High frequency printed polymer transistors

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“ORGANIC ELECTRONICS - Principles, devices and applications”

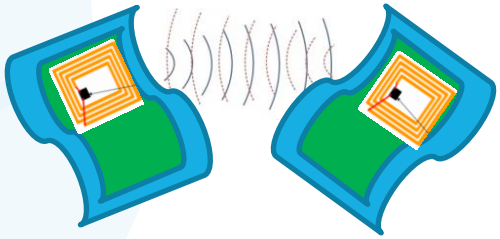
Politecnico di Milano, 26 November 2015

Why improving «speed»

GHz

Wang et al., TLIST, 2013

MHz

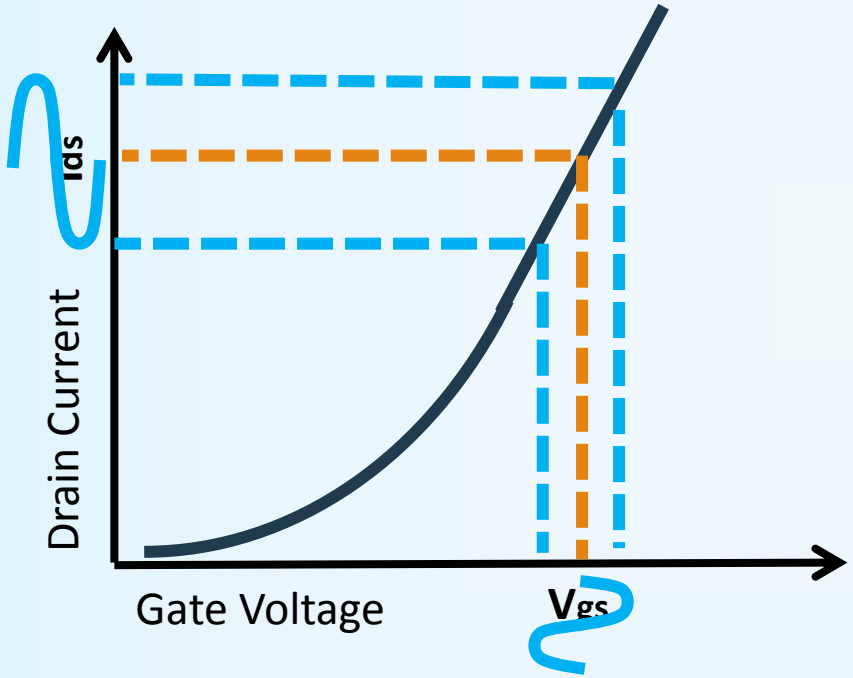


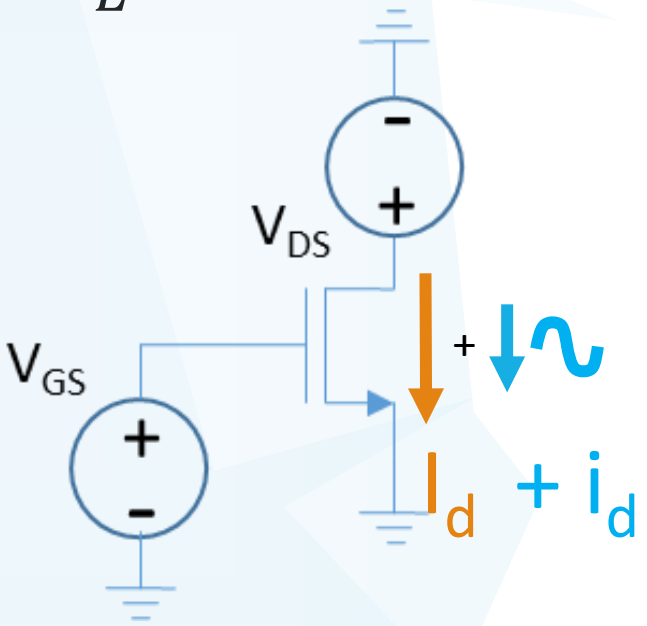
NEW OPPORTUNITIES

Further advantages if done with scalable and high-throughput printing processes

Transconductance

$$I_d = \frac{1}{2}\mu C'_{OX}\frac{W}{L}(V_{GS}-V_T)^2 = \frac{1}{2}\mu C'_{OX}\frac{W}{L}V_{od}{}^2$$

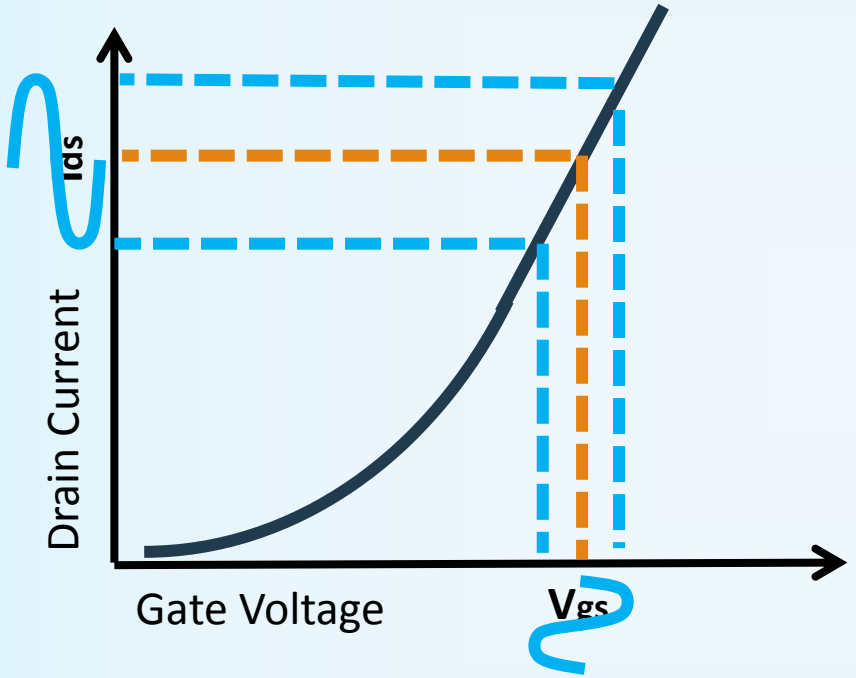


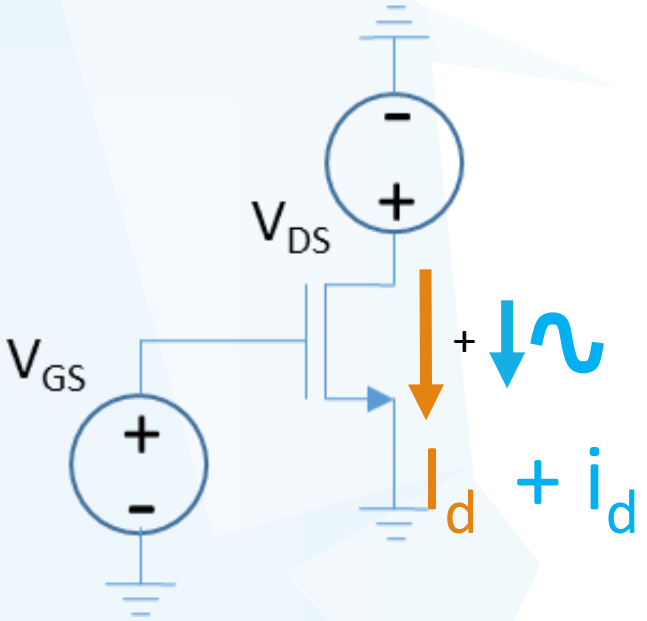


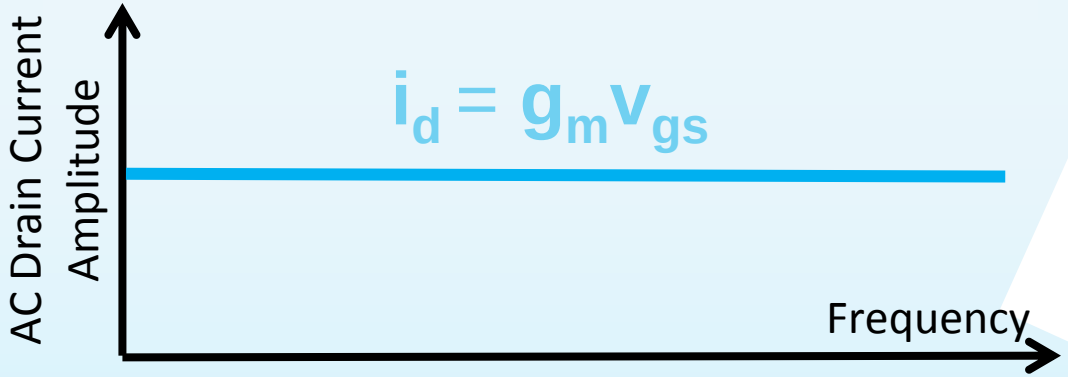
$$i_d = g_m v_{gs}$$

If $v_{gs} << V_{GS}$ $\quad g_m = \left.\frac{di_D}{dv_{GS}}\right|_{v_{GS}=V_{GS}} = \mu C'_{OX}\frac{W}{L}V_{od}$ (saturation regime)

Transconductance vs. *f*





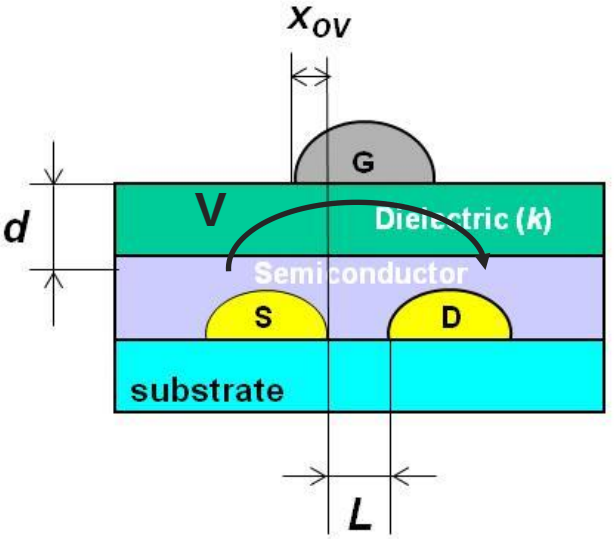


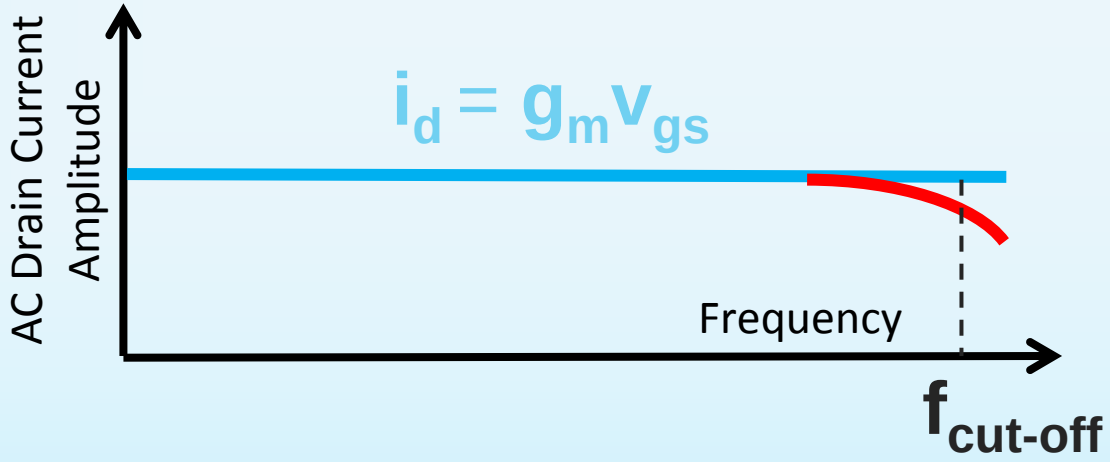
Transit time

$$v = \mu E = \mu \frac{V}{L}$$ Carrier velocity

$$\tau = \frac{L}{v} = \frac{L^2}{\mu V}$$ Carrier transit time

Cut-off Frequency $$f_{cut-off} = \frac{1}{2\pi\tau}$$

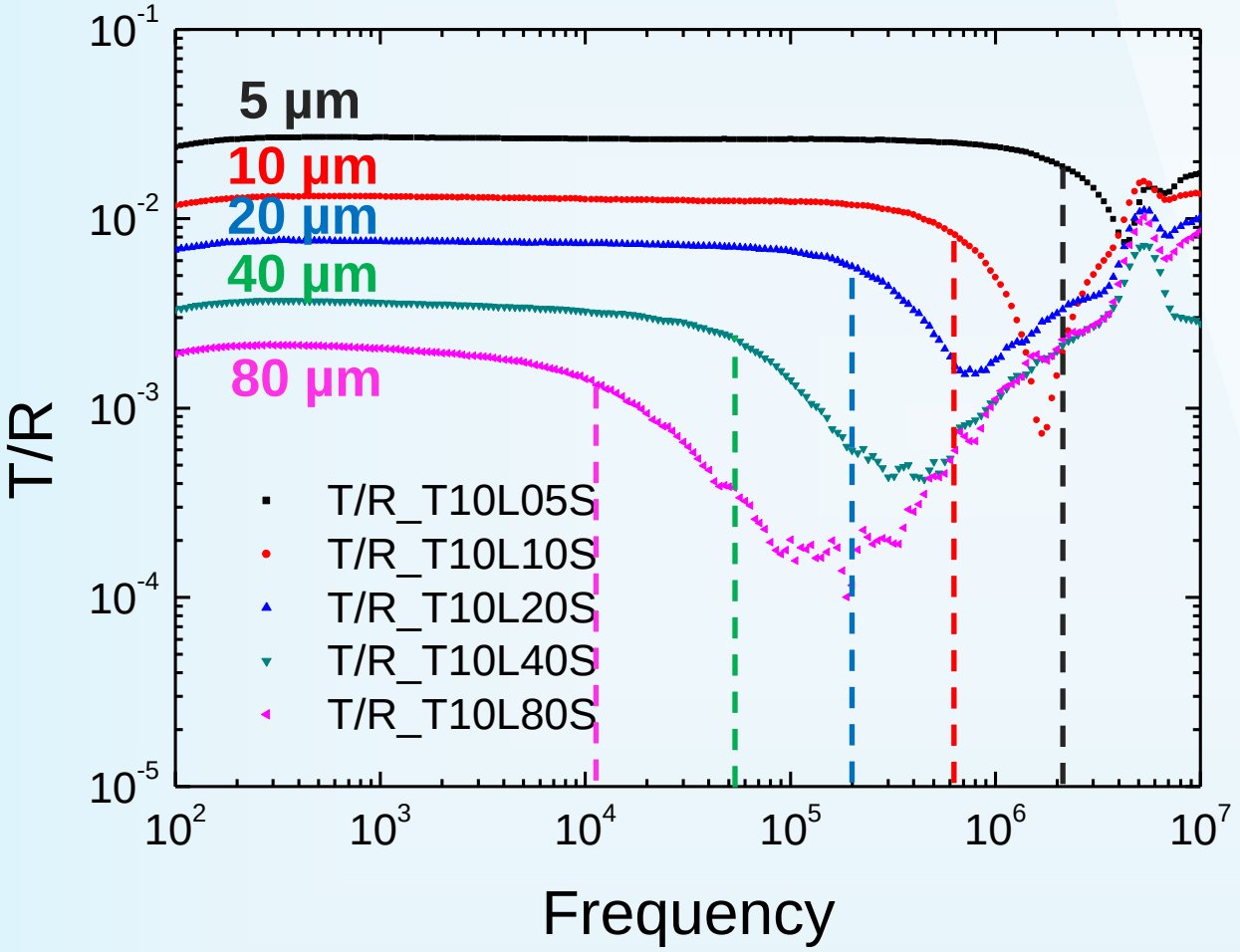


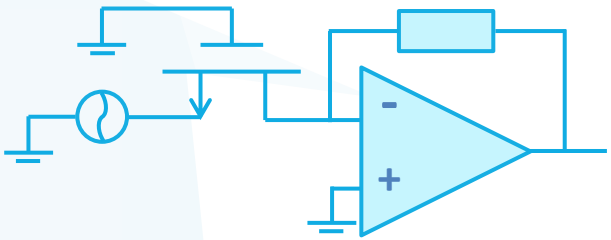


L = 10 µm
μ = 1 cm²/Vs

$f_{cut-off}$ ≈ 400 kHz @10V
≈ 2 MHz @50V

Measurement of $f_{cut\text{-}off}$

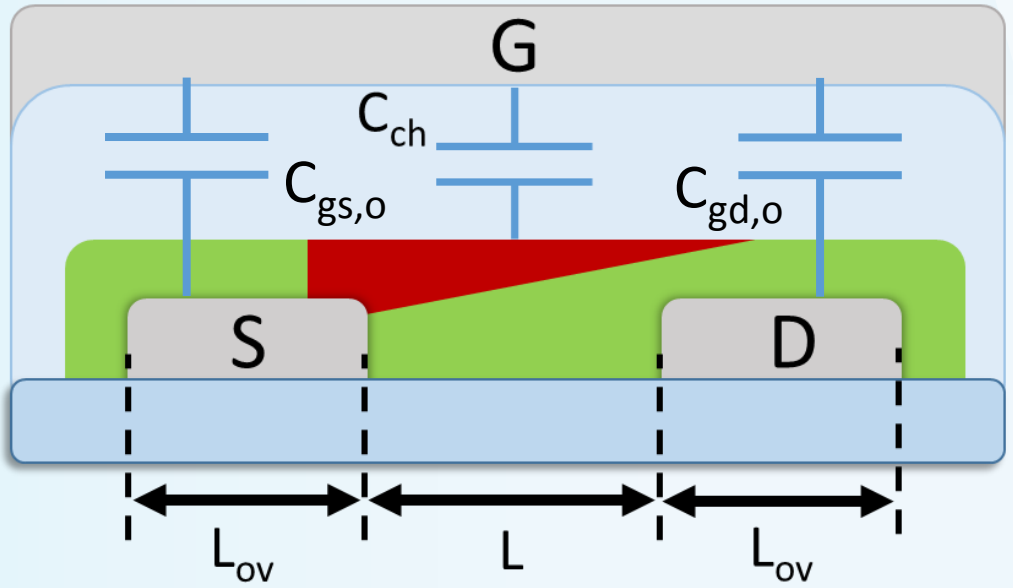


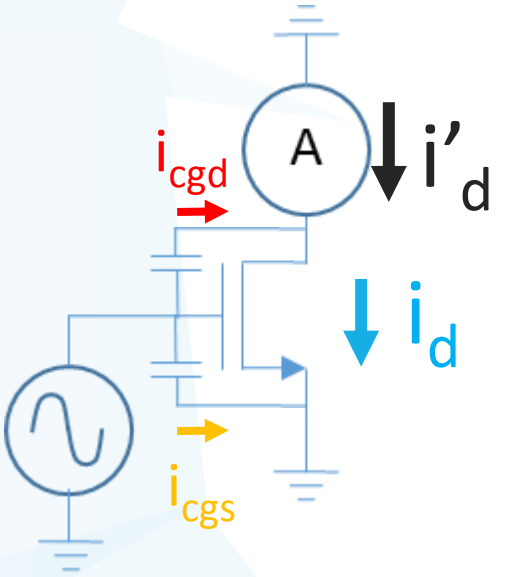


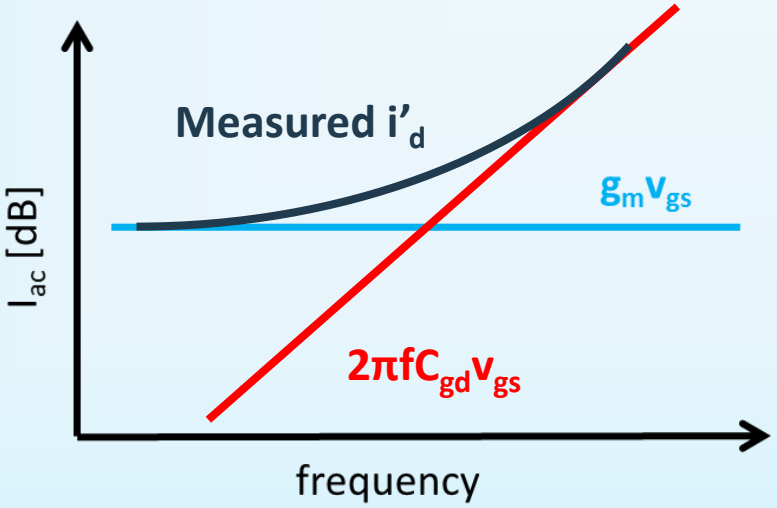
L (µm)	F_{sat} (Hz)
5	2M
10	600k
20	200k
40	40k
80	10k

L (µm)	5	10	20	40	80	
Gm	2.7	1.31	0.76	0.36	0.21	[µA/V]

Effect of Capacitances





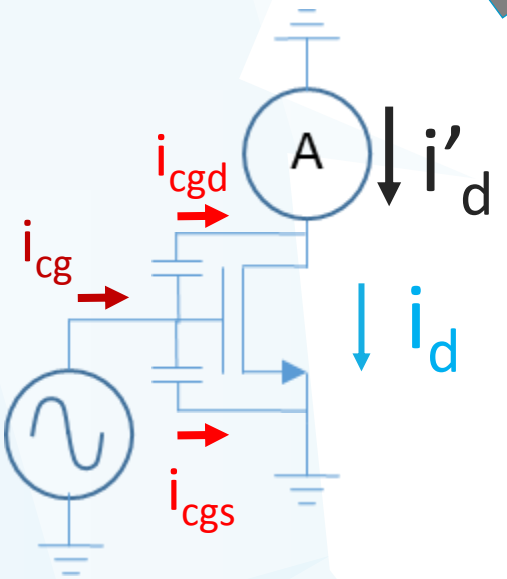


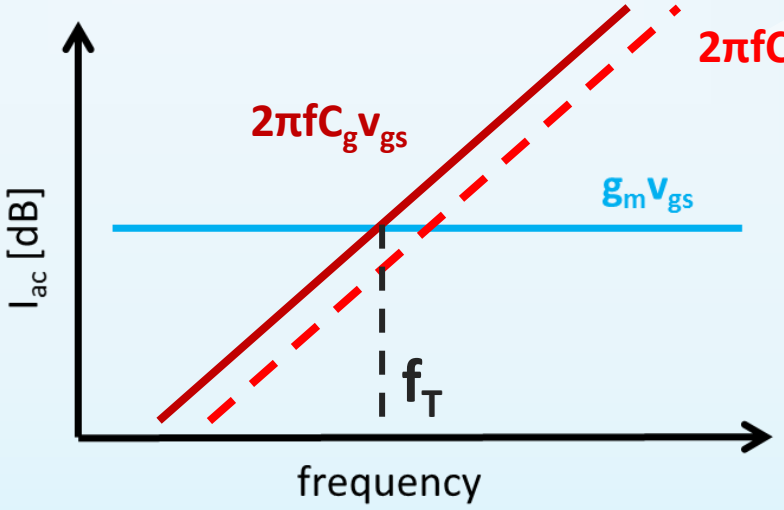
$$i_d' = i_d - i_{cgd} = g_m v_{gs} - j2\pi f C_{gd} v_{gs}$$

Frequency of Transition f_T

$$\frac{|i_d|}{|i_{cg}|} = 1 \qquad |g_m v_{gs}| = |j2\pi f C_g v_{gs}|$$

$$f_T = \frac{g_m}{2\pi C_g} = \frac{g_m}{2\pi\,(C_{gs} + C_{gd})}$$

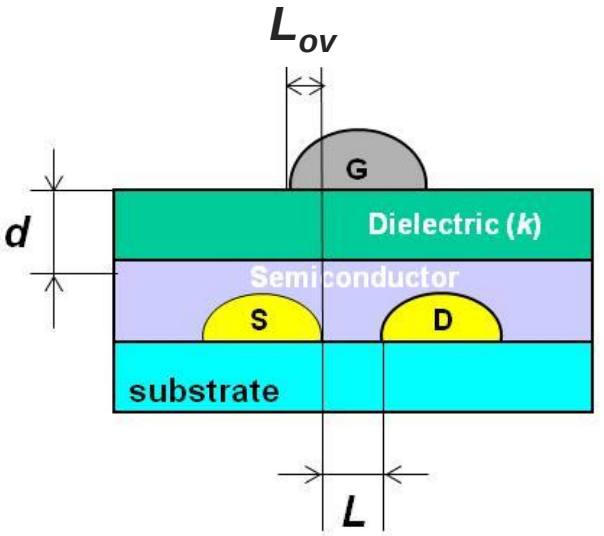




M. Caironi et al., Semicond. Sci. Technol. 26 (2011) 034006

Frequency of Transition f_T

$$f_T = \frac{g_m}{2\pi\,(C_{gs} + C_{gd})}$$



Ideal (no overlap): $$f_T = \frac{\mu_{app} V_{od}}{2\,\pi\,L^2}$$

Real (overlap): $$f_T \approx \frac{\mu_{app} V_{od}}{2\,\pi\,L\,(\,L + 2\,L_{ov}\,)}$$

M. Caironi et al., Semicond. Sci. Technol. 26 (2011) 034006
F. Ante et al., Small 8 (2012) 73

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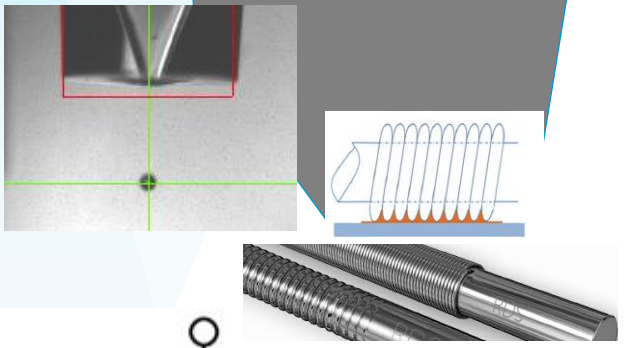
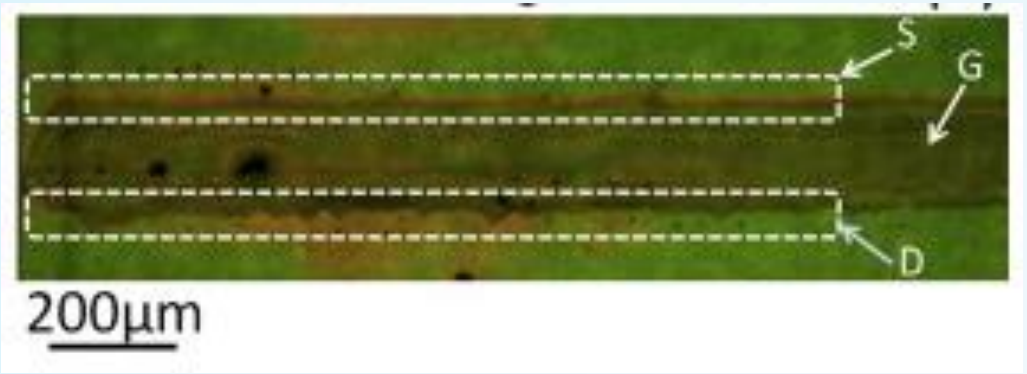
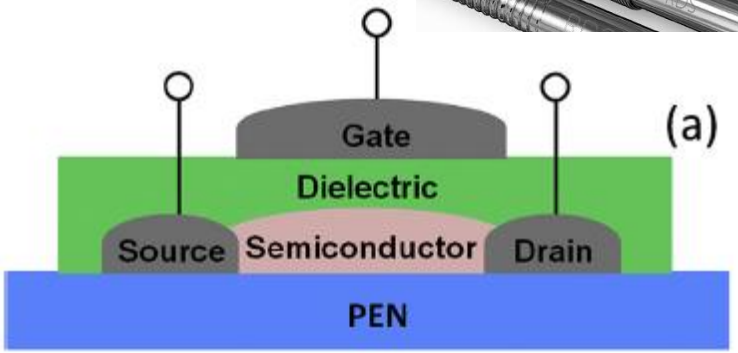
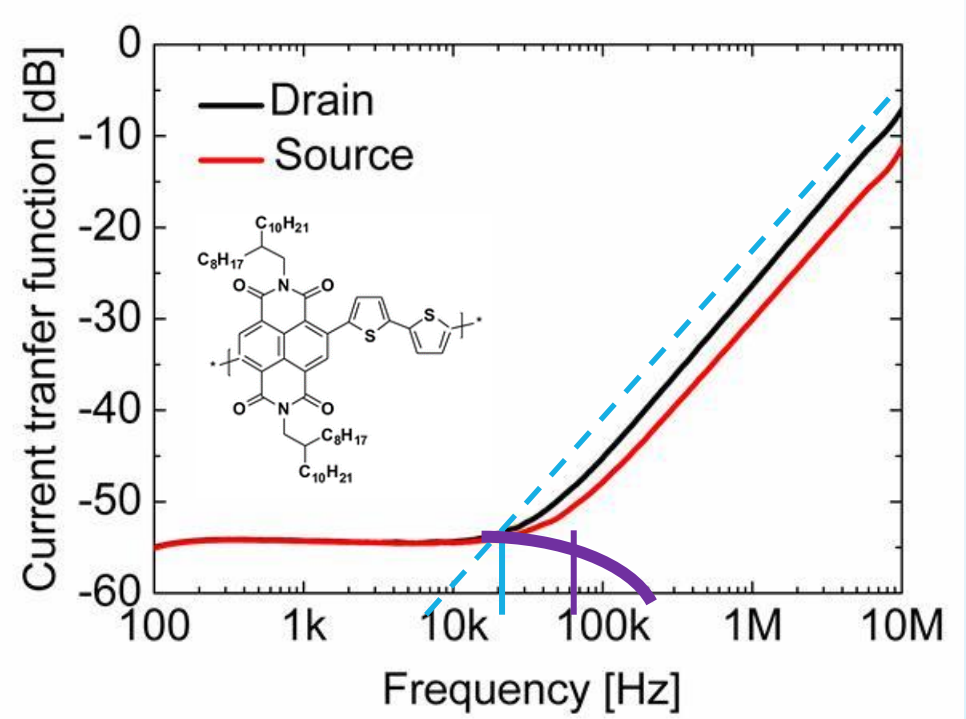
f_T for all printed OFET







L= 46 µm, W = 1180 µm, dielectric thickness = 700 nm, $V_g = V_d = 40$ V



$\mu \approx 0.2$ cm²/Vs

$g_m \approx 1$ µA/V

C_{gs} = 2.3 pF - C_{gd} = 3.8 pF

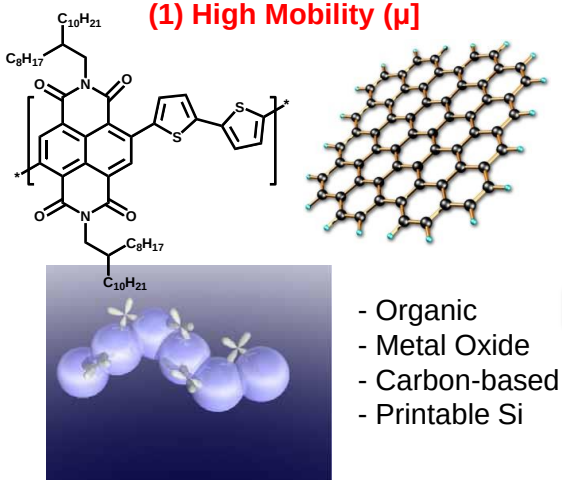
$$f_T = \frac{g_m}{2\pi(C_{gs}+C_{gd})} \approx 25 \text{ kHz}$$

$$f_{cut-off} \approx 60 \text{ kHz}$$

S. Mandal et al., Organic Electronics 20 (2015) 132-141

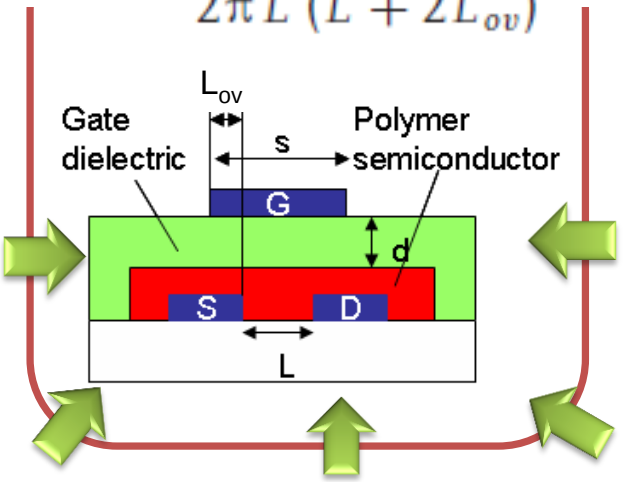
Challenges towards printed high-speed circuits

(1) High Mobility (μ)

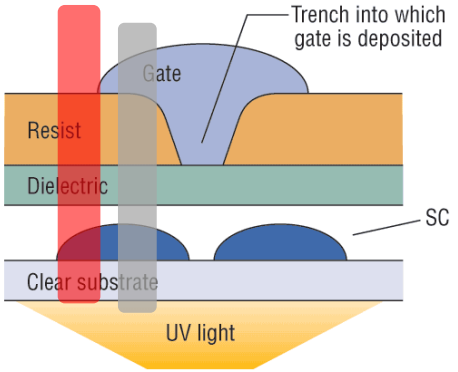


- Organic
- Metal Oxide
- Carbon-based
- Printable Si

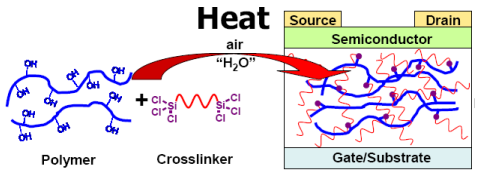
$$f_T \approx \frac{\mu_{app} V_{od}}{2\pi L (L + 2L_{ov})}$$

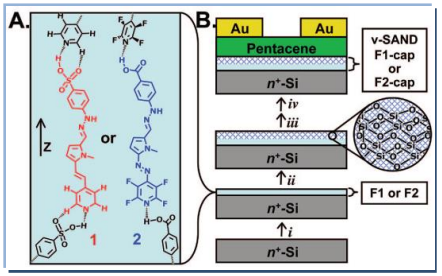


(4) Small Overlap Cap. [C_{ov}]

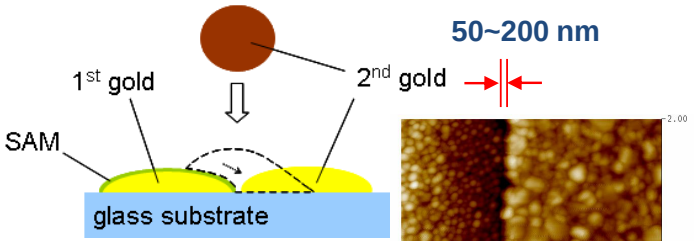


(5) High-Capacitance Dielectrics [C_i]



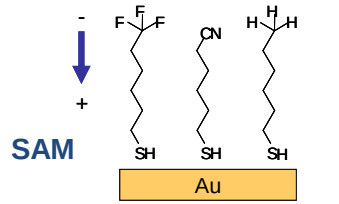


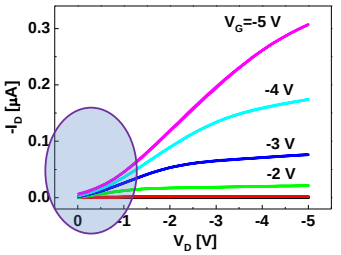
(2) Short Channel Length [L^2]



Self Aligned Printing
Nano-imprinting
EHD Jet printing

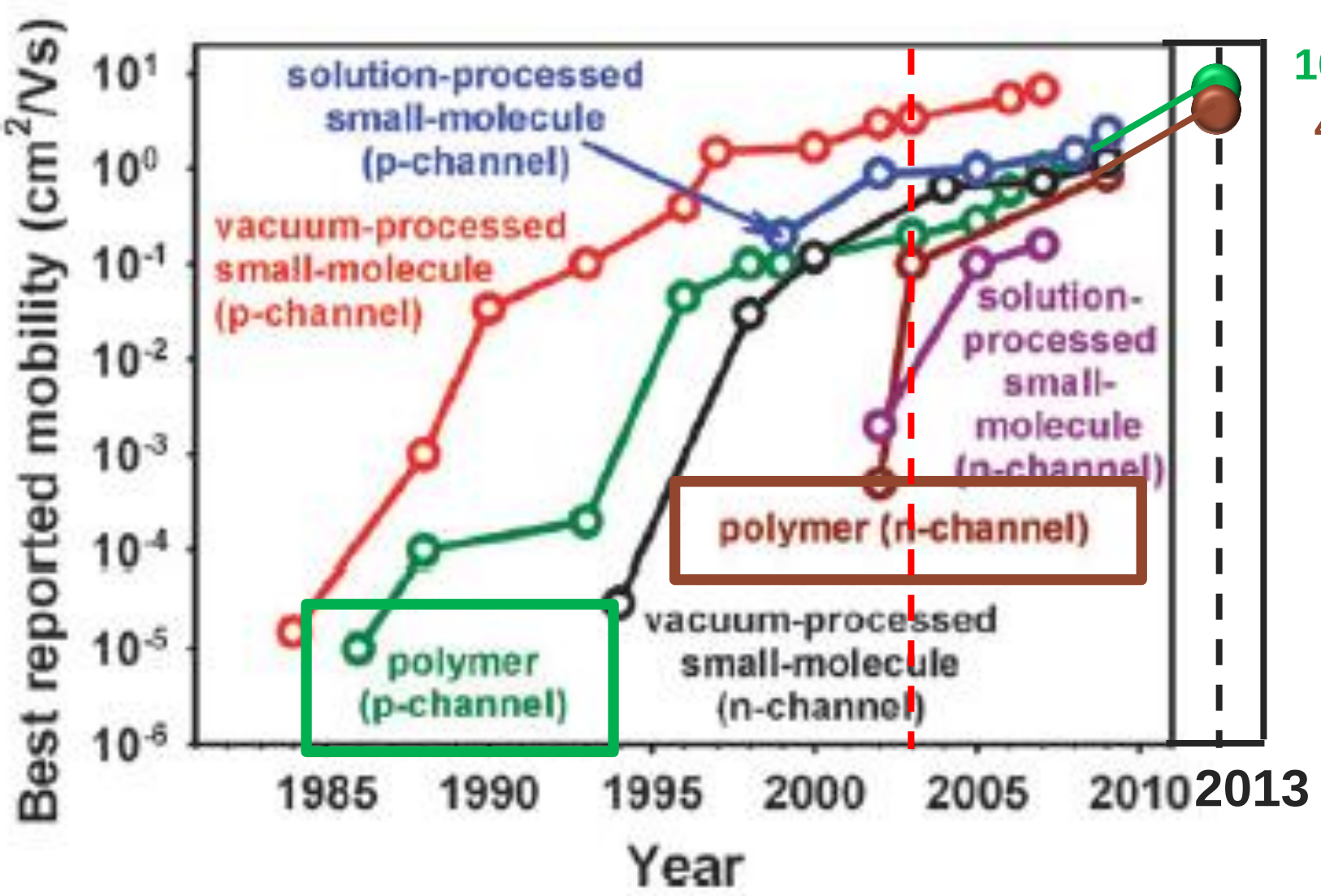
(3) Small Contact Resistance. [R_c]





K.-J. Baeg, M. Caironi, Y.-Y. Noh, Adv. Mater. 2013, DOI: 10.1002/adma201205361

Organic Semiconductors Mobility



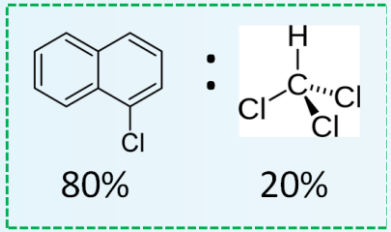
10 cm²/Vs

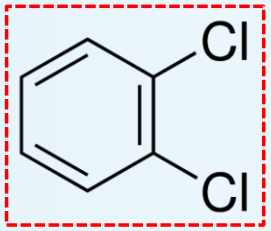
4 cm²/Vs

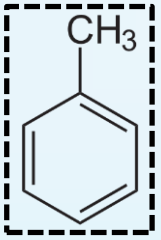
H. Klauk, Chem. Soc. Rev. 39 (2010) 2643

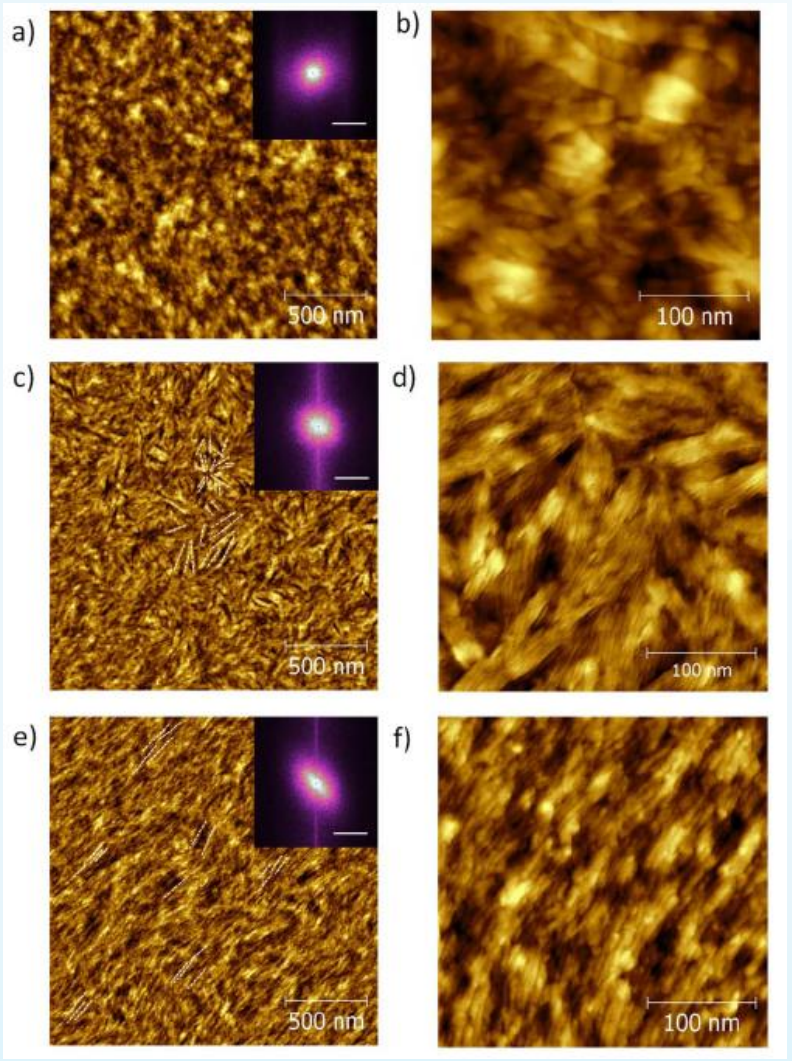
Effect of Pre-aggregation

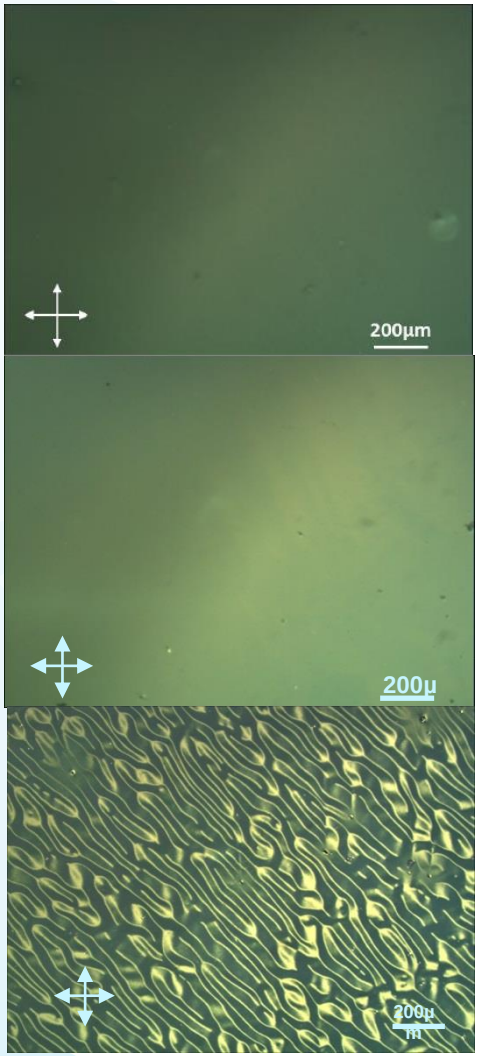
Degree of pre-aggregation in solution





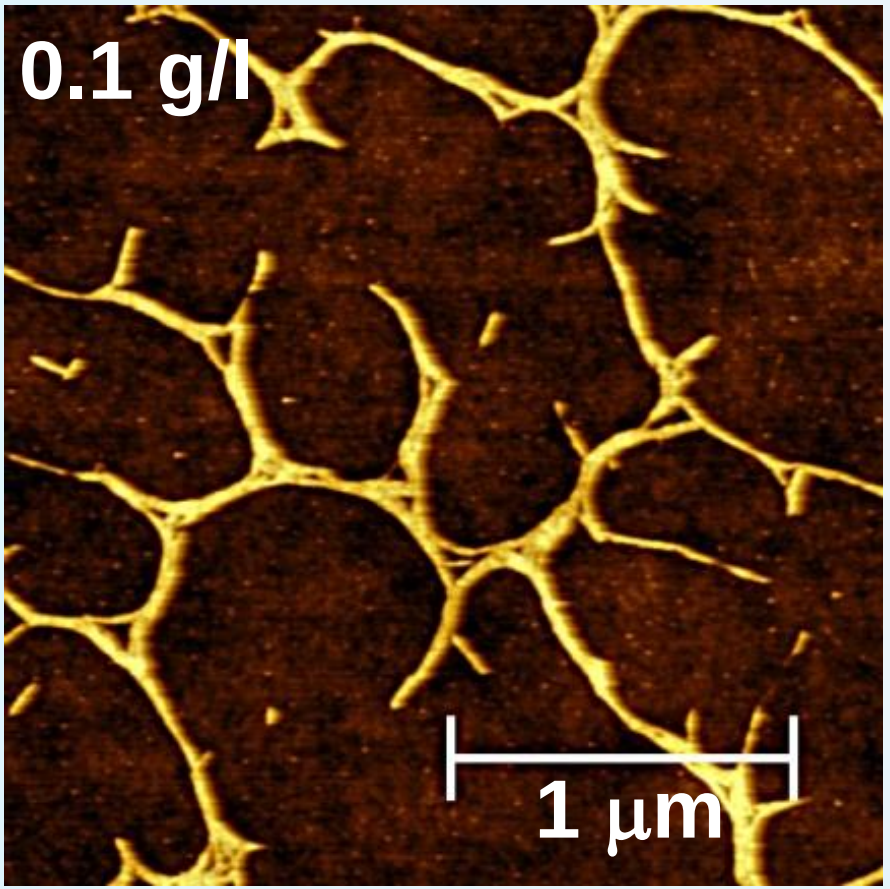


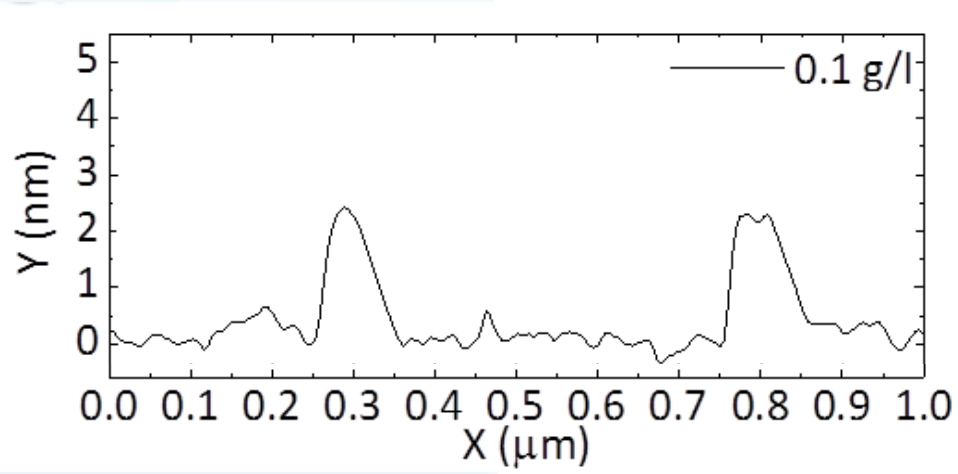


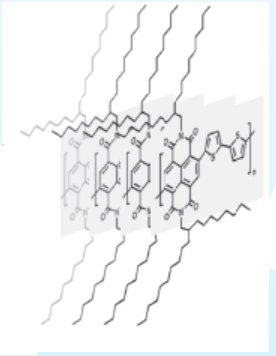


A. Luzio et al. Scientific Reports 3 (2013) 3425

Film formation (spin-coating)

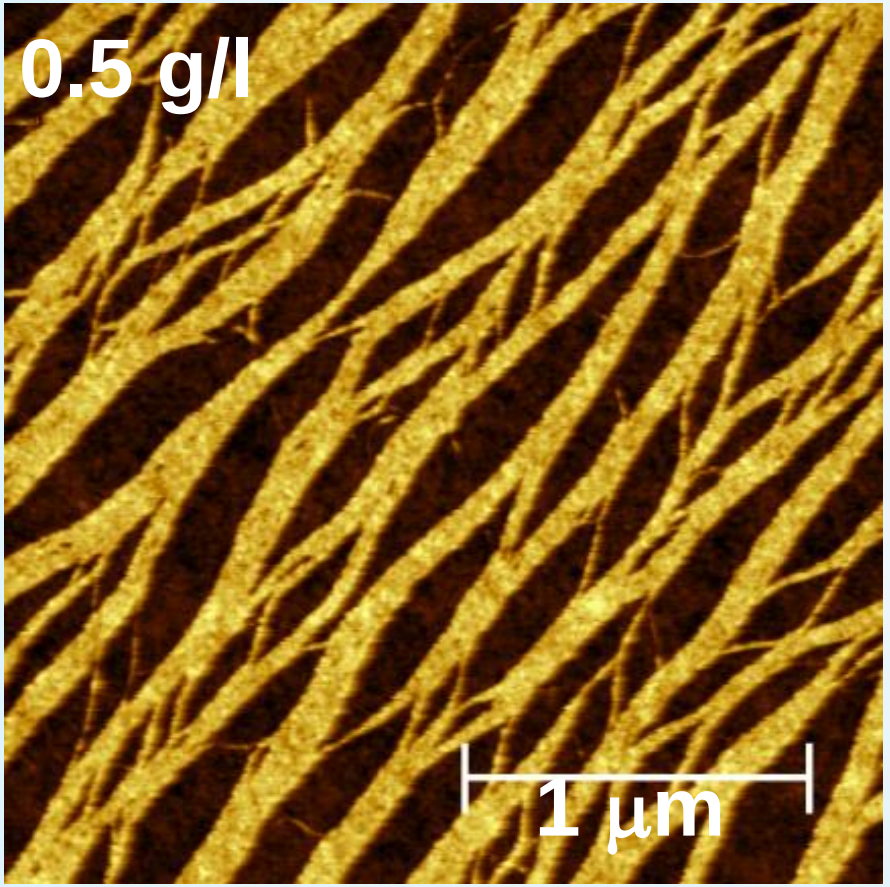


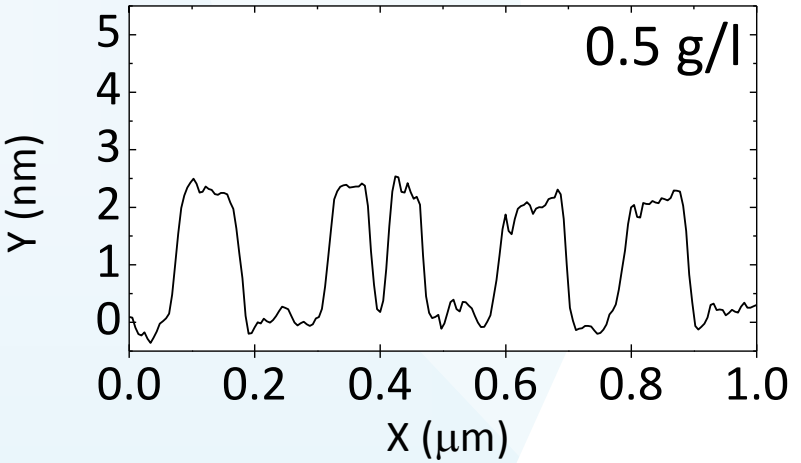




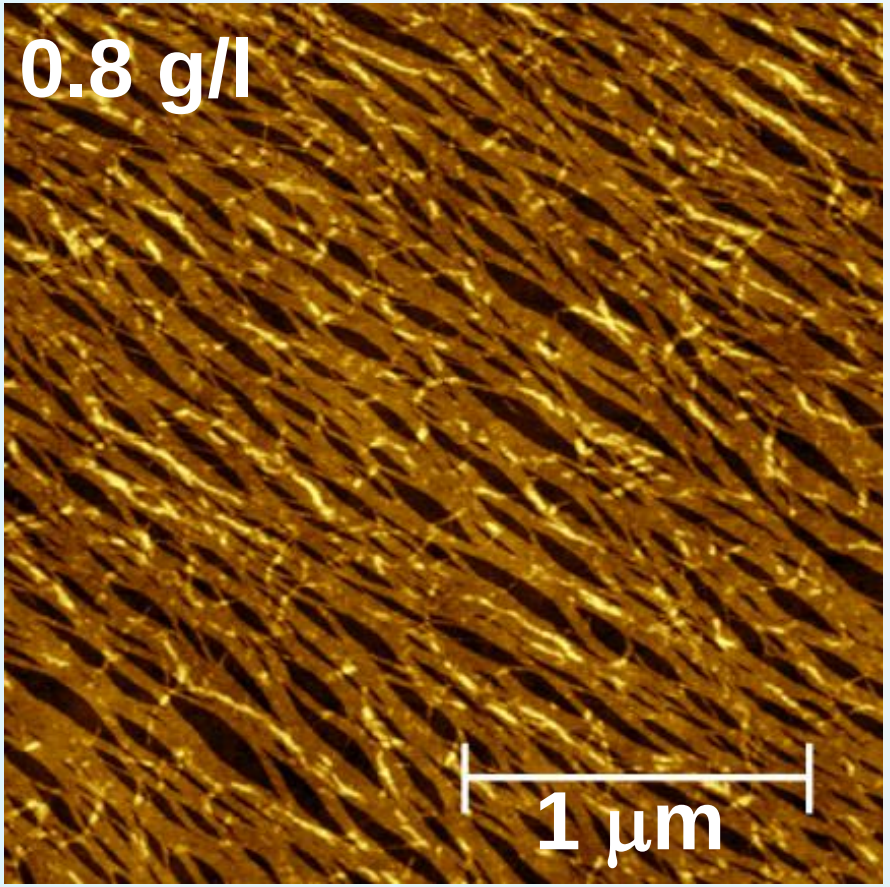
2.5 – 3.0 nm

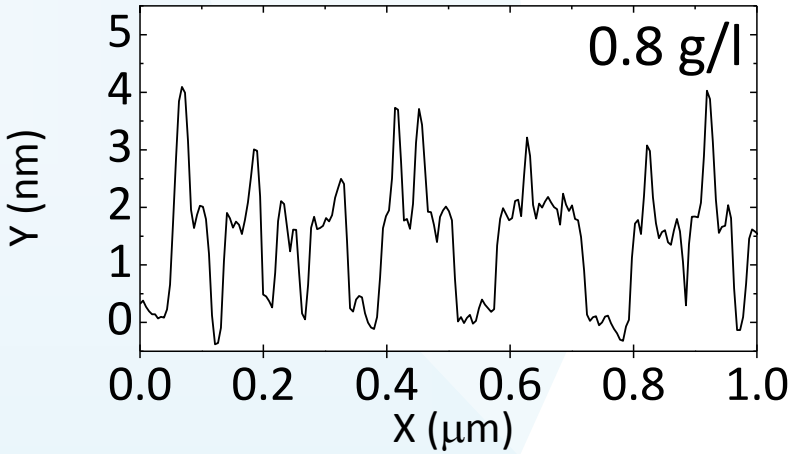
Film formation (spin-coating)



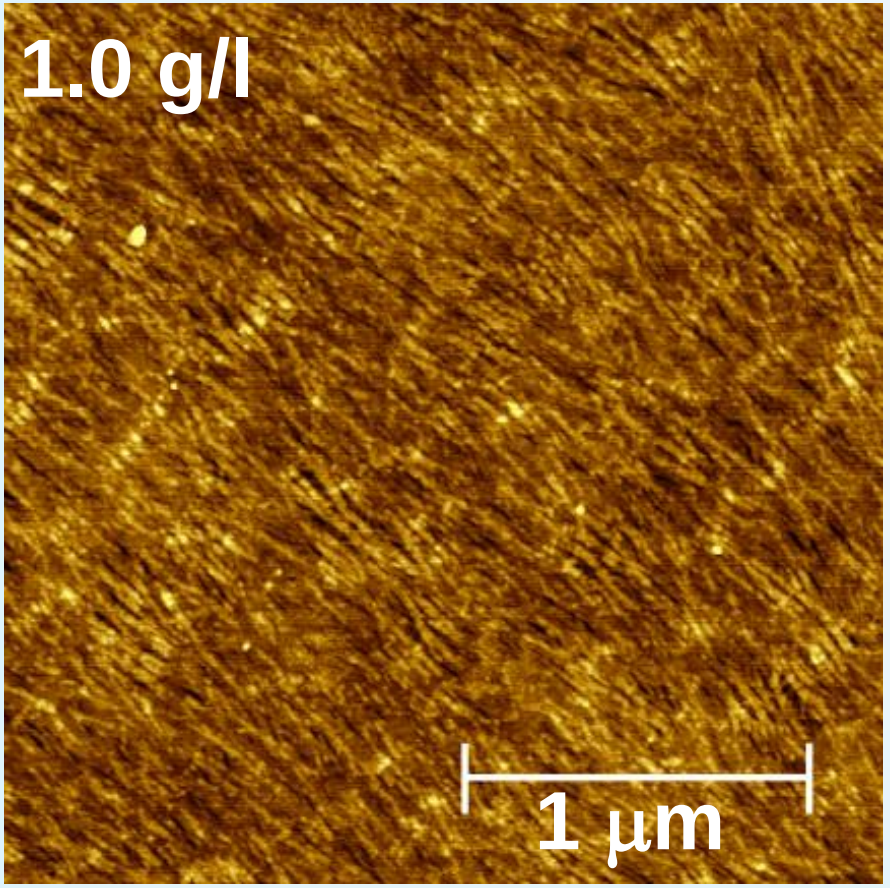


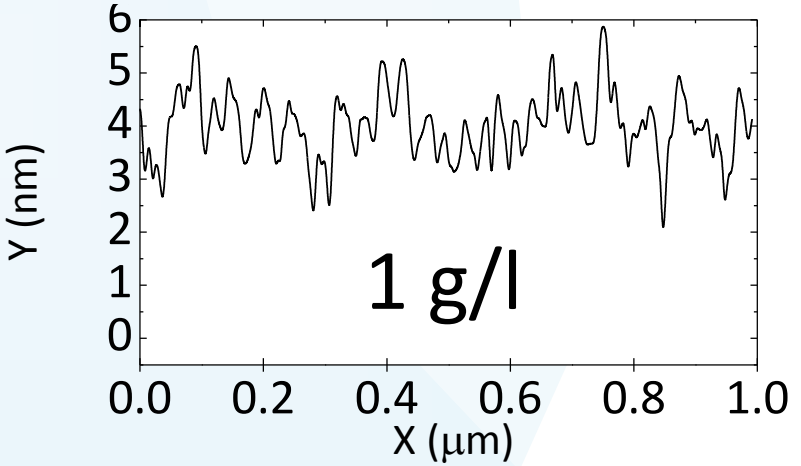
Film formation (spin-coating)





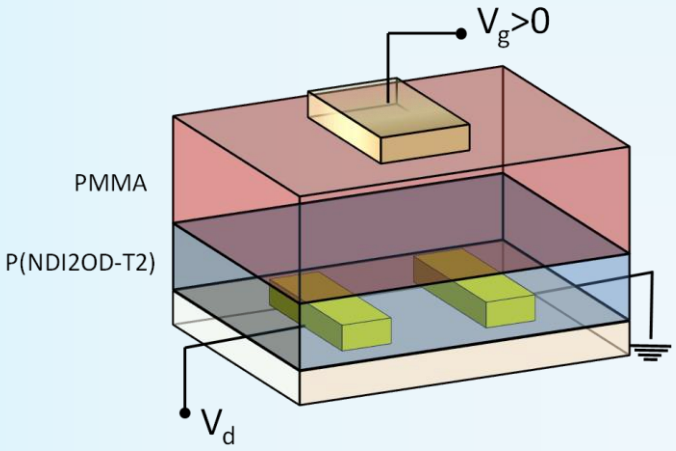
Film formation (spin-coating)

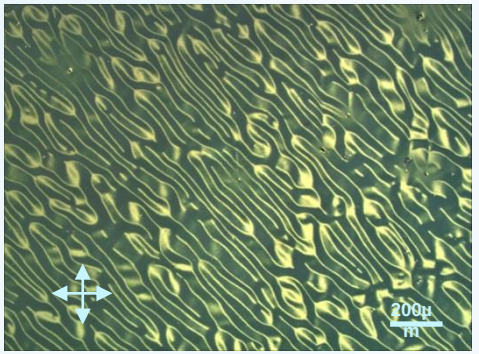


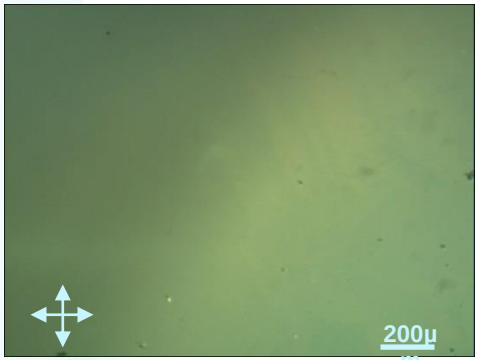


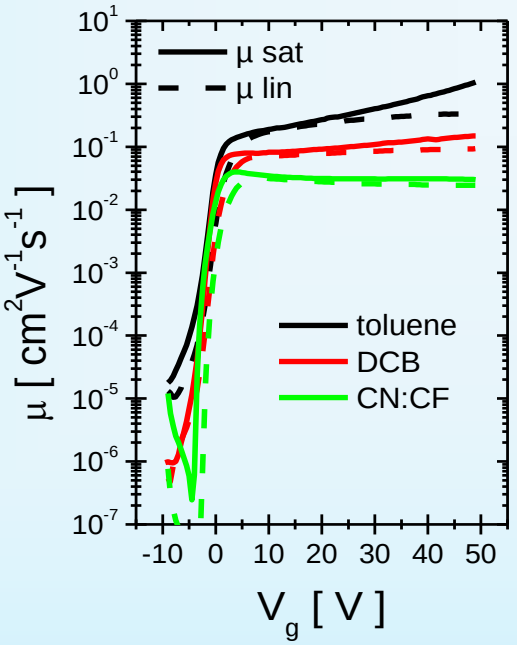
Bucella et al., Nature Communications, 6 (2015) 8394

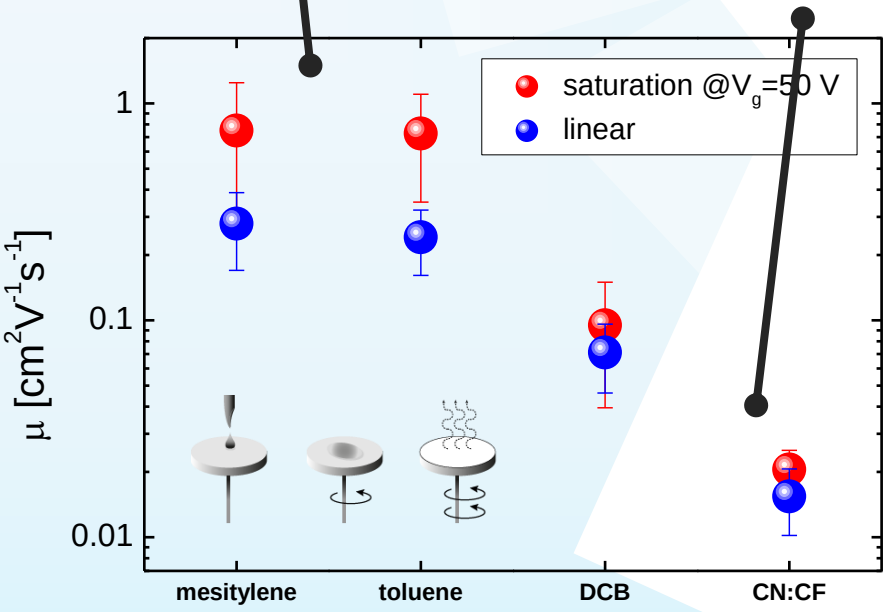
OFETs characterization









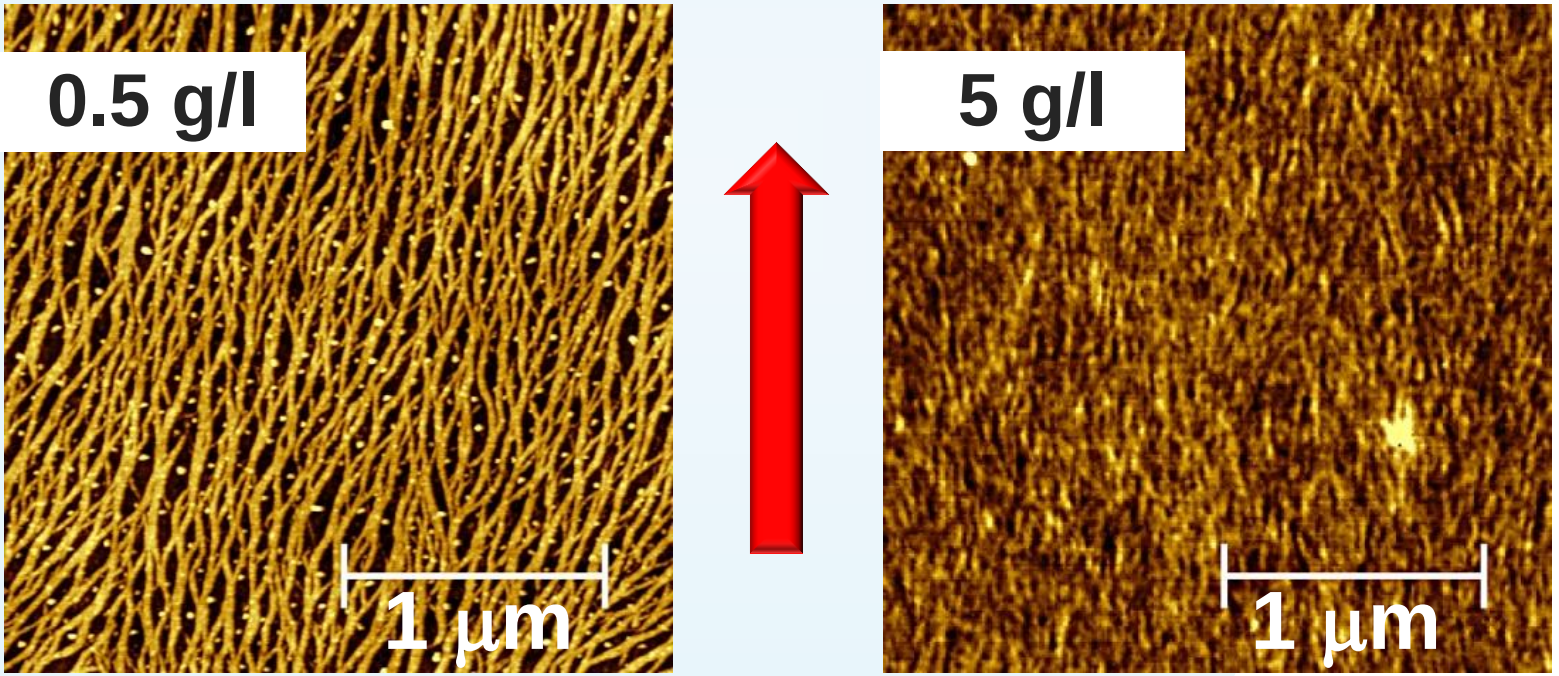


A. Luzio et al. Scientific Reports 3 (2013) 3425

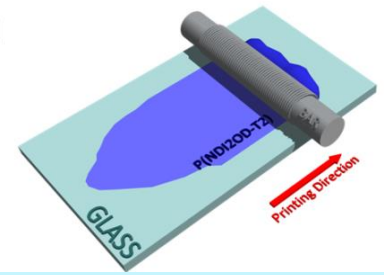
Macro-aligned nano-fibrils

Sub-monolayer
2.4 - 2.5 nm

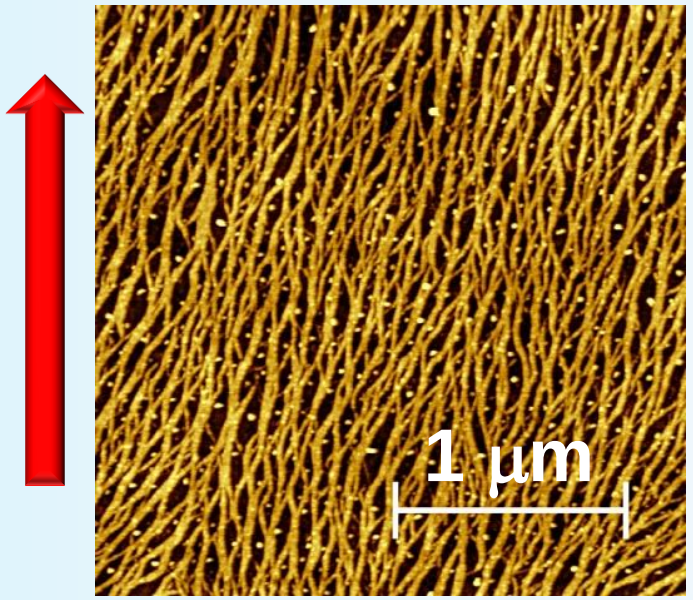
Thin film
10 nm

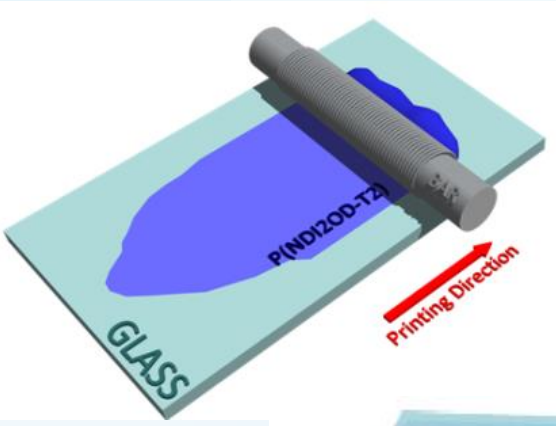


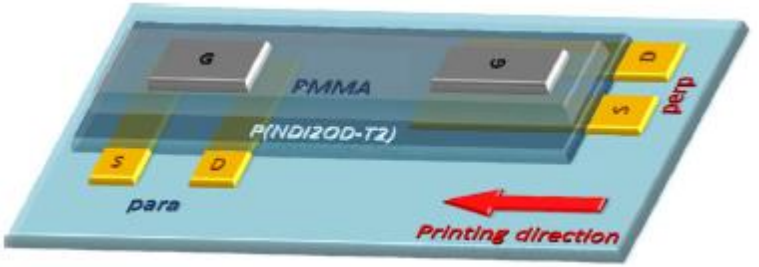
Solvent: mesitylene
Coating Speed: 3 min/min

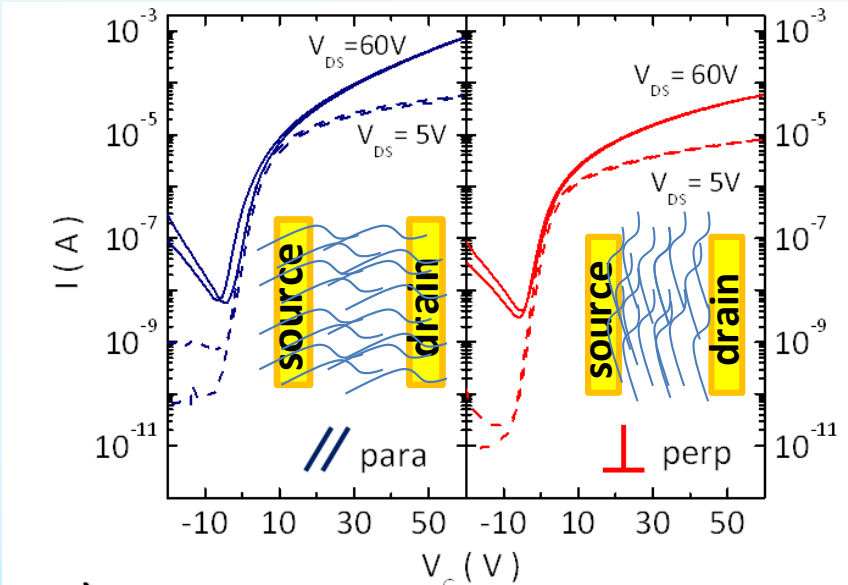


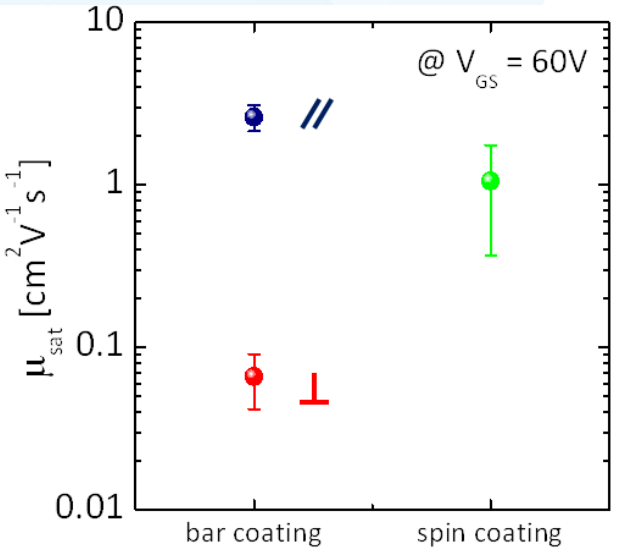
Macro-aligned nano-fibrils



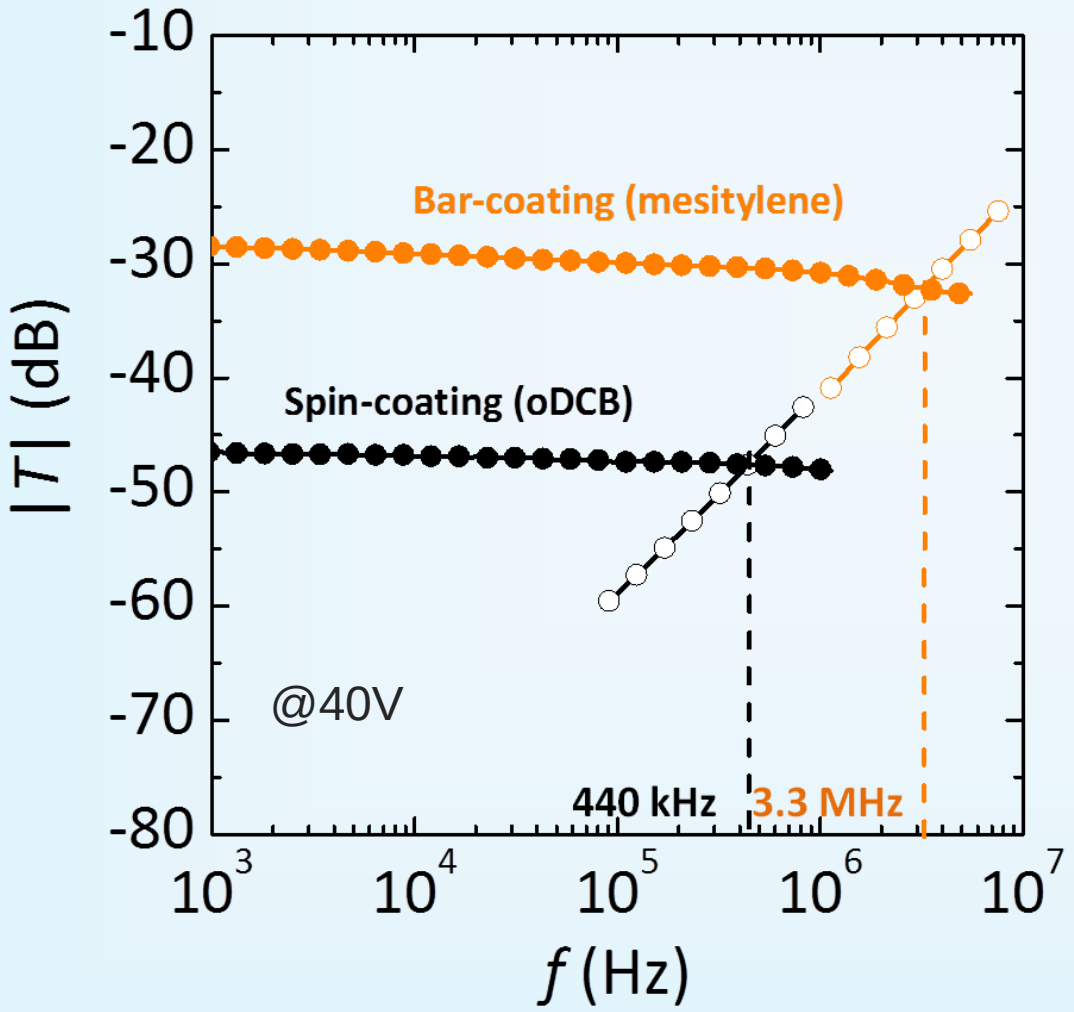




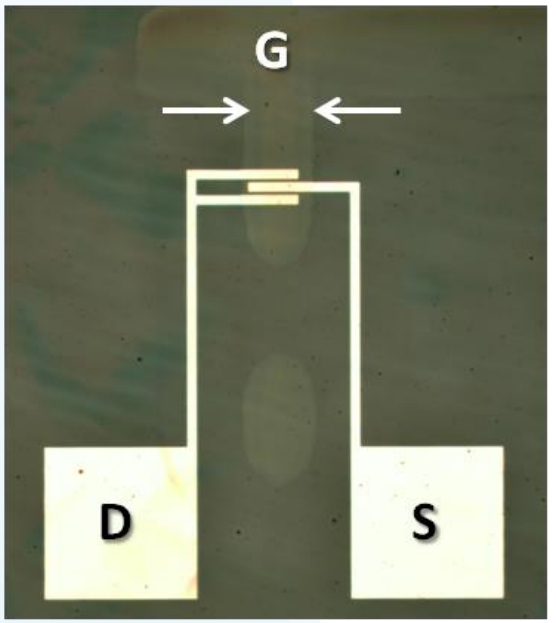




MHz Fast-coated OFETs



L = 5 μm



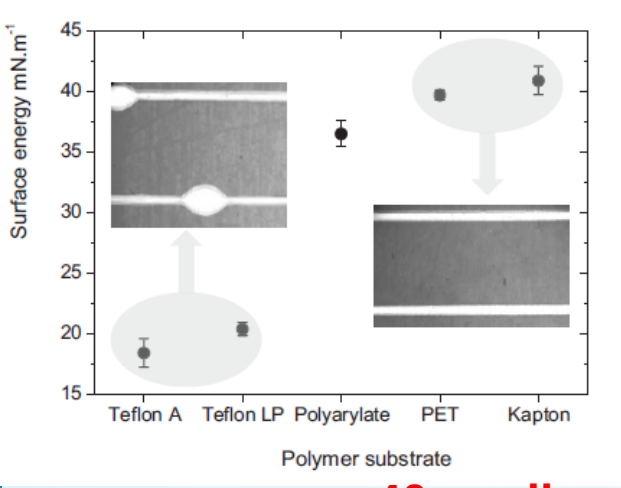
Non optimized architecture for frequency operation!

Bucella et al., Nature Communications, 6 (2015) 8394

Printing Techniques Patterning Resolution

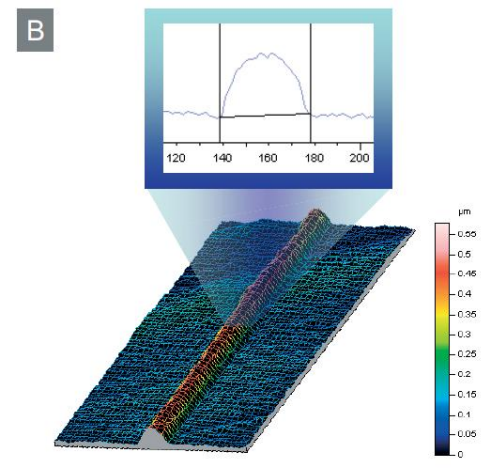
Printing Techniques	Viscosity [Pas]	Thickness [µm]	Feature Size [µm]	Throughput [m^2/s]	Registration [µm]	Features
Flexography	**0.05-0.5**	**0.04-2.5**	**80**	**3-30**	**<200**	Inexpensive plate pattern, high throughput, thick layer / low viscosity ink
Gravure	**0.01-0.2**	**< 0.1–8**	**75**	**3-60**	**>20**	Fast printing, high resolution, relatively high plate cost, low dot gain
Offset	**5-100**	**0.5–2**	**10–50**	**3–30**	**>10**	High quality, high throughput, need for ink additives
Screen	**0.5-50**	**0.015-100**	**20–100**	**2–3**	**>25**	Robust, simple, thick layer, large feature size, high ink viscosity, slow speed
Inkjet	**0.001-0.04**	**0.01-20**	**20–50**	**0.01–0.5**	**5–20**	Non-contact, small ink quantities, digital printing, low viscosity ink, slow speed

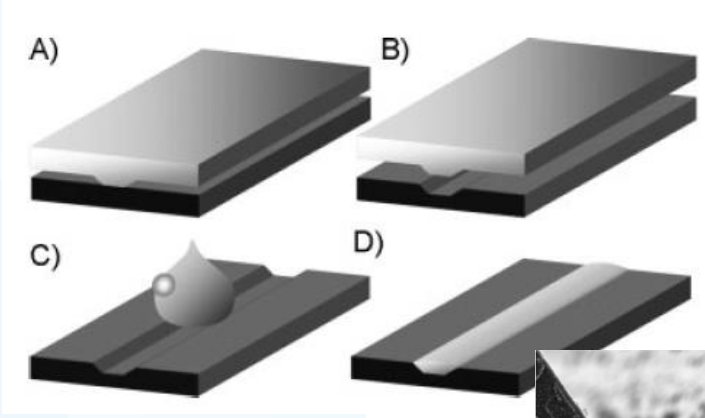
Ink-jet printing of narrow linewidths



40 µm linewidth

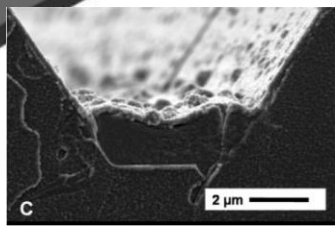
Adv. Mater. 20 (2008) 343



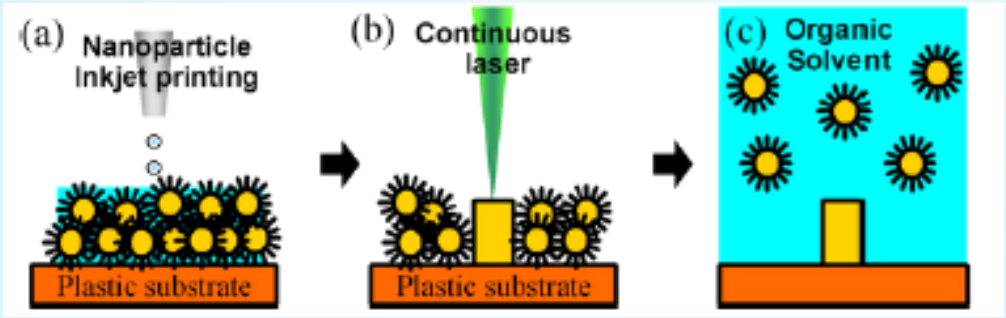


5 µm linewidth

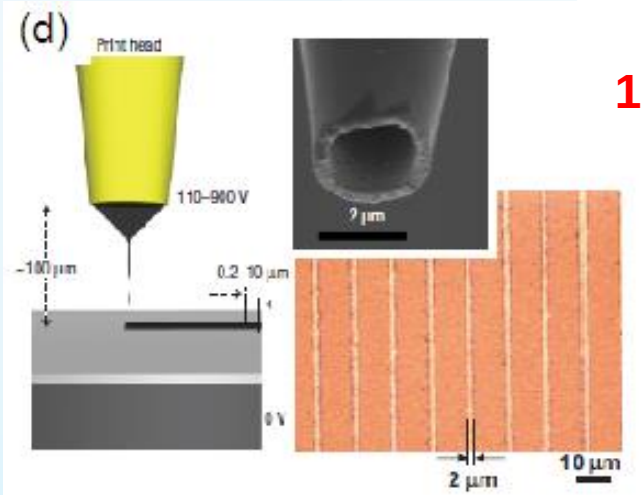
Adv. Funct. Mater. 18 (2008) 1031



1-2 µm linewidth



Nanotechnology 18 (2007) 345202

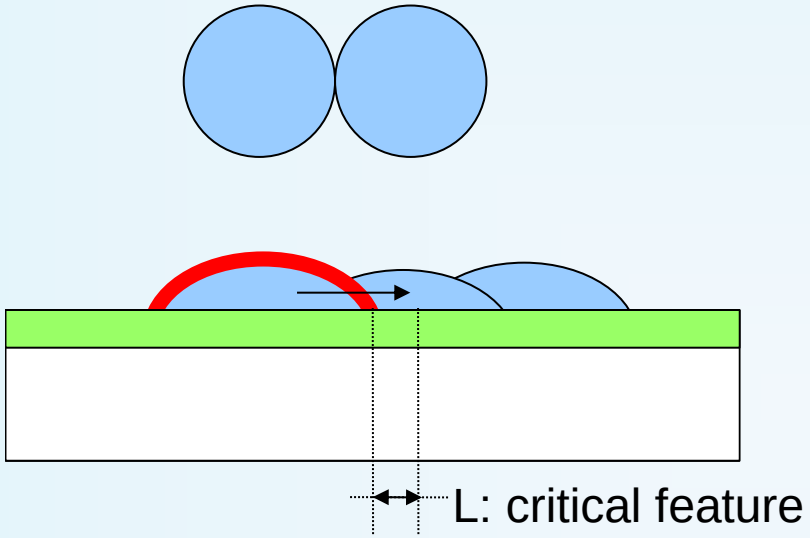


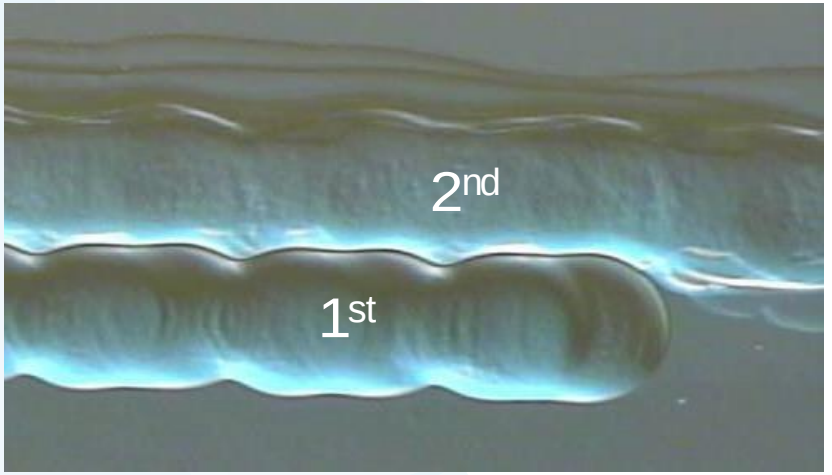
1 µm linewidth

Nat. Mater. 6 (2007) 782

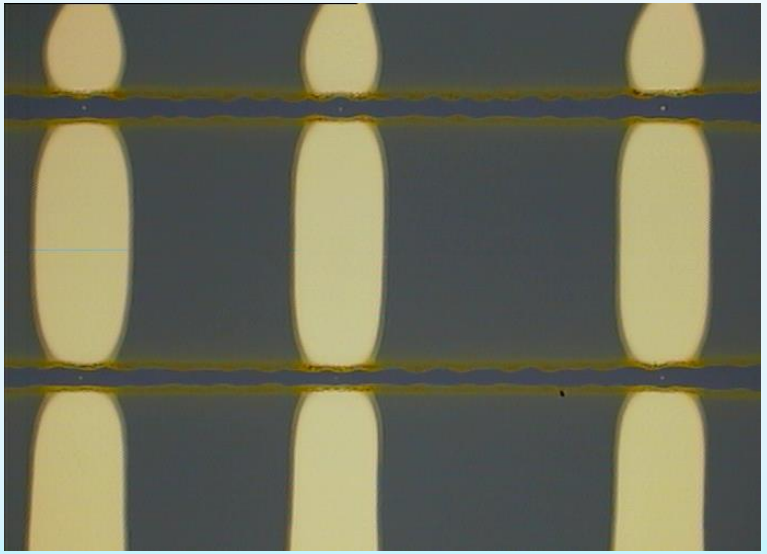
High resolution e-jet

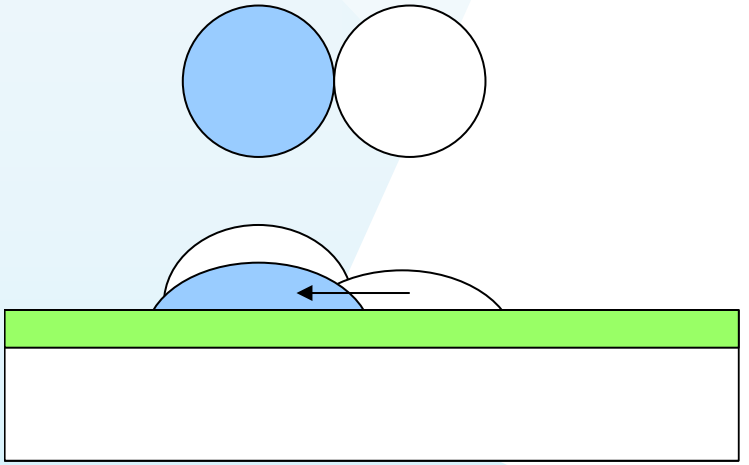
Self-Aligned Printing (SAP)



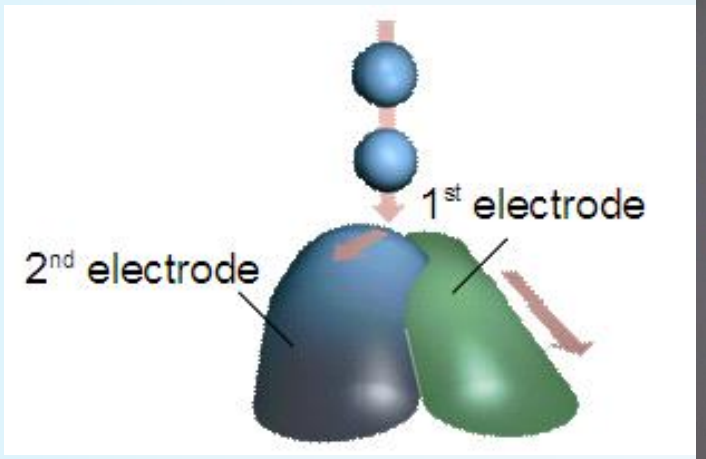


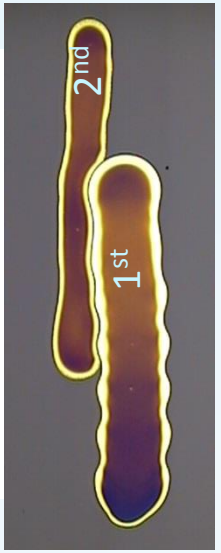
C.W. Sele et al., Adv. Mat. 17 (2005) 997

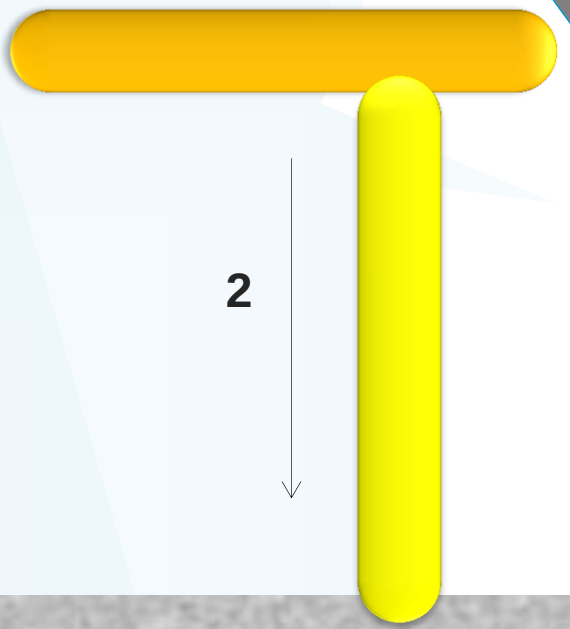


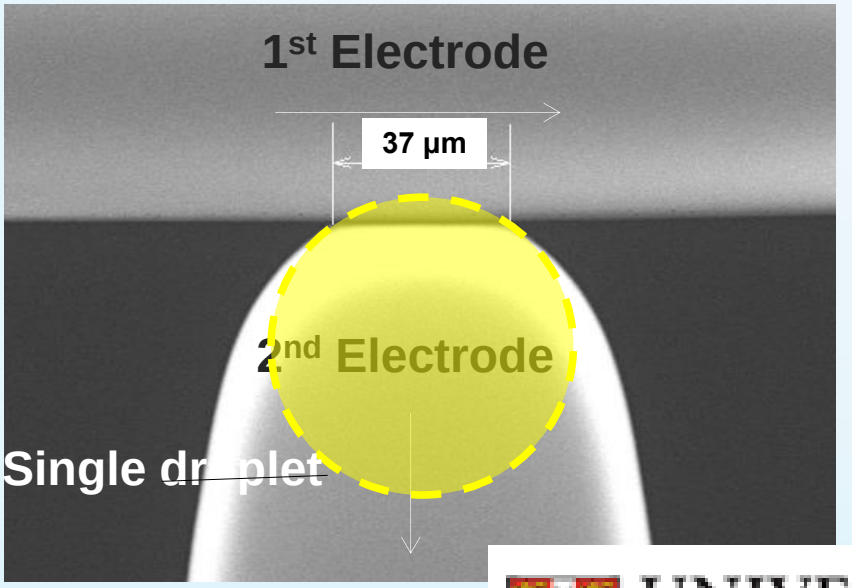


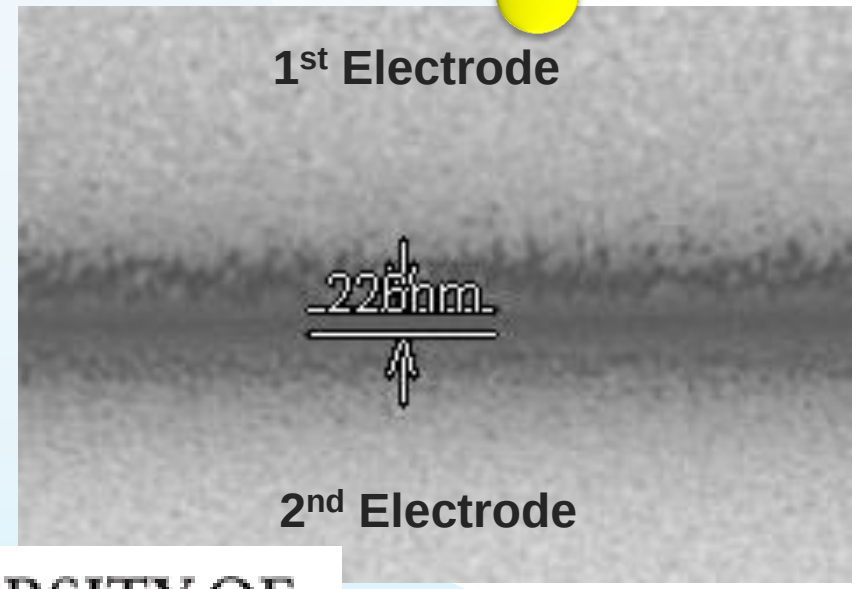
Single-droplet Contacts





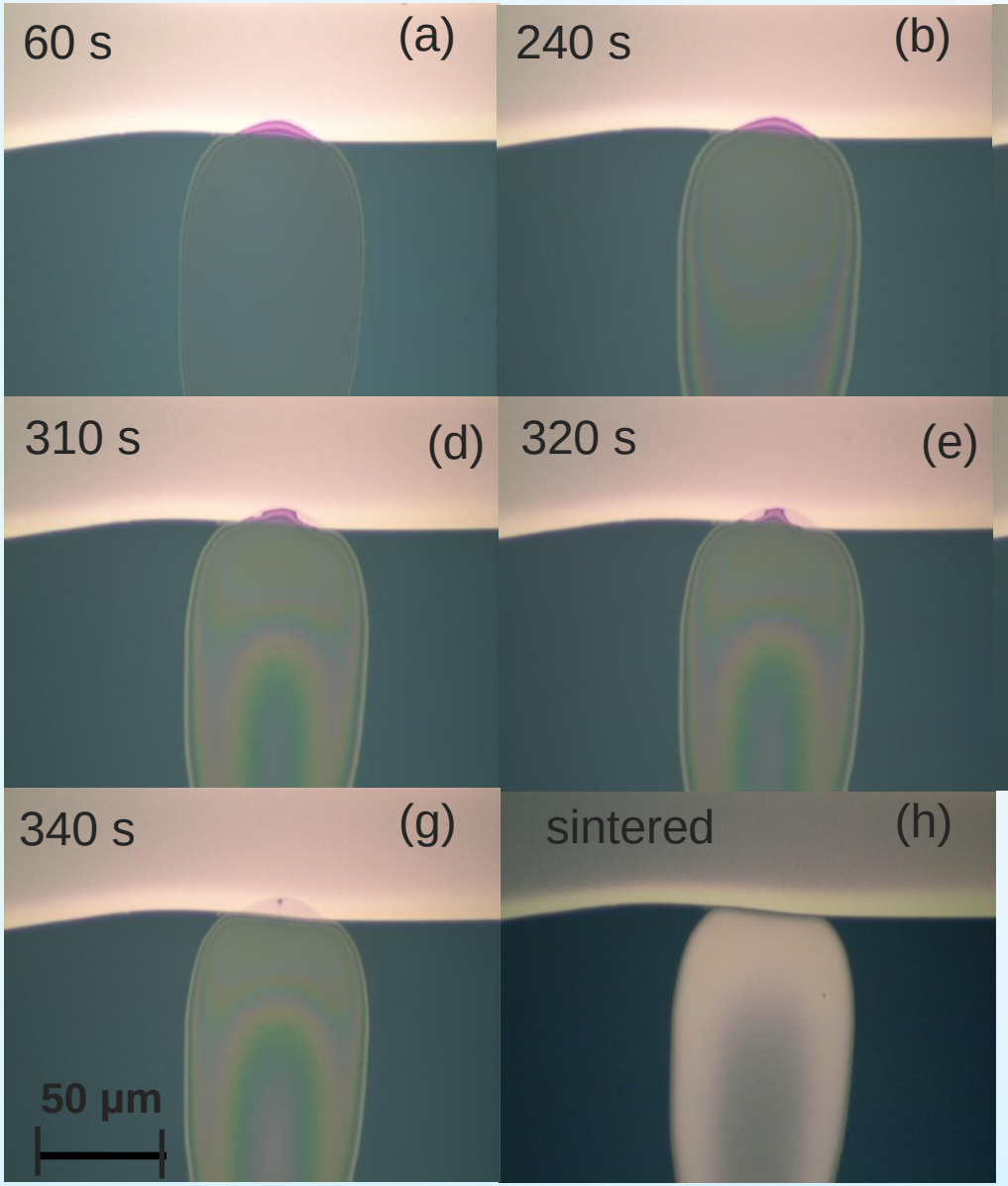






UNIVERSITY OF CAMBRIDGE

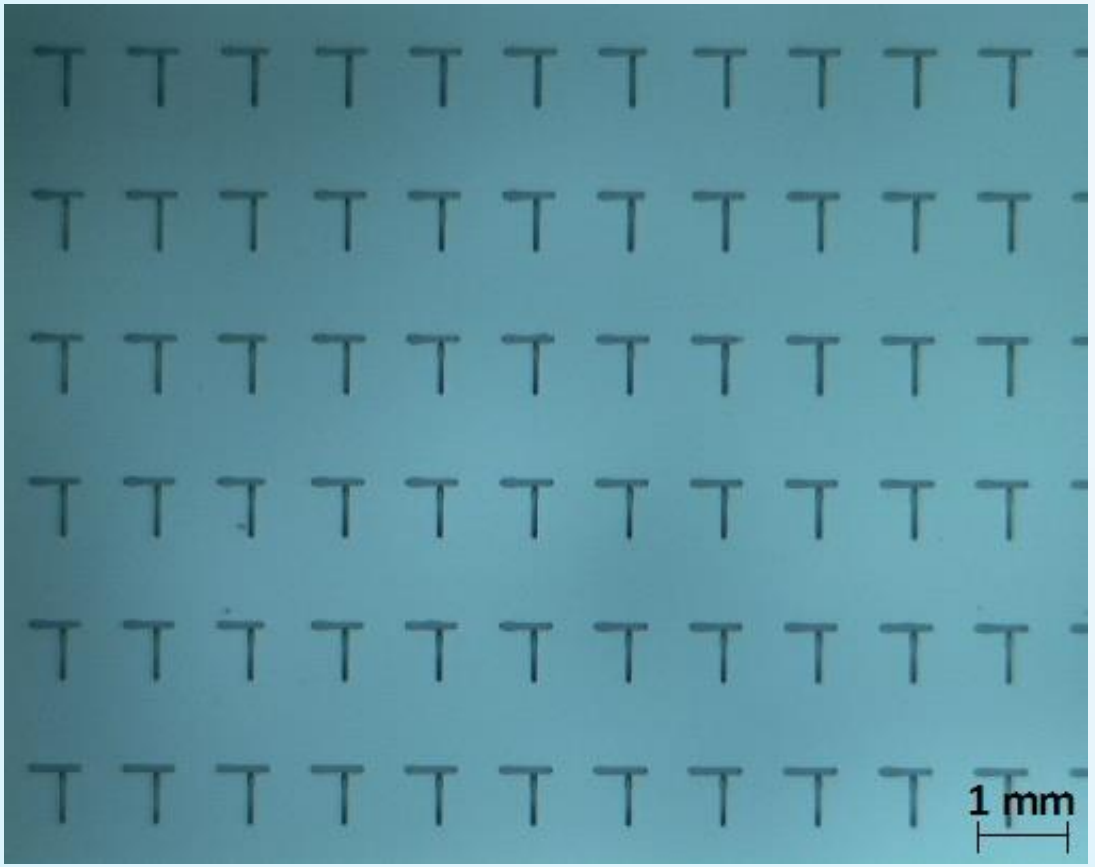
Drying Time of Ink is a Critical Factor

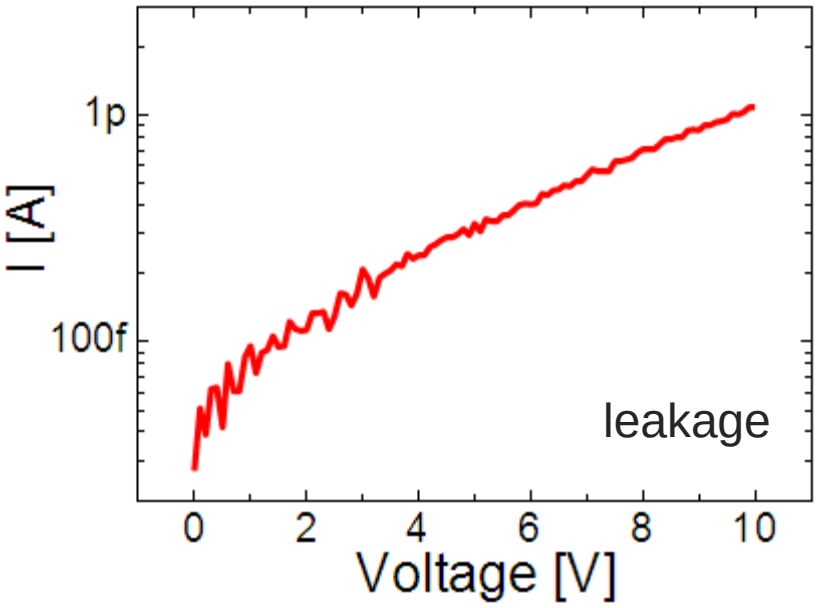


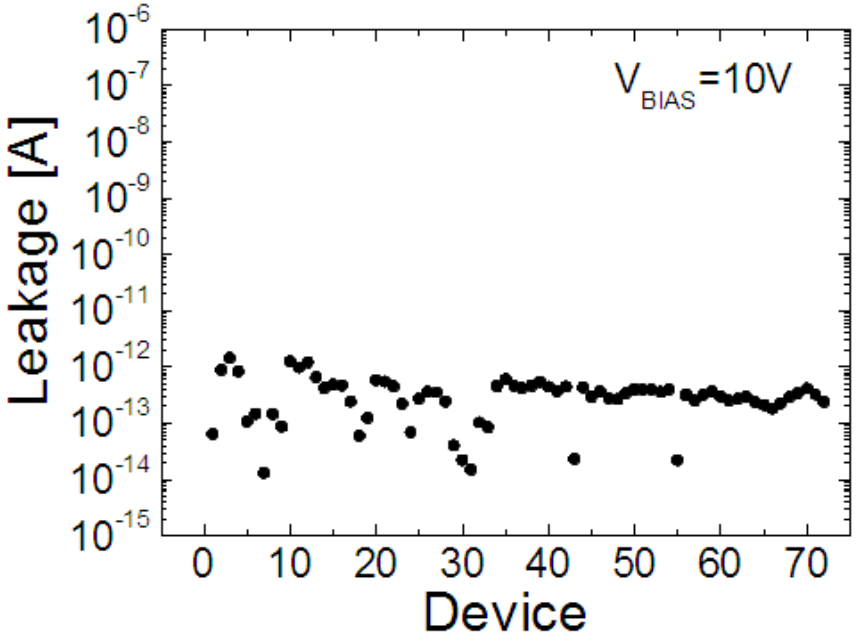
- **Extra force exerted by evaporation of the solvent**
- **Reliable dewetting, tolerant to surface defects**
- ***Process window >> 10 µm***

High Yield Electrodes Array

- **100% yield possible**
- **Very low leakage, < 2 pA at 10 V**
- **Breakdown voltage > 2 MVcm^{-1}**

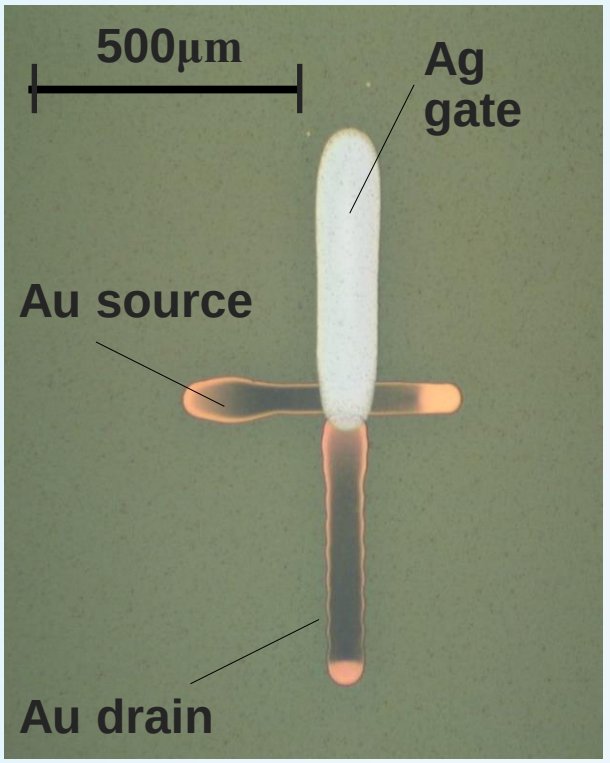


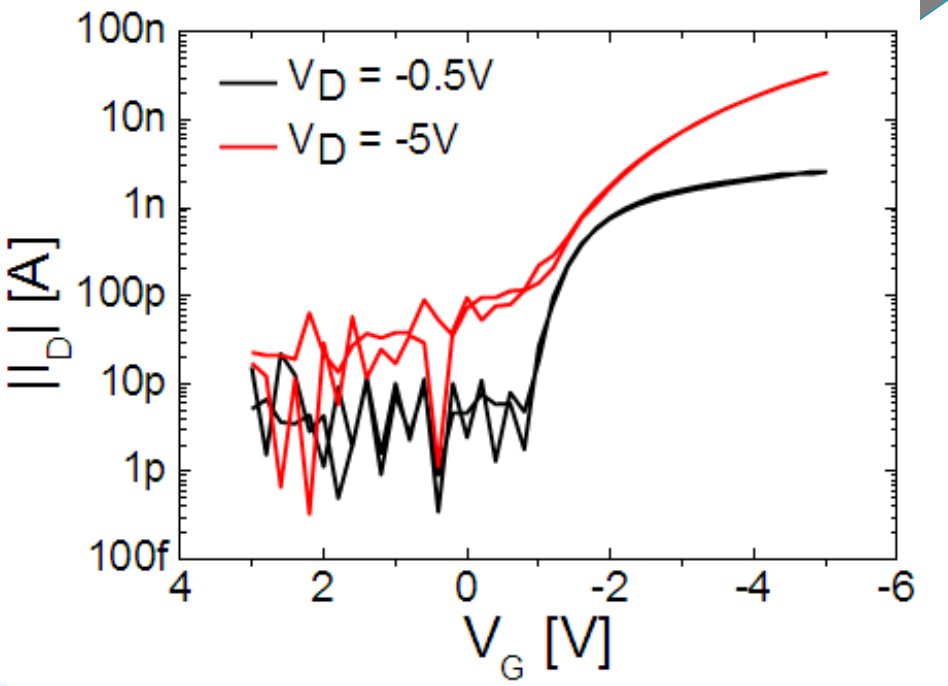


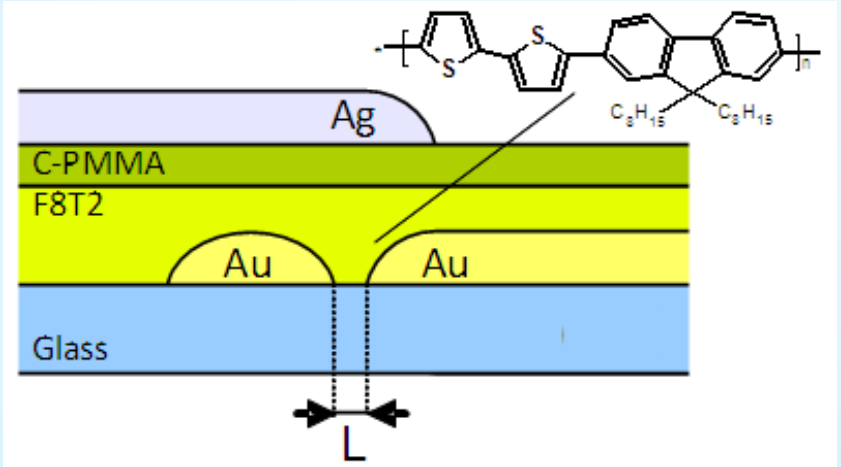


Caironi et al., ACS Nano 4 (2010) 1452

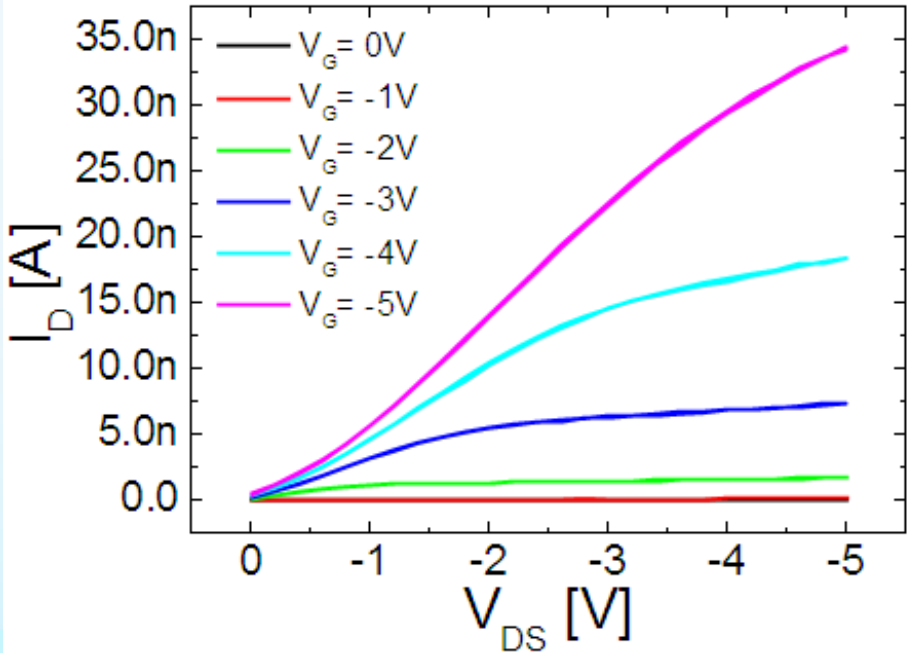
Fully Solution Processed SAP-FET





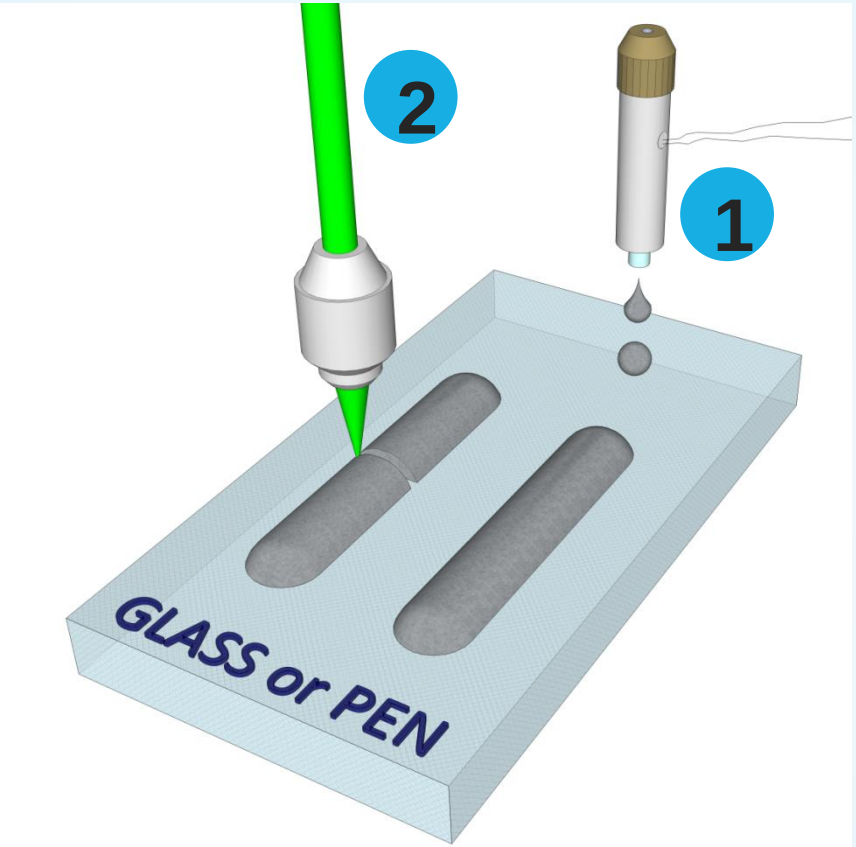


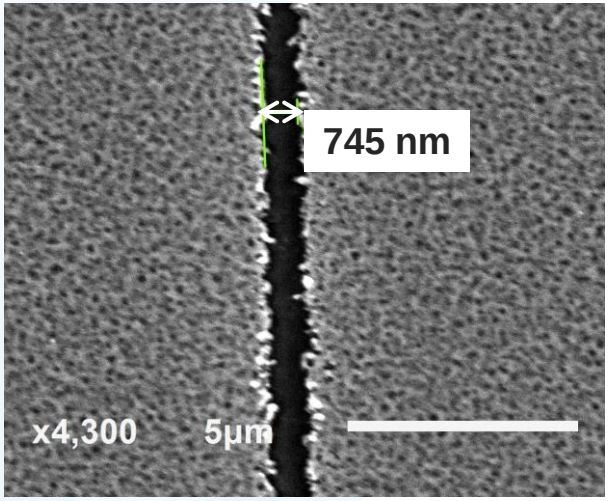
L ≈ 200 nm, W ≈ 40 µm

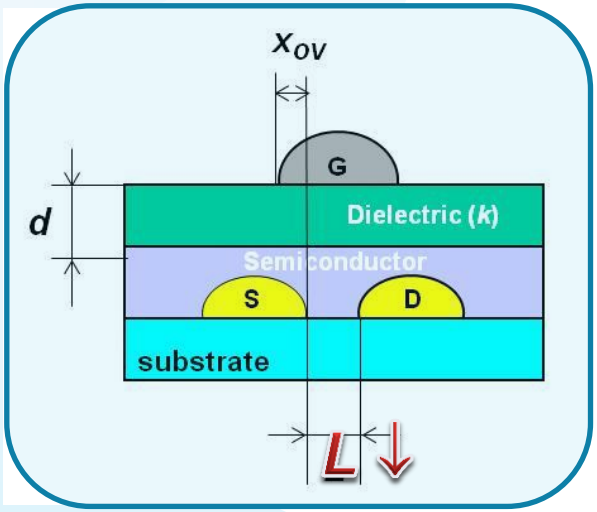


Caironi et al., ACS Nano 4 (2010) 1452

Direct-writing of submicron channels







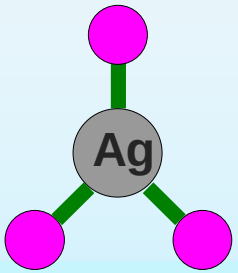
100X objective

Power = 2 mW

λ = 515nm

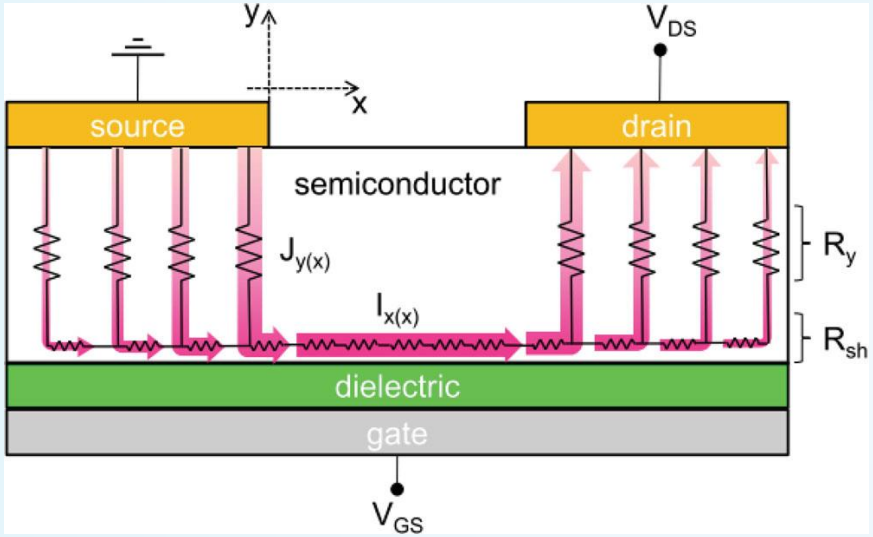
250 fs, 500 kHz

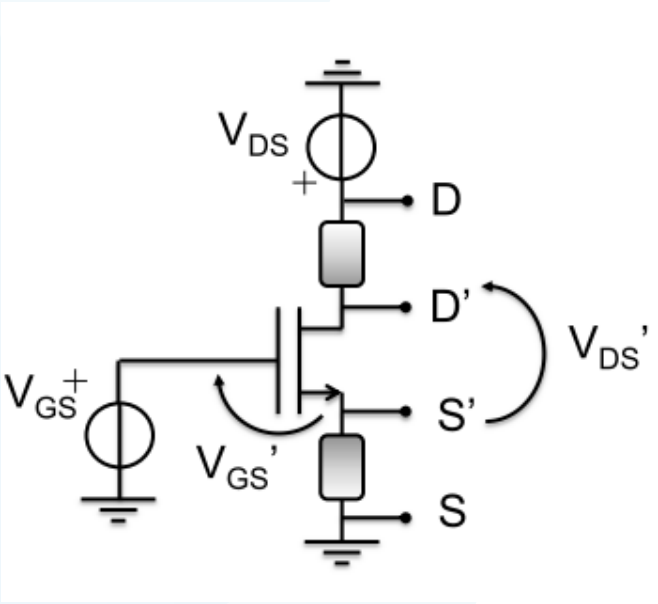
Ag-inks



S. Bucella et al., *Organic Electronics*, 14 (2013) 2249

Effect of Contact Resistance





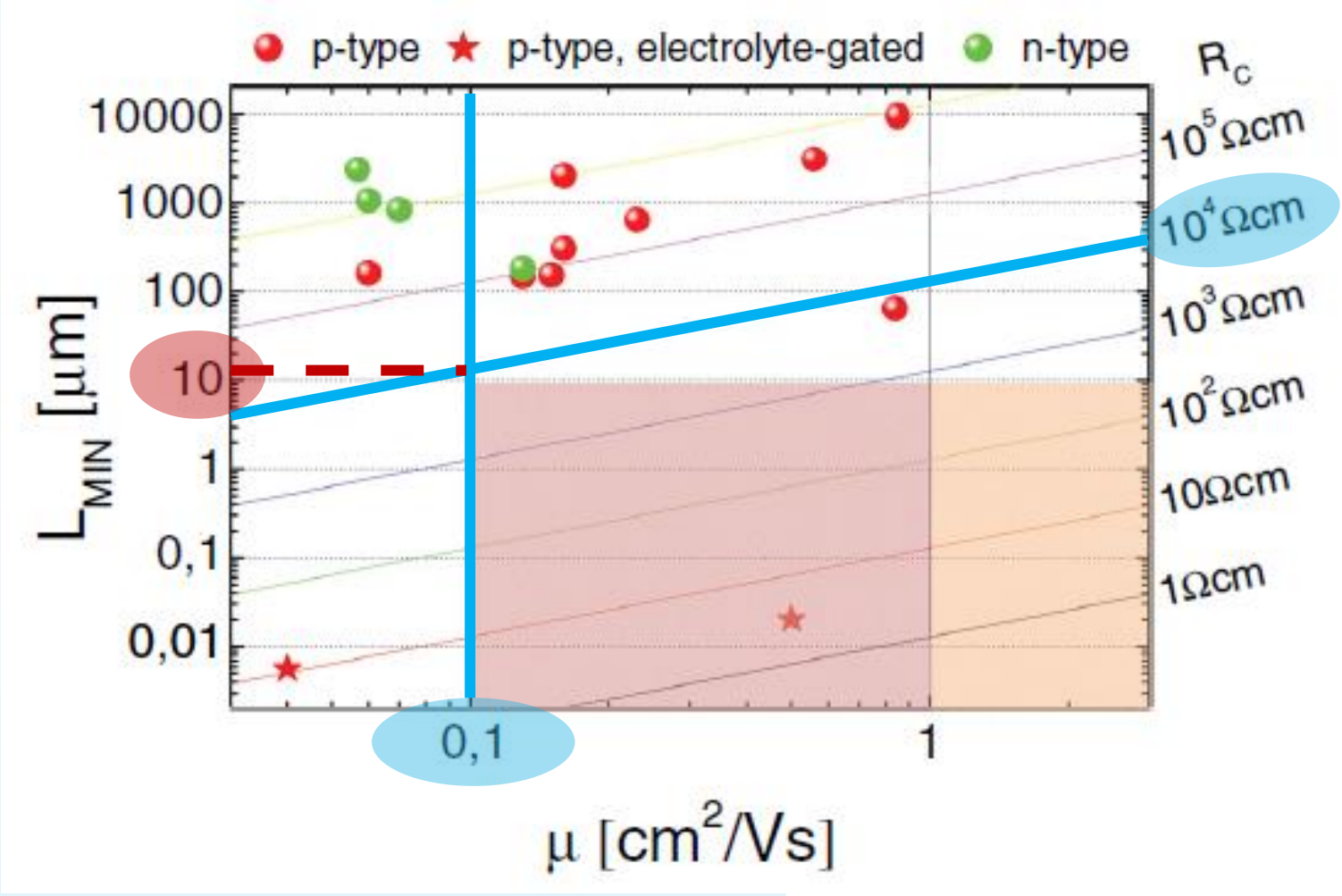
$$\mu_{app} \approx \mu_0 \left(1 - \left(\frac{\mu_0 C_i W R_C V_{od}}{L + \mu_0 C_i W R_C V_{od}}\right)^2\right)$$

$$f_{T0} \approx \frac{\mu_0 V_{od}}{2\pi L (L + 2L_{ov})} < f_T \approx \frac{\mu_{app} V_{od}}{2\pi L (L + 2L_{ov})}$$

Rule of Thumb for μ_{app}

$$I_{real} = I_0 \frac{R_{Ch}}{R_{Ch} + R_C}$$

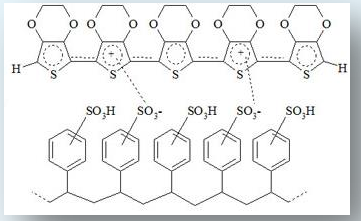
$$L_{MIN} \rightarrow R_C = R_{Ch}$$

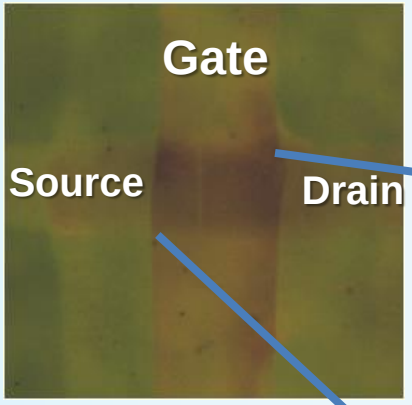


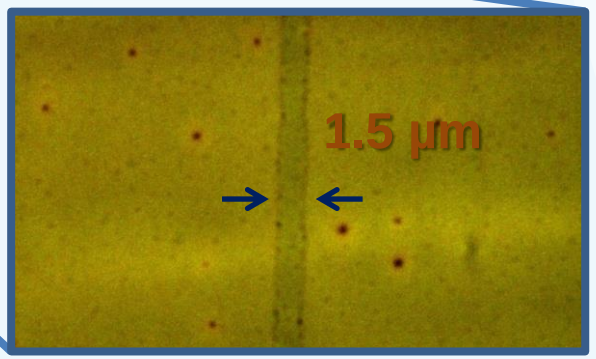
Natali, Caironi, Adv. Mater. 24 (2012) 1357

Laser-ablated Semi-transparent electrodes

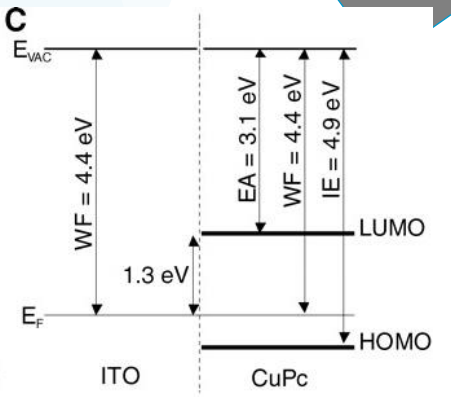
PEDOT:PSS

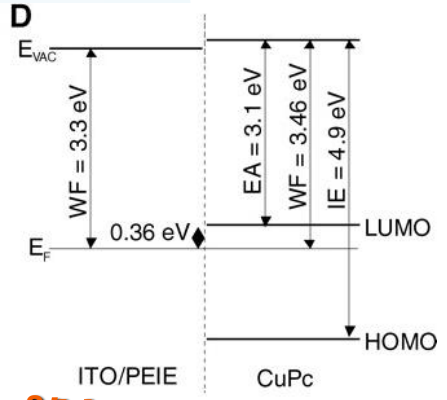




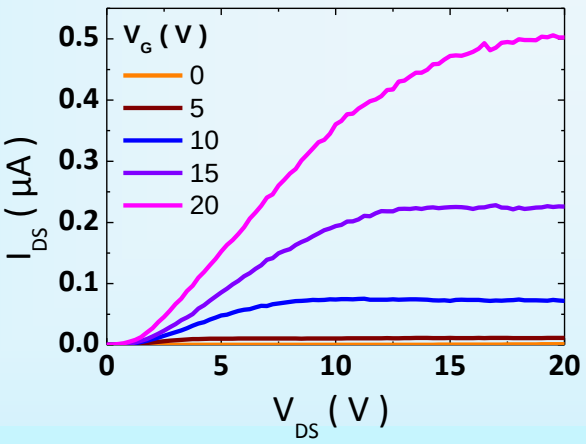


λ = 1030 nm
50X, 20 mW

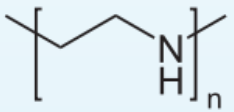




μ_{sat} ~ 10^{-2} cm^2/Vs

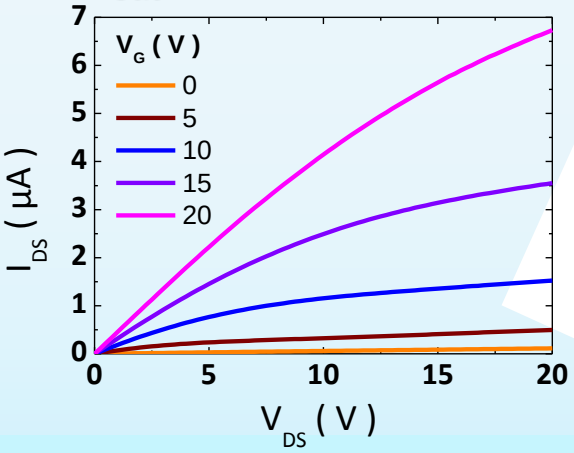


PEI



Y. Zhou et al, Science 336 (2012) 327

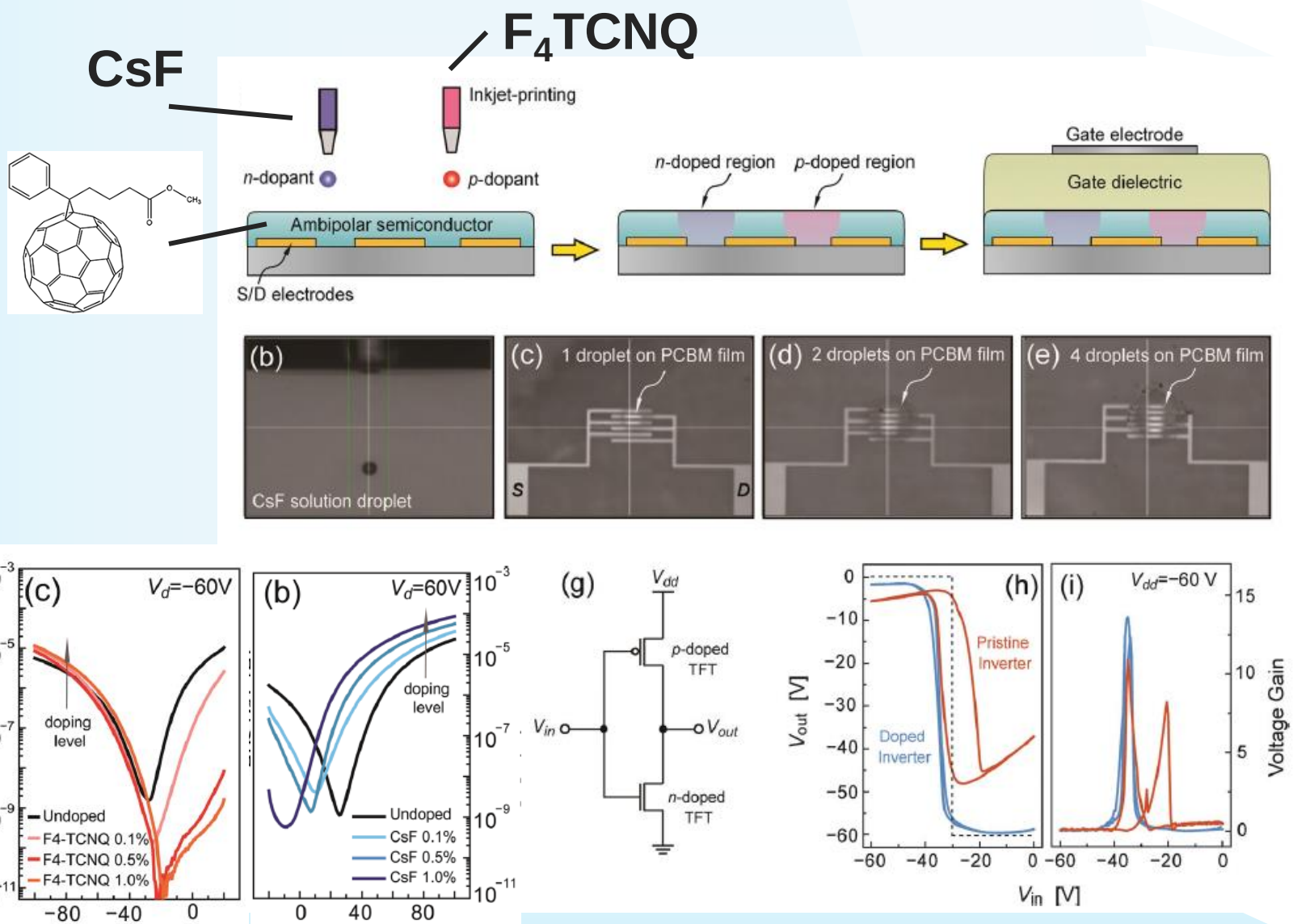
μ_{sat} ~ 0.1-0.2 cm^2/Vs



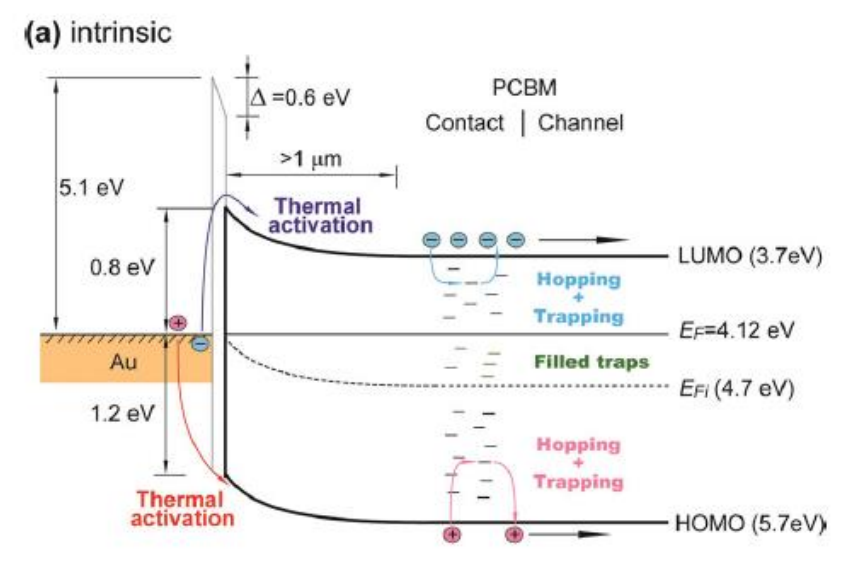
Geometry

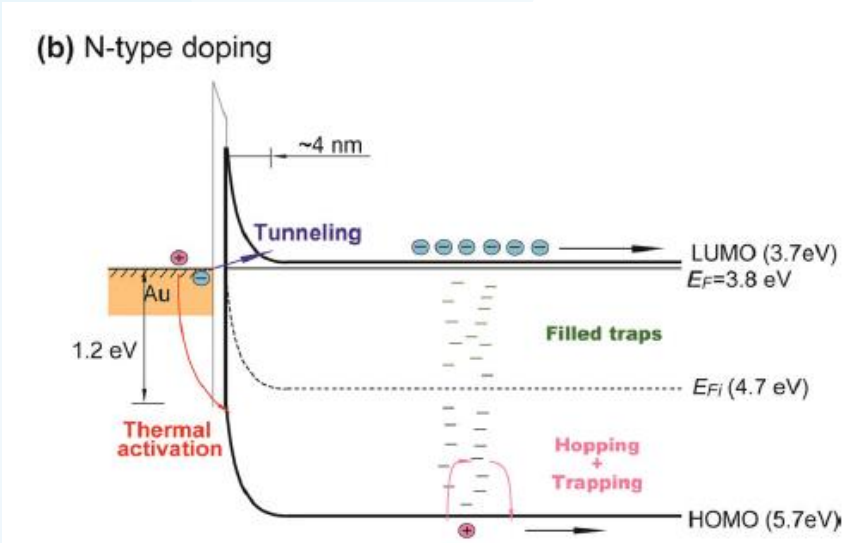
- **W = 60 µm**
- **L = 1.5 µm**

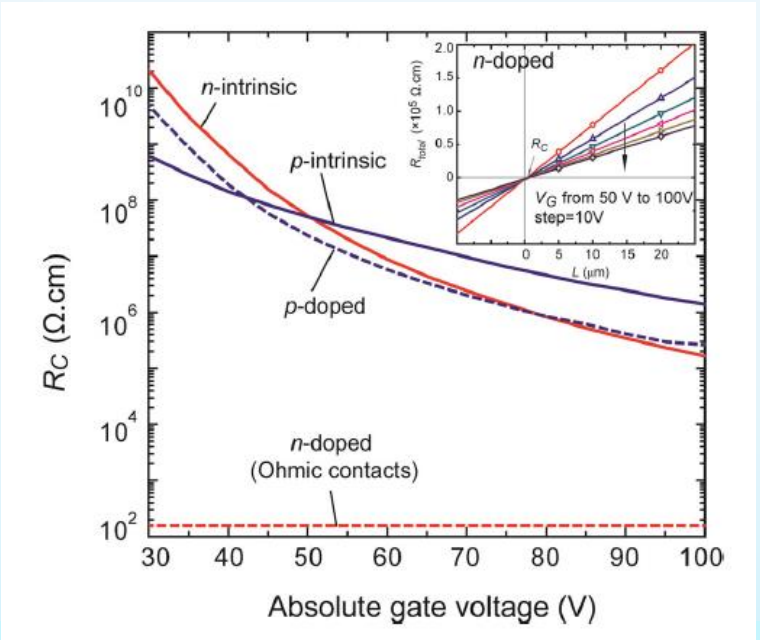
Doping as a way to control injection and uni-/ambi-polar transport



Effect of Doping

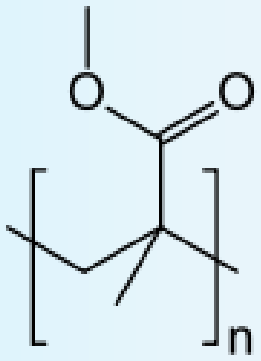






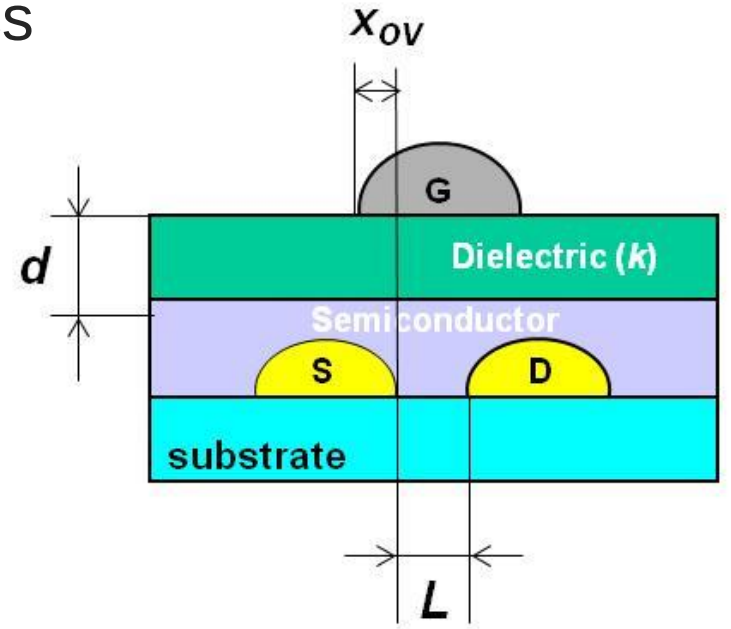
Adv. Funct. Mater. **2014**,
DOI: 10.1002/adfm.201400850

High Supply Voltage



Low-k polymer dielectrics
$\varepsilon_r = 2 - 3$

~ 500 nm

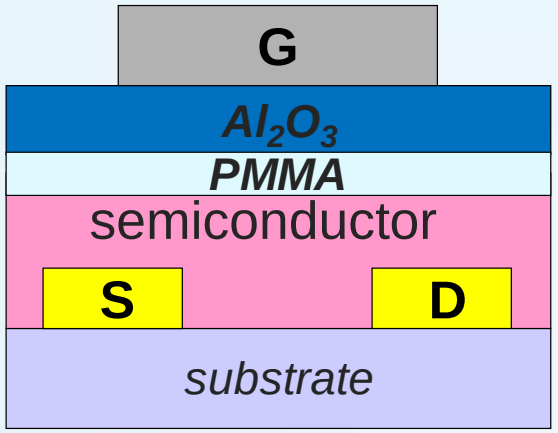


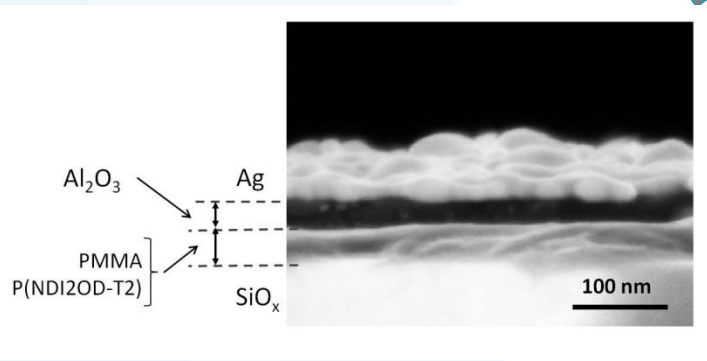
$$C'_{ox} = \frac{\varepsilon}{d} \approx 5 \frac{nF}{cm^2}$$

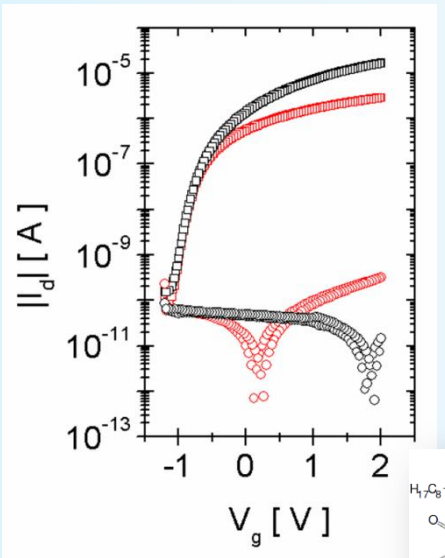
Forcing the use of gate voltages ≥ 40 V

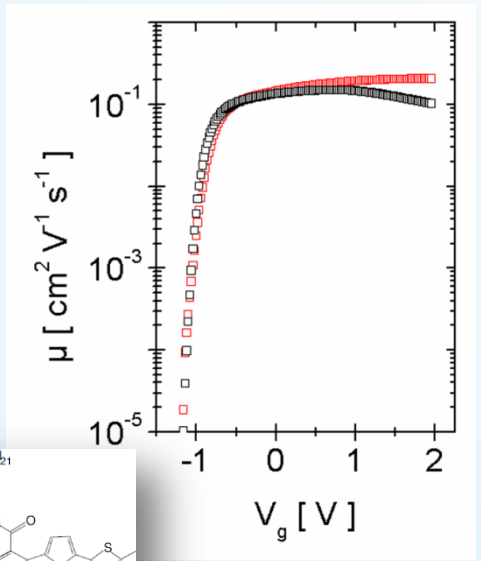
Low Voltage OFETs with Hybrid Nanodielectrics

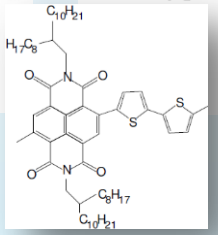
30 nm
10 nm

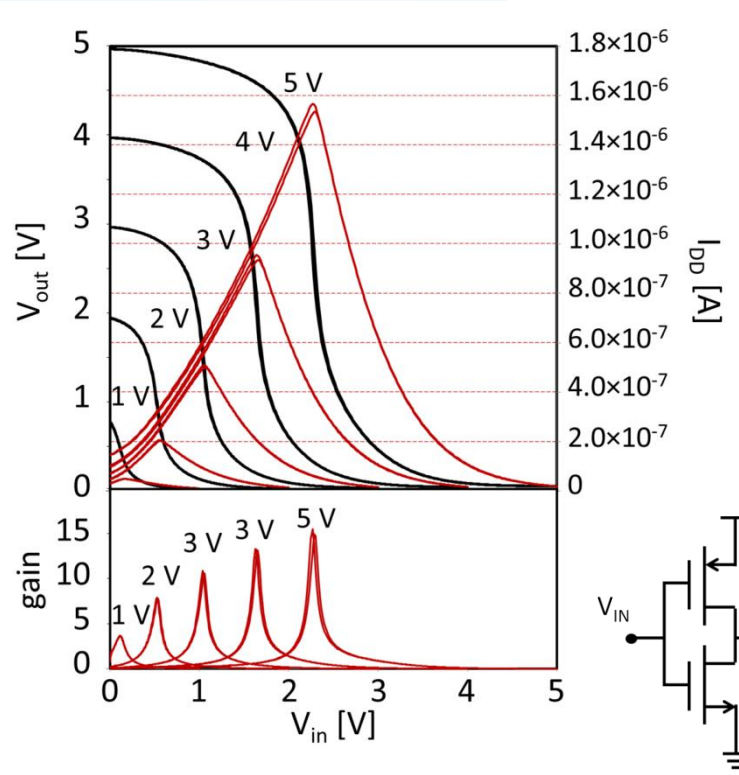


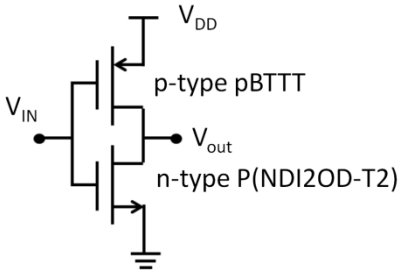






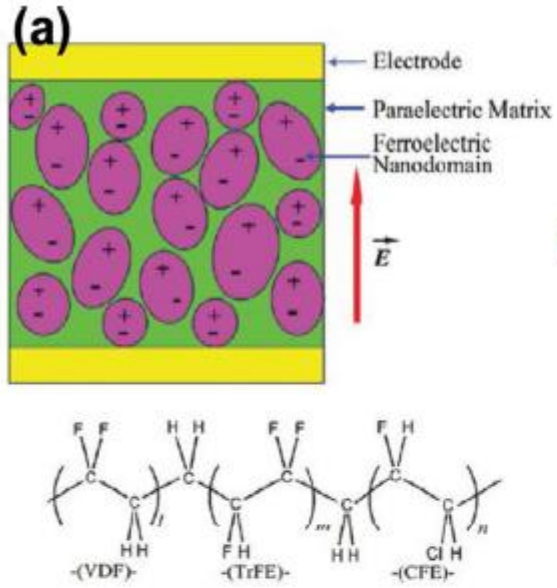


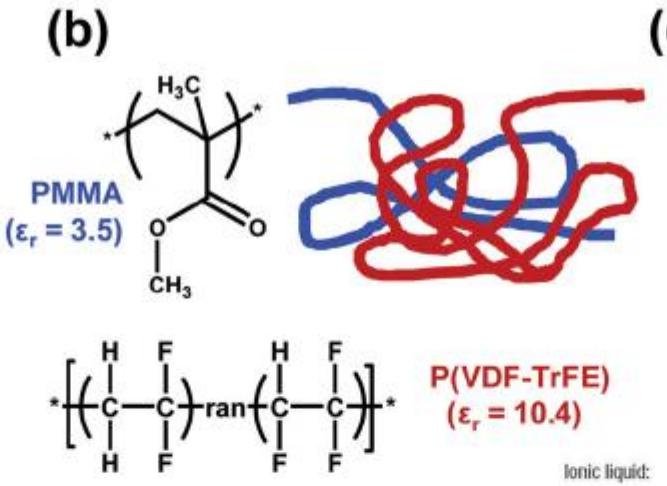


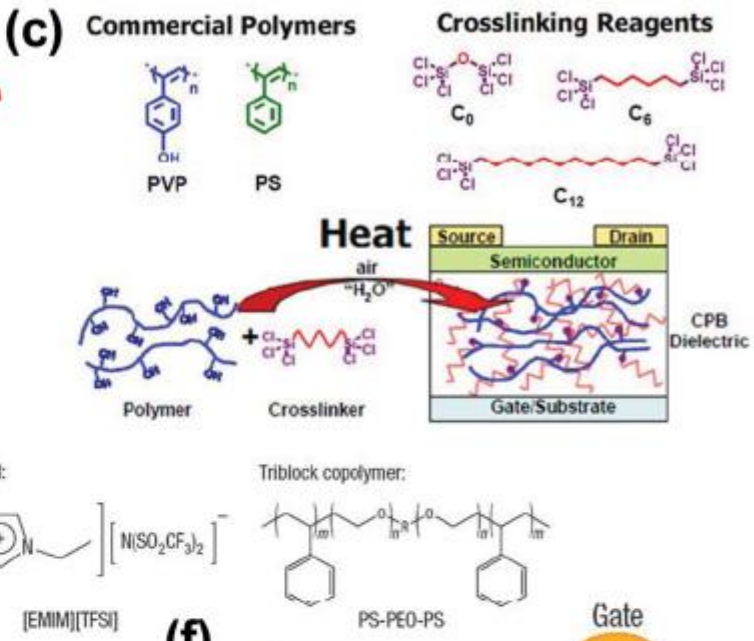


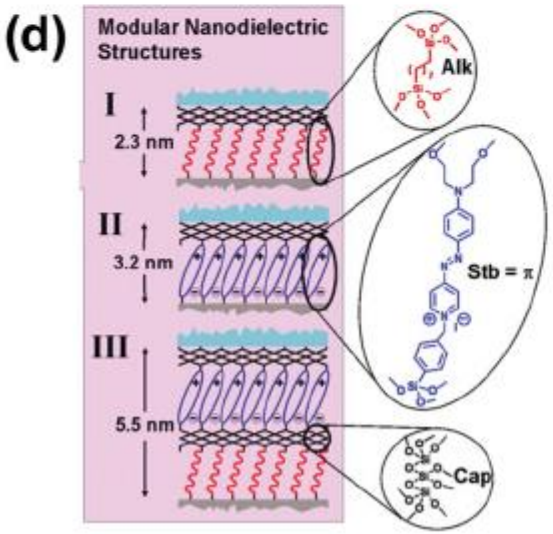
A. Luzio, et al. Adv. Funct. Mater. 24 (2014) 1790

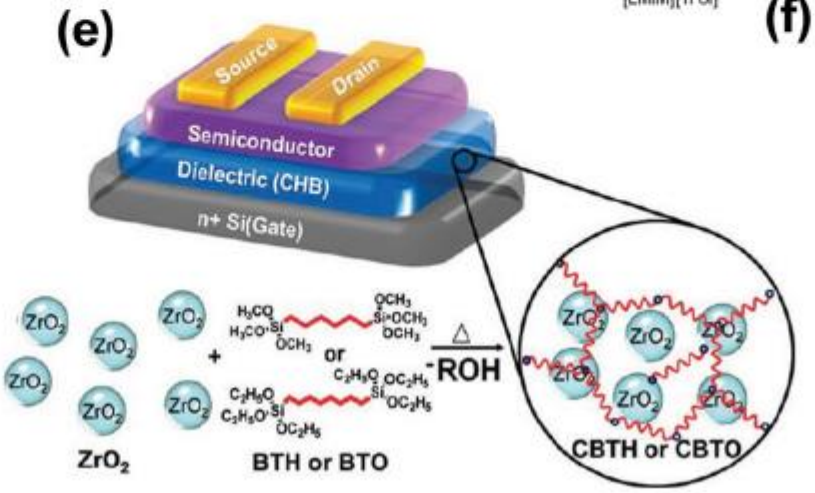
Printable dielectrics

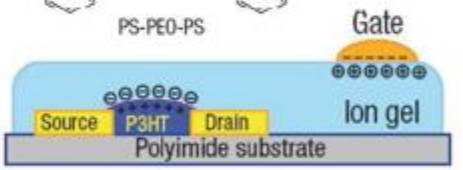


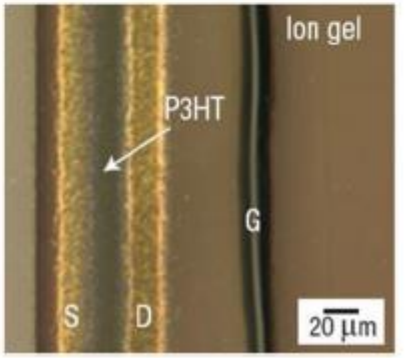










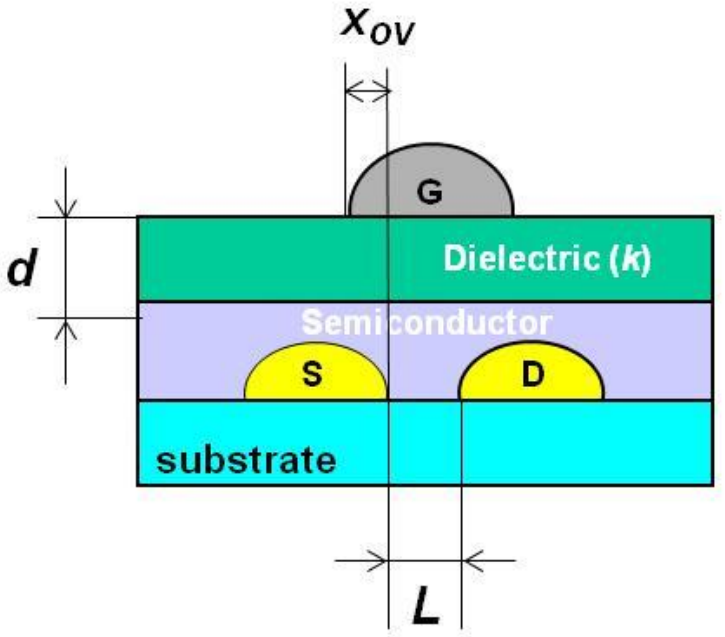


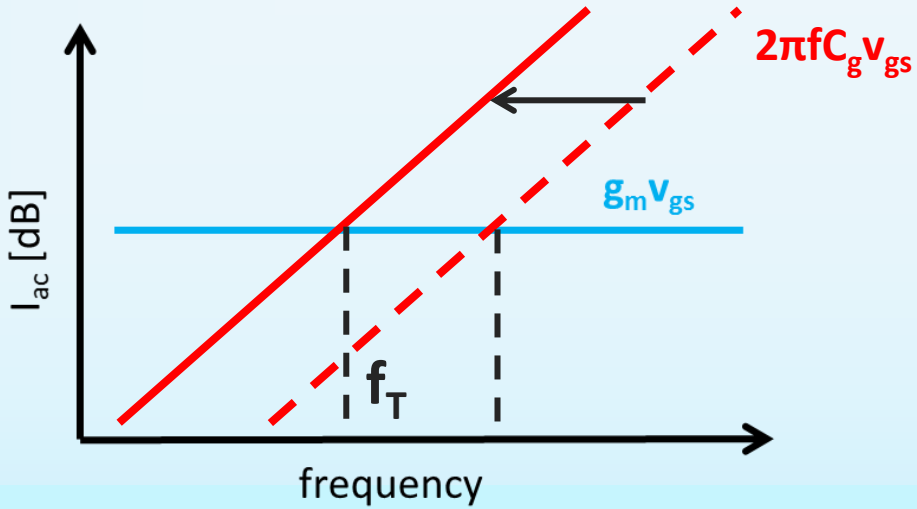
Issue with downscaling

$$g_m = \left.\frac{di_D}{dv_{GS}}\right|_{v_{GS}=V_{GS}} = \mu C'_{OX}\frac{W}{L}V_{od} \quad \text{(saturation regime)}$$

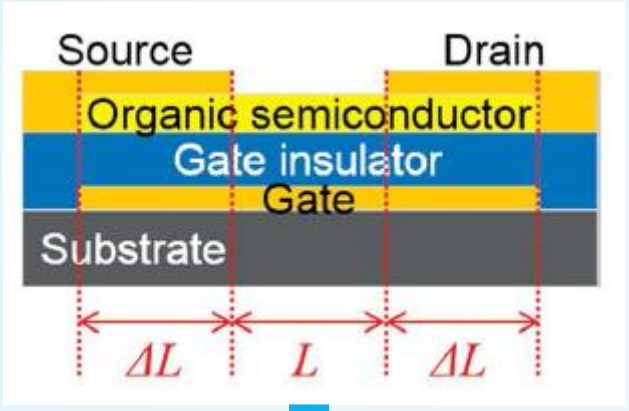
$$g_m \propto C'_{OX}V_{od} = const$$

$$C_{OV} = C'_{OX}x_{OV}W \propto C'_{OX}$$

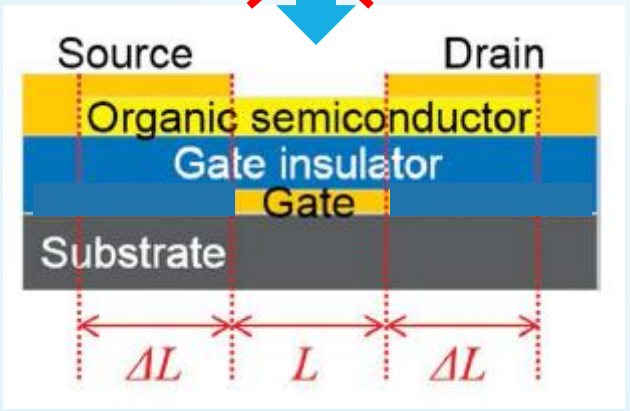


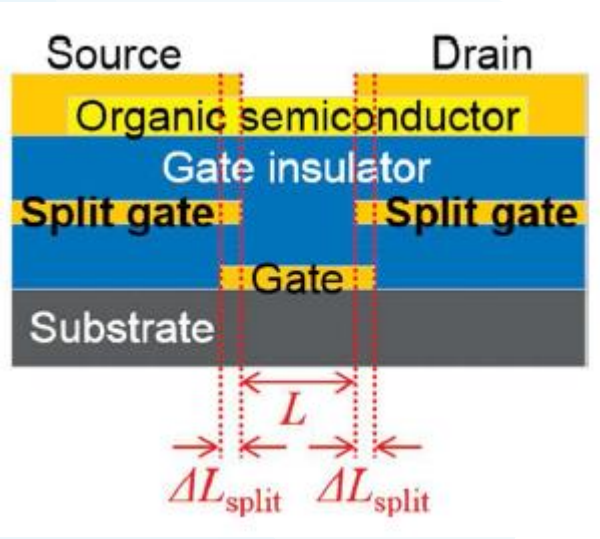


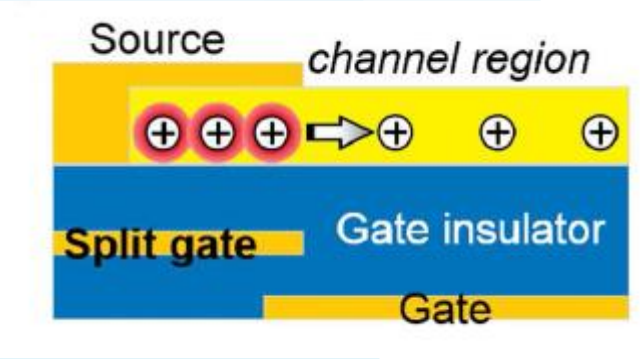
How to reduce Overlap Capacitance: 1. Split Gate



R_C !!

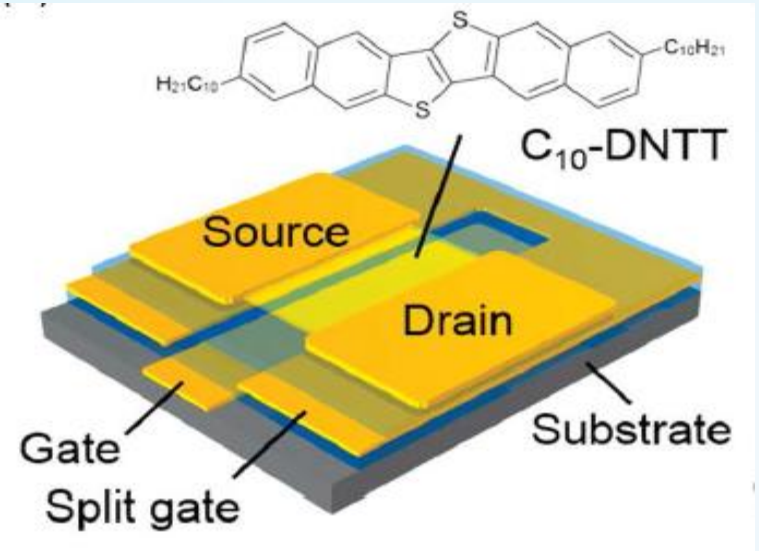


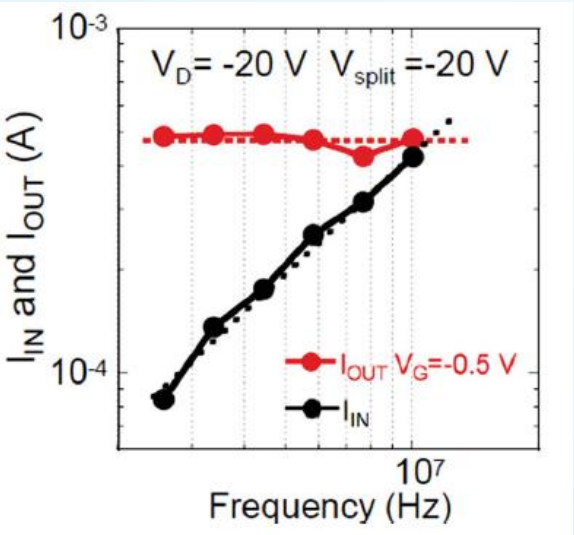


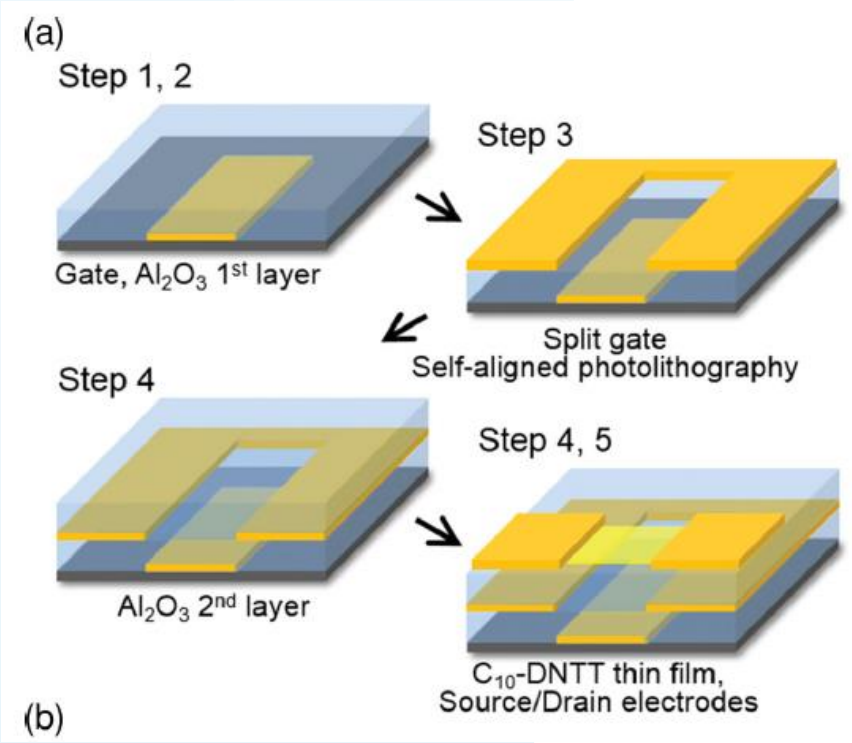


Jun Takeya et al., Adv. Mater. 2014 DOI: 10.1002/adma.201304976

Split gate via lithograpyhy

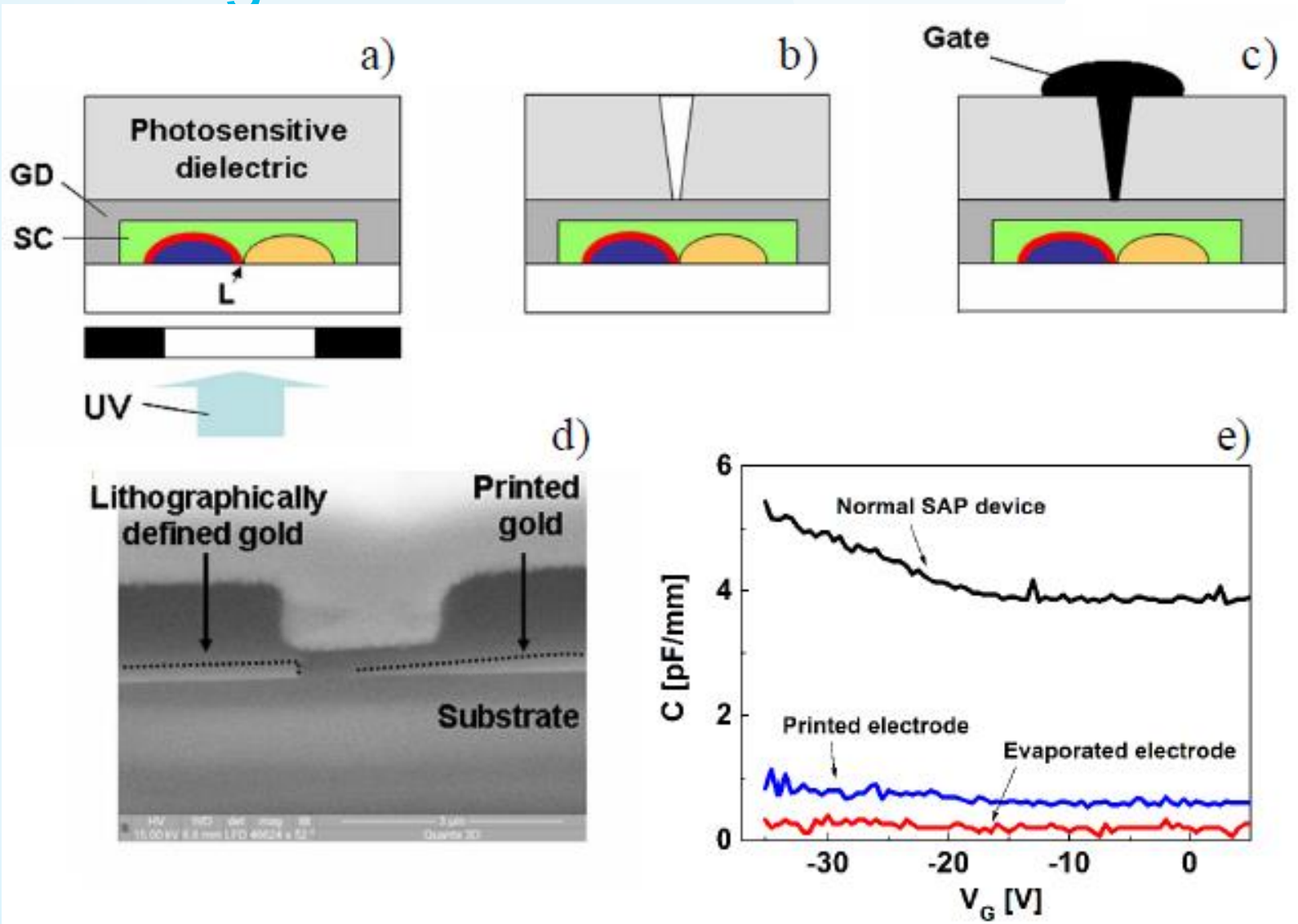






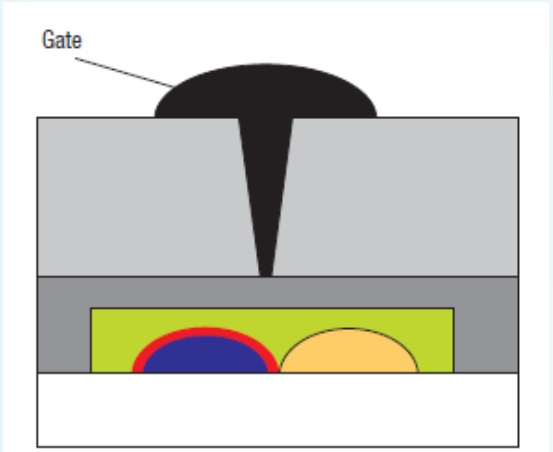
Jun Takeya et al., Adv. Mater. 2014 DOI: 10.1002/adma.201304976

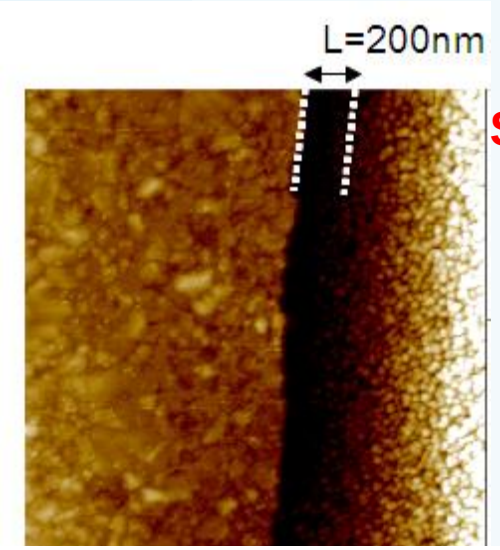
How to reduce Overlap Capacitance: 2. Self-Aligned Gate



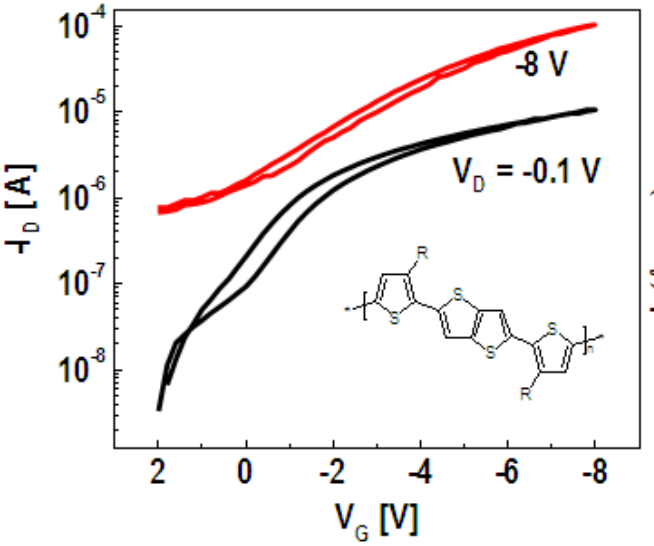
Y.Y.Noh et al, Nat. Nanotechnol. 2 (2007) 784-789

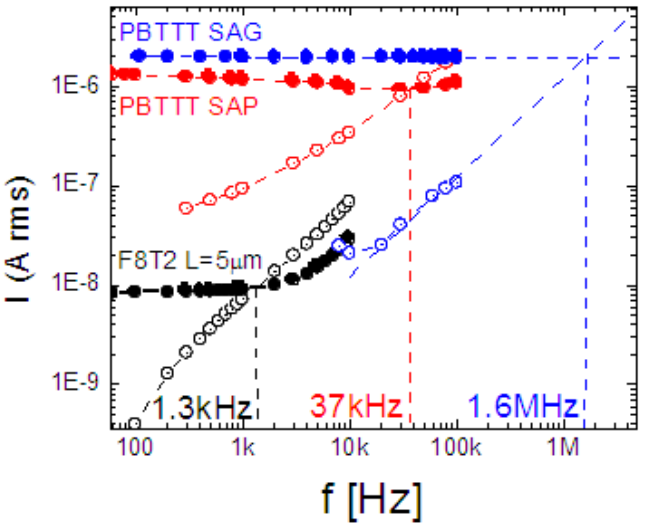
f_T of solution processed OFETs





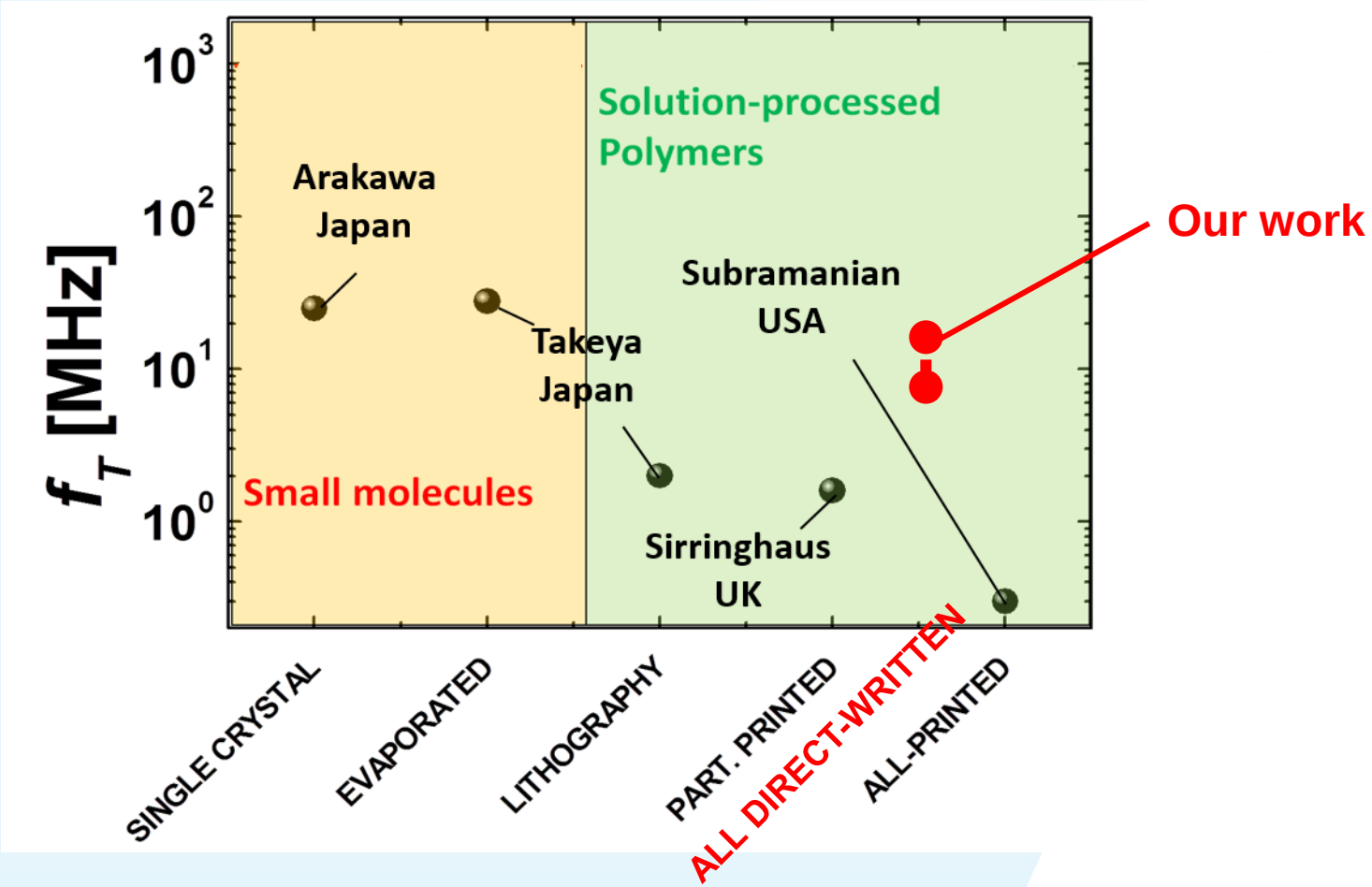
Self-Aligned Printed
100 - 500 nm gaps





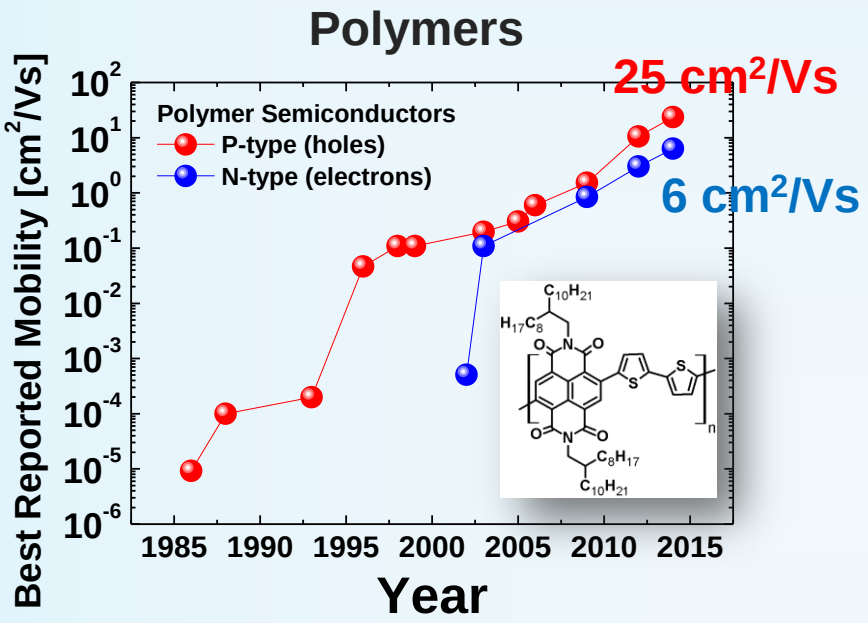
Y.Y.Noh et al, Nat. Nanotechnol. 2 (2007) 784

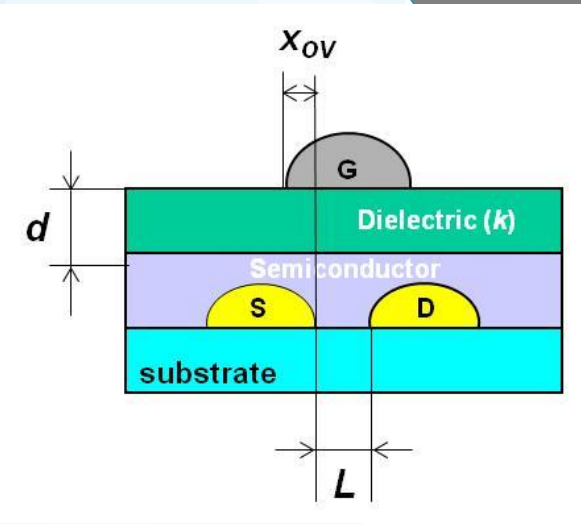
OFET f_T: record values



SCALABLE PRINTING and DIRECT-WRITING

Perspective?

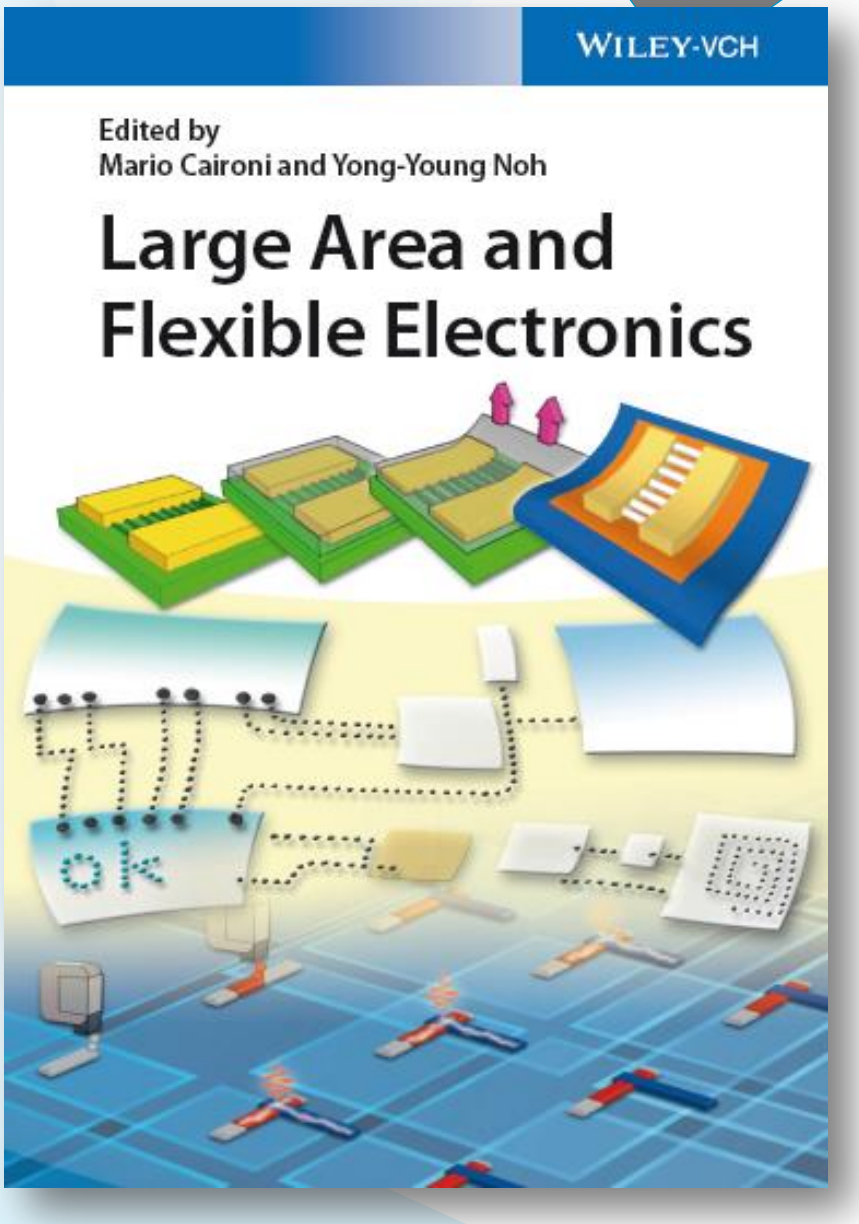




$$f_T \approx \frac{\mu_{eff} V_{OD}}{2\pi L(L + 2x_{OV})}$$

		f_T [MHz]		
L [μm]	x_{OV} [μm]	1 cm²/Vs	5 cm²/Vs	10 cm²/Vs
2	2	9.58	47.9	95.8
1	2	22.8	114	228
1	1	38.3	192	383
0.5	1	91.3	457	**913**
0.5	0.5	153	**767**	**1533**

Thank you for your kind attention



March 2015