Dynamic Performances of Carbon Nanotube Transistors and Programmable Devices for Adaptive Architectures

V. Derycke, G. Agnus, N. Chimot, A. Filoramo, J-P. Bourgoin

CEA Saclay, IRAMIS, SPEC

W. Zhao, C. Gamrat

CEA Saclay, LIST

L. Nougaret, A. Le Louarn, H. Happy, G. Dambrine
S. Lenfant, D. Vuillaume

IEMN, CNRS & Université de Lille

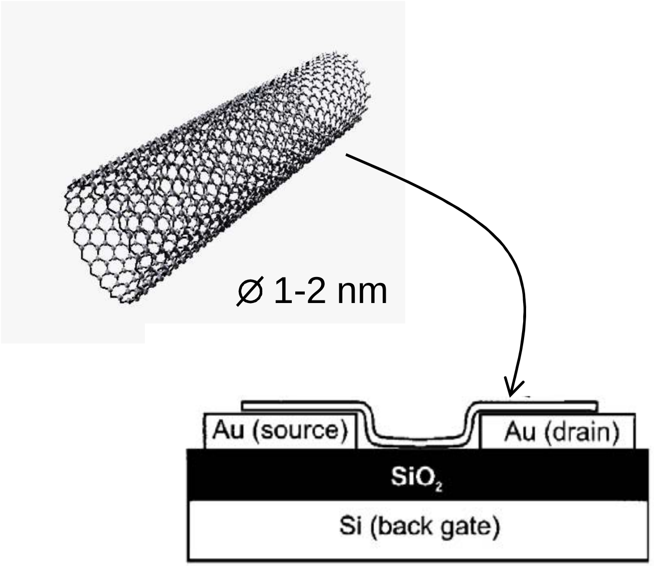
A. Green, M. Hersam

Northwestern University, Evanston, Illinois, USA

Trends in Nanotechnology, Barcelona Sept. 2009

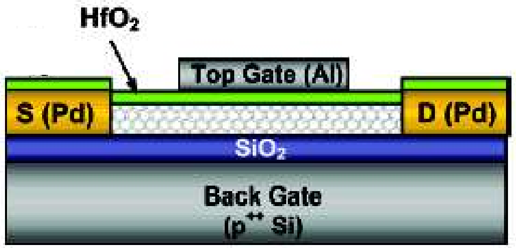
UMR CNRS 8520 Recherche Formation Transfert

Carbon Nanotube Field Effect Transistors



(DELFT / IBM)

1998



g_m ~ 20 µS (5000 µS/µm)

$I_{on\text{-}sat}$ ~ 15 µA (~3750 µA/µm)

G_{on} ~ 10% of $4e^2/h$

S ~ 80mV/dec

(STANFORD, BM, INFINEON…)

2004

Multiple gates
Ohmic contacts
Thin and high-k dielectrics
High mobility / Ballistic transport
L_g as short as 10 nm
…

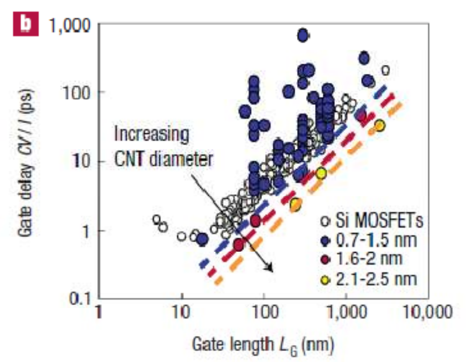
DC electrical characteristics of the best CNTFETs approach the theoretical limit for ideal 1D-FETs in the ballistic regime

Carbon Nanotube Field Effect Transistors

BENCHMARKING

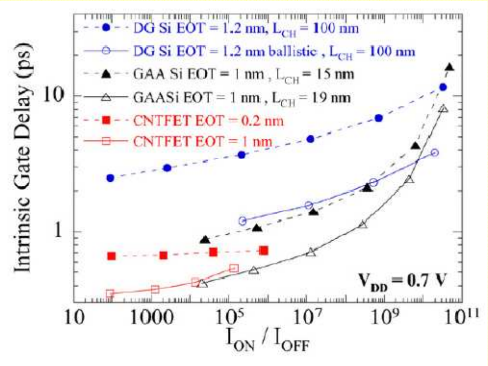
- Perdue 2002, 2005
- IBM 2002…
- INFINEON 2003

R. Chau et al., Nature Mat. **6** (2007).



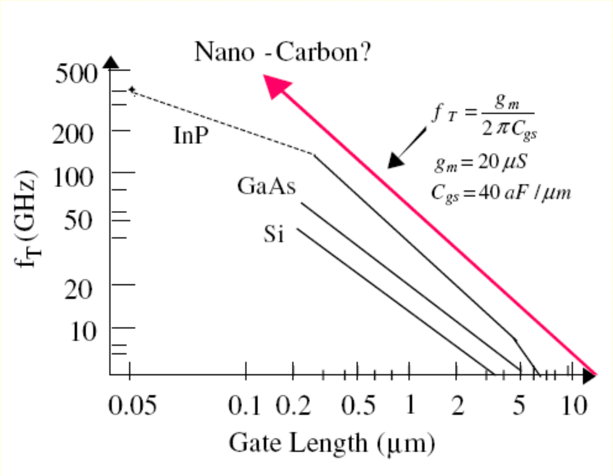
INTEL 2007

H. Cazin et al., C. R. Phys. **9** (2008).



IEF 2008

P. Burke, Solid-State Electronics **48**, 1981 (2004)



U.C. Irvine 2004

The improvement in performances could be significant but:

- □ What about demonstrated high-speed performances ?
- □ How do we place the good CNT at the good place a billion times ?
- □ How do we grow / sort CNTs that are 100% semiconducting ?
- □ Can we compute with high impedance objects ?
- □ Can we compute with devices showing large device-to-device variability ?

Exceptional electronic properties

+ sensing capabilities

+ properties preserved on most substrates

in particular :

□ flexible / organic / transparent substrates

□ above silicon CMOS circuits

OUTLINE

- High-frequency CNT transistors
- High-frequency *flexible* CNT transistors for ‘large scale’-electronics
- CNTFET as light sensors and memory devices
- CNT memory devices as *'synapses'* in adaptive architectures

HF measurement issues

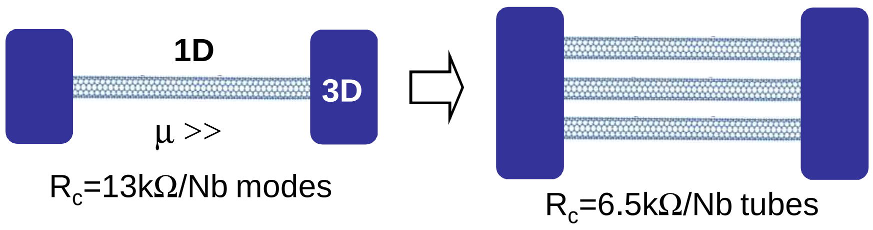
f_T in the THz range only if NTs are the limiting factor, but...

(1) Individual CNTs are high impedance objects (> 6.5 kΩ)
→ difficult to measure with standard 50 Ω equipment

(2) Nanometric objects in a macroscopic structure
→ detrimental influence of parasitic capacitances

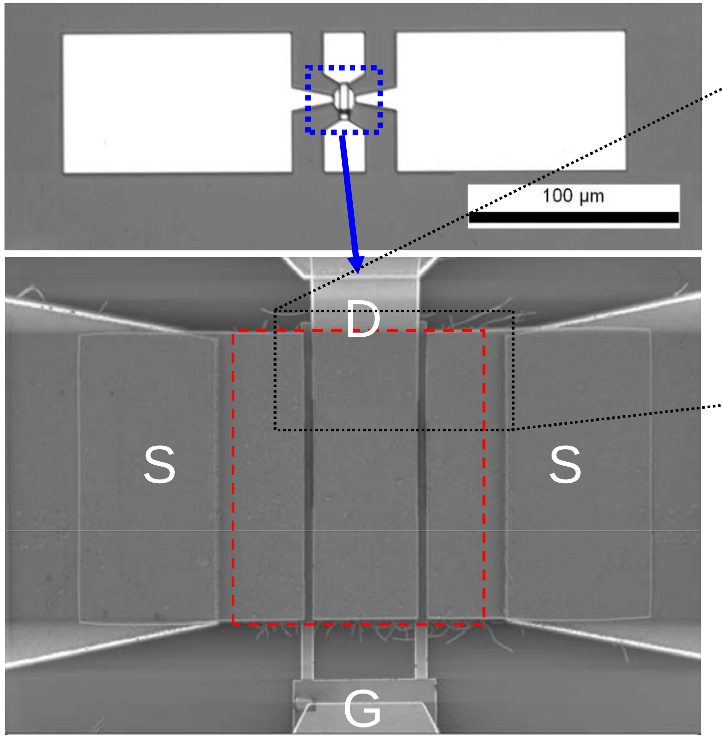
INDIRECT → Mixing techniques

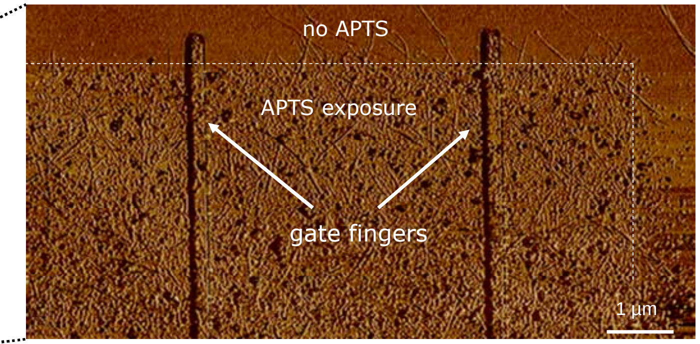
DIRECT → Configuration with several nanotubes

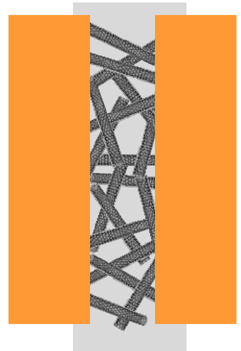


HF Nanotube transistors (from random networks)

J-M Bethoux, G. Dambrine, H. Happy (IEMN)

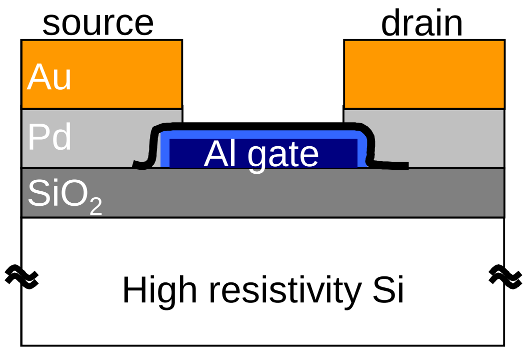






Large number of NTs → high drive current (>1 mA)

Thin Al_2O_3 oxide → high transconductance

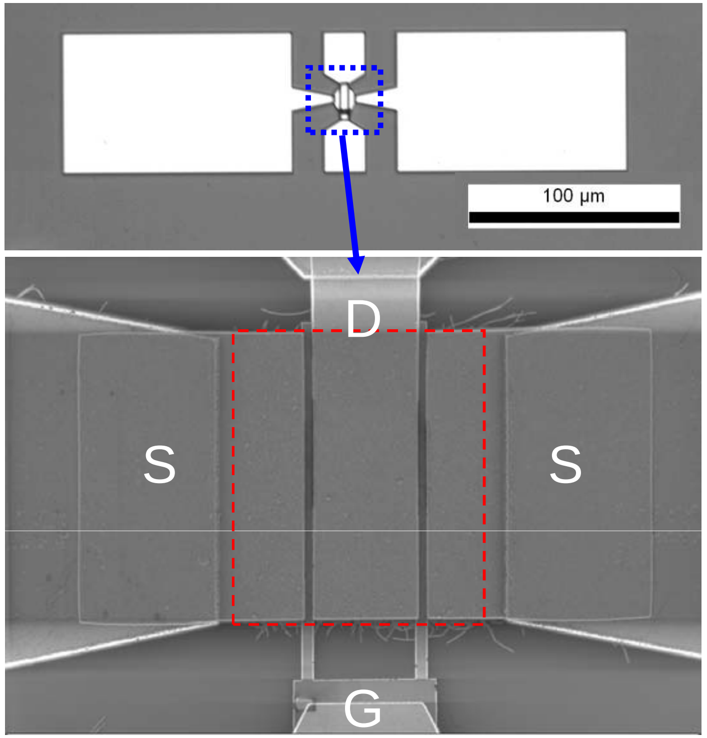


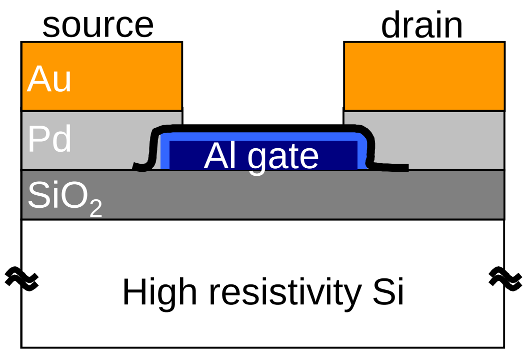
We inject RF power from the gate and from the drain and measure the transmitted and reflected power. From the S-parameters we extract some figures of merit:

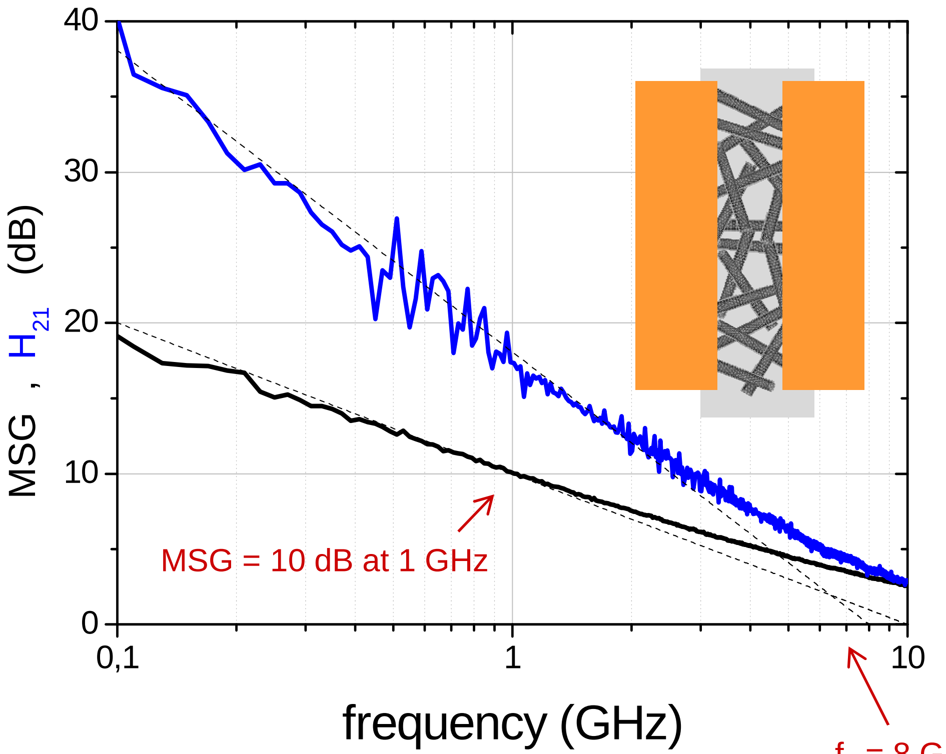
- the current gain H_{21} — $H_{21} = I_2/I_{1\ (V2=0)} = -2S_{21}/[(1-S_{11})(1+S_{22})+S_{12}S_{21}]$
- its cut-off frequency f_T
- the power gain MSG — $G_{MSG}=(S_{21}/S_{12})$

HF Nanotube transistors (from random networks)

J-M Bethoux, G. Dambrine, H. Happy (IEMN)







→ Highest f_T for a CNT device in 2006: 8 GHz

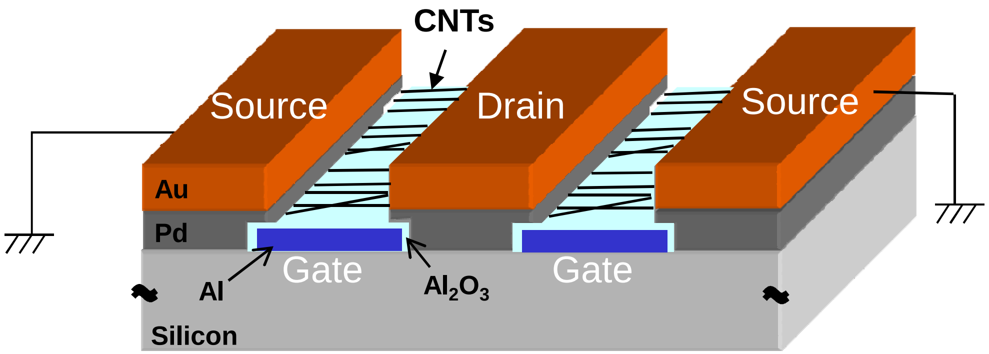
→ But 8 Ghz is low !

→ No off-state !

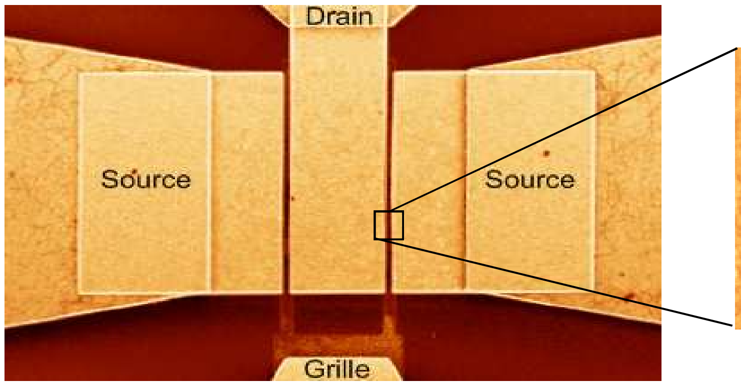
Bethoux et al, Elec. Dev. Lett. **27**, 681 (2006)

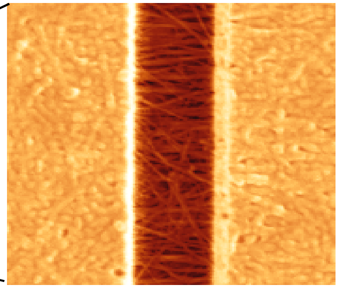
HF Nanotube transistors (from oriented networks)

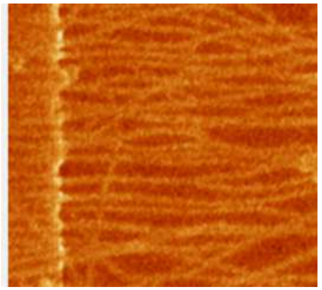
A. Le Louarn, G. Dambrine, H. Happy (IEMN)

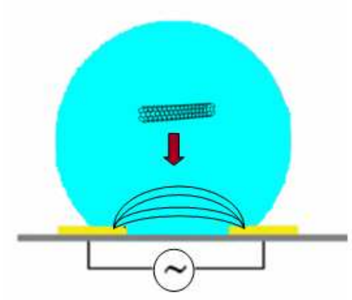


very high density of aligned CNTs depositied by dielectrophoresis → >10 mA of current drive

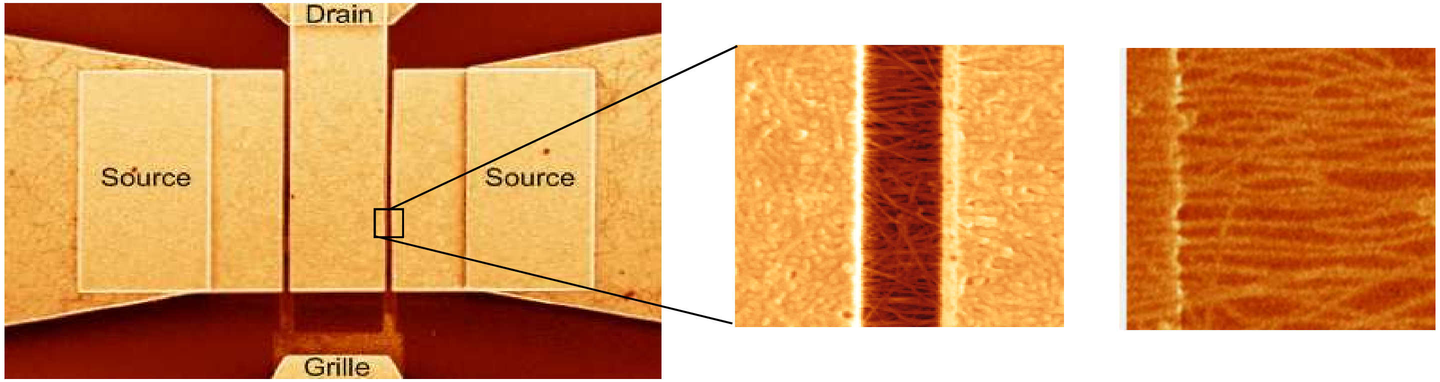


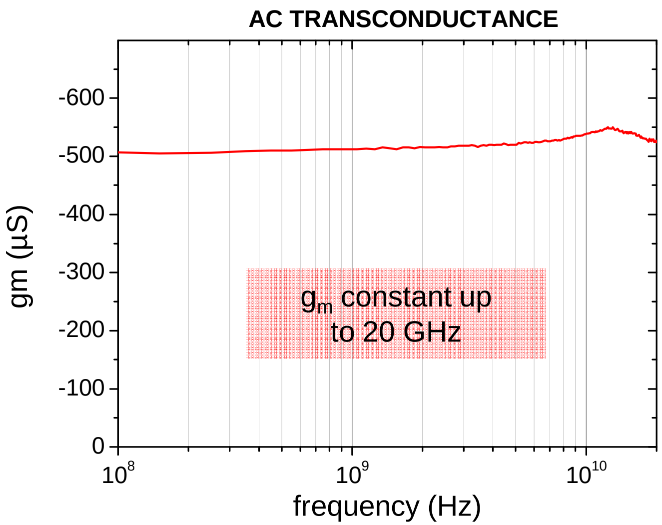


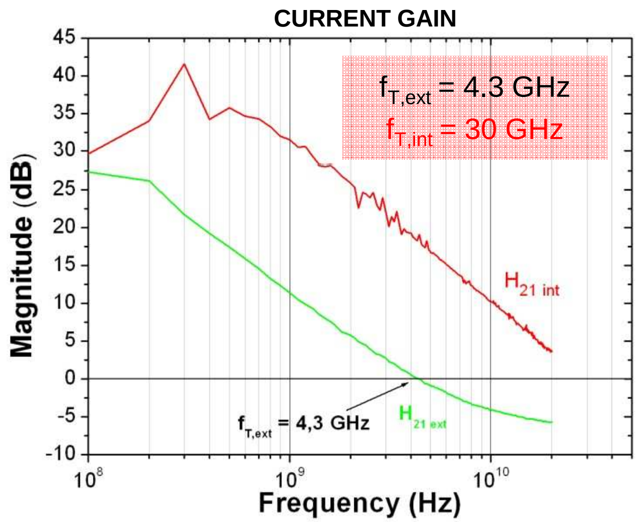




HF Nanotube transistors (from oriented networks)







→ Highest f_T for a CNT device in 2007: 30 GHz

→ but DEP is not a wafer scale technique

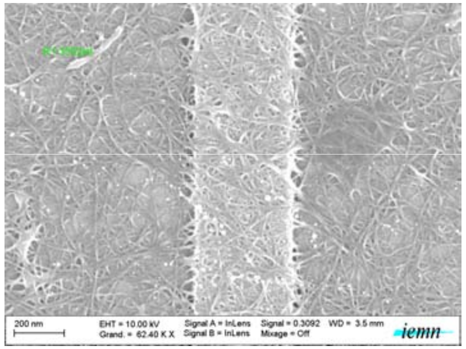
→ No off-state !

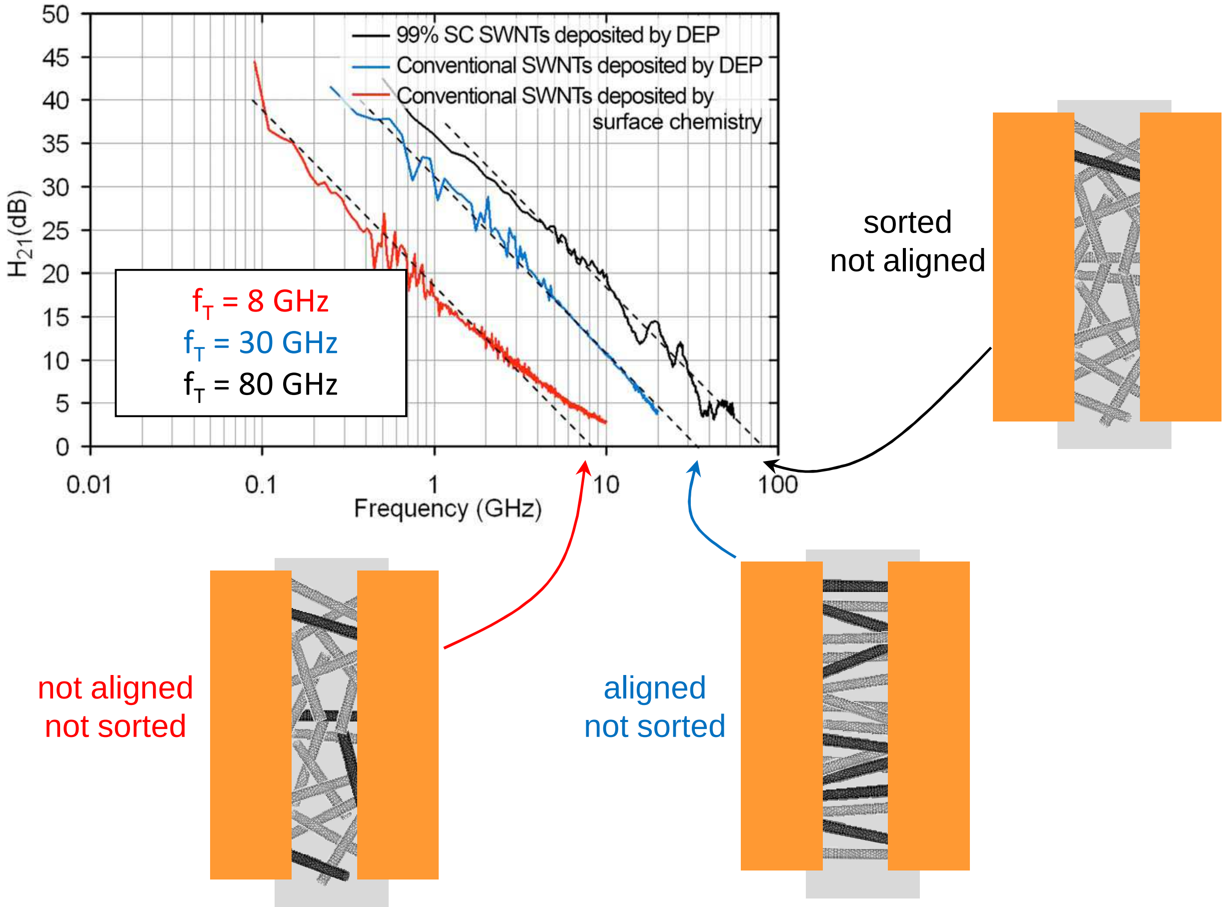
Le Louarn et al, Appl. Phys. Lett. **90**, 233108 (2007)

HF Nanotube transistors based on *99% semiconducting CNTs*

L. Nougaret, G. Dambrine, H. Happy (IEMN)

We used extra-high purity SWNTs sorted by electronic type in the group of ***Pr. Mark Hersam*** (Northwestern University)





→ Highest f_T for a CNT device in 2009: 80 GHz

→ no need for alignment

→ better off-state (but still need improvement)

L. Nougaret et al, Appl. Phys. Lett. **94** (2009) 243505

Toward *fast* and *flexible* circuits

→ Carbon nanotube FETs can indeed be fast

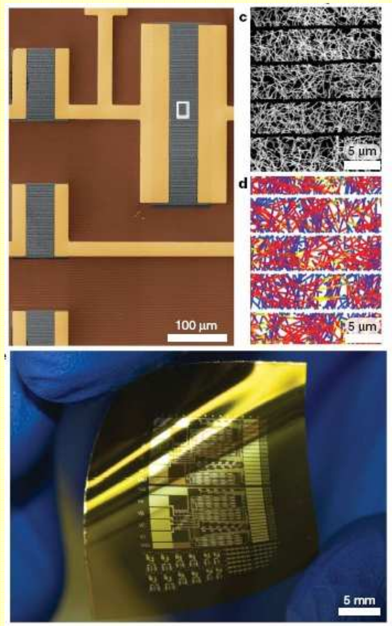
→ The measured f_T is still limited by the parasitics and the CNT quality

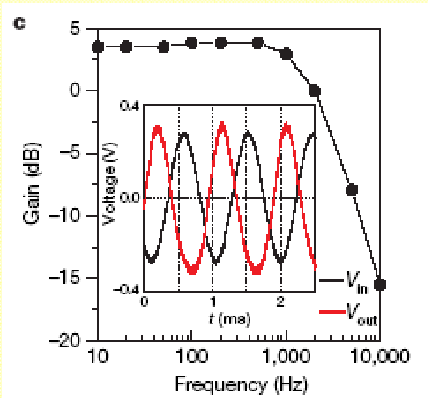
→ Scaled-down devices are very high impedance FETs

→ Good candidates for high-speed / large area electronics on "any"-substrates

Medium-scale carbon nanotube thin-film integrated circuits on flexible plastic substrates

Qing Cao[1], Hoon-sik Kim[2], Ninad Pimparkar[7], Jaydeep P. Kulkarni[7], Congjun Wang[2], Moonsub Shim[2], Kaushik Roy[7], Muhammad A. Alam[7] & John A. Rogers[1–6]





Flexible 100-transistors circuits with
μ = 80 cm^2/V.s and **f ~ 1 kHz**

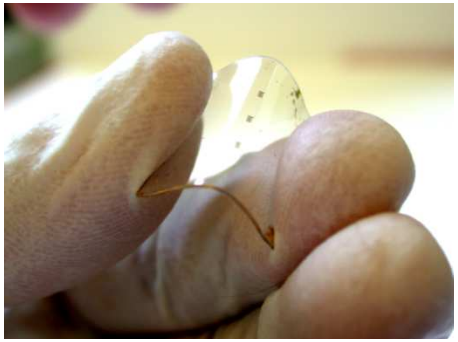
J. Rogers et al, Nature 2008

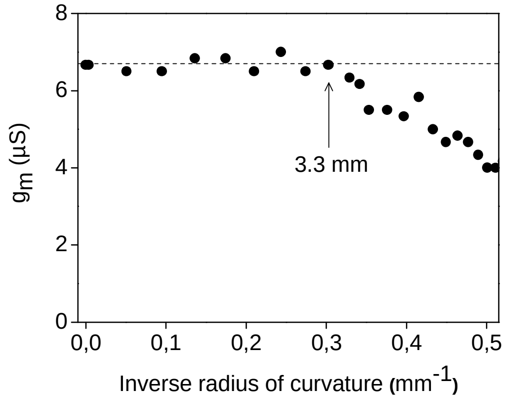
CNT network-transistors are serious competitor for organic electronics

Can work in frequency range out of reach of polymers and small molecules

Flexible HF Nanotube transistors

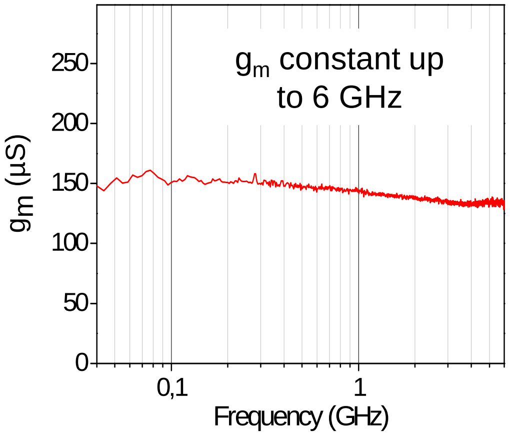
The process we used on silicon can be adapted to plastic substrates

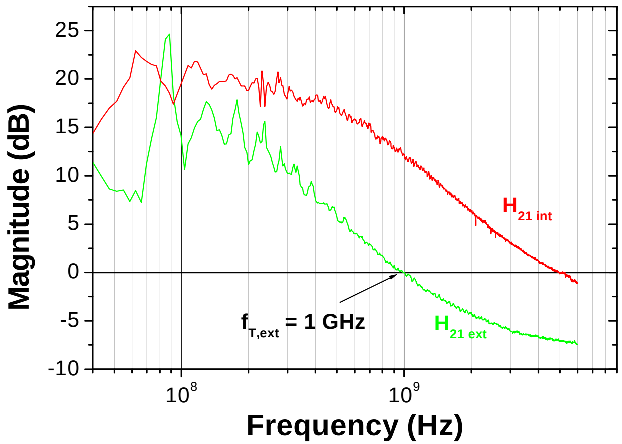




A 1 GHz flexible nanotube transistor with unchanged transconductance for radius of curvature down to 3.3 mm

Chimot et al., Appl. Phys. Lett. **91**, 153111 (2007)





→ Comparable to results obtained with Si flexible ribbons and GaAs nanowires…

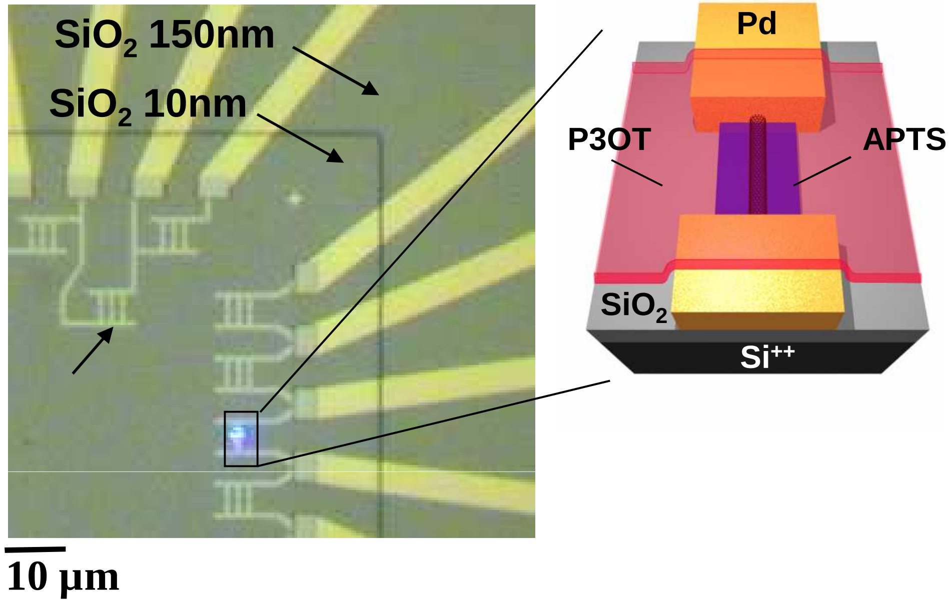
→ Way above frequency range achieved by organic electronics

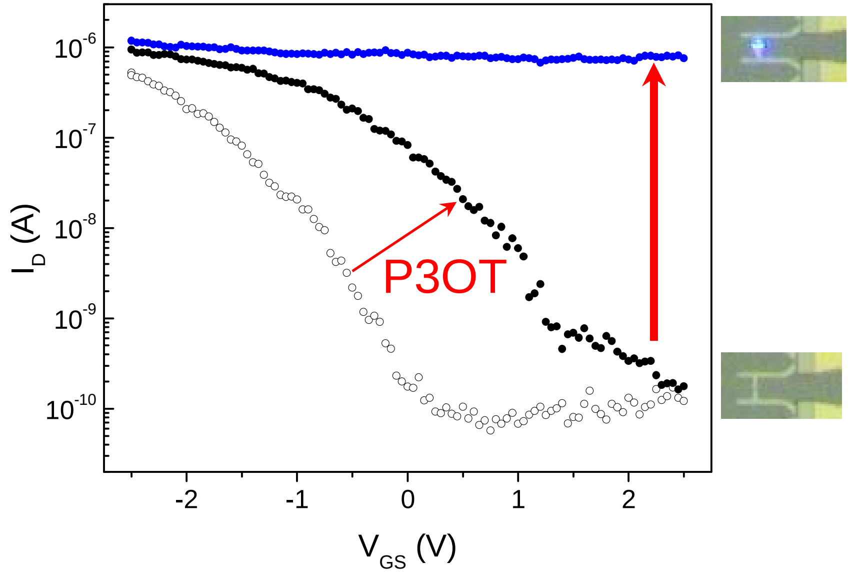
OUTLINE

- High-frequency CNT transistors
- High-frequency *flexible* CNT transistors for ‘large scale’-electronics
- CNTFET as light sensors and memory devices
- CNT memory devices as *'synapses'* in adaptive architectures

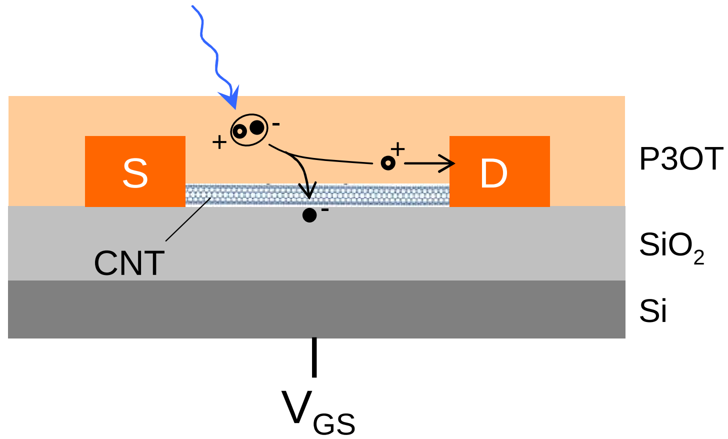
CNTFETs as light sensors

S. Lenfant, D. Vuillaume (IEMN)



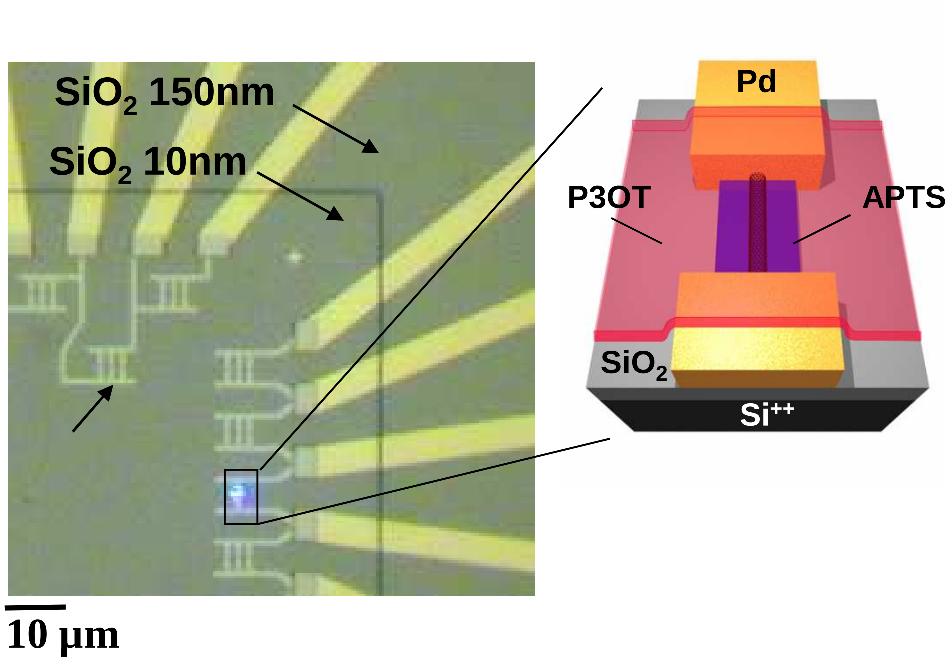


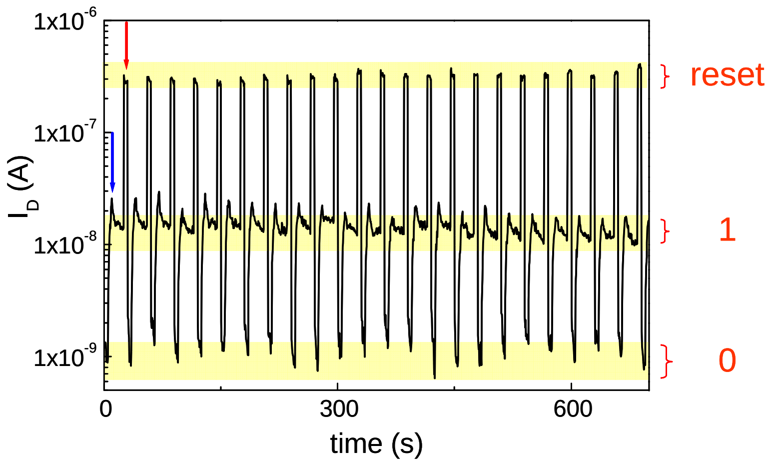
CNTFETs built using APTS on 10 nm thick SiO_2 back-gate
+ Pd electrodes for improved performances
+ coated with ~5 nm of P3OT for light sensitization

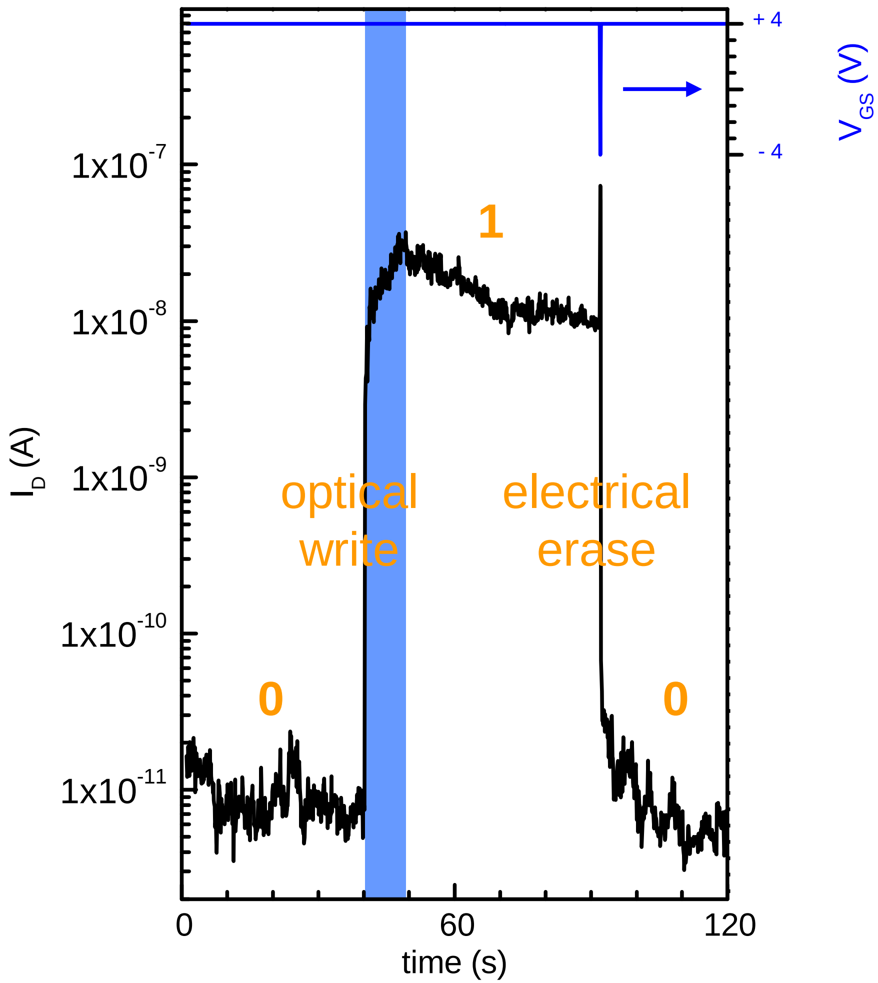


The photo-excited polymer act as a ‘optical gate’
more efficient than the electrostatic gate

Opto-electronic memory



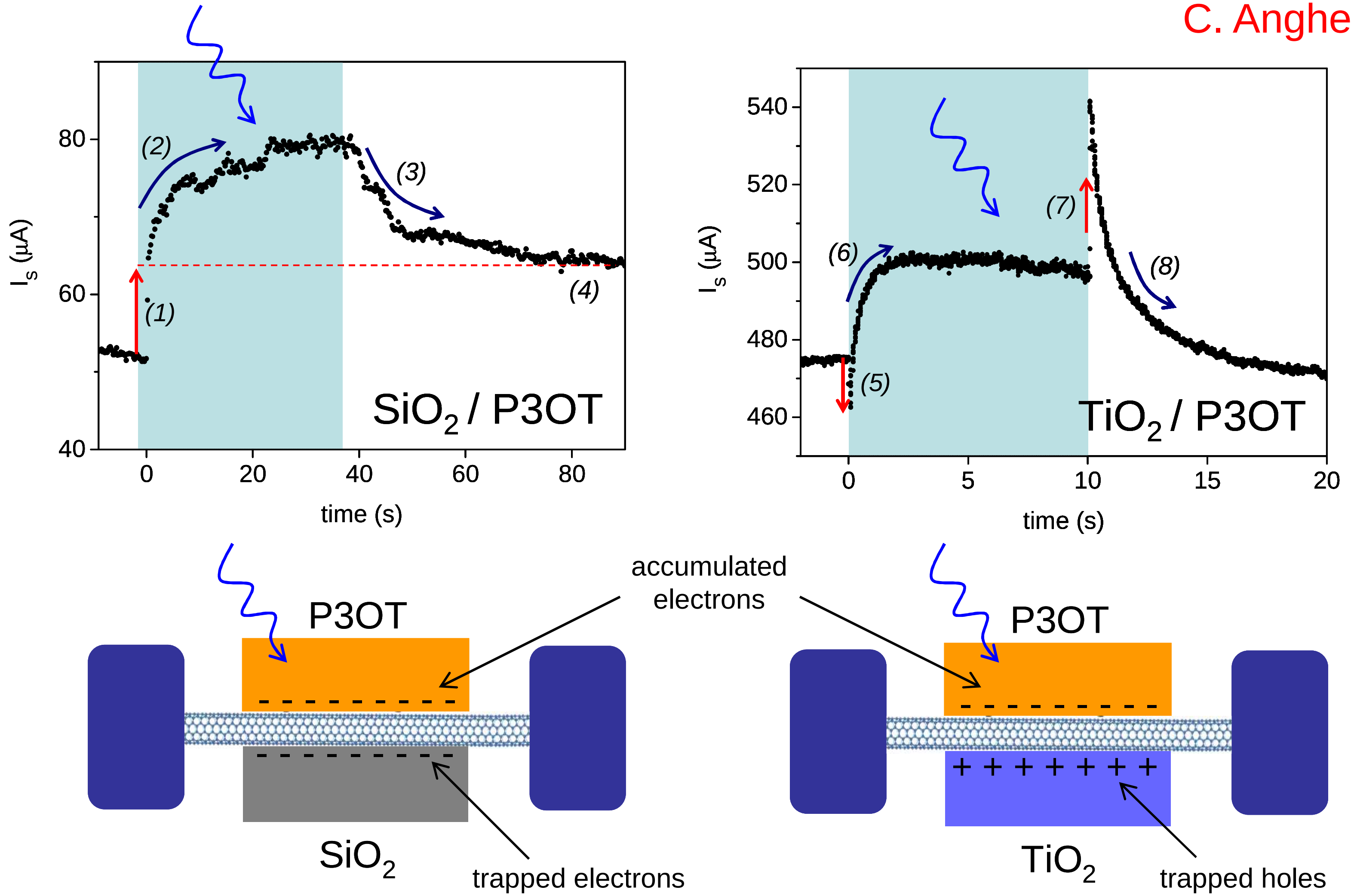




Borghetti et al, Advanced Materials **18**, 2535 (2006)

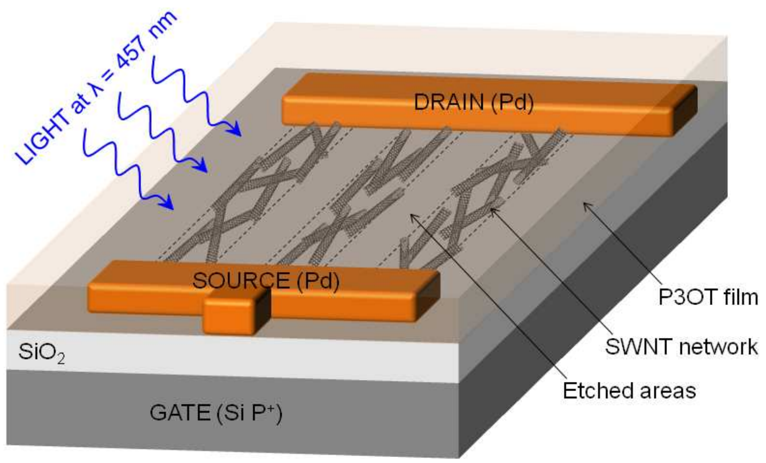
Role of the dielectric in the optical gating mechanism

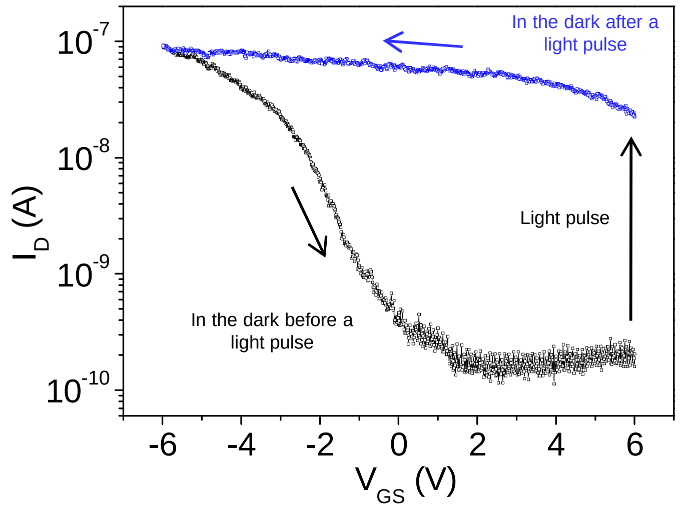
C. Anghel (CEA)

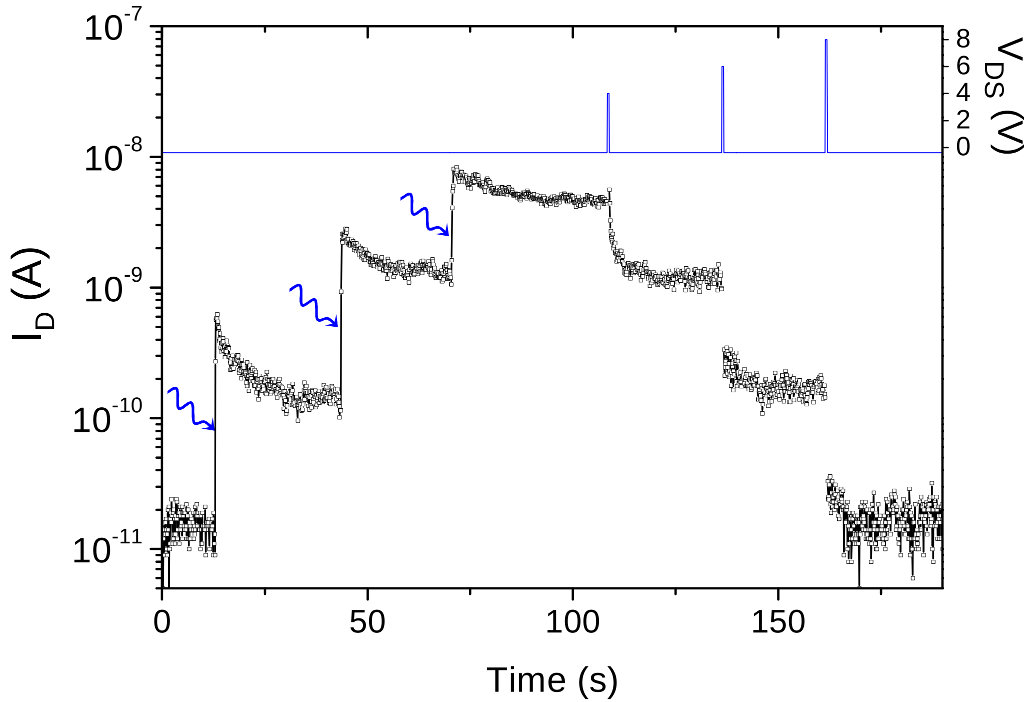


Anghel et al, Nano Letters **8**, 3619 (2008)

OG-CNTFET as 2-terminal programmable resistors

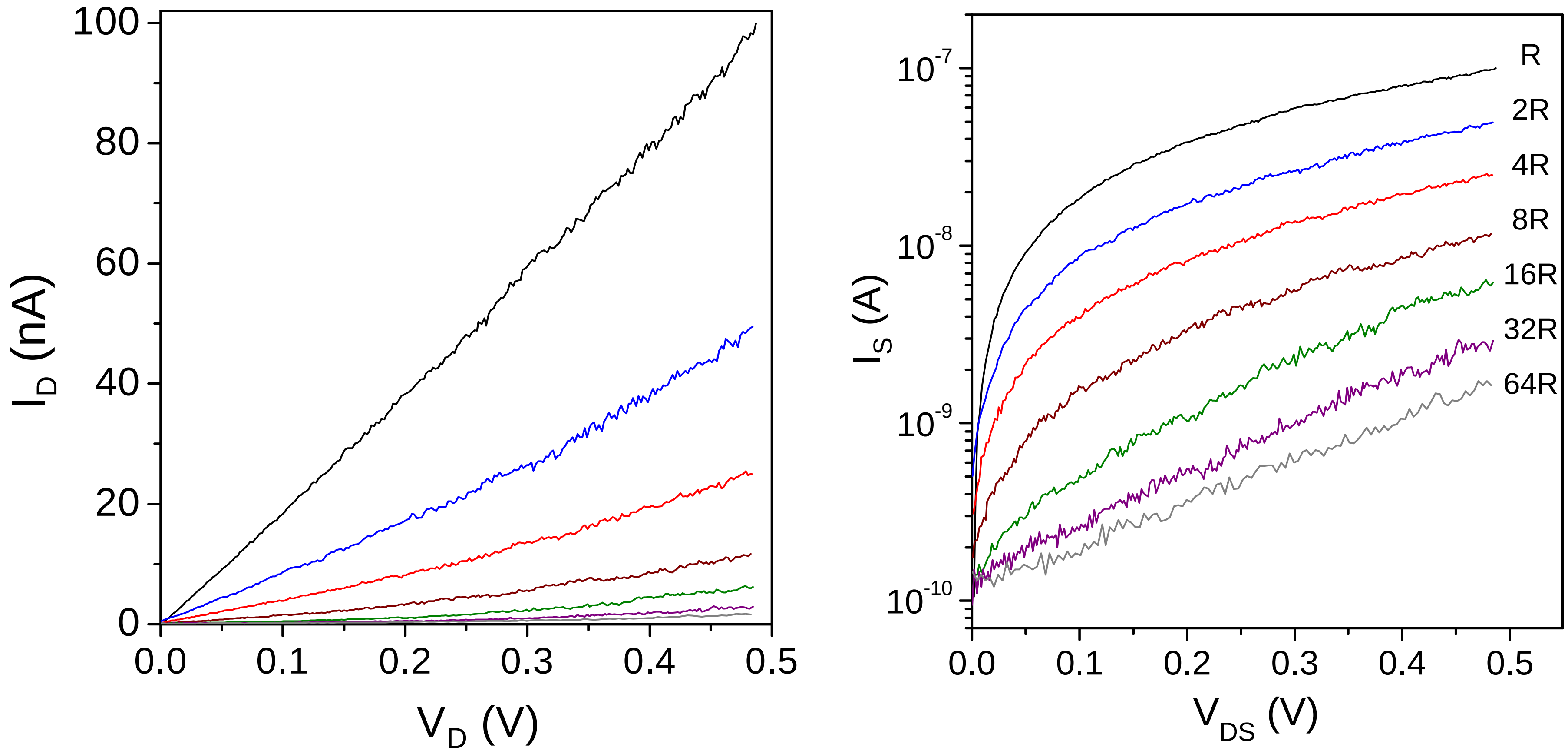






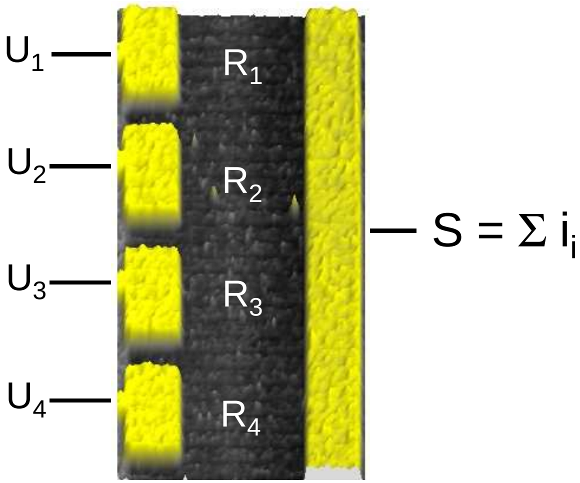
We fix V_{GS} and use V_{DS} to program the resistivity

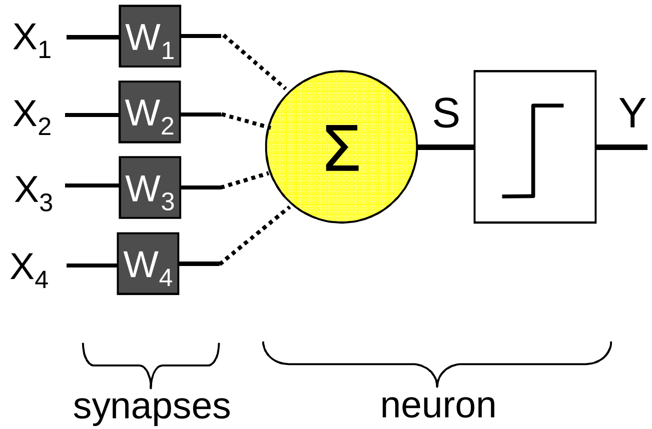
OG-CNTFET as 2-terminal programmable resistors

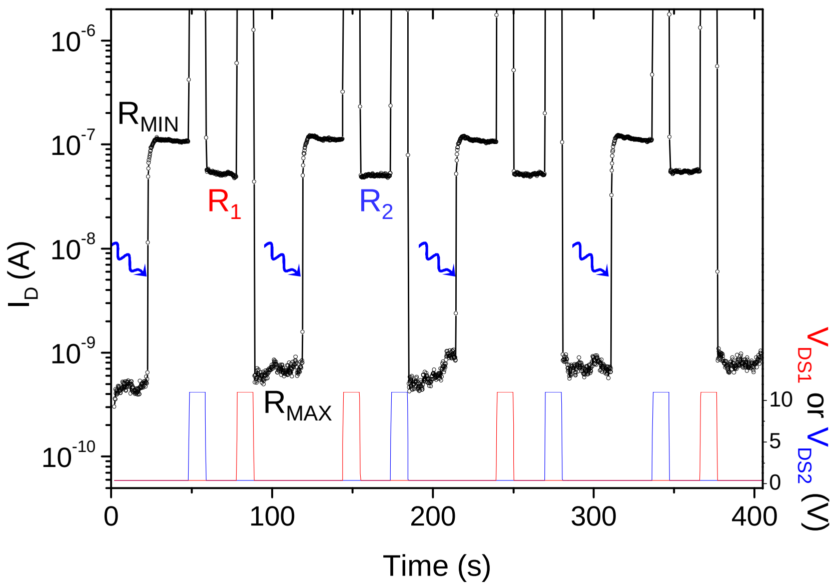


2-terminal programmable resistors as synapses

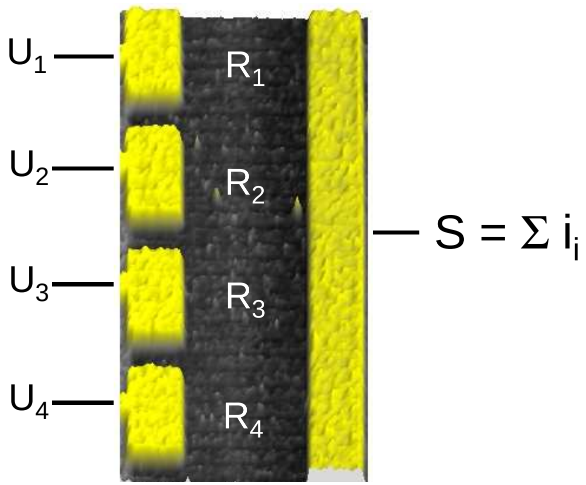
W. Zhao, C. Gamrat (CEA-LIST)



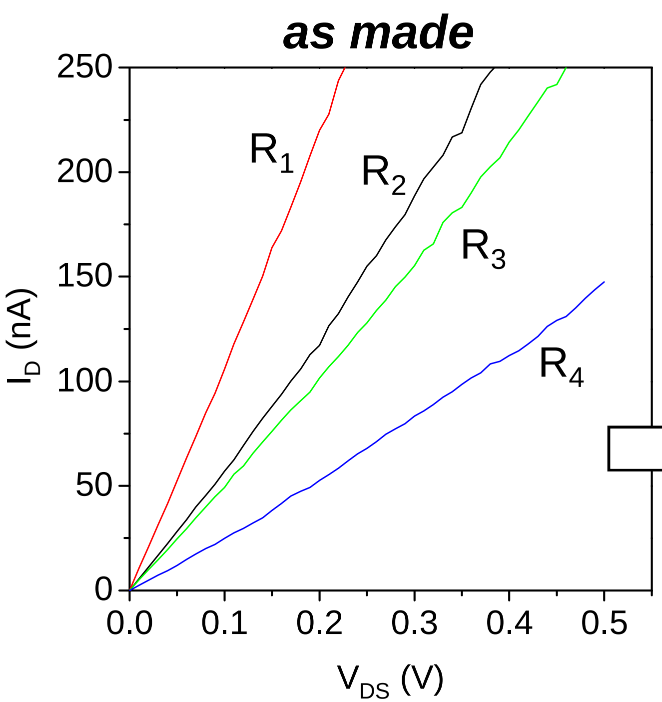


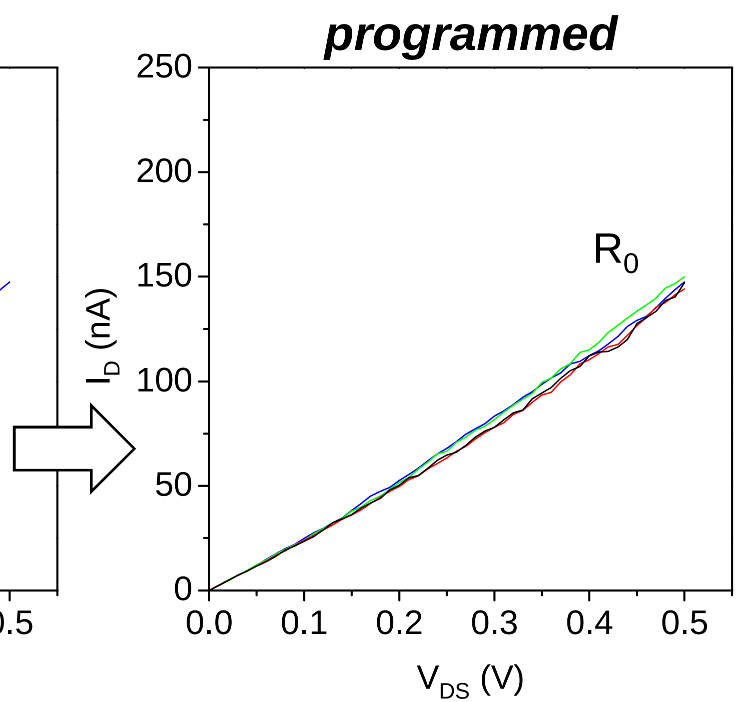


Programming compensates for variability

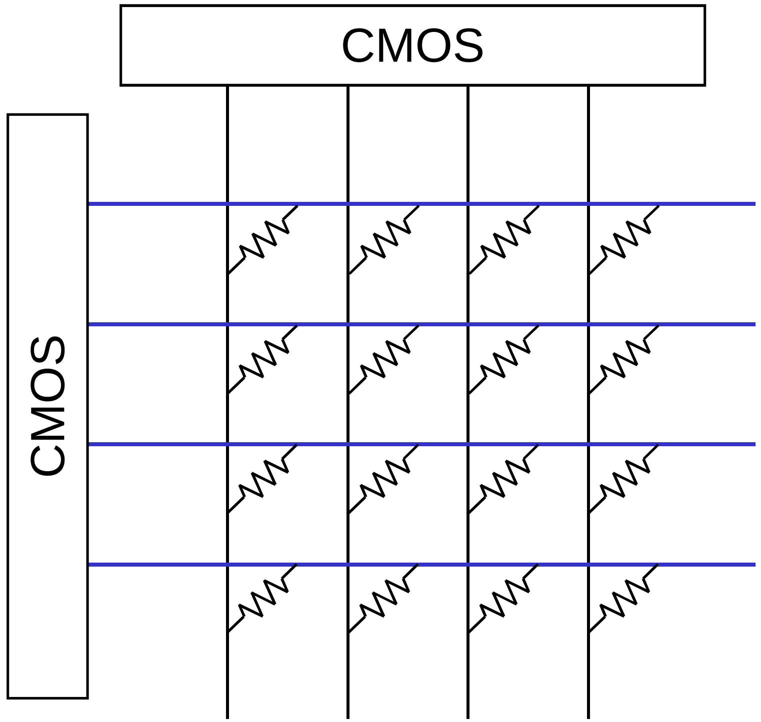


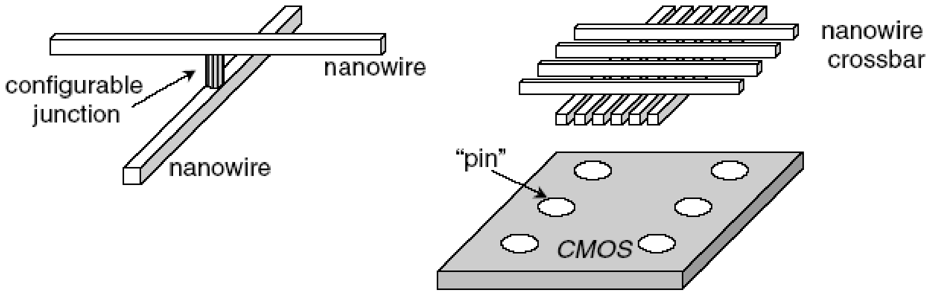
Agnus et al, Advanced Materials (2009)





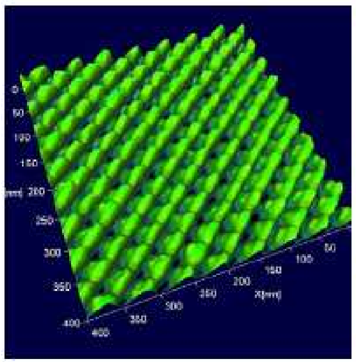
Crossbar of memristors *(the HP way)*

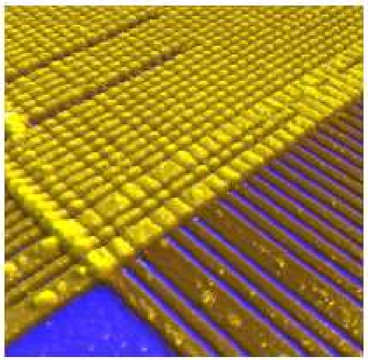


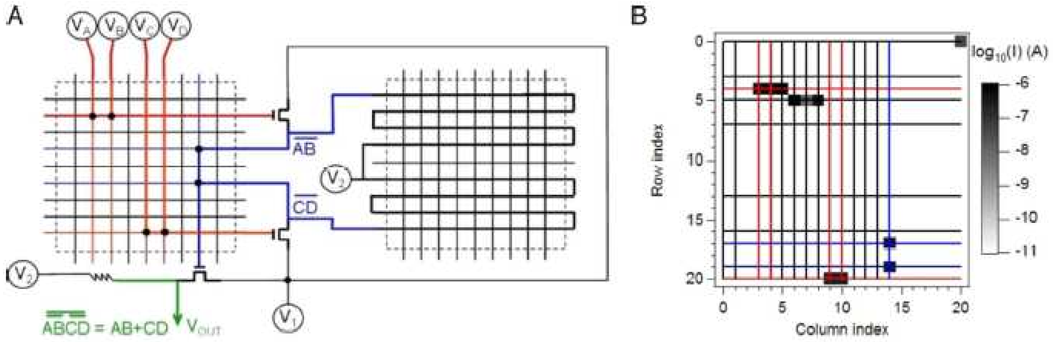


A hybrid nanomemristor/transistor logic circuit capable of self-programming

Julien Borghetti, Zhiyong Li, Joseph Straznicky, Xuema Li, Douglas A. A. Ohlberg, Wei Wu, Duncan R. Stewart, and R. Stanley Williams[1]

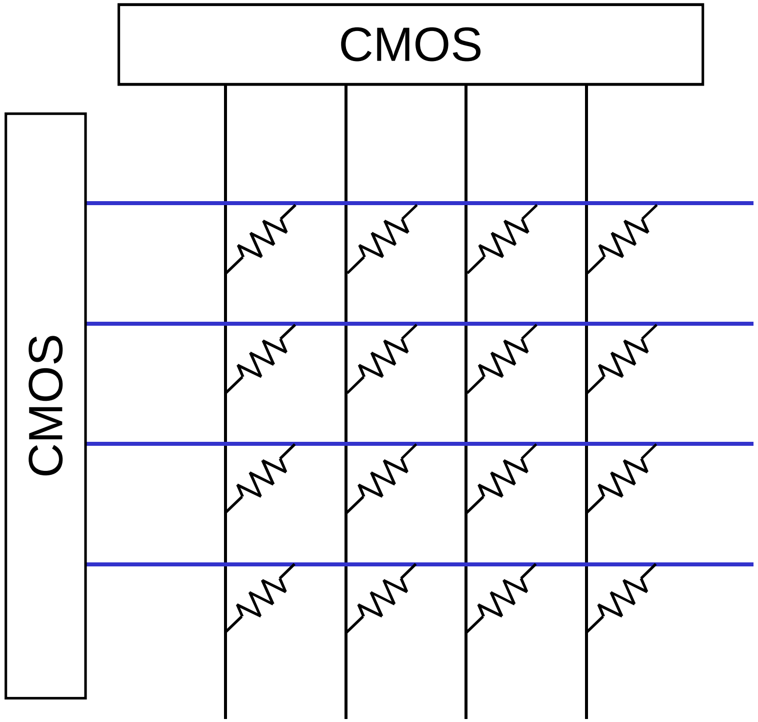


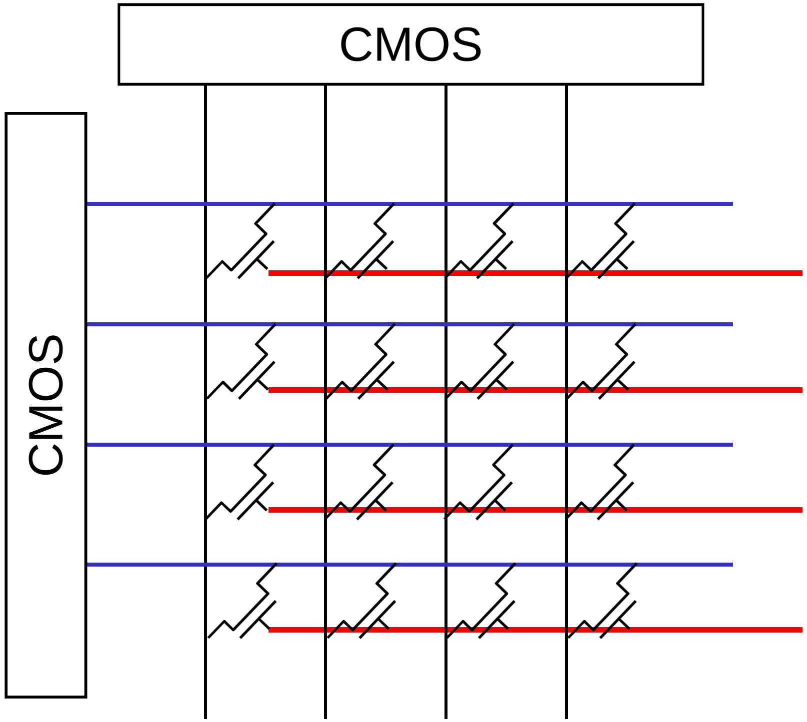




Proc. Nat. Acad. Sci. (2008)

Crossbar of memristors





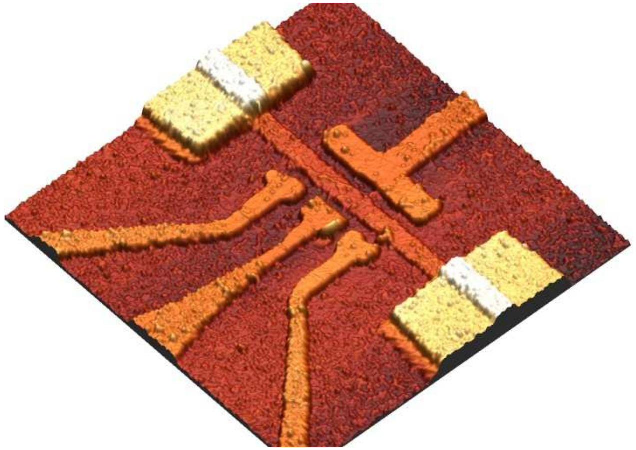
No gate electrode or one global gate electrode:

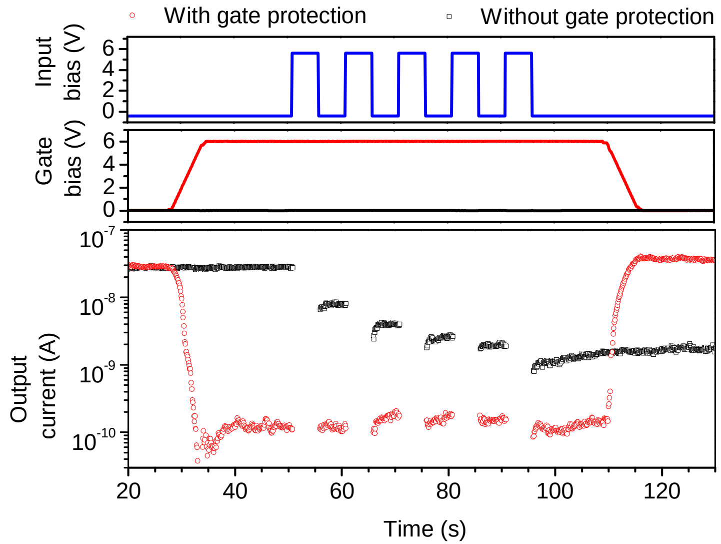
Compact but difficult to address devices individually

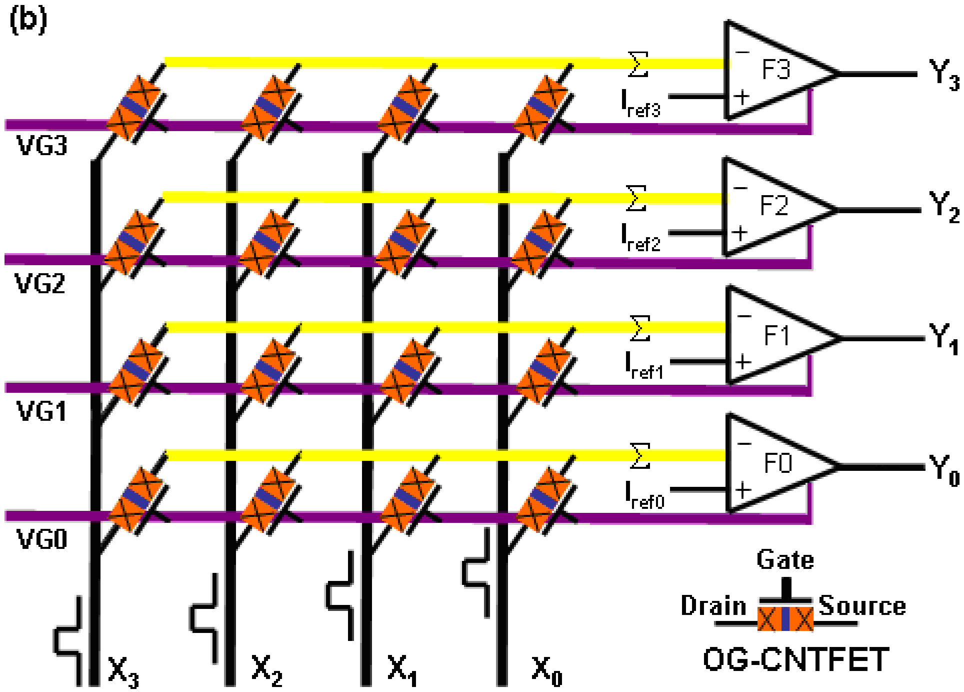
Individual gate electrodes: limited by interconnects complexity

→ One gate per row

The proposed circuit topology for parallel learning







W. Zhao (CEA-LIST)

ACKNOWLEDGMENTS

Dynamic Performances of Carbon Nanotube Transistors and Programmable Devices for Adaptive Architectures

V. Derycke, **G. Agnus**, **N. Chimot**, A. Filoramo, J-P. Bourgoin

CEA Saclay, IRAMIS, SPEC

W. Zhao, C. Gamrat

CEA Saclay, LIST

L. Nougaret, A. Le Louarn, H. Happy, G. Dambrine
S. Lenfant, D. Vuillaume

IEMN, CNRS & Université de Lille

A. Green, M. Hersam

Northwestern University, Evanston, Illinois, USA

J-O. Klein

IEF, Univ. Paris-sud Orsay, France

PNANO ***HF-CNT***
ARFU ***PANINI***

FP7 ***NABAB***