Enhanced OTFT performance by optimized trap control

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Thanks to

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Tobias Morf
Simon Haas
Kurt Mattenberger
Thomas Mathis
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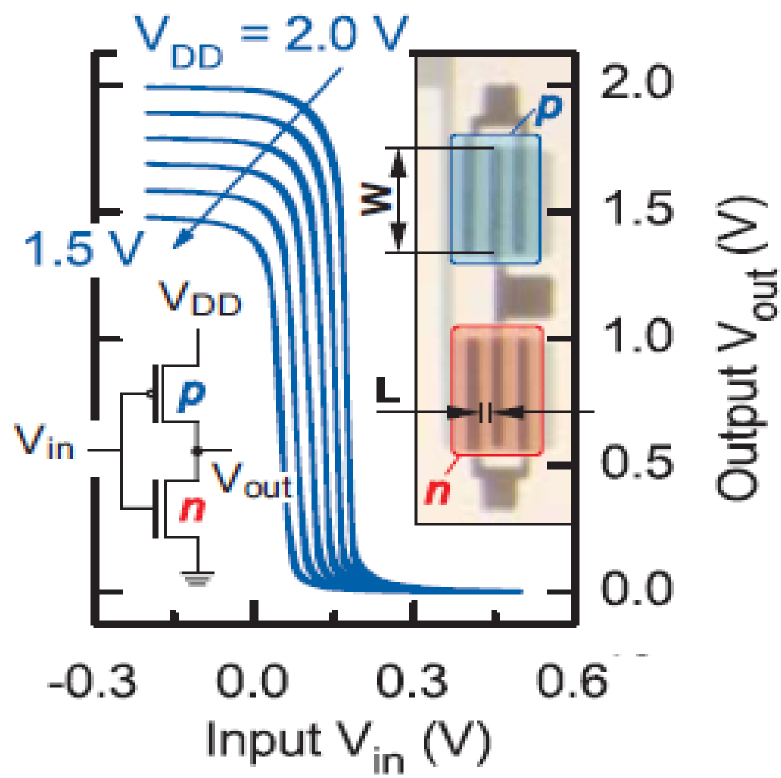
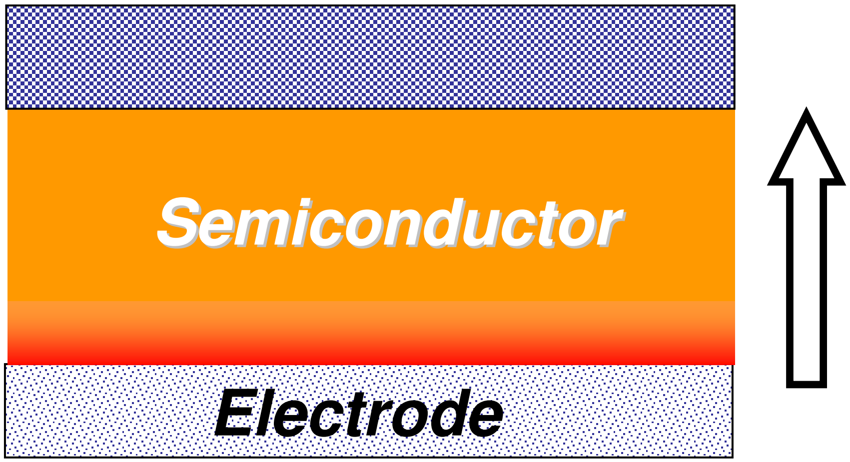


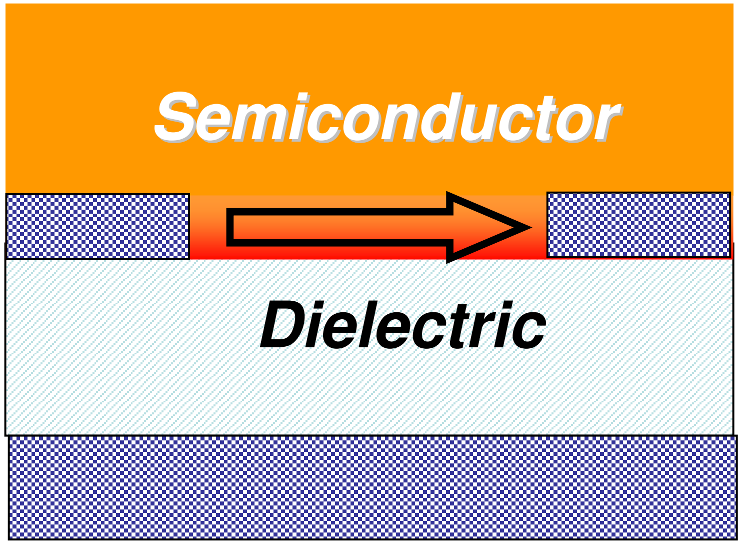
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

PHYSICS OF NEW MATERIALS

Organic electronics: bulk and interfaces issues

The FET is an "interface" - device :
charge is concentrated at semiconductor – dielectric interface

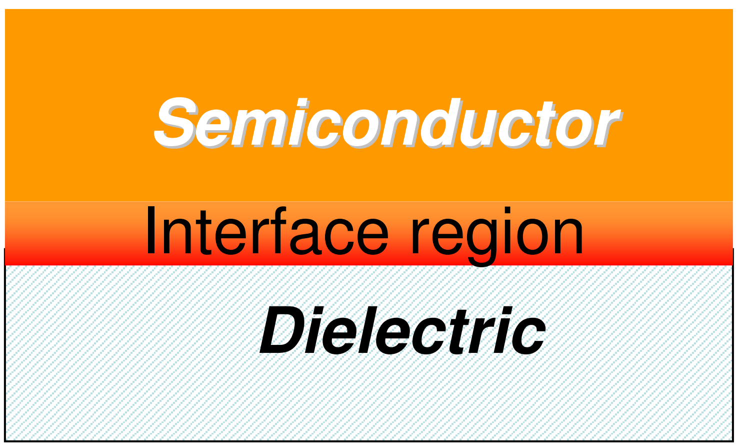




Charge traps:
Barriers against charge injection

Charge traps:
Reduction of mobile charge density

- Identify trap DOS
- Quantify trap DOS (bulk, thin film, interface)
- Eliminate traps



Measure the trap DOS

bulk
TFT
SC FET

Trap reduction by RT annealing

O_2 induced traps in Pc thin films

choice of dielectric material

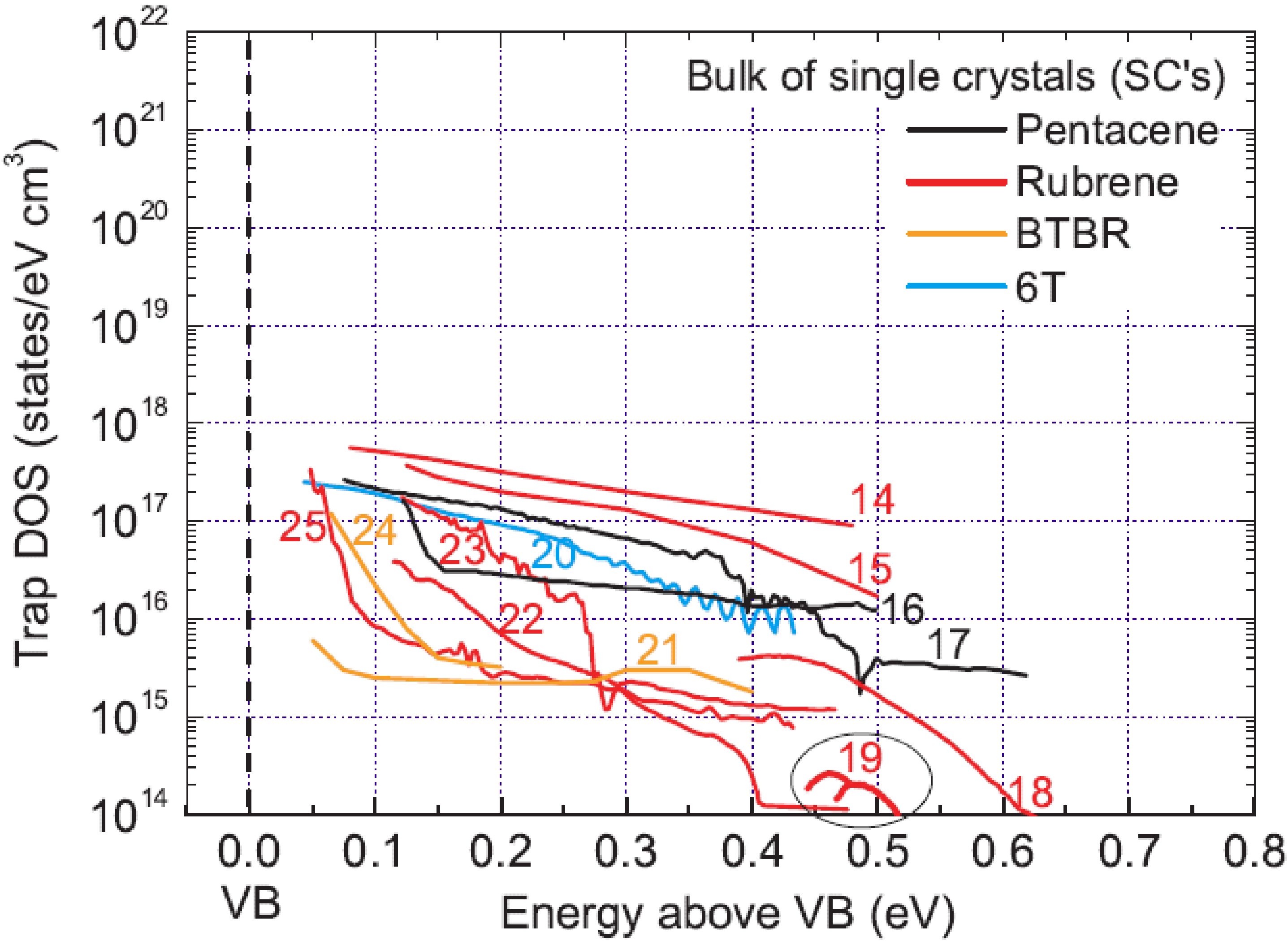
high-quality complementary TFTs

low-voltage TFTs

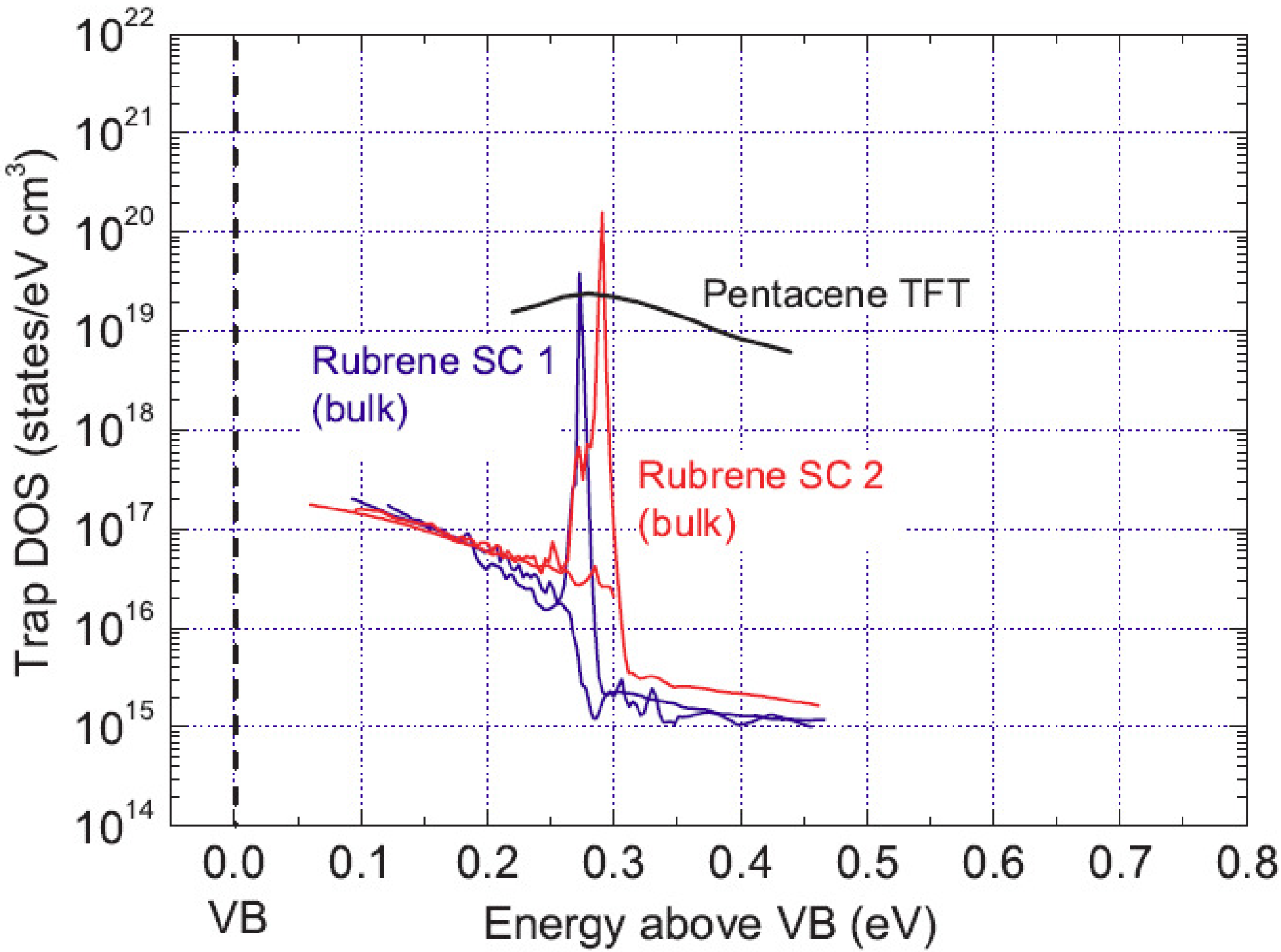
Comparison of trap DOS in organic and in inorganic semiconductors ?

Interface traps compared to bulk traps?

Bulk trap DOS in organic molecular crystals

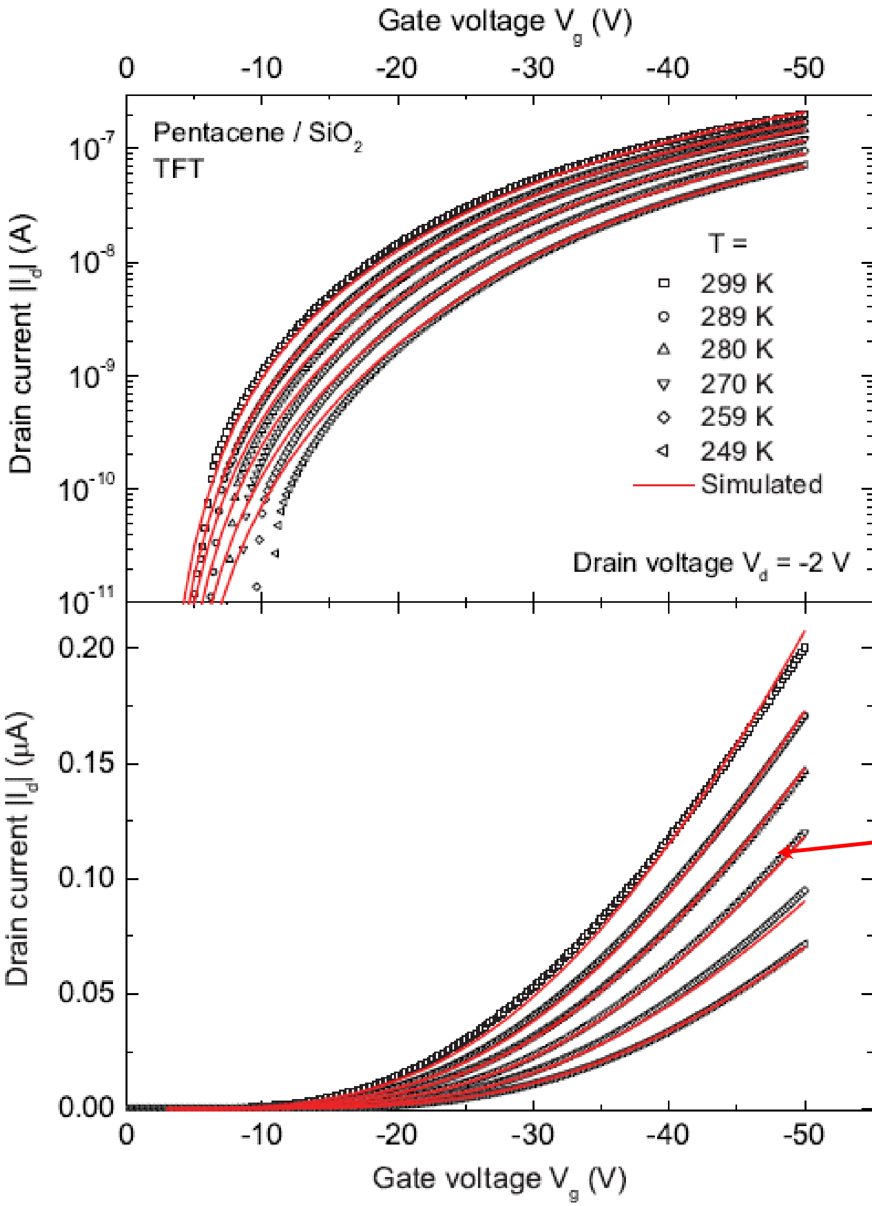


Oxygen induced trap levels



C. Krellner et al. Phys. Rev. B 2007

Quantitative evaluation of trap DOS in TFTs



Starting data set:

Transfer characteristics of a Pentacene TFT on SiO_2

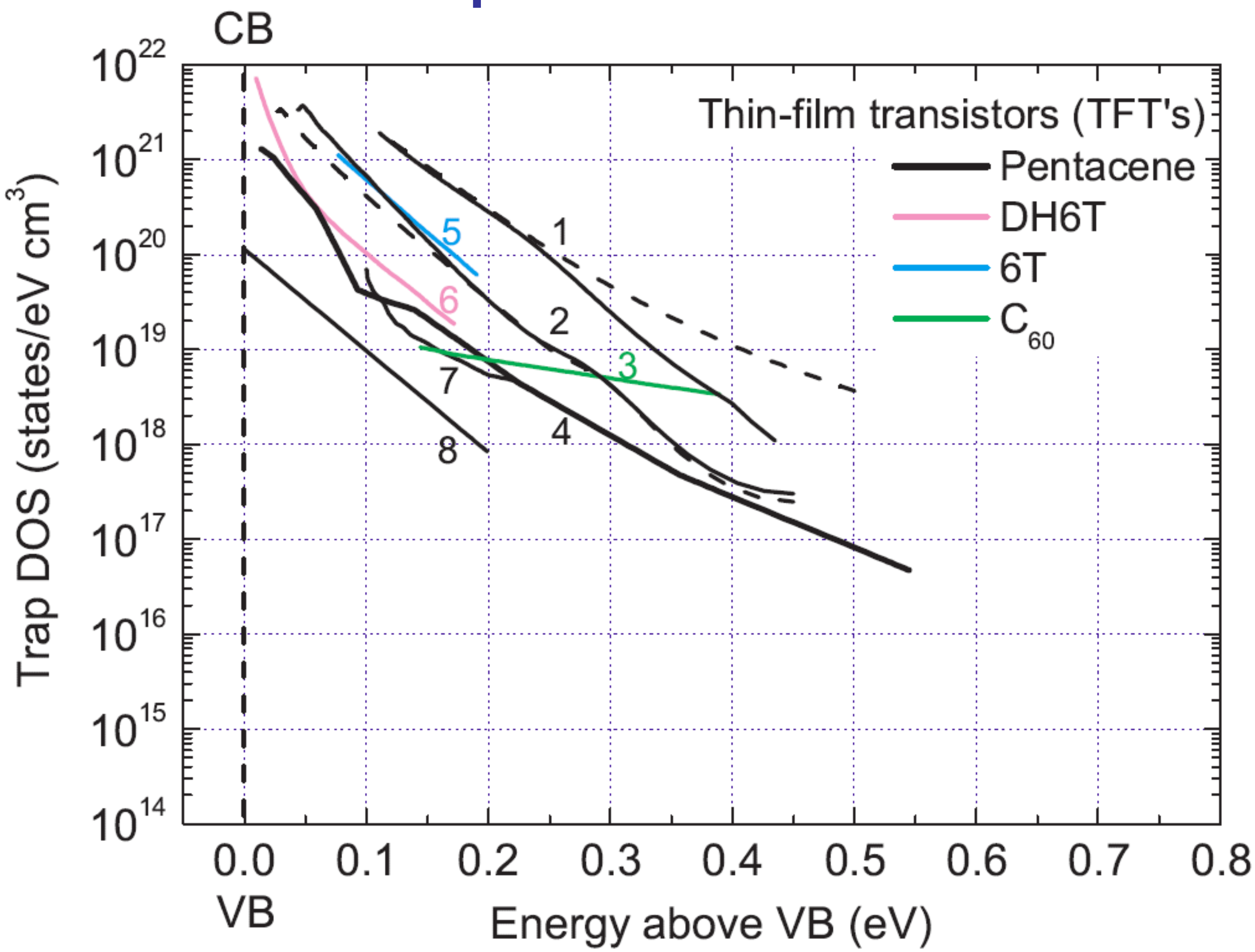
Relatively high trap density :
subthreshold swing
reduced FET mobility : ~0.2 cm^2/Vs

Simulation result (DOS, mobility)
(code by Oberhoff et al., ETH ZH)

W. L. Kalb and BB,
Phys. Rev. B 81, 035327 (2010)

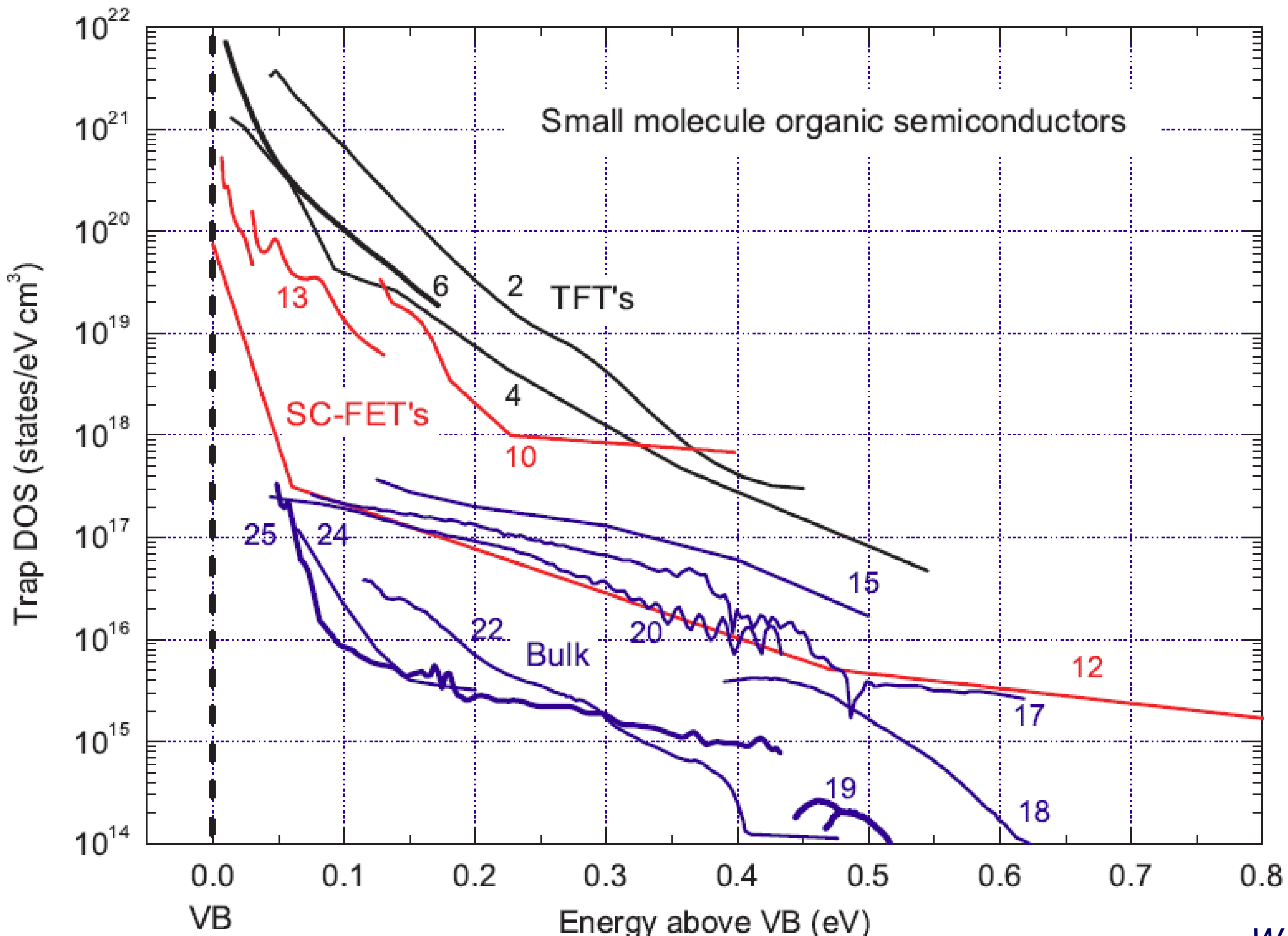
D. Oberhoff, K. P. Pernstich, D. J. Gundlach, and B. B.,
IEEE Trans. Electron Devices 54, 17 (2007)

Trap DOS in TFT



1 Pc W. L. Kalb, et al. Phys. Rev. B 78, 035334 (2008).
2 Pc W. L. Kalb, et al., Appl. Phys. Lett. 90, 092104 (2007).
3 C_{60} N. Kawasaki, et al. Appl. Phys. Lett. 91, 243515 (2007).
4 Pc F. De Angelis, et al.,Appl. Phys. Lett. 88, 193508 (2006)., Appl. Phys. Lett. 86, 203505 (2005).
5 6T G. Horowitz et al., J. Phys. III France 5, 355 (1995).
6 DH6T G. Horowitz, et al., J. Phys. III France 5, 355 (1995).
7 Pc C. Vanoni, et al., Appl. Phys. Lett. 94, 253306 (2009).
8 Pc A. R. Volkel, et al., Phys. Rev. B 66, 195336 (2002). D. Knipp, et al.,Proc. SPIE 4466, 8 (2001).

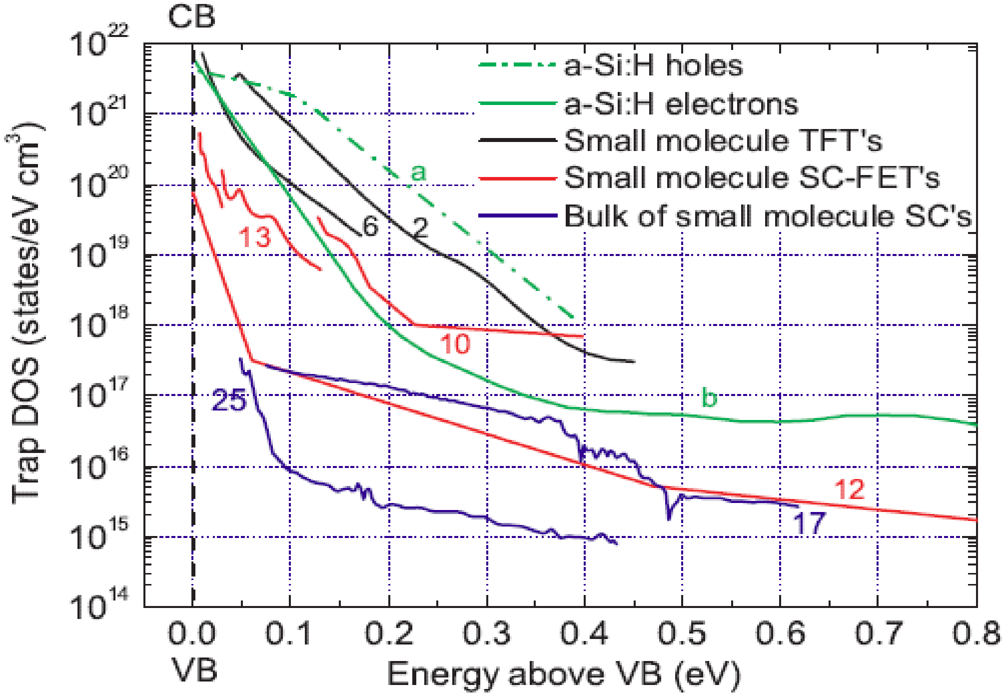
Comparison :
trap DOS in small-molecule organic semiconductors



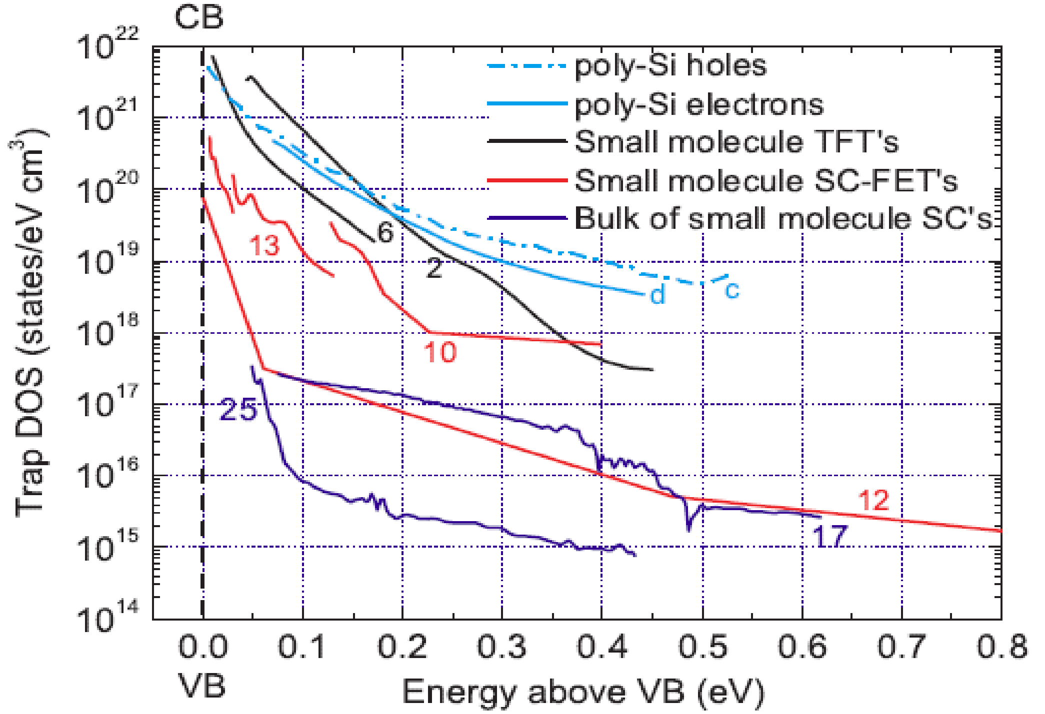
W. L. Kalb et al.,
Phys. Rev. B (2010)
arXiv:1002.1611v1

Electronic trap DOS : OMC compared to a-Si:H and poly-Si

a-Si:H

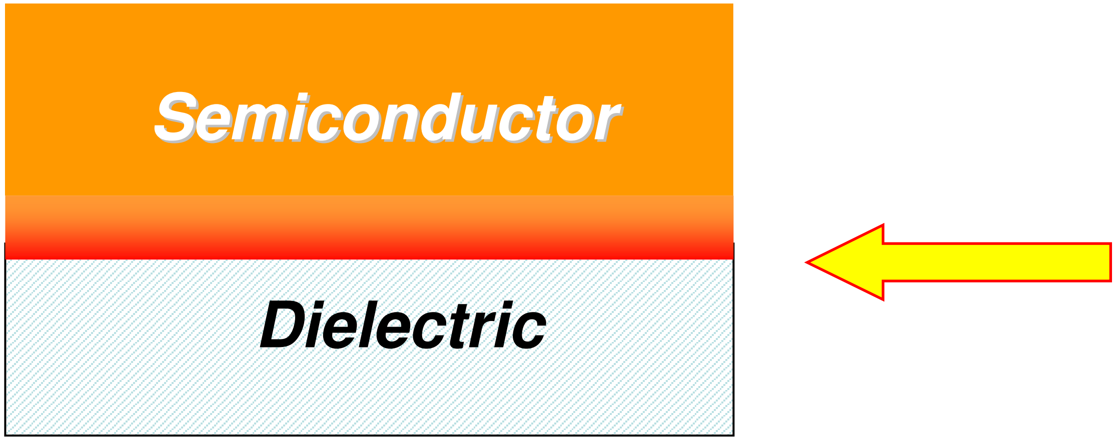


Poly Si



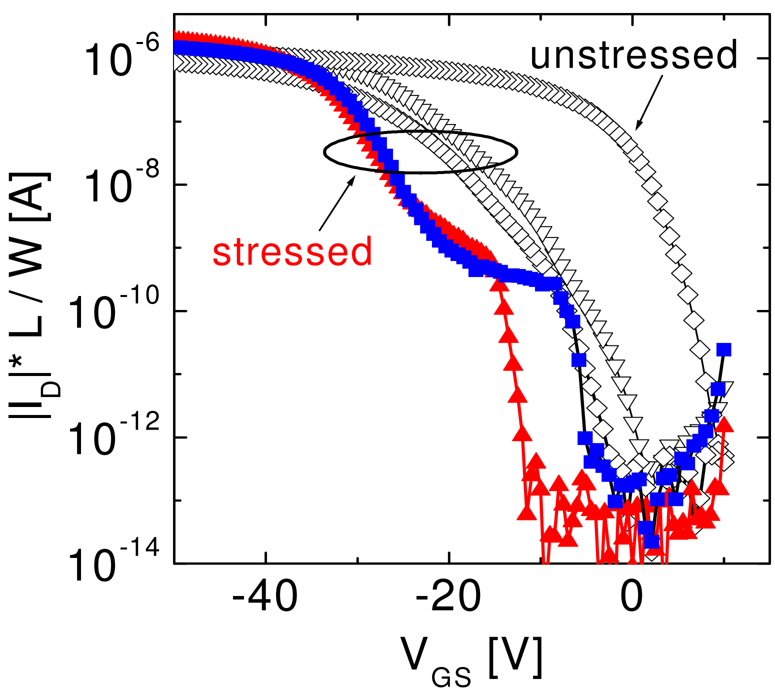
W. L. Kalb et al., Phys. Rev. B (2010) arXiv:1002.1611v1

Traps associated with the dielectric – semiconductor ***interface***

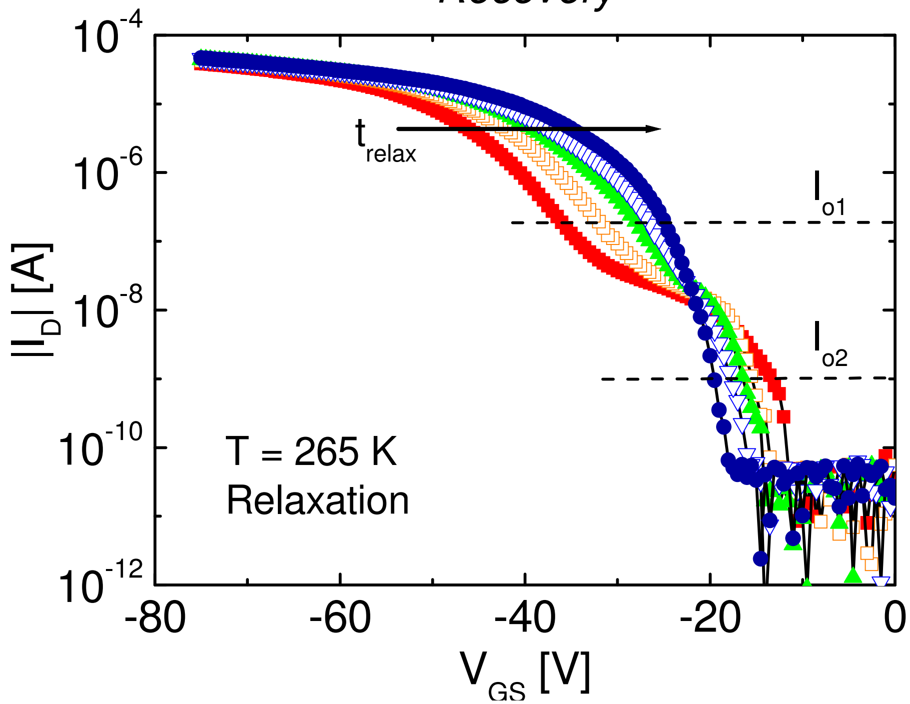


Example of interface trap states: ***water-related*** discrete trap level in Pentacene SC-FET

Gate-bias stress



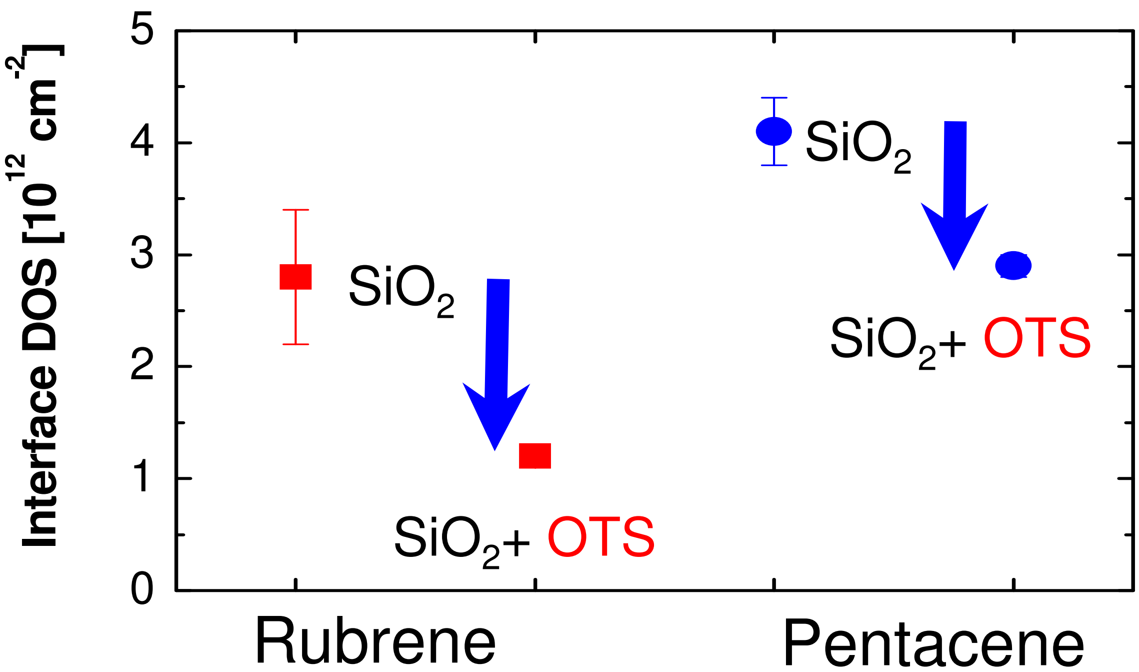
Recovery

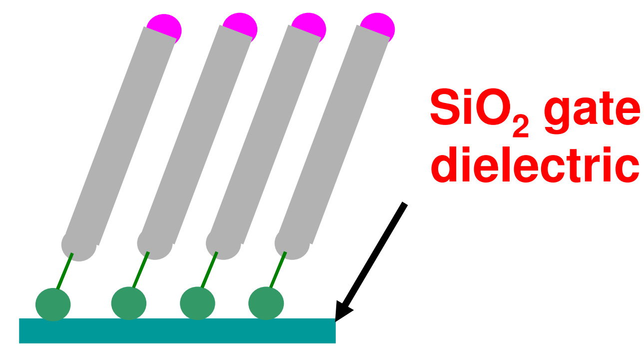


C. Goldmann et al., Appl. Phys. Lett. 88, 063501 (2006)
K. P. Pernstich et al., Appl. Phys. Lett. 89, 213509 (2006)

H. L. Gomes et al., Appl. Phys. Lett. 88, 082101 (2006)
M. L. Chabinyc et al., Appl. Phys. Lett. 88, 113514 (2006)

Interface traps in Rubrene & Pentacene s.c. FETs hydrophilic – hydrophobic dielectric surface

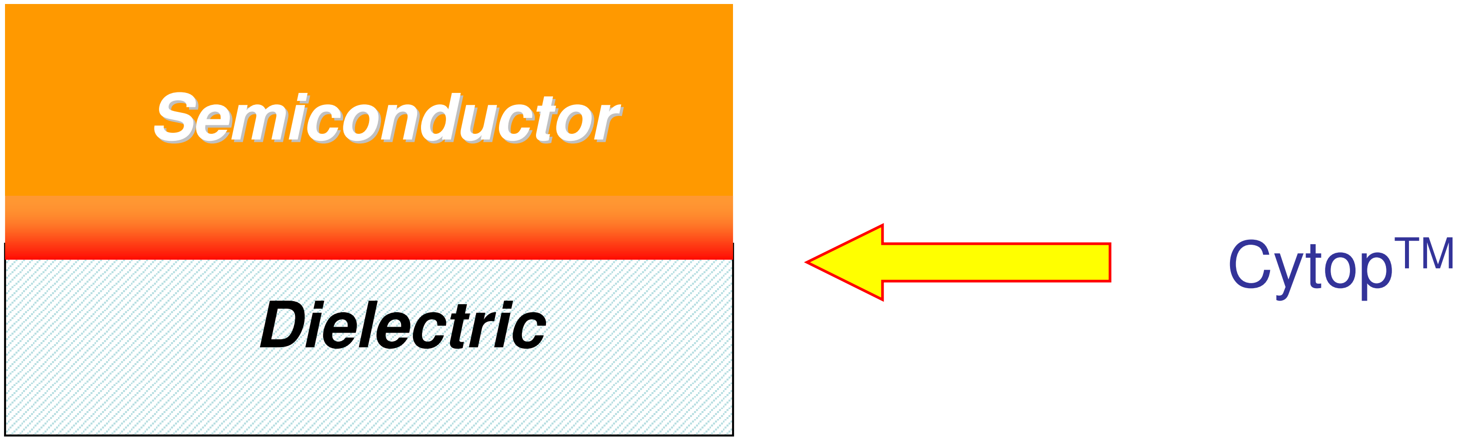




$$D = n_{average,2D} \cdot 1.5 \big/ \left(1.5nm \cdot \Delta E_F\right)$$

C. Goldmann et al. ; J. Appl. Phys. 99, 034507 (2006)

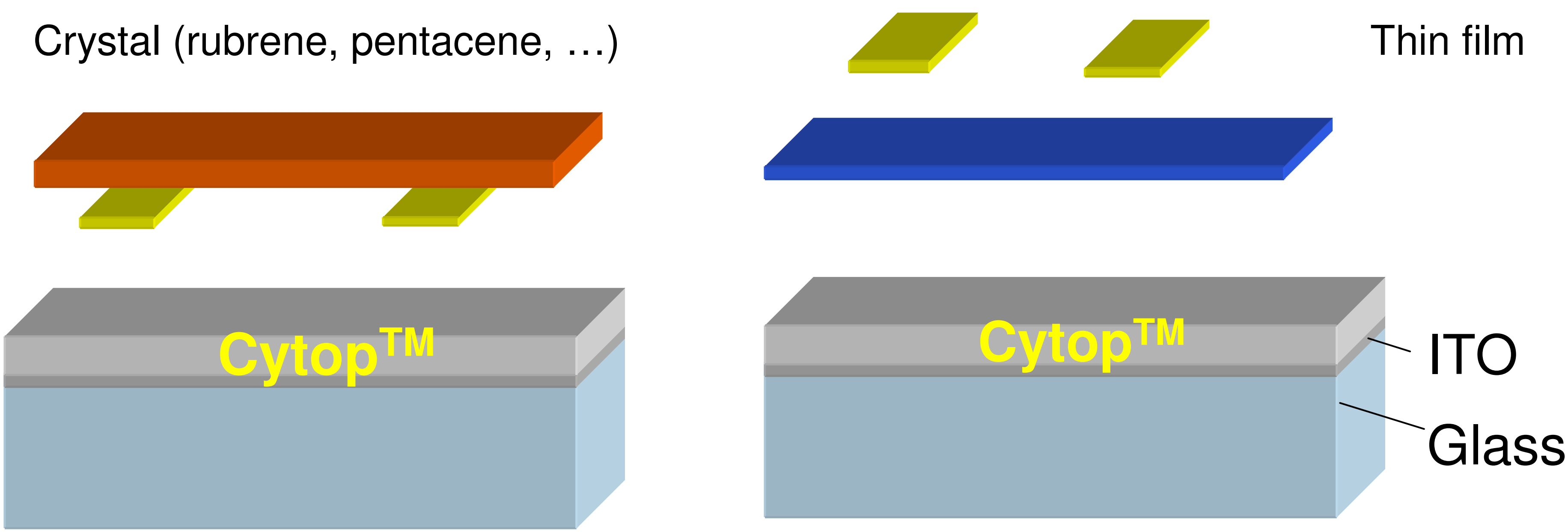
Interface trap DOS reduction : fluorinated polymer Cytop^{TM}



W. L. Kalb, T. Mathis, S. Haas, A. F. Stassen, B. B.,
Appl. Phys. Lett. 90, 092104 (2007)

Device fabrication

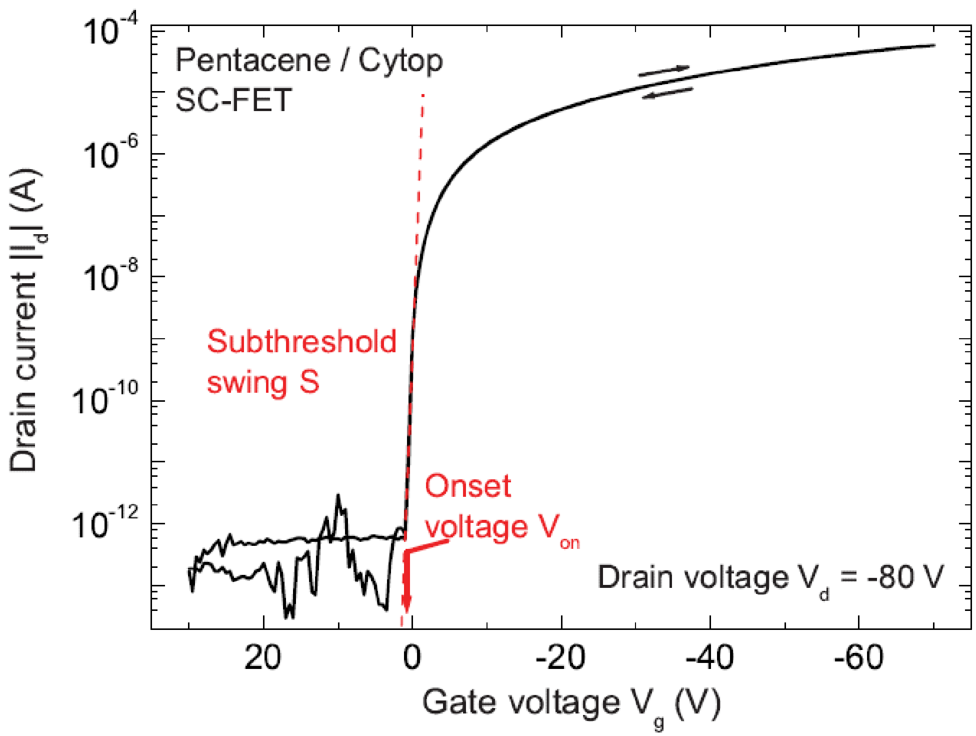
- Common bottom gate structure
- ITO gate / Cytop™ films by spin-coating
- Thickness : 430 to 700 nm (C_i = 4.4-2.7 nF/cm^2)

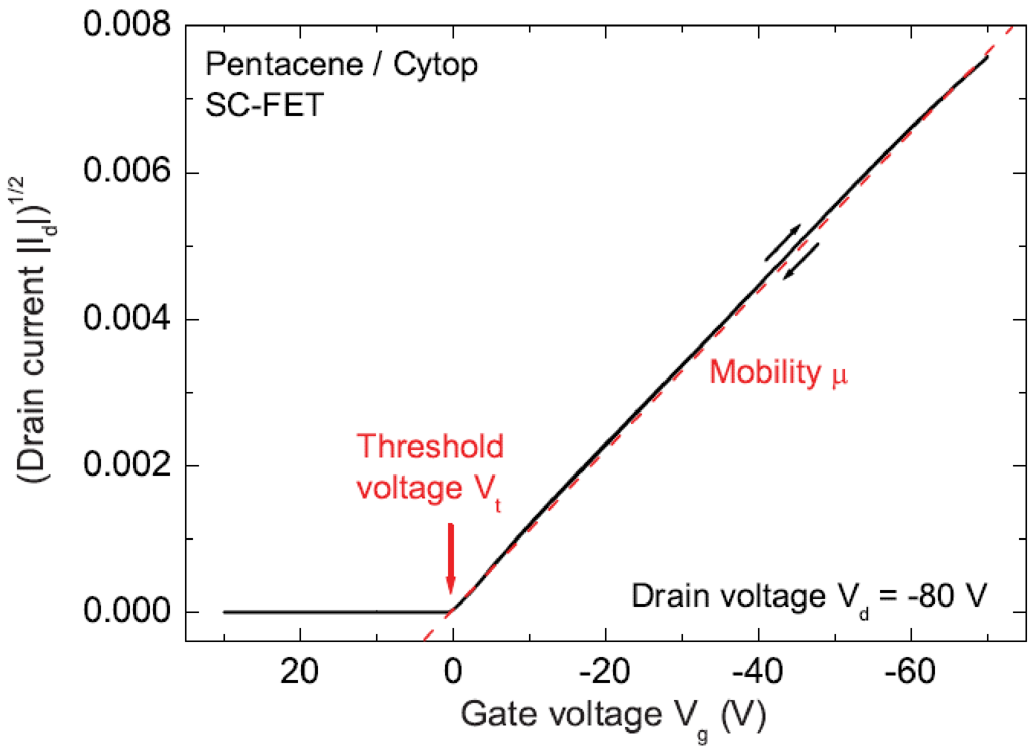


W. L. Kalb, T. Mathis, S. Haas, A. F. Stassen, B. B., Appl. Phys. Lett. 90, 092104 (2007)

Interface trap DOS reduction : Cytop™

Single-crystal / Cytop FET

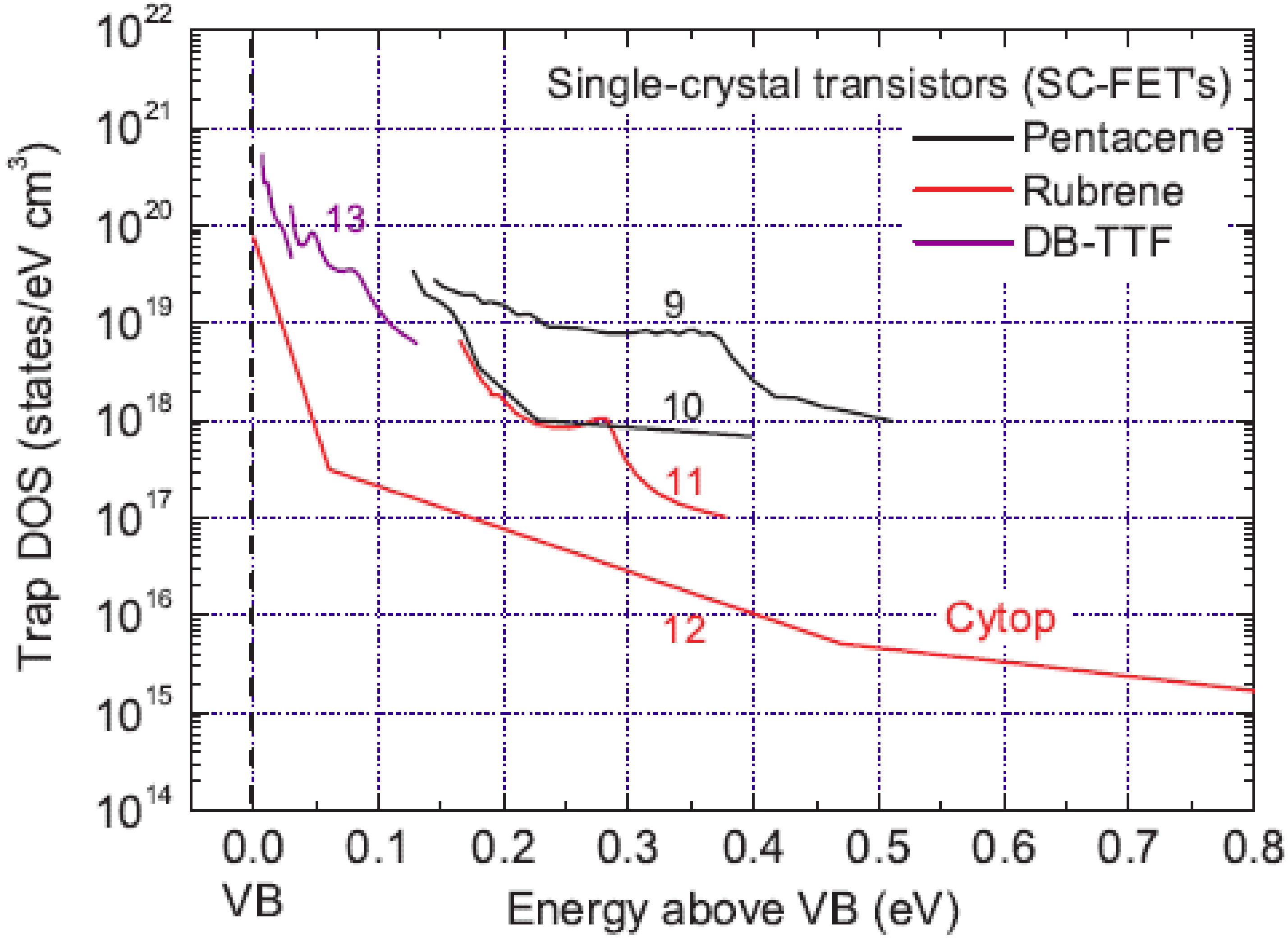




$$S = \frac{kT\ln 10}{e}\left[1 + \frac{e}{C_i}\left(\sqrt{\epsilon_s N_{bulk}} + eN_{int}\right)\right]$$

$$S = \frac{kT\ln 10}{e}\left[1 + \frac{e^2}{C_i}N_{\square}\right]$$

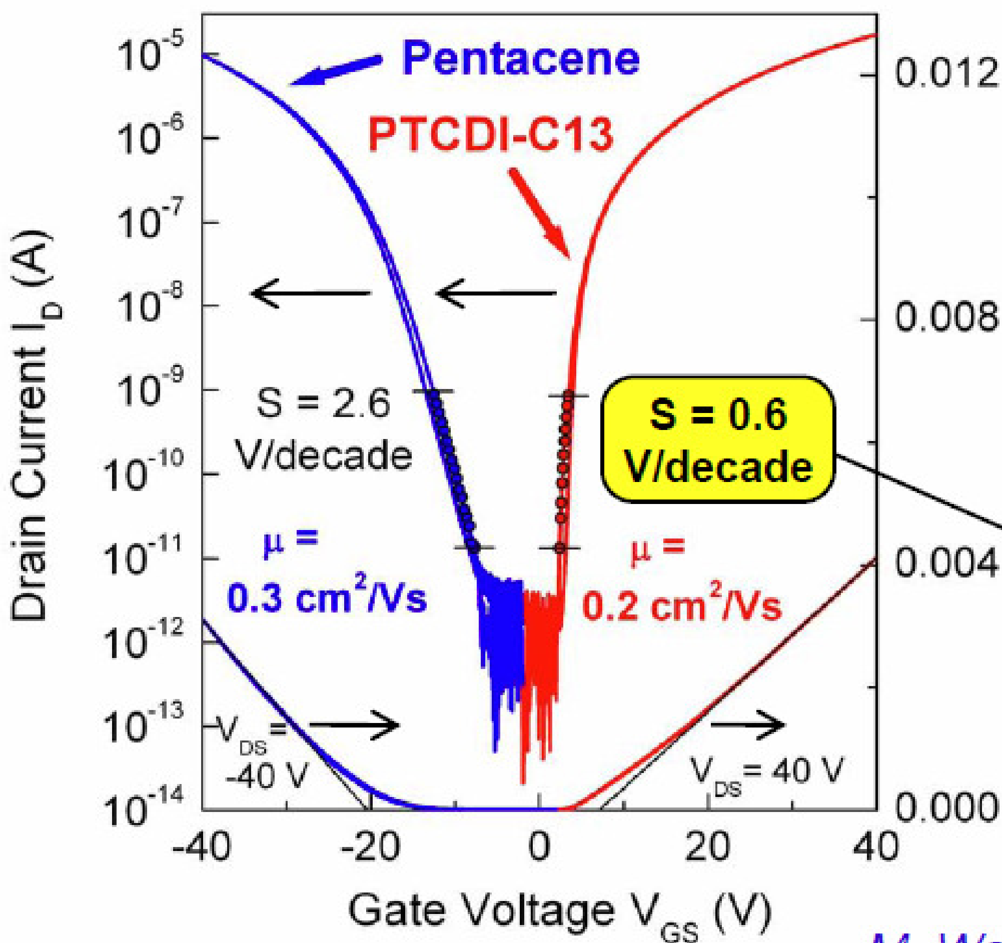
Single crystal FET trap DOS



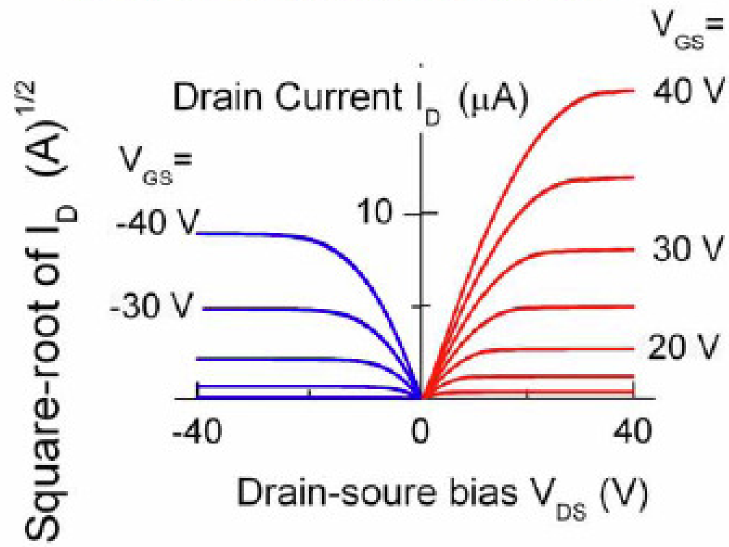
W. L. Kalb et al.,
Phys. Rev. B (2010)
arXiv:1002.1611v1

SiO_2 + 8nm Cytop

Transfer characteristics



Output characteristics



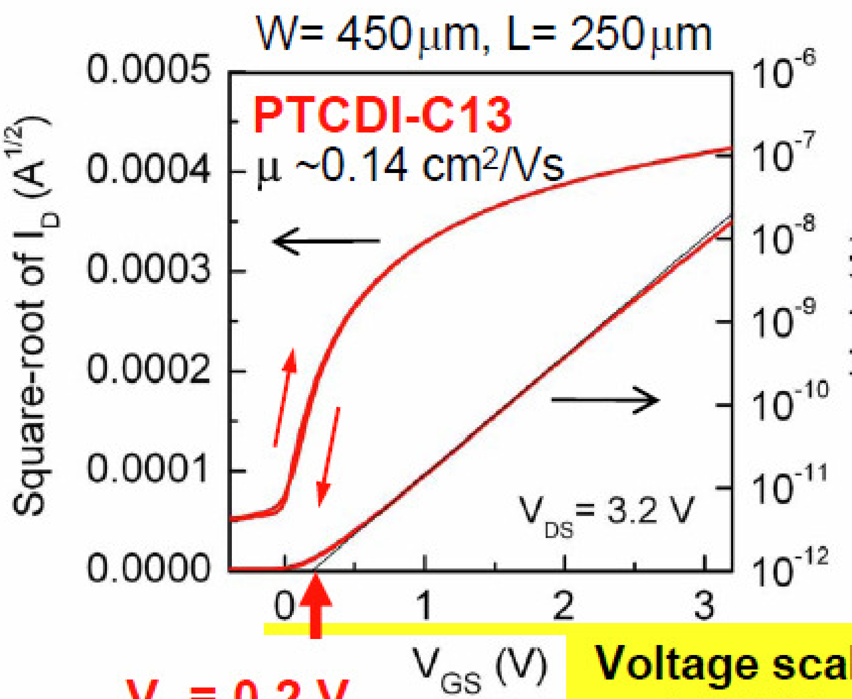
Steep current onset
Nearly no hysteresis
⇒ Low interface trap density

*M. Walser et al., APL **95**, 233301 (2009)*

Increasing the capacitance

18 nm Cytop™ only

~ 100 nF/cm²



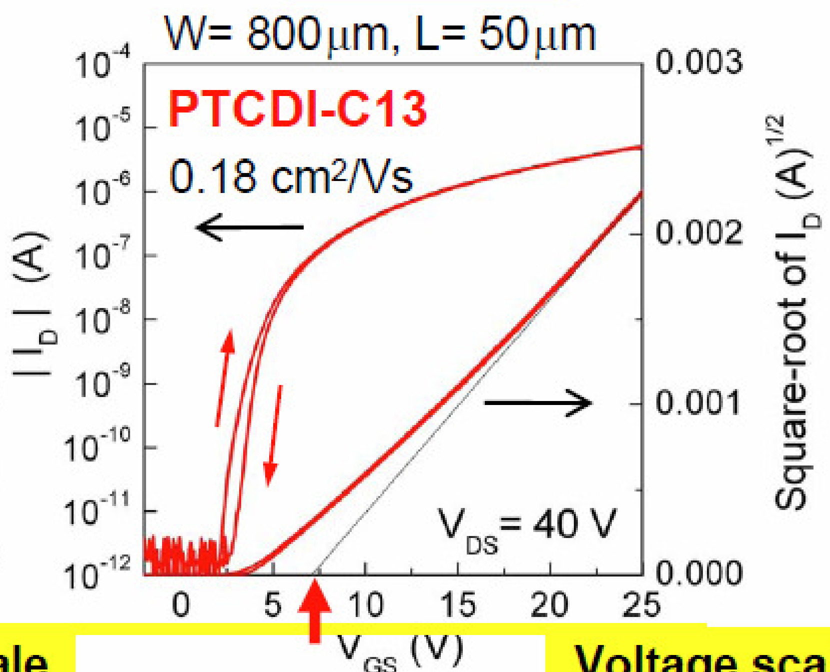
$V_T = 0.2$ V

Voltage scale 1 - 10 V

*M. Walser et al., APL **95**, 233301 (2009)*

SiO_2 + 8 nm Cytop™

~ 12 nF/cm²



$V_T = 7$ V

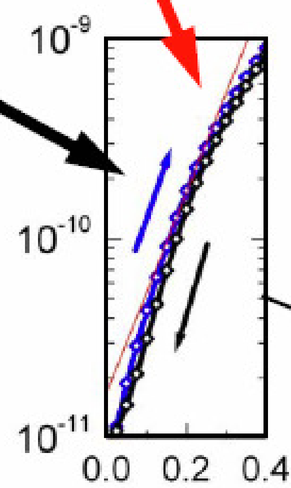
Voltage scale 10 - 100 V

*M. Walser et al., APL **94**, 053303 (2009)*

Low-voltage transistor

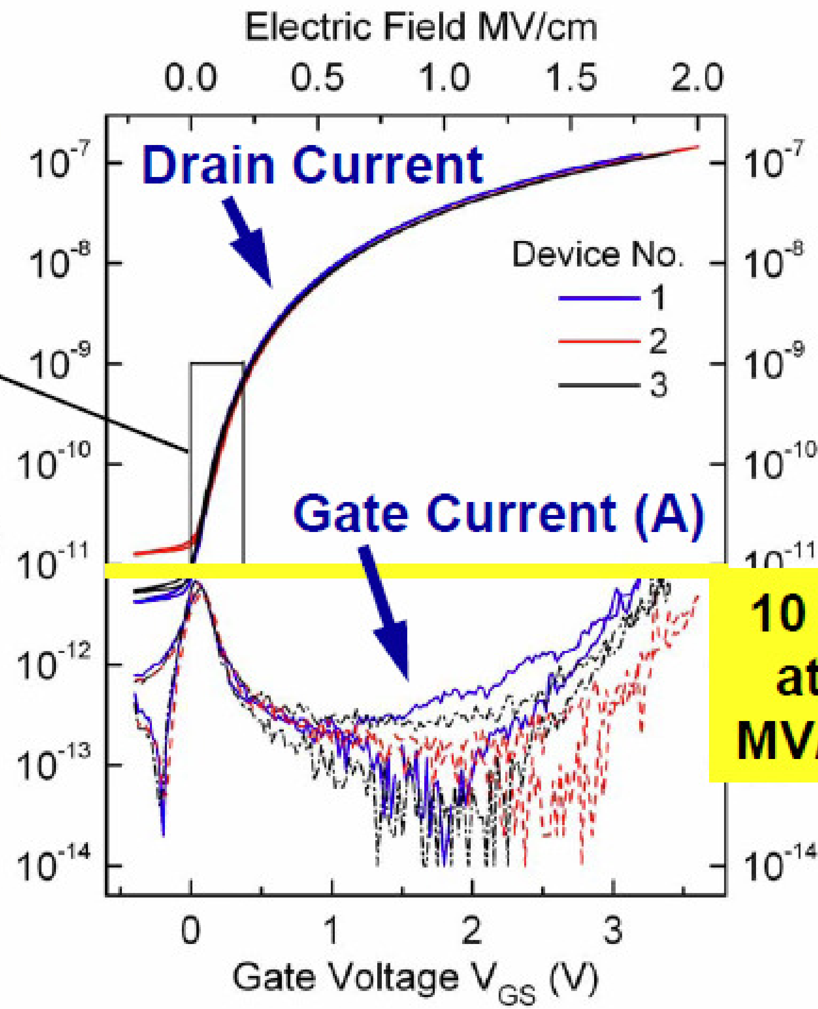
Steep onset ~ 0.2 V/decade

No hysteresis
Electrically stable

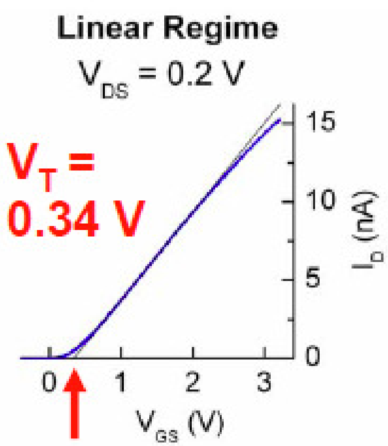


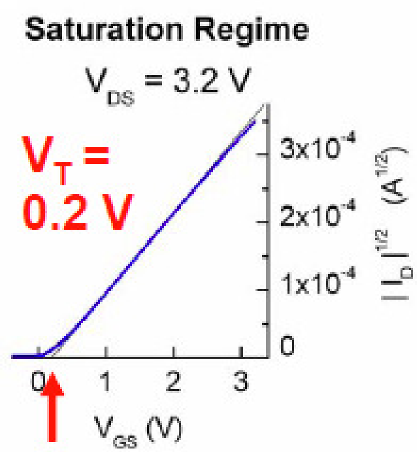
Low and stable
Threshold voltage

(14mV shift after 3h at 2V)



10 pA at 2 MV/cm



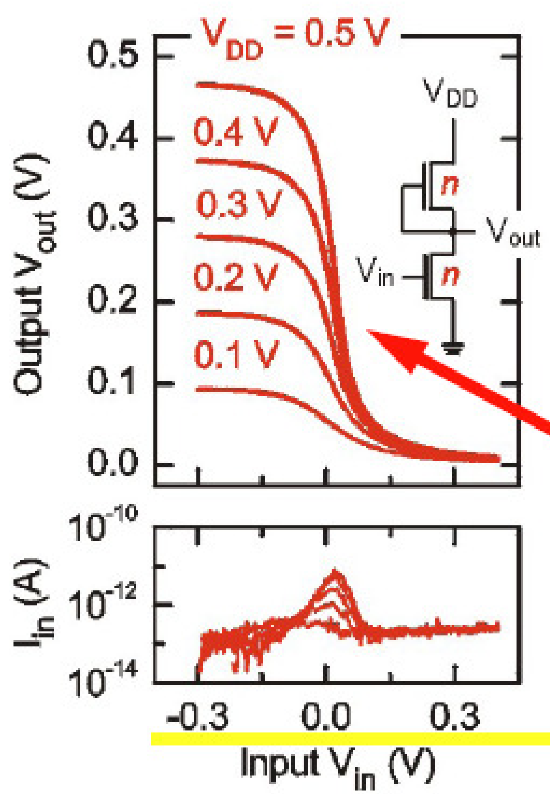


M. Walser et al., APL ***95****, 233301 (2009)*

Low voltage inverters

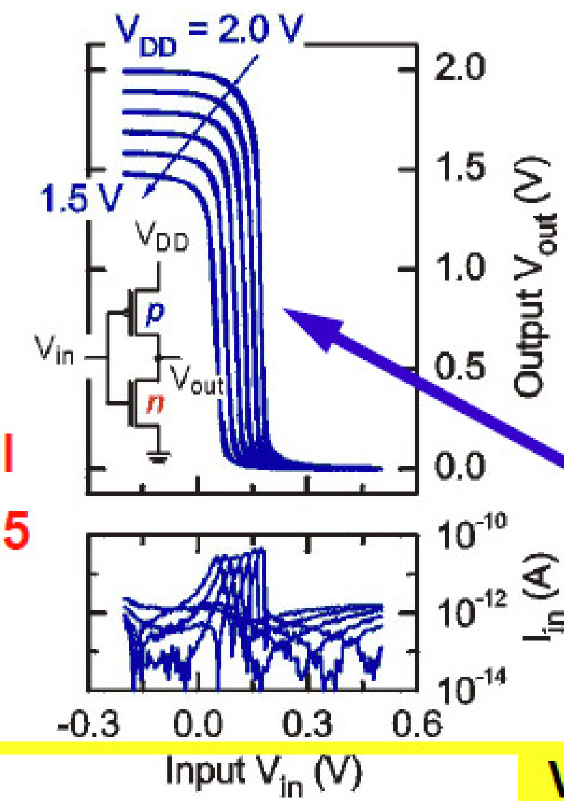
- Thin gate dielectric
  ⇒ Low operating voltage
- P-type and n-type
  ⇒ Complementary inverter

***N*-type inverter**



Maximal Gain - 4.5

Complementary inverter



Maximal Gain -80

Voltage scale 0.1 - 1 V

*M. Walser et al., APL **95**, 233301 (2009)*

Summary

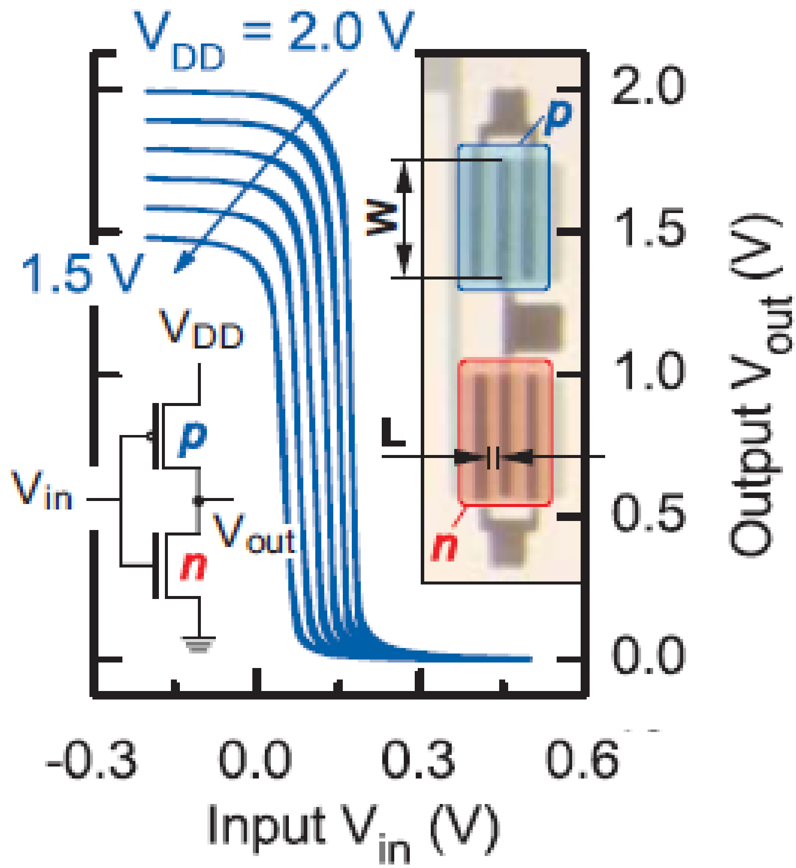
Trap DOS in organic TFTs :
very similar to DOS in a-Si:H

Organic semiconductor :
Stable in appropriate combination

Impressive progress in recent years

-semiconductors:
- *sufficiently high mobility*
- *n - and p- conducting*
- *stable*

-gate dielectrica
- *low interface trap density*
- *ultrathin*



Integrated p- & n-type FETs
with fluorinated Cytop dielectric

Recent pertinent papers

Calculating the trap density of states in organic field-effect transistors from experiment: A comparison of different methods
Wolfgang L. Kalb and Bertram Batlogg
PHYSICAL REVIEW (2010)

The trap DOS in small molecule organic semiconductors:A quantitative comparison of thin-film transistors with single crystals
Wolfgang L. Kalb, Simon Haas, Cornelius Krellner, Thomas Mathis, and Bertram Batlogg
PHYSICAL REVIEW (2010)

Low-voltage organic transistors and inverters with ultrathin fluoropolymer gate dielectric
M. P. Walser, W. L. Kalb, T. Mathis, and B. Batlogg
APPLIED PHYSICS LETTERS 95, 233301 (2009)
Also:
APPLIED PHYSICS LETTERS 94, 053303 (2009)