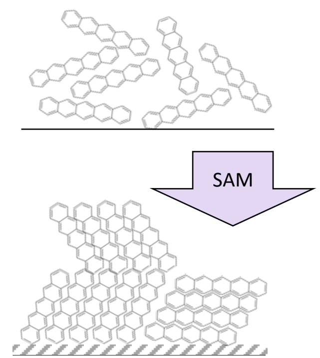
Self-Assembled Monolayer (SAM) can be used to improve (bottom) contacts, while enhancing adhesion and/or affinity



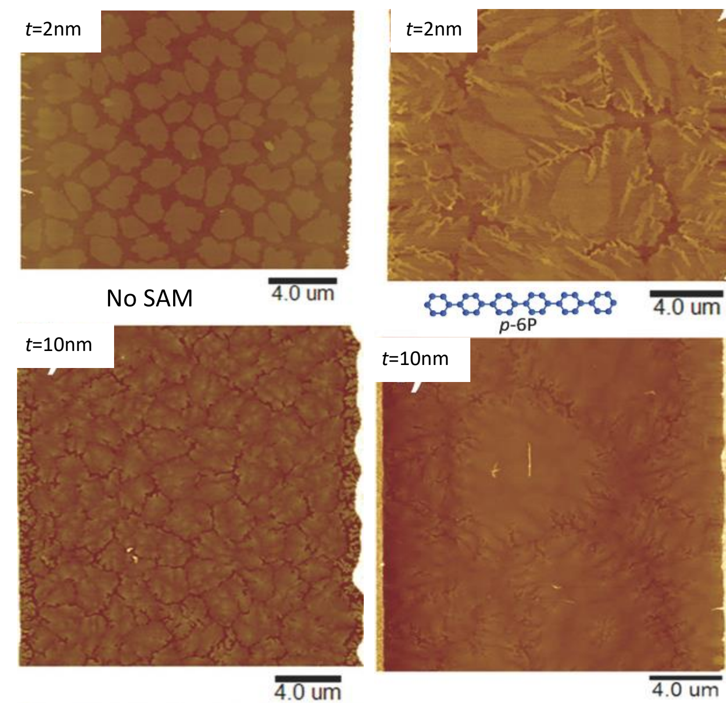
thiols attach to Au, Pt and other metals and creates low-surface energy layer on electrodes (thin enough to allow tunneling)

SAM can be selective:

- attachment selectivity
- cross-linking
- hydrophobic/hydrophilic nature
- amine termination
- fluorination
- selective tail reactivity



pentacene on Au surface

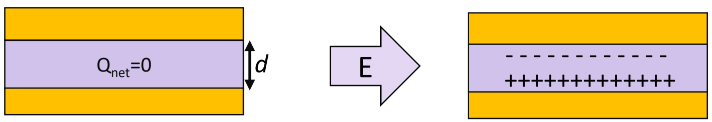


Different morphology of pentacene depending on the presence of SAM (*p*-6P) on underlying surface

Adv. Elec. Mat. 3(11), 1700128 (2017)

OFET: Gate Dielectric

Charge redistribution at the dielectric surface can affect the properties of adjacent materials (electronic states and transport)



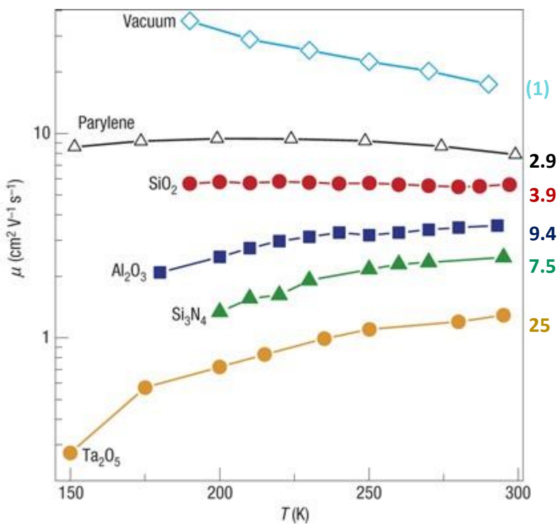
dielectric constant — vacuum permittivity

$$Q = \varepsilon E = \frac{\varepsilon V}{d} \rightarrow \quad C = \frac{Q}{V} = \frac{k\varepsilon_0}{d}$$

Carrier mobility depends on ***device features*** and ***OSC/diel*** interface:

- W, L, dielectric geometry and properties (C_i)
- conduction regime (linear and/or saturation)

V_{th} strongly depends ***dielectric/OSC interface*** due to ***impurities*** and ***charge trapping sites*** tend to increase this value. V_{th} can be modulated through value of C (tuning charge density at interface)



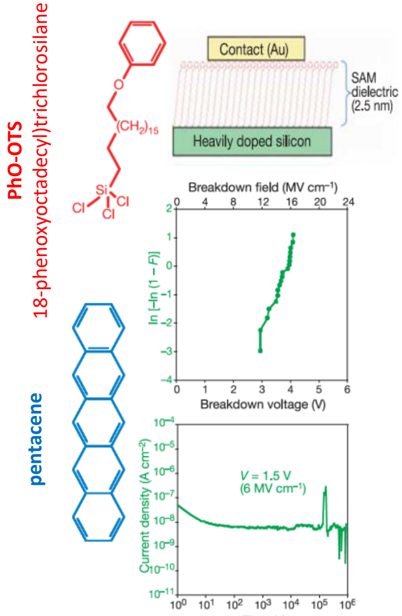
Nat. Mat. **5**, 982 (2006)

Temperature dependence of the mobility in single-crystal rubrene FETs with six different gate dielectrics (@V_G~−15 V)

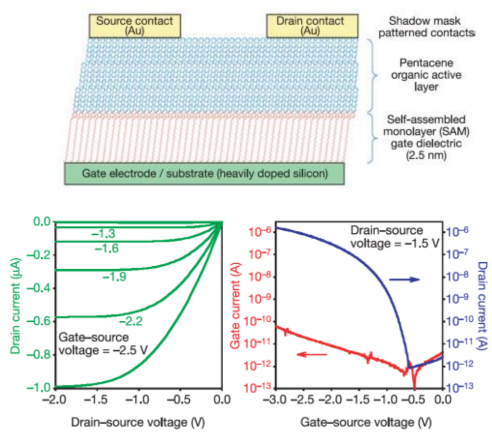
OFET: SAM as Gate Dielectrics

SAM: ultimate thinnest gate dielectric with high capacitance and low leakage current

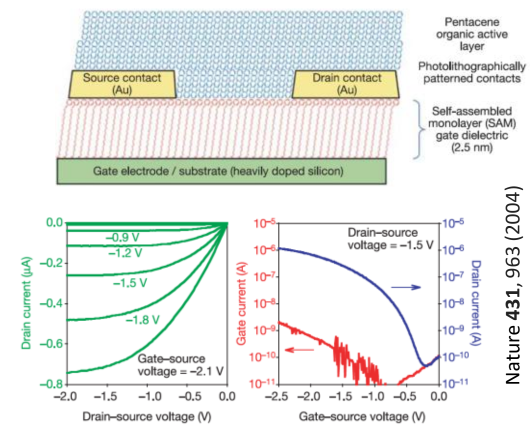
capacitor MIS structure



OFET structure (BG-TC)



OFET structure (BG-BC)

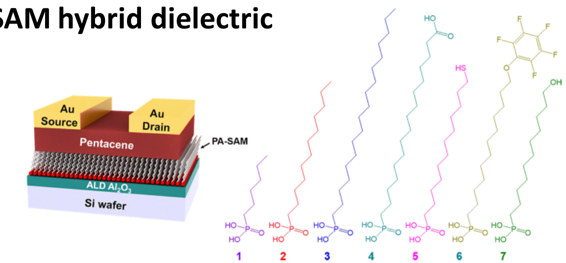


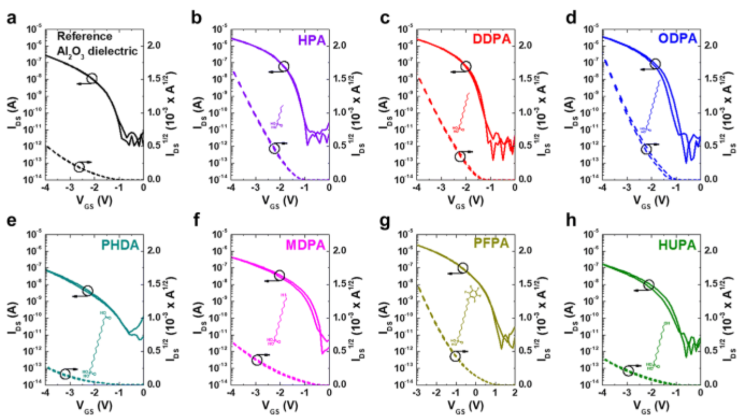
Nature **431**, 963 (2004)

Schematics and electrical characterization of (left) capacitor-like structure and (middle) BG-TC and (right) BG-BC pentacene-based OFETs using PhO-OTS as dielectric layer.

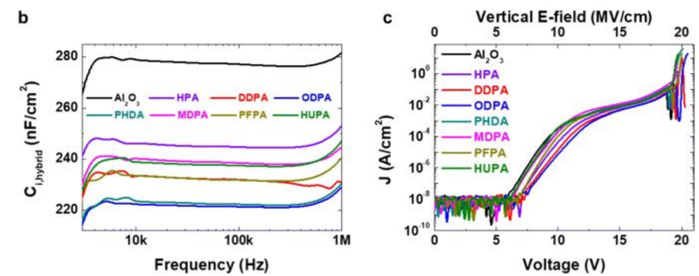
OFET: Hybrid SAM/Oxide Gate Dielectrics

Al_2O_3/SAM hybrid dielectric





Transfer characteristics (solid) and sqrt(I_{DS})(dashed) of OFETs with hybrid dielectrics with various PA-SAMs (as labelled)



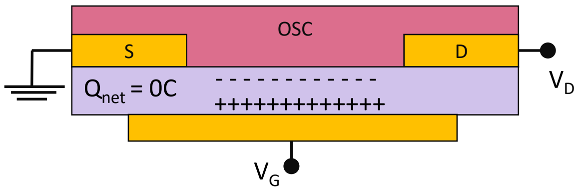
Nano Conv. **5**, 20 (2018)

b. capacitive densities–frequency (C_i–F) and **c.** leakage current densities-voltage (J–V) of hybrid dielectrics with various PA-SAMs

Dielectric	Contact angle (°)	μ_{sat} (cm^2/Vs)	V_{Th} (V)	I_{on}/I_{off}
Al_2O_3	< 10	0.05	− 2.18	~ 10^5
HPA	102	0.35	− 1.71	~ 10^6
DDPA	105.5	0.41	− 1.83	~ 10^6
ODPA	109.8	0.58	− 1.84	~ 10^6
PHDA	25.9	0.02	− 2.35	~ 10^4
MDPA	65.1	0.05	− 1.64	~ 10^5
PFPA	102	0.27	− 0.58	~ 10^6
HUPA	28.5	0.03	− 1.95	~ 10^5

Al_2O_3 → high-k dielectric
SAM → favor interface with OSC

OFET: Gate Leakage



For an ideal (gate) dielectric, I_G = 0A for any applied bias (V_D, V_G)

conservation of charge

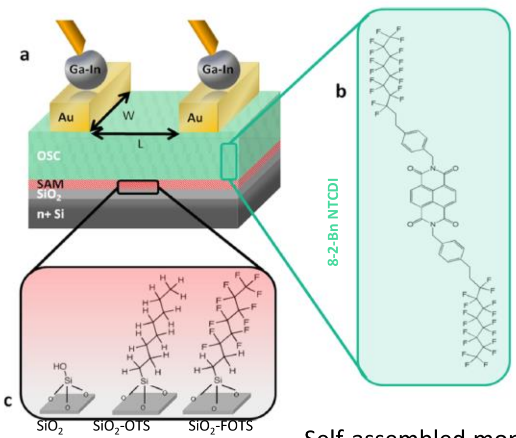
$$I_D + I_S + I_g = 0$$

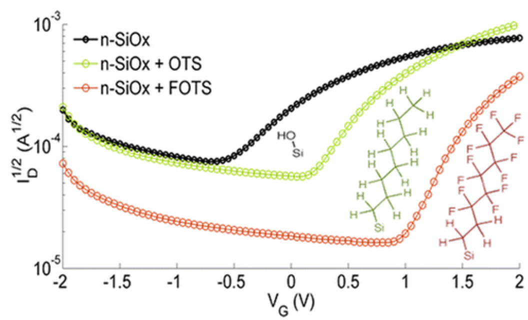
ideal OFET (I_G = 0)

$$I_D = -I_S$$

leakage current

- imperfect gate dielectrics
- surface conduction
- bulk device transport
- no OSC patterning



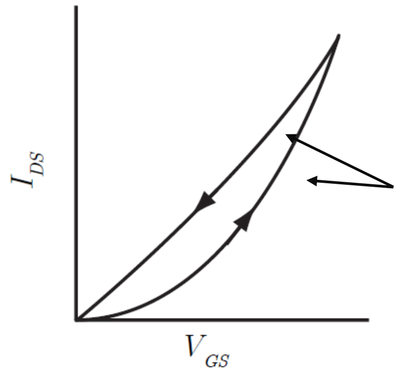


ACS Appl. Mat. & Int. **5**, 7025 (2013)

Self-assembled monolayer dipole as an electrostatic barrier to reduce leakage currents in n-channel OFETs on SiO_2 dielectrics

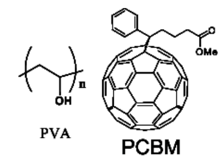
OFET: Hysteresis

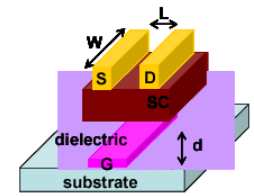
Hysteresis appears when ***gate voltage sweeps result in shift*** (left or right) of the transfer characteristic, with subsequent change of the device V_{th}

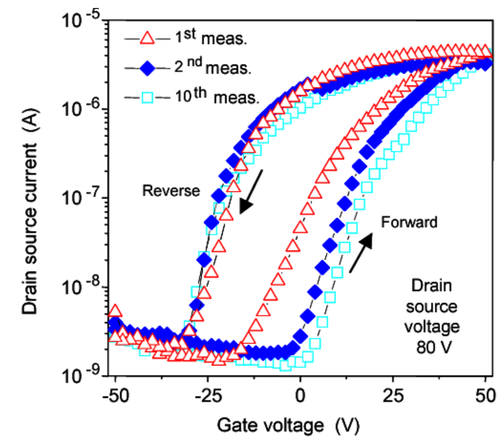


difference in charge distribution (and thus device properties), given the same bias condition

- ***dielectric charge storage*** injection of charge in the dielectric reduces the field felt by the OSC
- ***water incorporation*** in the gate dielectric (*i.e.* polymer dielectric with strong polar group), which leads to *slow dielectric relaxation*
- ***traps*** in the OSC can decrease/increase I_D; traps are often ***extrinsic*** (*i.e.* water, oxygen) and this process can be reversible

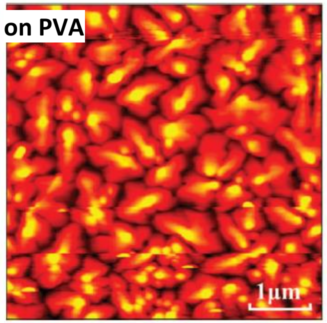


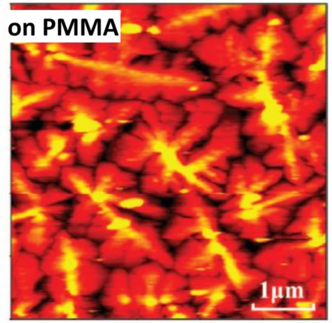




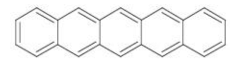
IEEE Trans. on Diel. and Elect. Insul. **13**(5), 1082 (2006)

OFET: *Reducing* Hysteresis



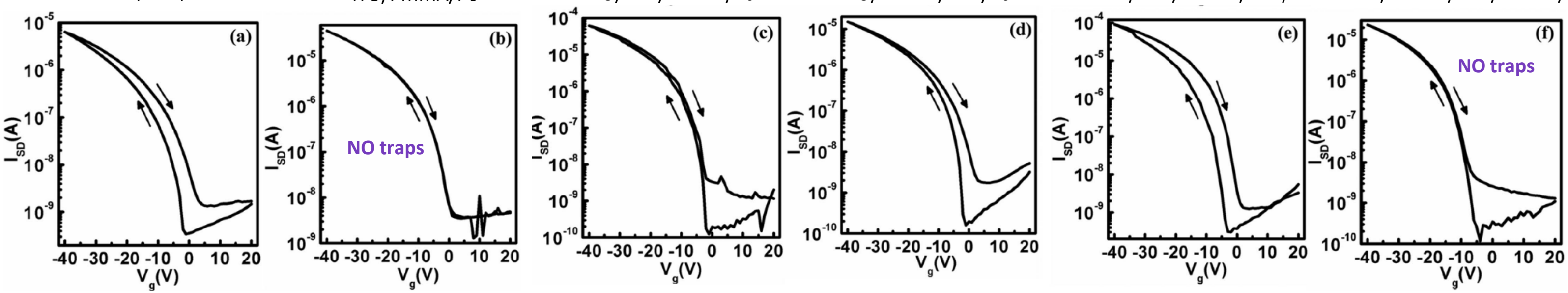


Pentacene, P6 (50nm)



- charges from pentacene are trapped at the PVA/pentacene interface and PVA bulk
- charge (from gate) are trapped at PVA/gate interface and PVA bulk

ITO/PVA/P6 ITO/PMMA/P6 ITO/PVA/PMMA/P6 ITO/PMMA/PVA/P6 ITO/PVA/PMMA/PVA/P6 ITO/PMMA/PVA/PMMA/P6

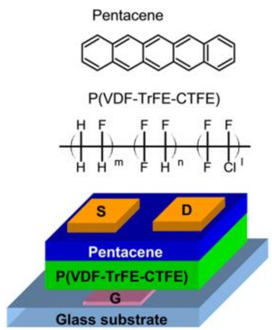


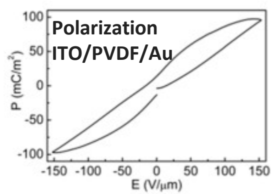
AIP Adv. **3**, 052122 (2013)

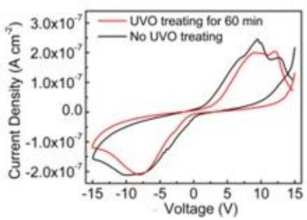
sandwich structure (PMMA/PVA/PMMA) allows controlling hysteresis in 0-10V range

OFET: *Exploiting* Hysteresis

Hysteresis is NOT ALWAYS *DETRIMENTAL* (if controllable) → **memory devices:** modulation of channel conductance by remnant polarization of dielectrics after programming (P)/erasing (E) bias





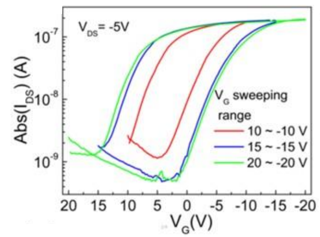


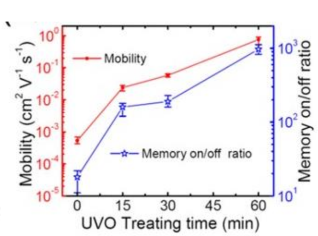
ferroelectric P(VDF-TrFE-CTFE)

- high dielectric constant
- remnant polarization (P_r) of 12.9mC/m^2 @150MV/m
- low coercive field ~14V/µm

UV-ozone

modifies surface → pentacene with different grain size





Sci. Rep. **6**, 36291 (2016)

- high mobility of 0.8 cm^2/Vs, low P/E voltage of ±15 V
- large memory window (ΔV_T) of 15.4~19.2 V
- good memory ON/OFF ratio ~10^3
- endurance over 100 cycles, stable retention ability

Summary

Today´s Class

- ***Building blocks*** and **characteristics** of ***OFET*** (electrodes, dielectric, hysteresis)

Next

- ***Applications*** of **organic field-effect transistors**