Prospects for graphene electronics

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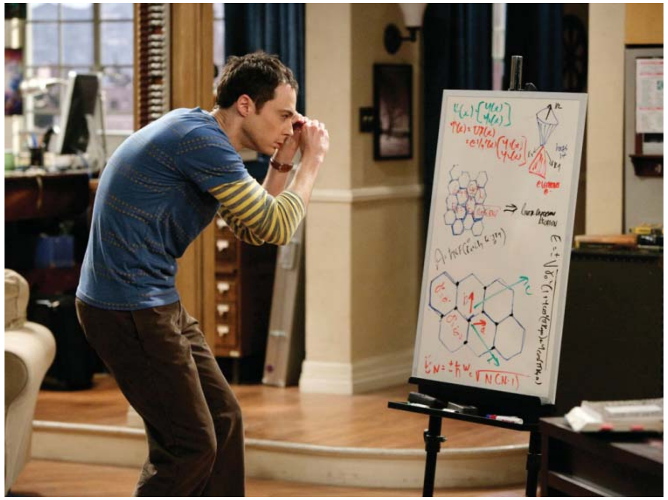
Graphene-based electronics

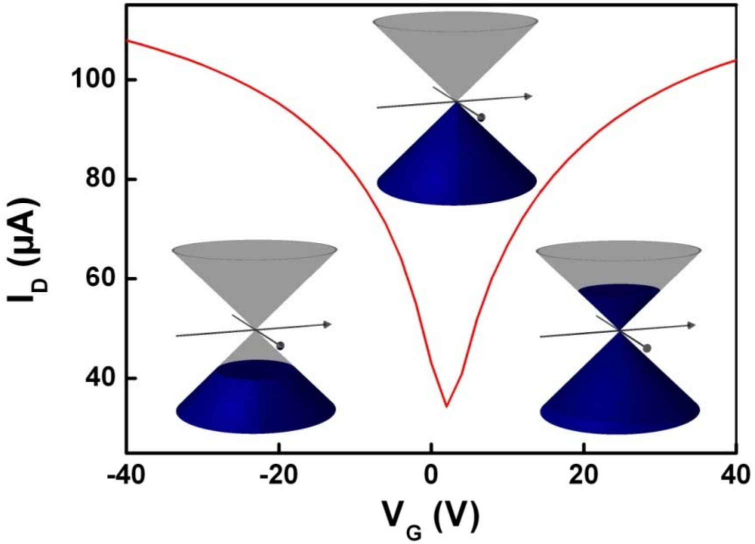
- At its infancy: *Si anno 1955*
- Not just graphene but also other two-dimensional materials (BN, MoS_2, $MoSe_2$, $NbSe_2$, Bi_2Te_3,…): *a whole new palette*

- Different aspects:
  - Pre-requisites: materials and device fabrication
  - Digital vs. analog
  - Consumer vs. high-performance
  - Integrated systems: optical, flexible
  - Novel components
- For recent reviews, see
  D. Reddy *et al*., J. Phys. D **44**, 313001 (2011);
  F. Schwierz, Nature Nanotechnology **5**, 487 (2010);
  S.K. Banarjee *et al*., Proc. IEEE **98**, 2032 (2010)

What's so special about graphene?

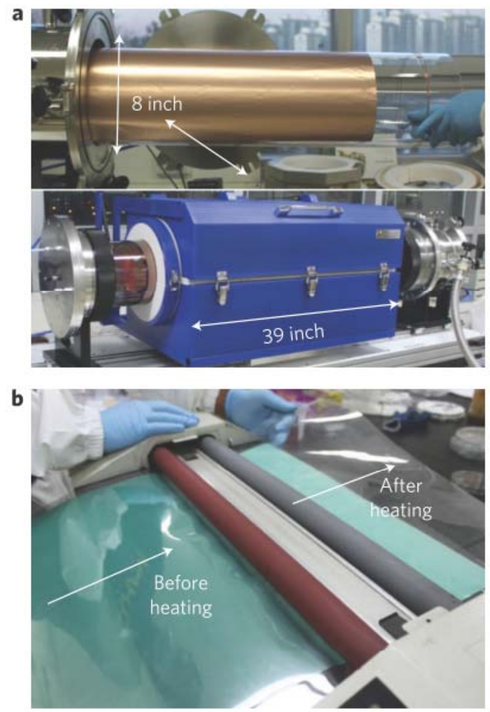


- Conducting (semi-metal: *ambipolar*)
- High carrier mobility (up to 200 000 cm²/Vs, on substrate ~10 000 cm^2/Vs)
- Large saturation velocity (4 x10^5 m/s)
- High current-carrying capacity
- Linear dispersion relation (*Dirac fermions*)
- Ultimately thin
- Compatible with planar technology
- Optically transparent (absorption $\pi\alpha \approx 2.3$ %)
- Flexible and strong (100-300 stronger than steel)
- Best conductor of heat
- Chemically inert
- Biocompatible



Materials production

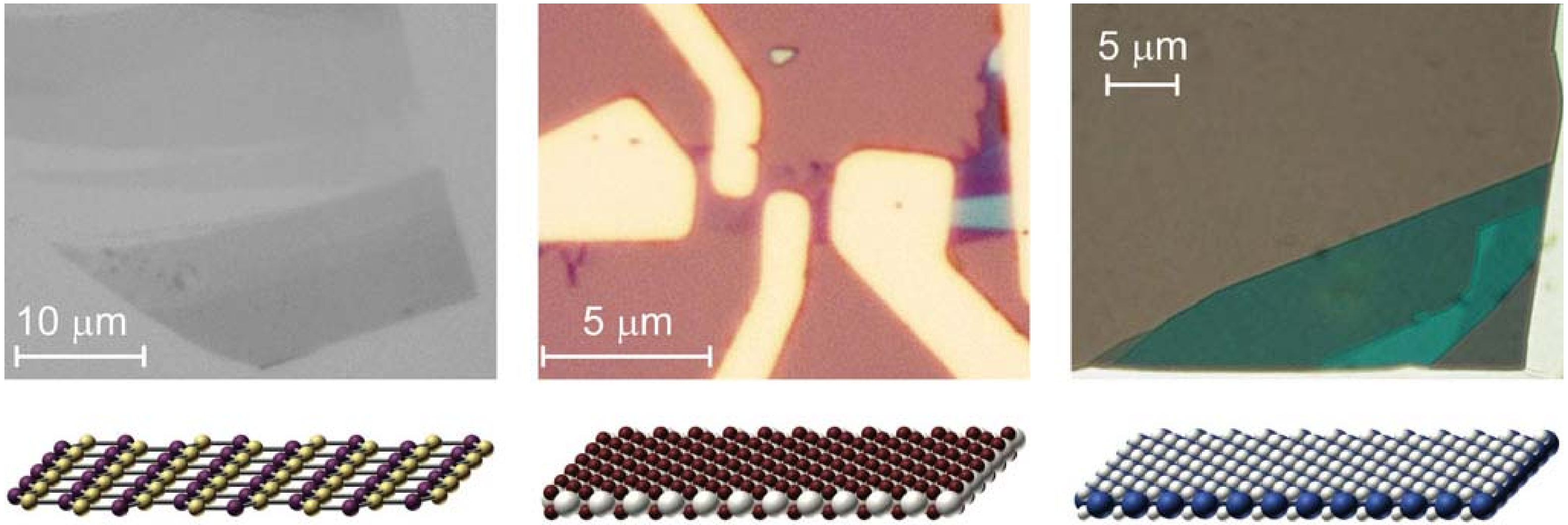
- Exfoliation
  - Mechanical: highest quality, not scalable
  - Chemical: mostly flakes, OK for many applications
  - Mobility up to 200 000 cm^2/Vs and higher (suspended)
- **CVD**
  - Scalable, transferable, rapidly developing
  - Usually on Cu but also other metals and insulators
  - Roll-to-roll production
  - Mobility up to 7 000 cm^2/Vs on SiO_2, 3x higher on h-BN (A. Venugopal et al., J. Appl. Phys. **109**, 104511 (2011))
- SiC sublimation
  - High electrical quality, expensive, not transferable
- Chemical synthesis
  - Atomistic control, placement issues similar to CNTs
- Exploratory techniques



S. Bae et al. Nature Nano. 5, 571 (2010)

Other (mono-)layered materials

- Graphene is the first material in a palette of monolayers from layered materials



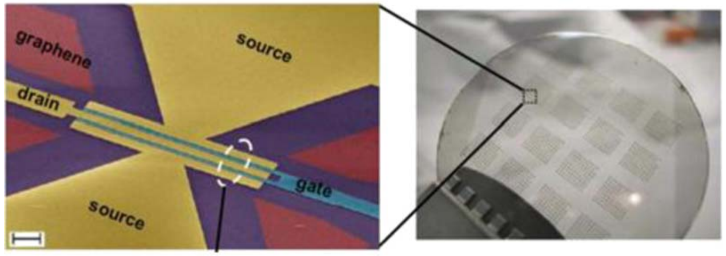
Hexagonal BN
Insulator

$NbSe_2$
semimetal

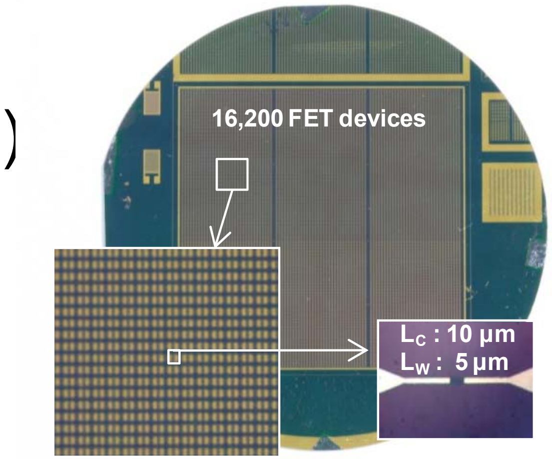
MoS_2
Direct-bandgap SC
(MoS_2 FET:
Nature Nano **6**, 147 (2011))

(K. Novoselov, Rev. Mod. Phys. **83**, 837 (2011))

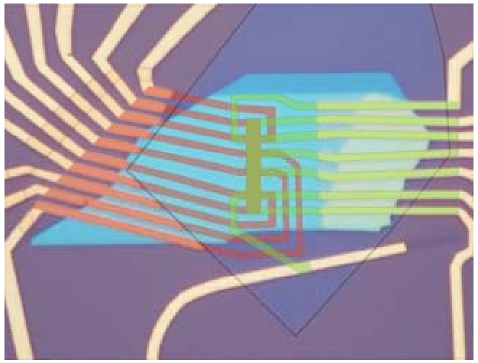
Device fabrication



- Planar technology:
  conventional lithography is applicable
  → integrable
- Sandwich structures G-BN-G
  (L.A. Ponomarenko et al., to appear in Nature Phys.)



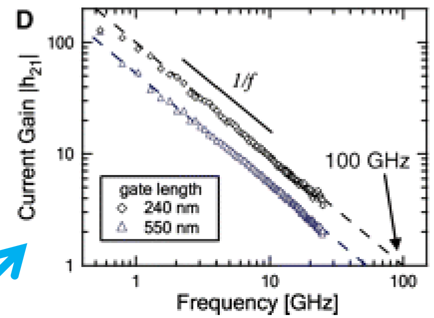
2 graphene layers, individually contacted and separated by 5 BN layers
→ Coulomb drag etc.

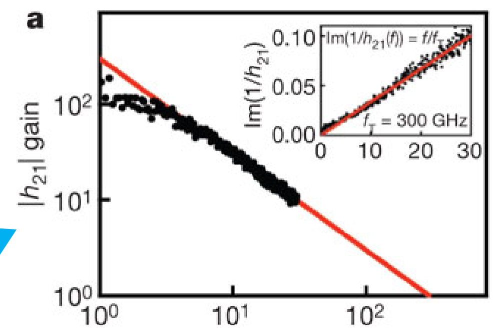


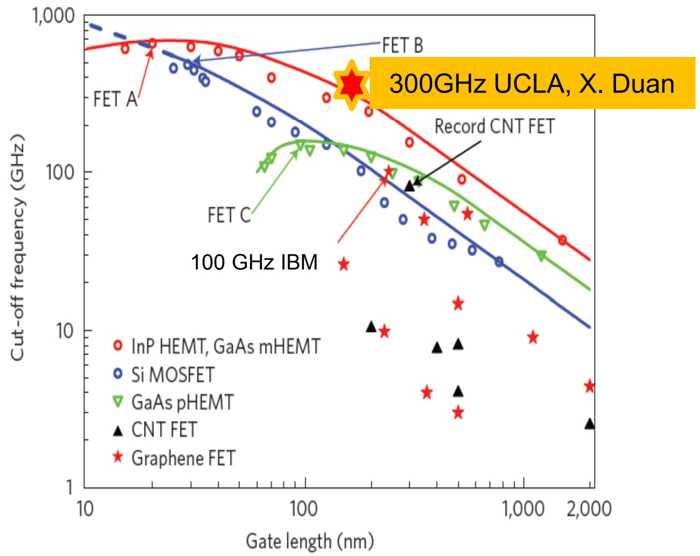
- Challenge is to use CVD or similar but without having to transfer!

Analog electronics

- High mobility and high saturation velocity give promise for fast electronics
- Extrapolated performance
  IBM: f_T = 100 GHz @ 240 nm;
  UCLA: f_T = 300 GHz @ 144 nm
- Poor power gain due to absence of a gap
- Ambipolar: new design feature that enables novel devices (Palacios)







(adapted from F. Schwierz)

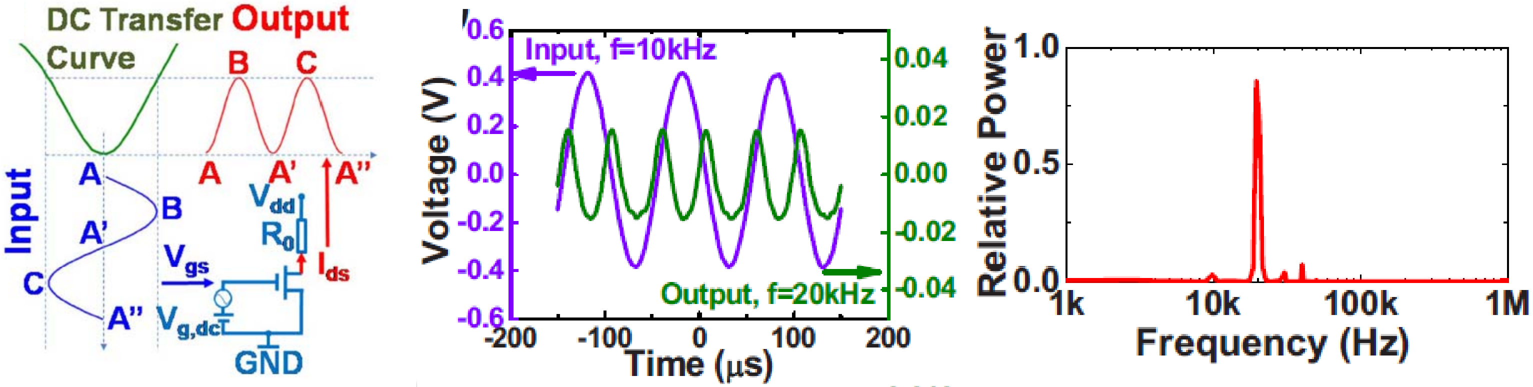
Comparison of graphene RF-transistors in terms of maximal transconductance g_m, minimal source-drain conductance g_0, and maximum power gain A

	Oxid (EOT)	**g_m max (mS/µm)**	**g_0 min (mS/µm)**	**A max**
IBM (SiC)	PHS/HfO_2 (17 nm)	0.15	0.4	<<1
IBM (CVD)	Al_2O_3 (10 nm)	0.04	0.2	<<1
UCLA (Exfoliated)	Al_2O_3 (8 nm)	1.2	2	<1
Columbia (BN)	BN (8 nm)	0.4	0.05 - 0.1	4 - 8
Columbia(pulsed)	PVA/HfO_2 (7nm)	0.5	0.1 - 0.2	2.5 - 5
AMO (E_G = zero)	Al_2O_3 (8nm)	0.12	0.02	6
AMO (E_G ~ 100meV)	Al_2O_3 (8nm)	0.12	0.002	60

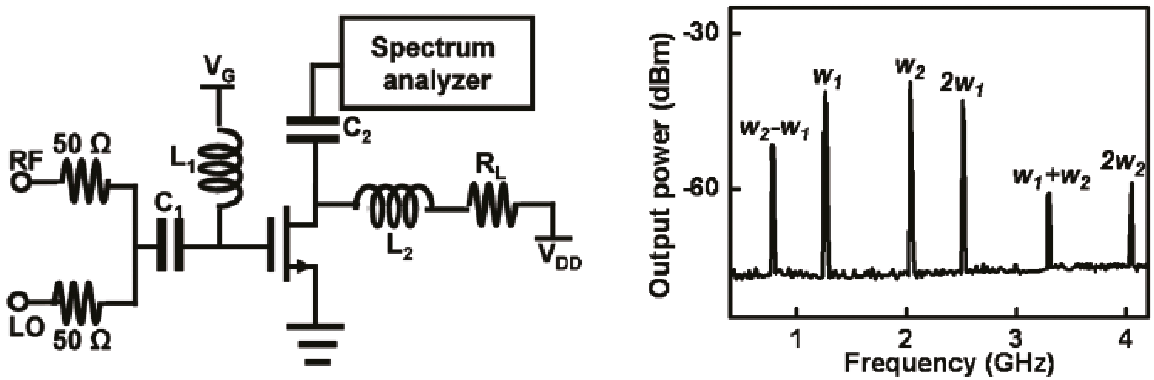
AMO unpublished

Exploiting ambipolarity for RF applications

Frequency doubling
(Z. Wang et al., APL **96**, 173104 (2010))



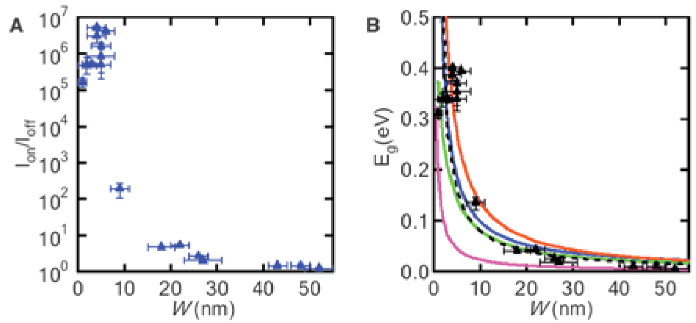
Mixer with one transistor
(L. Liao et al., Nano Lett, June 7, 2011)



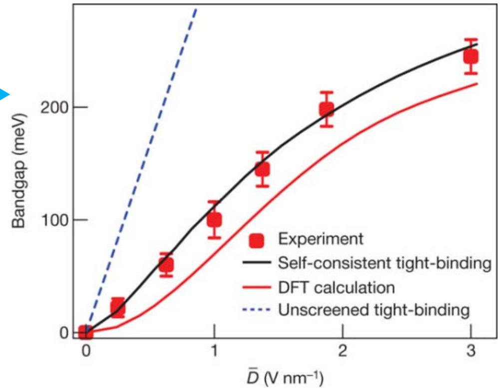
Room for many more innovations!

Digital electronics

- Challenge: absence of a band gap makes it hard to turn the devices off
- Old thinking: create a gap
  - Graphene nanoribbons (GNR)
    $E_g \approx 0.8$ eV nm/W
    - Lithographically: hard, need width 2-5 nm, good edges
    - Chemical synthesis: on metals, hard to position, no transport measurements exist yet
    - Unzipping of CNTs or synthesis inside a CNT
  - Bilayer graphene with electric field: gap 100-200 meV, required V_{bg} ~100 V
  - Chemical modification (*e.g.*, nitrophenyl), gap 0.4 eV (S. Niyogi *et al*., Nano Lett. **10**, 4061 (2010))
- New thinking: under research
  - BiSFET, tunnel FET, Veselago lens device: both BiSFET and tunnel FET are predicted to have very low switching energies, but they have not been demostrated experimentally

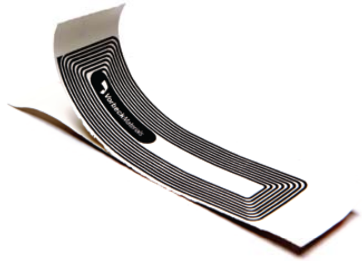


X.Li *et al*., Science **319**, 1229 (2008)



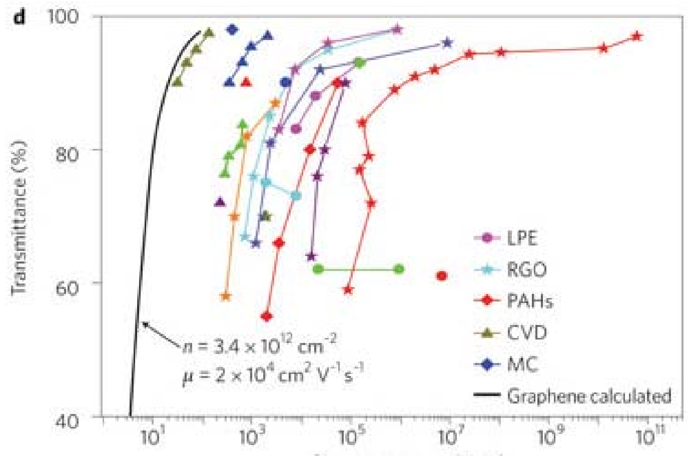
Y. Zhang *et al*., Nature **459**, 820 (2009)

Consumer electronics



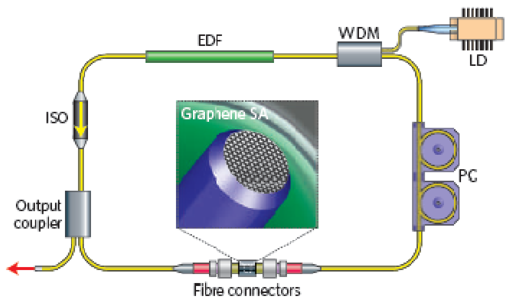
- Printable electronics
  - Thin film transistors with μ up to 100 cm^2/Vs (private information): no longer slow, still cheap → may capture some markets from conventional electronics
  - Approaching maturity: Vorbeck Materials conducting ink on market in 2012

Optoelectronics



- ITO replacement
  - In is a scarce resource with few suppliers
  - Sheet resistance and transparency OK
  - Samsung prototype AMOLED

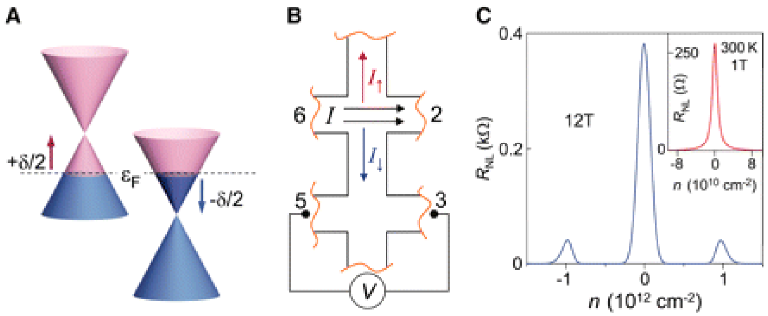
- Fast lasers, photodetectors, modulators
  - Saturable absorbtion enables fast lasers with sub-ps pulses
  - Unique, universal wideband absorption can be exploited in photodetectors
  - *Etc*. – graphene photonics and plasmonics is one of the fastest growing research areas at the moment

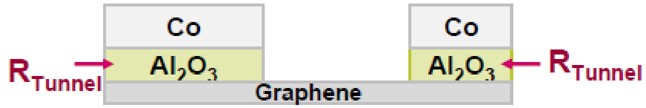


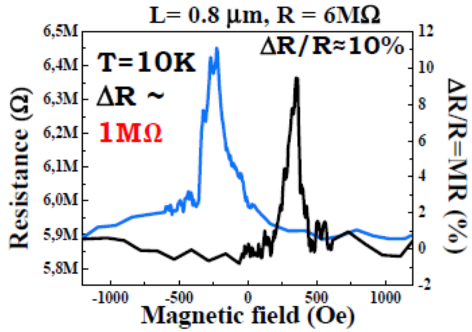
F. Bonaccorso et al. Nature Phot.. 4, 6111 (2010)

Beyond CMOS

- Spintronics:
  - large spin coherence lengths and pure spin currents (D.N. Ababnin et al., Science 332, 328 (2011))
  - large resistance signal for spin-dependent transport in spintronic logic devices (A. Fert, talk in Graphene2020, March 2011)
- NEMS:
  - low mass and large Young's modulus are promising advantages high frequency NEMS
  - larger area implies larger signals than for CNT-devices
  - possibility to shape and to sensitively control nonlinearities by tension yield new design freedoms







Benchmarking Beyond CMOS Devices

Technology	Graphene
Gain **Signal/Noise ratio** **Non-linearity**	Poor, would benefit from a gap
Speed **Power consumption**	High Low – high mobility, good gate coupling
Architecture/Integrability **(Inputs/outputs, digital, multilevel, analog, size etc.)**	Demonstrated integrability.
Other specific properties	System level integration - multifunctional
Manufacturability **(Fabrication processes needed, tolerances etc.)**	Mostly OK, except for ribbon fabrication Challenges in transferless fabrication
Timeline **(When exploitable or when foreseen in production)**	Optical and printable first (~2 years). Analog a few years later. Digital last. Non-standard devices (BiSFET etc.) not demonstrated yet.