DATE 14
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Advancing CMOS with Carbon Electronics

Prof. Dr. Franz Kreupl
Department of Hybrid Electronic Systems
Technische Universität München (TUM)
Munich, Germany
franz.kreupl@tum.de

Outline

- ❑ Introduction: The Quest for a New Logic Switch
- ❑ Graphene Nanoribbons or Carbon Nanotubes?
- ❑ Consequences of missing current saturation in FETs
- ❑ Disadvantages of Graphene Nanoribbons FETs
- ❑ Advantages of Carbon Nanotube Transistors
- ❑ Carbon Nanotubes as Tunneling FETS (TFET)
- ❑ The Big Challenge: How to make them

The Quest for a New Logic Switch

- **Key drivers**
  - **enhanced drive current**
  - **lower power**
  - **better electrostatics**
  - **variability**

mobile application

materials /contacts

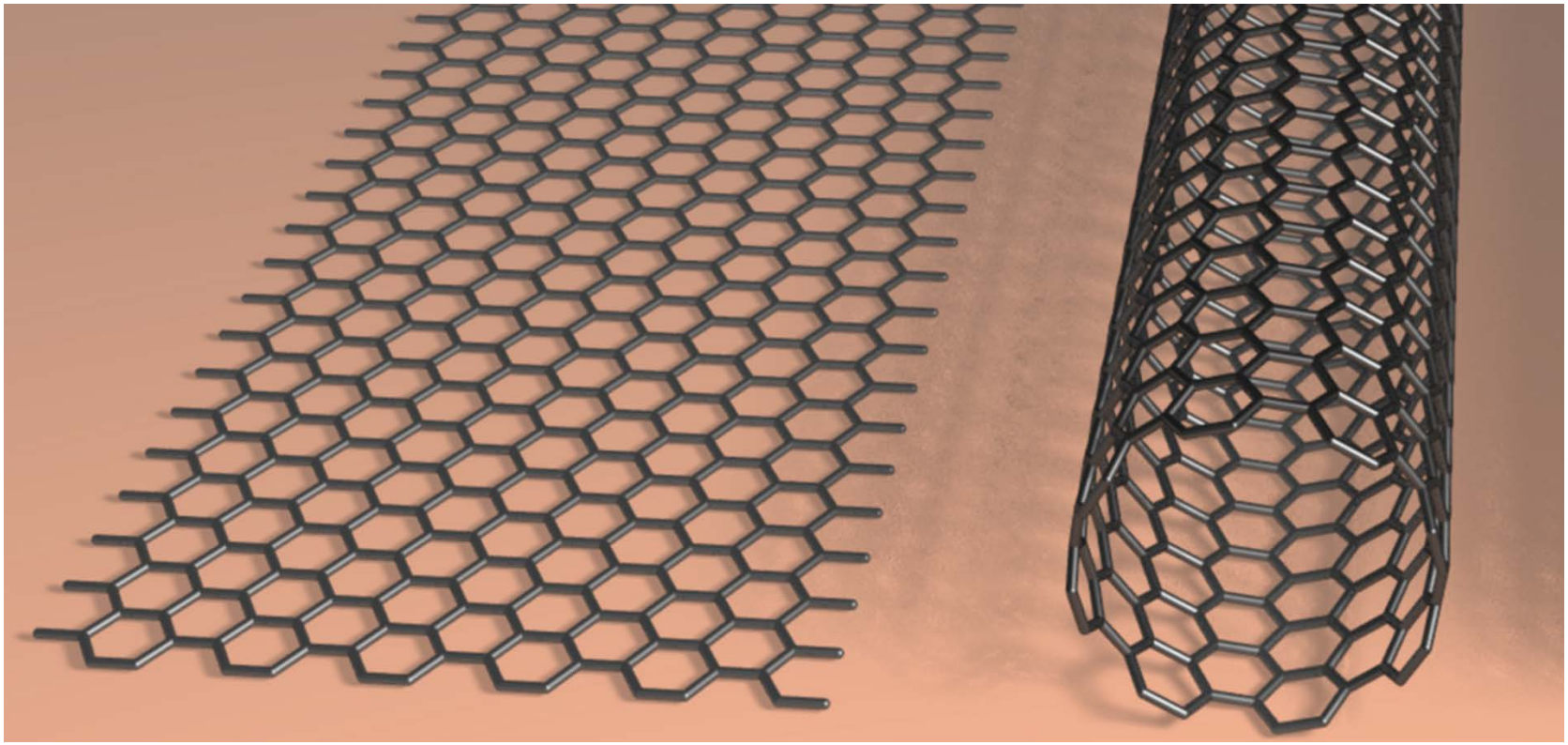
low voltage /leakage

gate-all-around

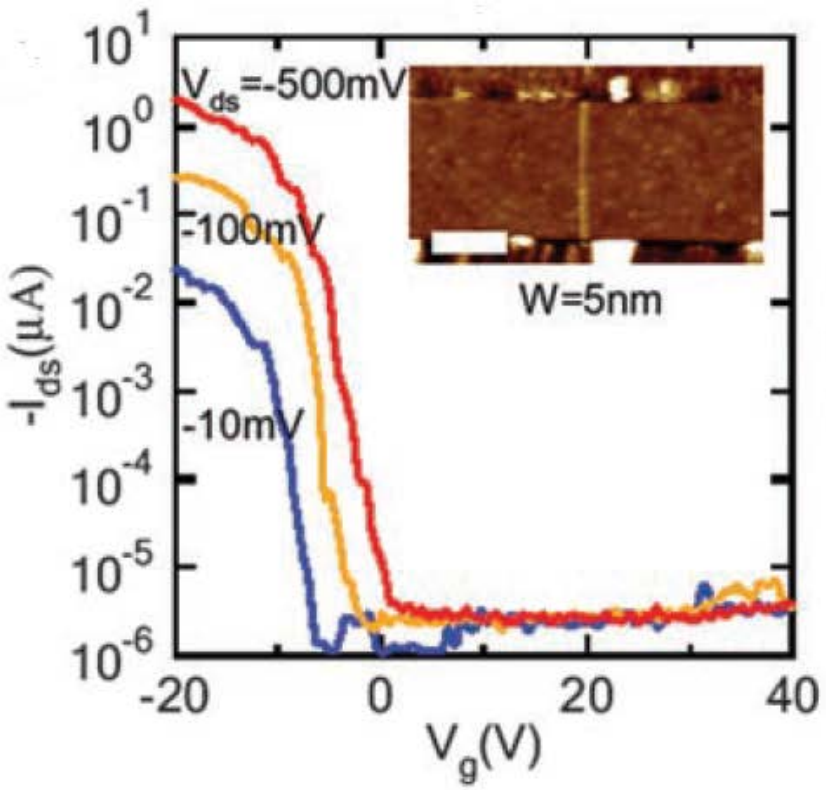
no doping

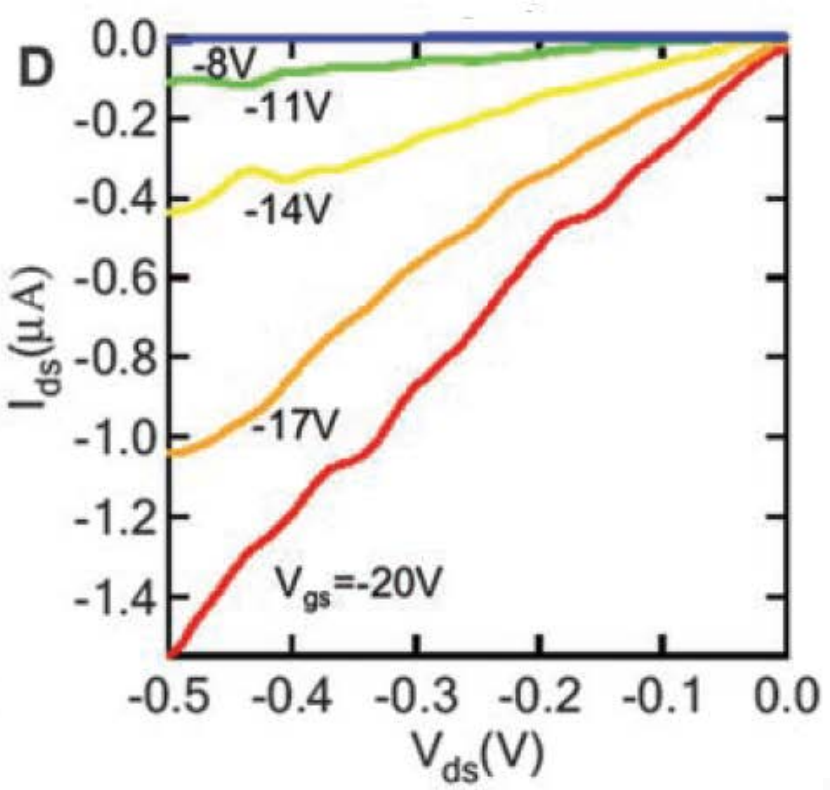
Graphene Nanoribbons or Carbon Nanotubes ?

- Leading candidates for high mobility materials
- Graphene (ribbons) or single-walled carbon nanotubes

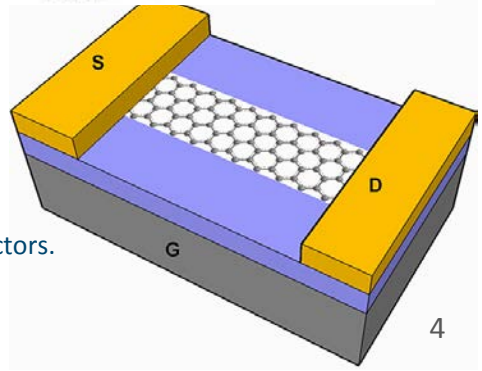


Graphene nanoribbon do have band gap





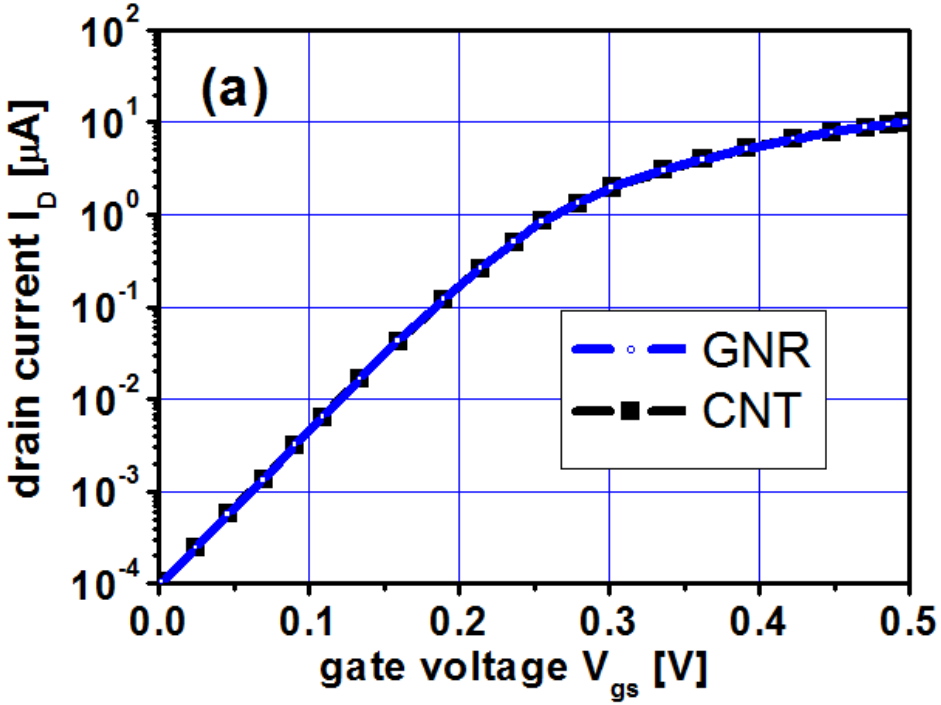
- ❑ band gap introduction leads to mobility loss
- ❑ device can be turned off

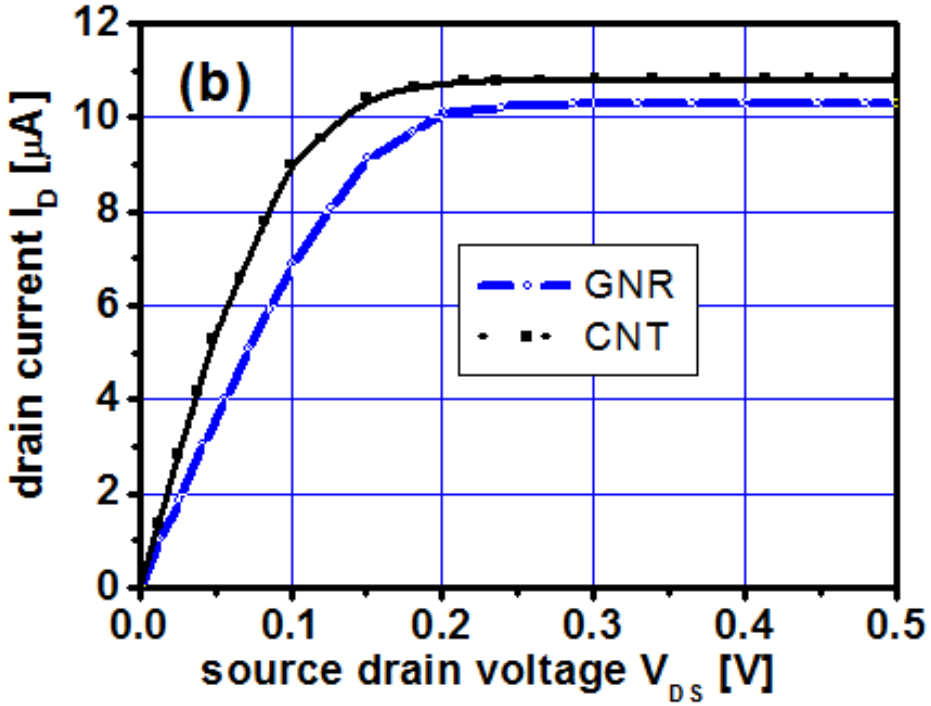


Li, X., Wang, X., Zhang, L., Lee, S. & Dai, H. Chemically derived, ultrasmooth graphene nanoribbon semiconductors. Science 319, 1229–1232 (2008)

Graphene (GNR) versus Carbon Nanotubes

data taken from: Y. Ouyang, Y. Yoon, J. K. Fodor, J. Guo," Comparison of performance limits for carbon nanoribbon and carbon nanotube transistors", Appl. Phys. Lett. 89, 203107 (2006).

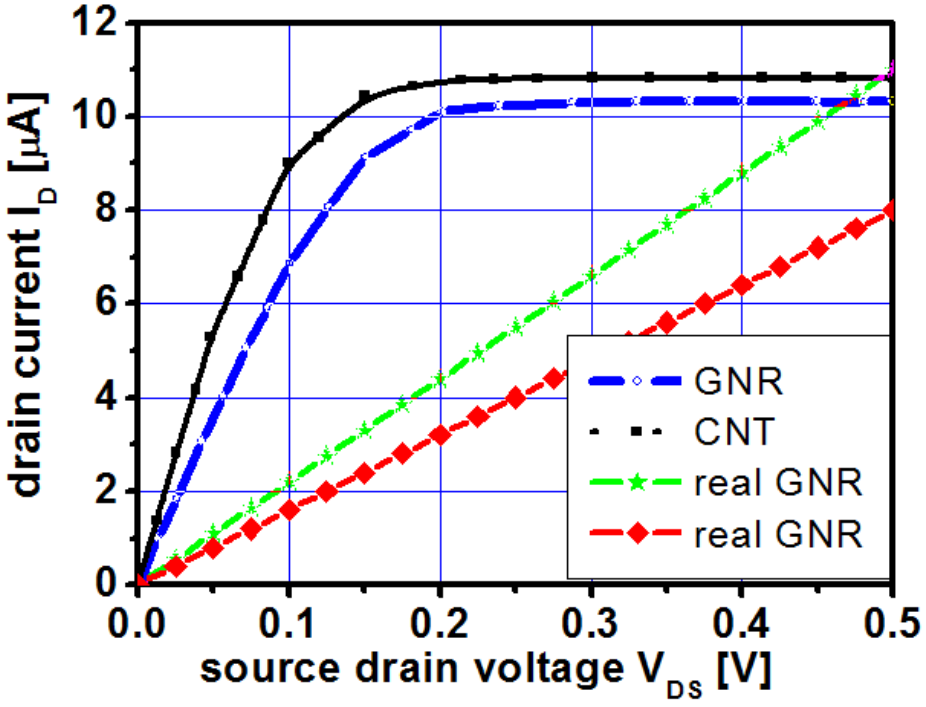


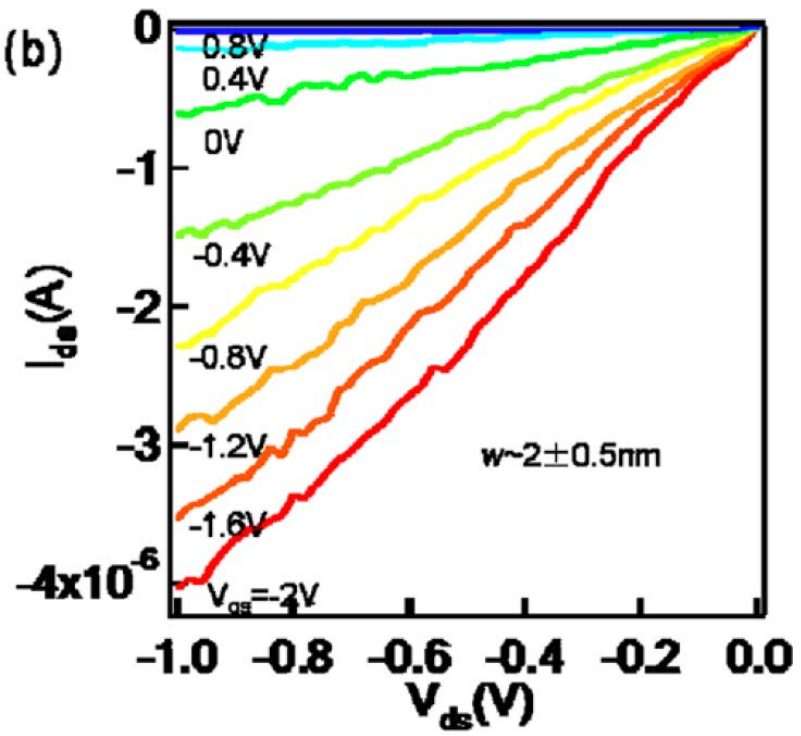


- ❑ almost no difference between GNR and CNTs in simulation
- ❑ both show excellent FET behavior at low voltages
  with current saturation
- ❑ GNR with bandgap should solve the problem that CNT have!

Graphene (GNR) vs. Carbon Nanotubes

real GNR do not show current saturation



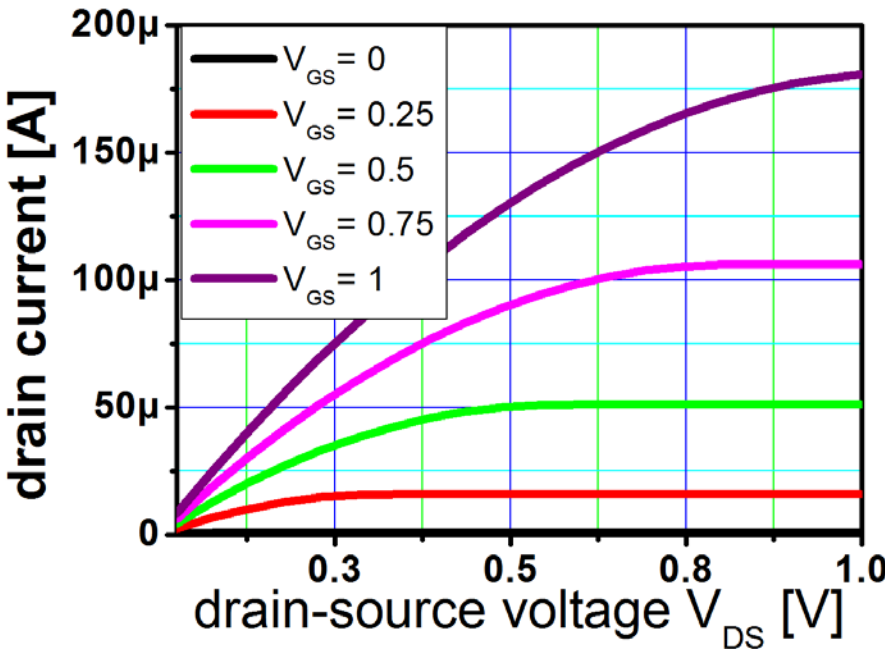


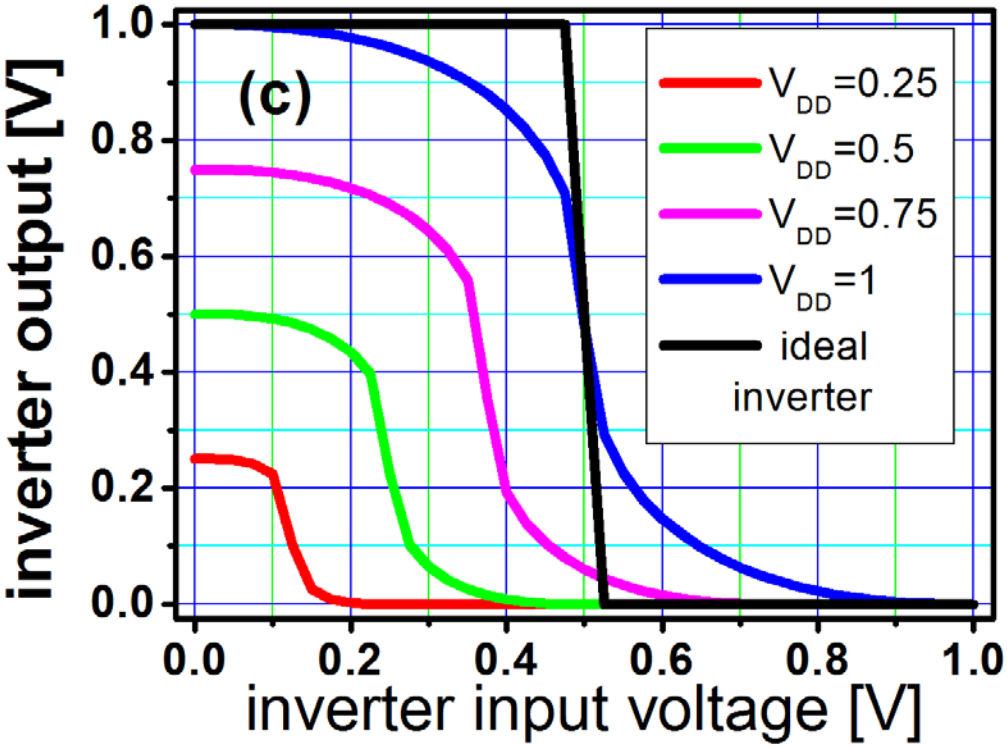
- real GNR exhibit a linear dependence of I_D on V_{DS}
- current saturation is only observed at **long gate length** **high V_{DS}** and **high current density**

X. Wang, Y. Ouyang, X. Li, H. Wang, J. Guo, and H. Dai, "Room-temperature all-semiconducting sub-10-nm graphene nanoribbon field-effect transistors", Phys. Rev. Lett. 100, 206803 (2008).

Transistors with current saturation

Effect on Inverter

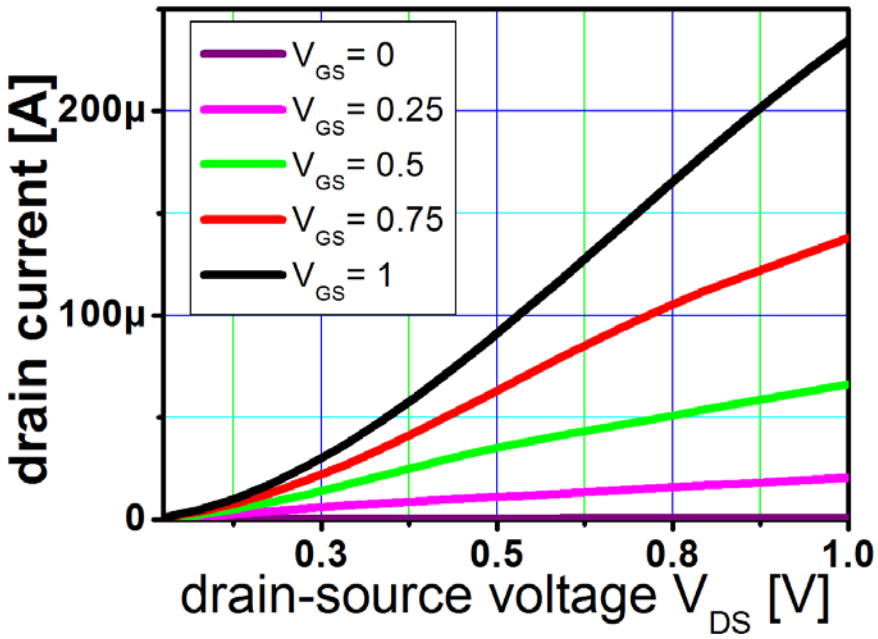


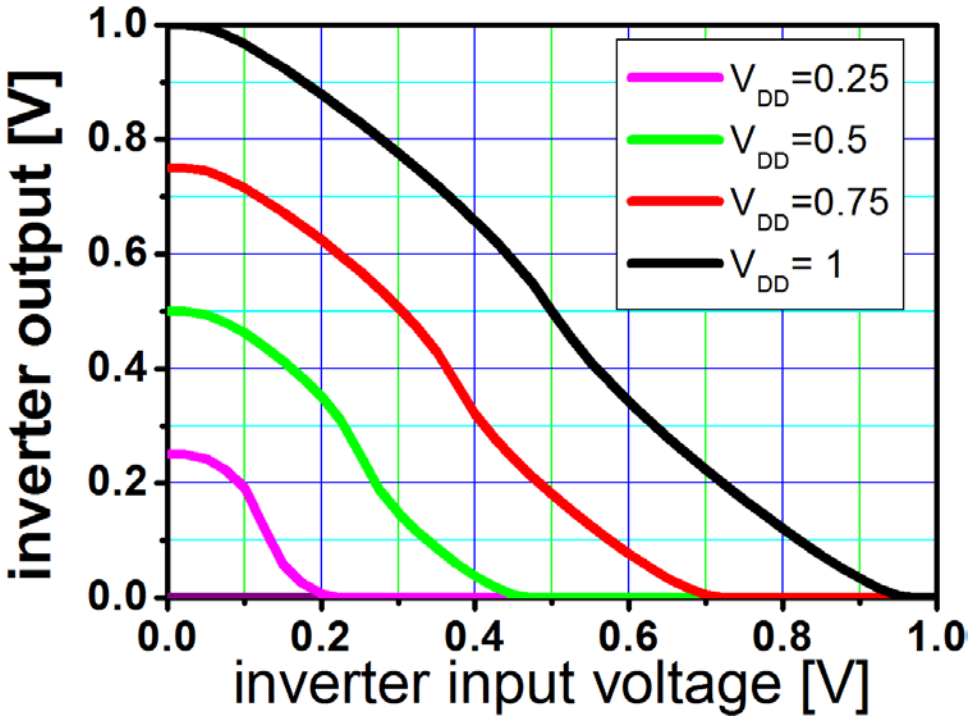


- absolute **gain >> 1** at $V_{DD}/2$
- **sharp transitions** for cascaded logic
- **useful** for SRAM, sense amp etc..

Transistors without current saturation

Effect on Inverter





- **absolute gain only ~ 1 at $V_{DD}/2$**
- no noise immunity, burns constantly current
- no sharp transitions for cascaded logic
- **not useful for logic, SRAM or latch-type sense amp etc..**

F. Kreupl, Nature 484, 321–322 (2012)

Graphene transistors: bad devices

even graphene nanoribbon transistors (which do have a band gap)

failed to show:

current saturation @ low voltage and @ short gate length

Therefore: no voltage gain = bad RF-FET

low gain inverters = bad logic-FET

nice overview article for RF devices:

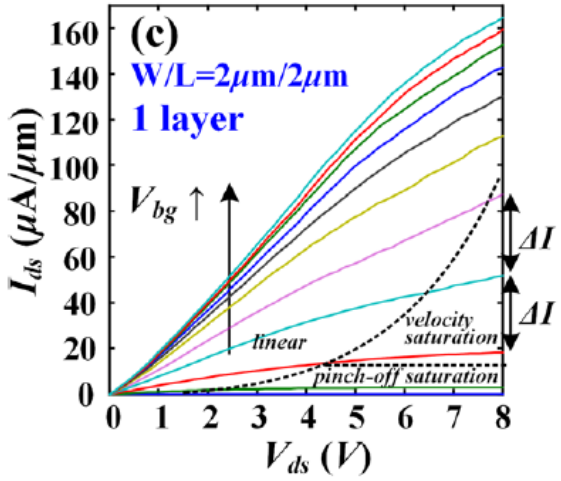
Frank Schwierz:
Graphene Transistors: Status, Prospects, and Problems

Proceedings of the IEEE Vol. 101, No. 7, July 2013

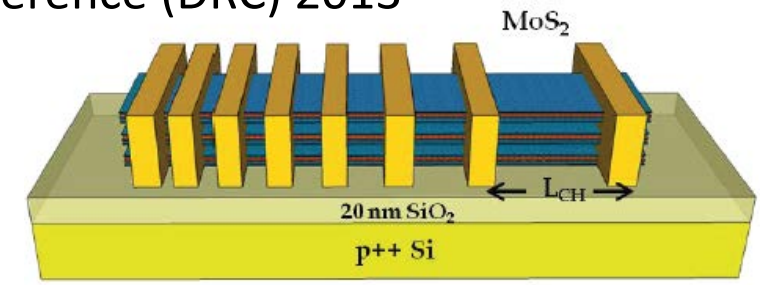
…. same for MoS_2 transistors (& other 2D)

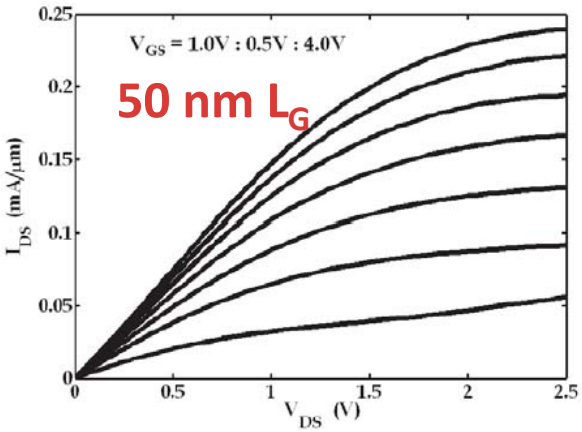
no current saturation @ low voltage and @ short gate length

High-performance MoS_2 transistors with low-resistance molybdenum contacts, Kang, Liu, and Banerjee
Appl. Phys. Lett. 104, 093106 (2014)

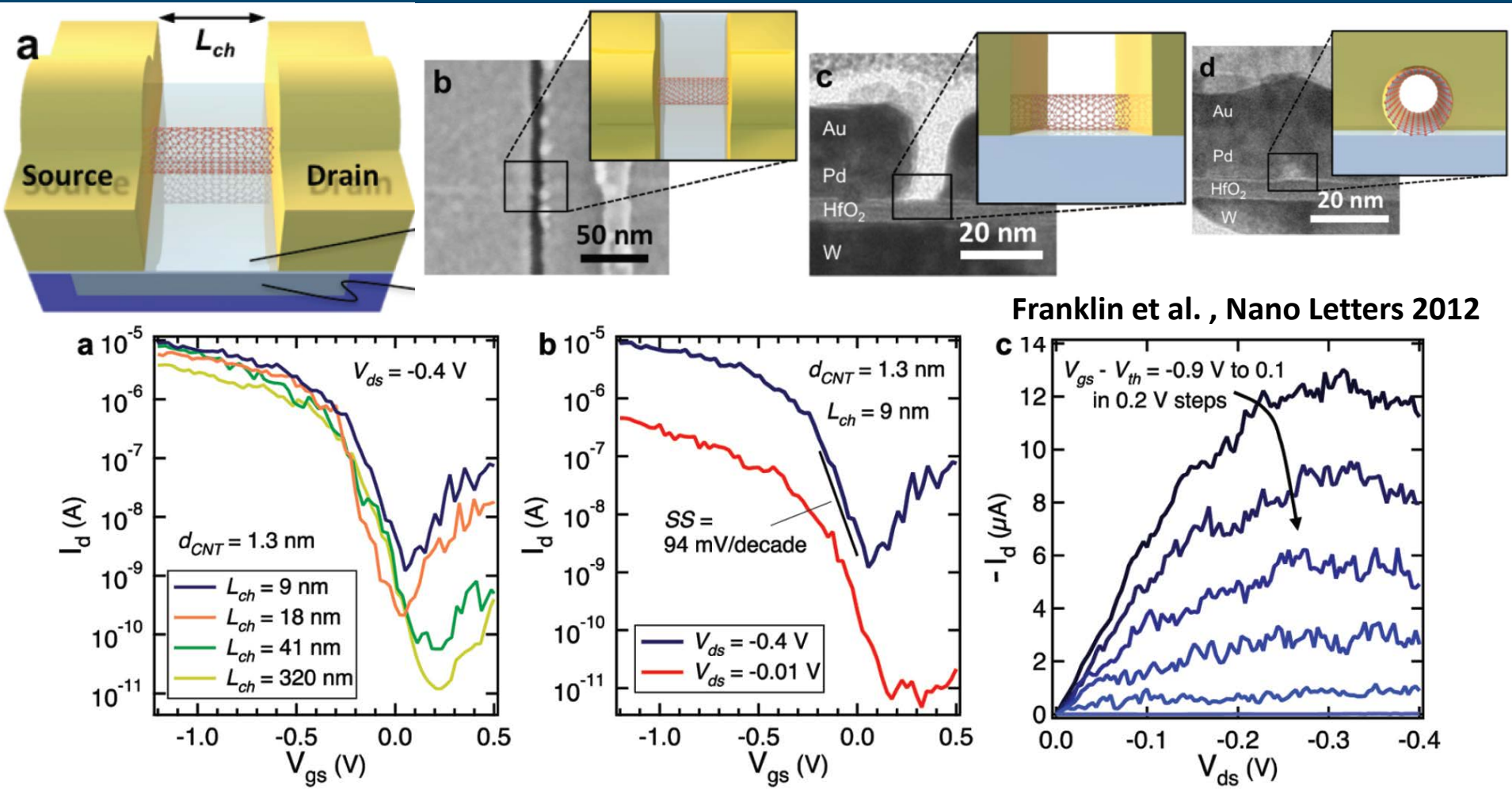


Evaluating the scalability of multilayer MoS_2 transistors
S. Das, J. Appenzeller
Device Research Conference (DRC) 2013





Sub-10 nm carbon nanotube transistor



Franklin et al. , Nano Letters 2012

Operation at low V_{DS} (0.4V) and short L_{gate} of 9 nm

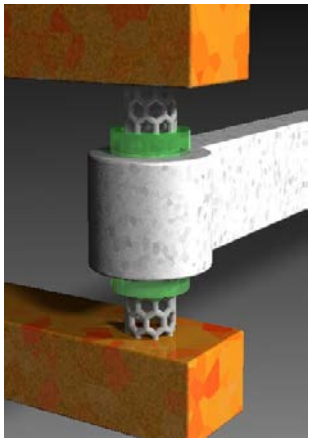
A. D. Franklin, M. Luisier, S.J. Han, G. Tulevski, C.M. Breslin, L. Gignac, M.S. Lundstrom, W. Haensch, "Sub-10 nm Carbon Nanotube Transistor", Nano Lett., 12 (2), 758–762 (2012). F. Kreupl, Nature 484, 321–322 (2012)

Advantages of Carbon Nanotubes FETs

Carbon Nanotubes fullfill our wishlist for a new switch

- ❑ Gate-all-around structure
  - ❑ No/low DIBL, very high on-current
- ❑ Doping-free for reduced variability
- ❑ Metallic, scalable source/drain contacts
  - ❑ ~6 kOhm for a 1 nm wide channel!
- ❑ Compatibility with high-k materials
  - ❑ LaOx, HfOx, ZrOx, TaOx, AlOx, TiOx all work
- ❑ Scalability demonstrated down to 9 nm
  - ❑ short L_G data is not available for InGaAs, Ge, GeSn, SiGe….
  - ❑ dark space might worsen situation for InGaAs, Ge, GeSn

work: Franklin et al. , IEDM 2012
patent: Kreupl & Seidel US 7646045 B2



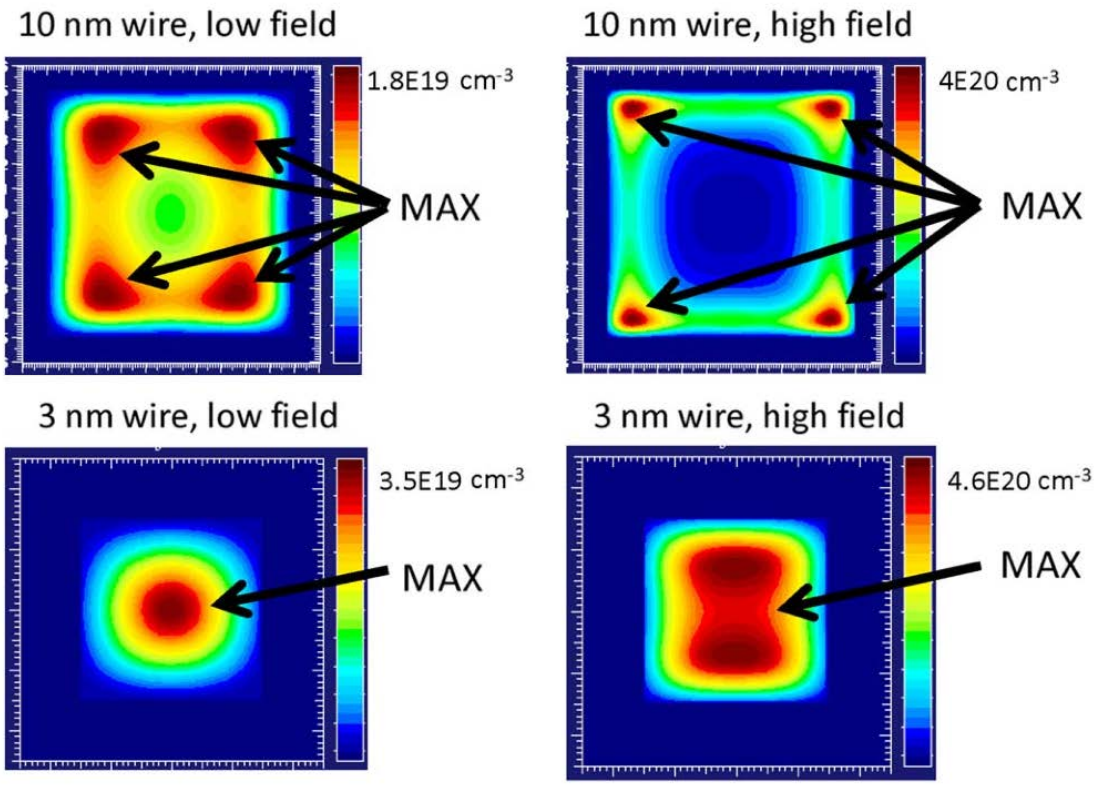
Kreupl, IFX 2003

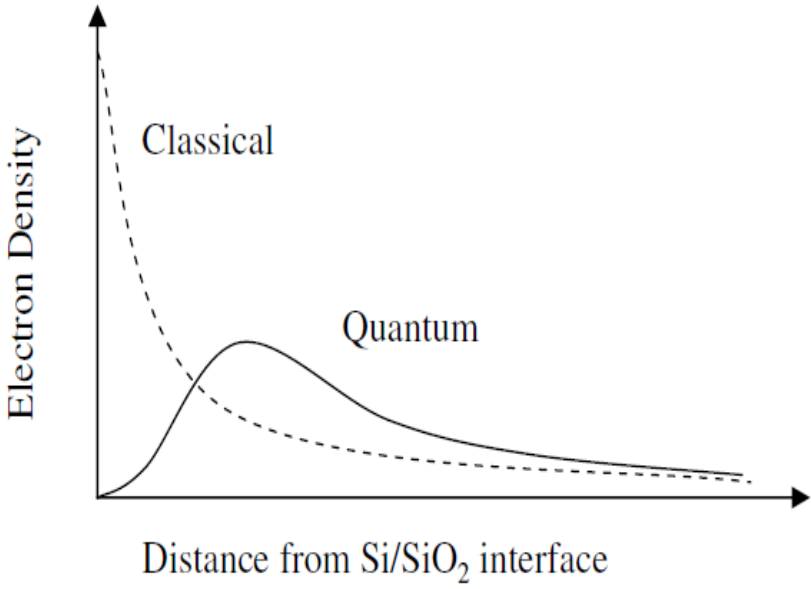
Franklin et al, Nature Nanotech. 2010

Franklin et al. , Nano Letters 2012

http://www.hes.ei.tum.de/fileadmin/w00bjl/www/uploads/Kreupl_New_materials_on_horizon_for_advanced_logic.pdf

Dark space in silicon / high-μ channels





in Silicon Kelin J. Kuhn, TED 2012

- ❑ **Dark space gets worse due to reduced DOS – C_{inv} α 1/DOS**
- ❑ **No matter how high the k-value ➔ dark space destroys it**
- ❑ **Severe limiter for channel control ➔ SS / DIBL deterioration**

Skotnicki & Boeuf, VLSI 2010

Ge- , InAs-Scaling – dark space

25 nm Germanium Quantum Well pMOS FinFETs

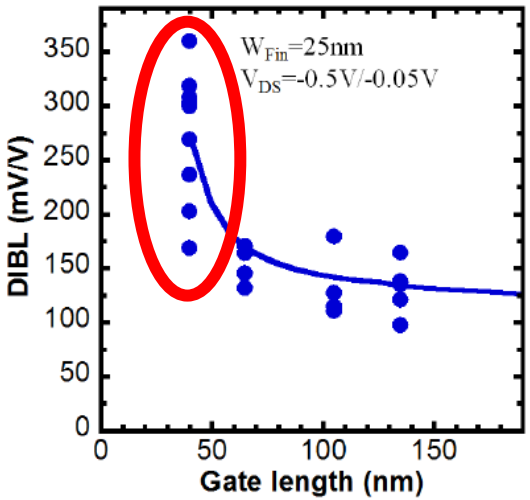


Fig. 12. DIBL versus L_G for sGe/SiGe Fin devices. Electrostatics are not significantly degraded with L_G scaling down to ~65nm due to the additional isolation from the quantum barrier between sGe and SiGe SRB

L. Witters et al. IMEC, IEDM 2013

No data on SS @ short L_G
Why?

20 nm InAs-on-insulator Tri-gate

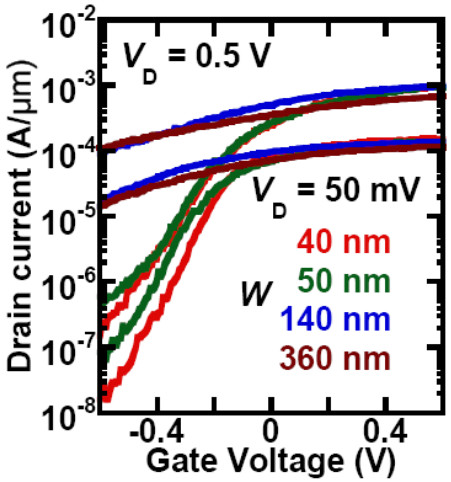


Fig. 14 W dependence of transfer characteristics at L_{ch} = 20 nm.

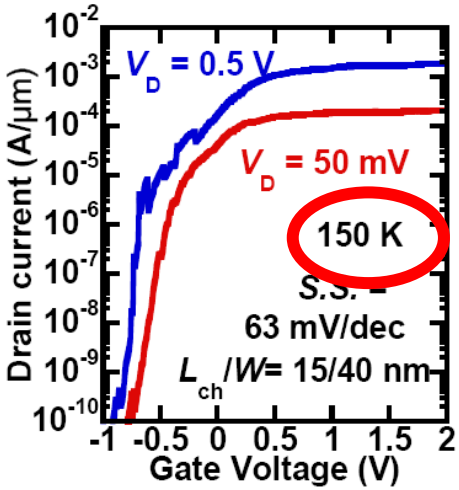


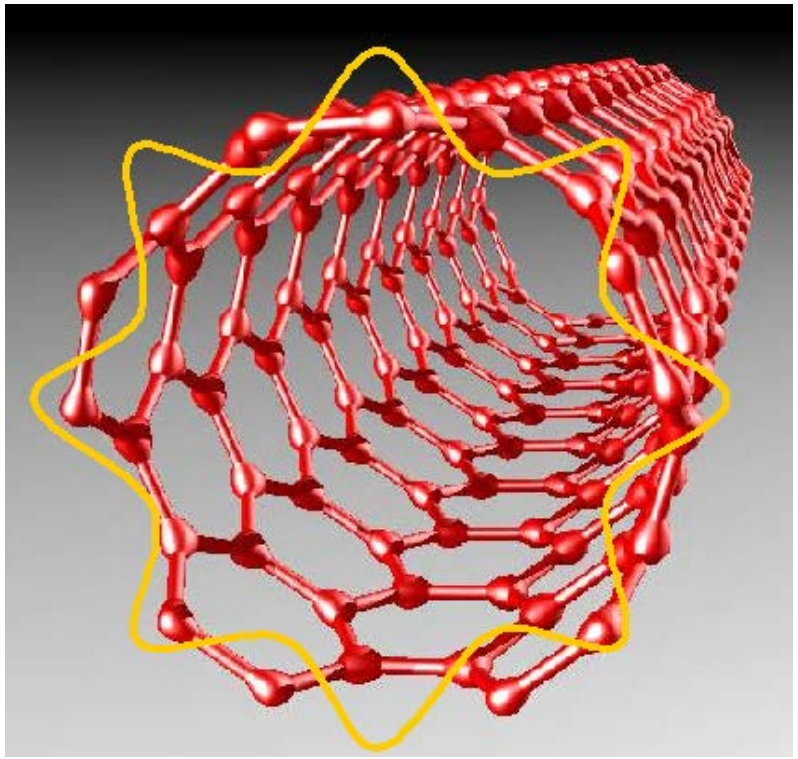
Fig. 15 Transfer characteristics of InAs-OI MOSFETs with L_{ch}/W = 15/40 nm at 150 K.

SangHyeon Kim et al., Tokyo U, IEDM 2013

some data only at 150 K
Why?

Severe limiter for channel control ➔ SS / DIBL deterioration **Skotnicki & Boeuf, VLSI 2010**

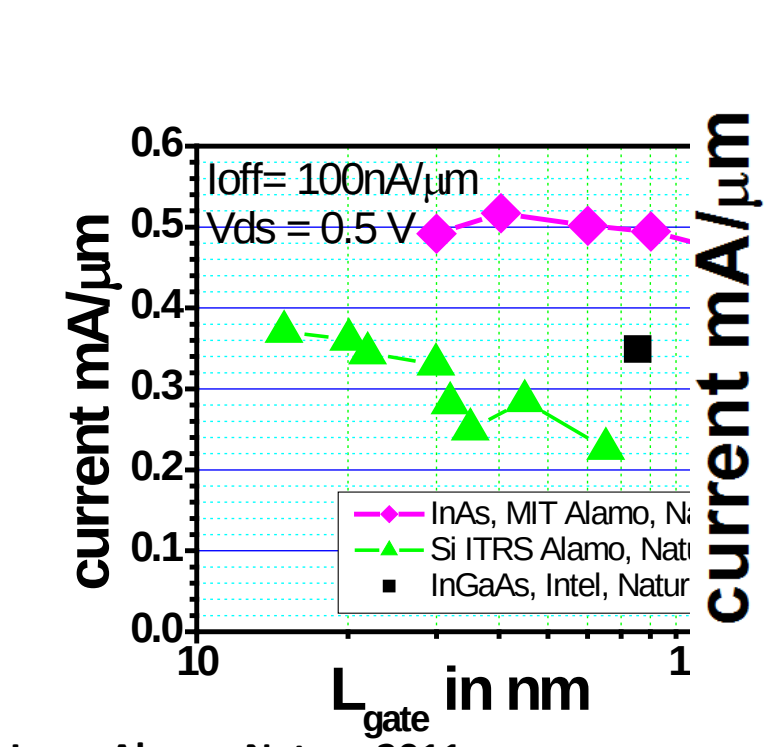
Carbon Nanotubes have no dark space



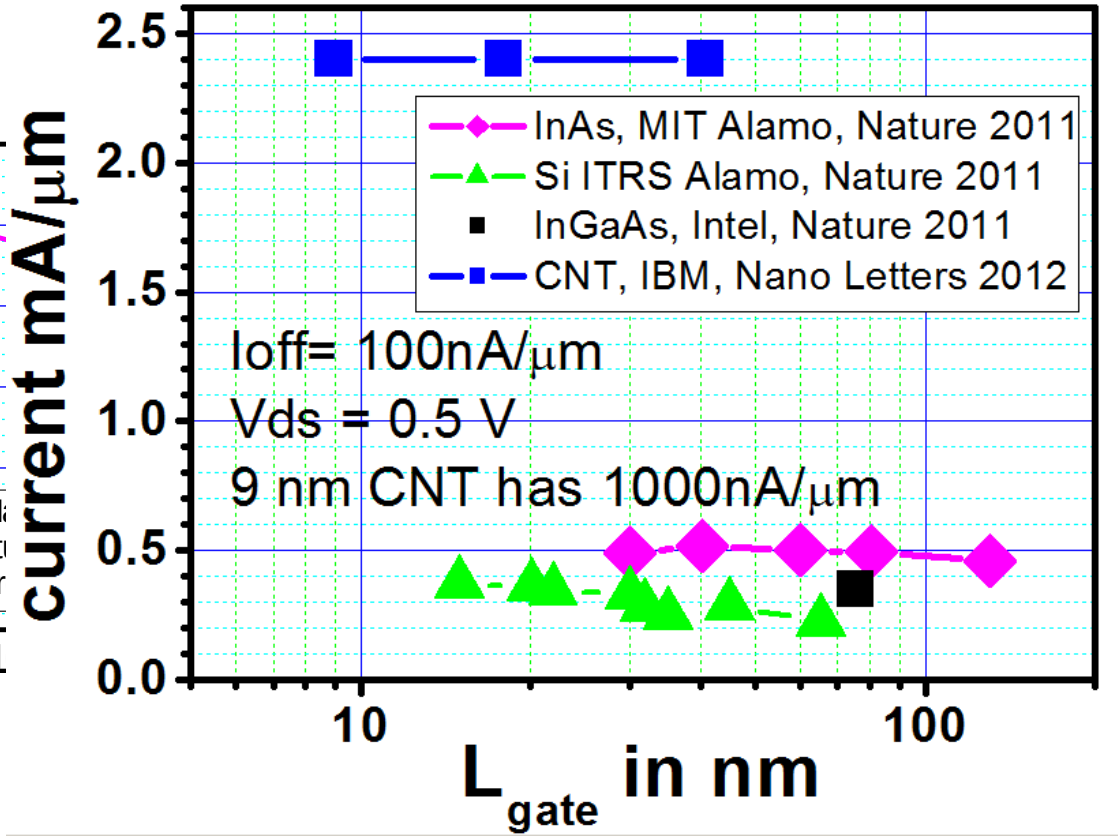
- Current is confined to a single atomic layer
- Intimate channel control & low DOS
- Operation in the quantum capacitance limit (QCL) possible
- In QCL, the potential in channel is determined by the gate potential
- short channel effects are suppressed
- Nanotube have no dopants

c.f. Knoch et al. EDL, 2008

Carbon nanotubes outperform alternatives



Jesus Alamo, Nature 2011

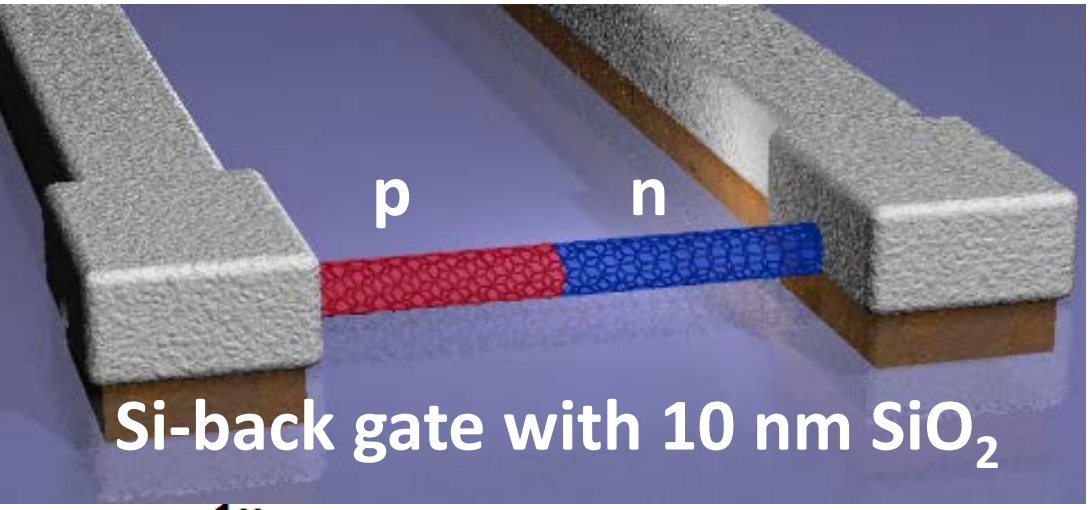


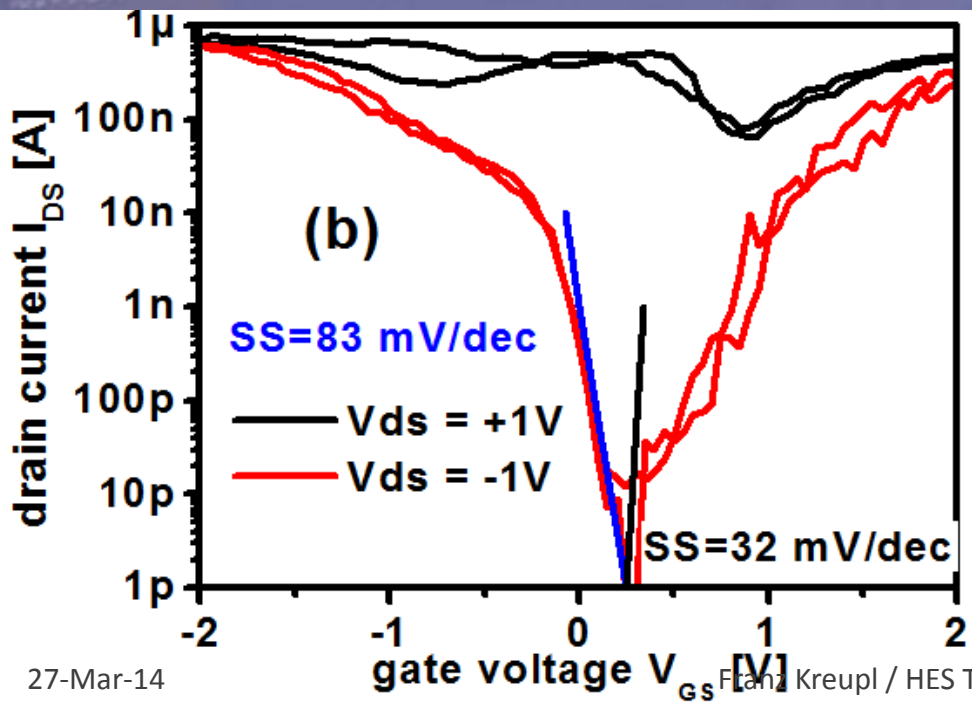
enhanced current drive due to material and contacts

F. Kreupl, Nature 484, 321–322 (2012)

CNT Ioff: 1000nA/µm for 9nm !
100nA/µm for >= 18nm

Carbon Nanotubes Tunneling FETs (TFET)





- gated PIN diode based on a CNTFET
- n-doping by PEI polymer
- p-doped by contacts & atmosphere
- SS of 83 mV/dec and current drive of ~ 1mA/µm
- unknown doping profile
- E field sharper by local screening gates?

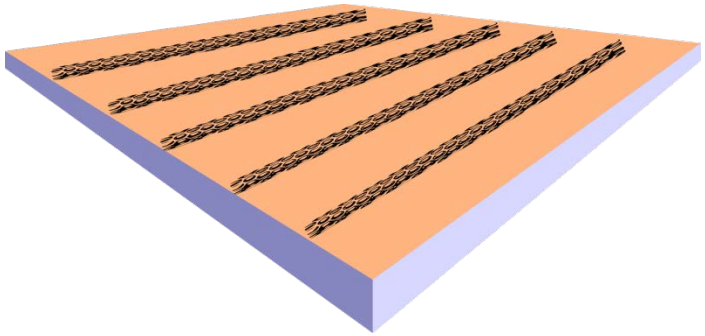
F. Kreupl, "Carbon Nanotubes in Microelectronic Applications", in Advanced Micro & Nanosystems Vol. 8. Carbon Nanotube Devices, edited by Christofer Hierold, WILEY-VCH (2008)

Great News – how to proceed?

Please give instructions

➔ **how to place billions of nanotubes with**

- **one type of chirality**
- **equal length**
- **on a substrate**
- **well aligned at some nanometer pitch**
- **with a throughput of 120 wafers per hour**

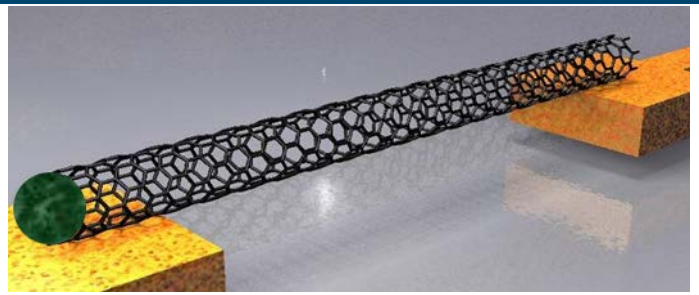


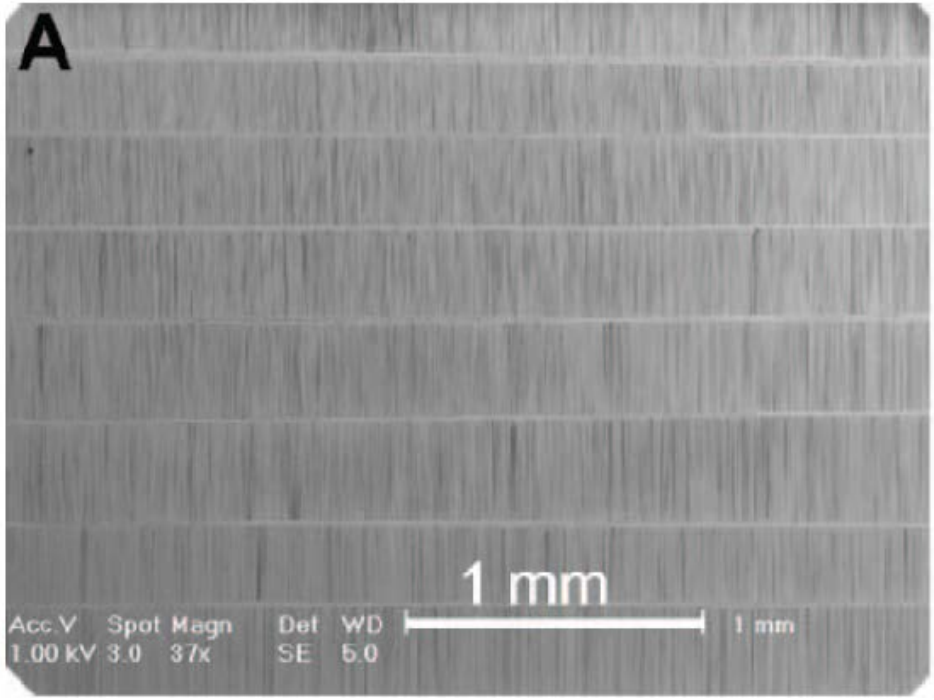
Solution: Just issue a purchase order for the new Applied Materials *Nano-Wonder™* machine

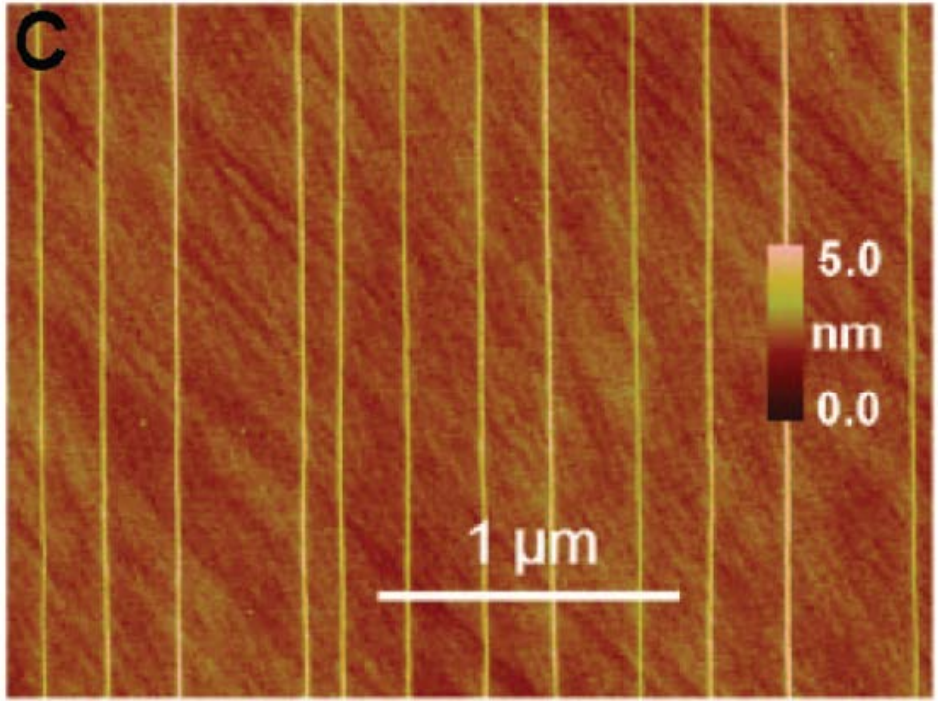
No - unfortunately – I am kidding

Placement strategies are to be investigated

- Grow in place or transfer
- Use self-assembly







- aligned growth is possible, pitch not (yet) suitable

(Selective Growth of Well-Aligned Semiconducting Single-Walled Carbon Nanotubes
Lei Ding, Alexander Tselev, Jinyong Wang, Dongning Yuan, Haibin Chu, Thomas P. McNicholas, Yan Li, and Jie Liu
Nano Lett., 2009 DOI: 10.1021/nl803496s)

Summery and Conclusion

- There is no single experimental evidence that Graphene and other 2D materials are suitable for further scaling of FETs
- The main culprit is missing current saturation
- Opportunity window for alternative channel materials is closing due to dark space effects
- Performance-wise carbon nanotube devices outperform any alternative
- Huge gap for industrial integration exists
- A possible roadmap exists based on self-assembly and/or grow in place
- What remains is hard work to make it happen – not ideally suited for academia