Advancing CMOS with Carbon Electronics

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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
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

Graphene (GNR) versus Carbon Nanotubes


- 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!
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

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.

![Graph showing the effect of different $V_{DD}$ values on the inverter output.](image)
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..**
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
.... 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

Evaluating the scalability of multilayer MoS$_2$ transistors
S. Das, J. Appenzeller
Device Research Conference (DRC) 2013

![Graph showing device characteristics](image)
Sub-10 nm carbon nanotube transistor

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

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**

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

Franklin et al, Nature Nanotech. 2010
Franklin et al. , Nano Letters 2012

Dark space gets worse due to reduced DOS – $C_{\text{inv}} \propto 1/\text{DOS}$

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

L. Witters et al. IMEC, IEDM 2013

20 nm InAs-on-insulator Tri-gate

SangHyeon Kim et al., Tokyo U, IEDM 2013

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

No data on SS @ short $L_G$

Why?

Severe limiter for channel control $\Rightarrow$ SS / DIBL deterioration Skotnicki & Boeuf, VLSI 2010

Why?

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.

some data only at 150 K
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

Carbon nanotubes outperform alternatives

Enhanced current drive due to material and contacts


CNT $I_{off}$: $1000\text{nA/µm}$ for 9nm!
$100\text{nA/µm}$ for $\geq 18\text{nm}$
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?

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**