"Electromagnetic Compatibility at Nanoscale"

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Classical EMC concepts

- **What is EMC?**
- **Coupling mechanisms**
- **Design guidelines**

Current trends and challenges for nanoscale circuits

Carbon-based materials to enable nanoelectronics

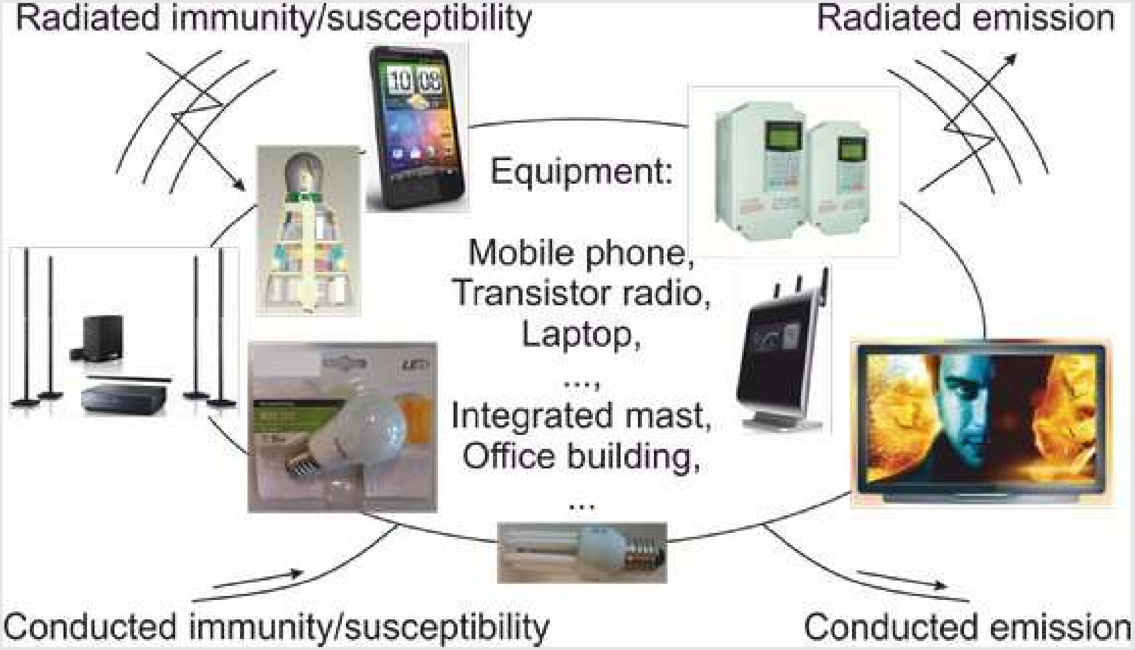
Novel EMC concepts at nanoscale

What is the Electromagnetic Compatibility (EMC)?

Electrical and electronic devices and systems are characterized by wanted or unwanted emissions of **electromagnetic signals** which propagate:

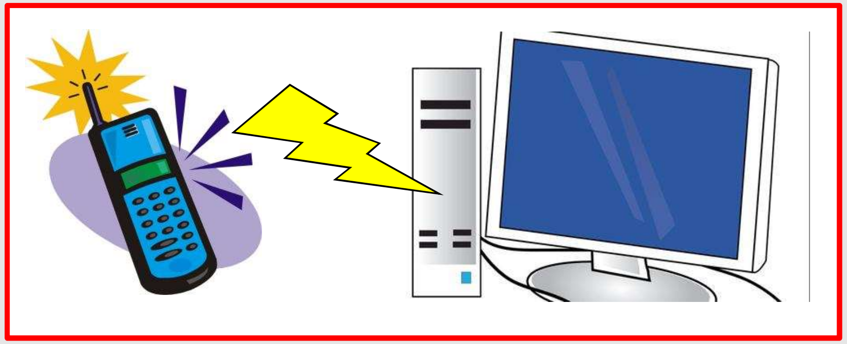
- along the conductors **(guided propagation)**

- in the free space **(radiated propagation)**



Such signals may capted by other devices, producing **disturbances and malfunctioning**

Electromagnetic Compatibility (EMC)



Each device/system under test is requested:

1) to **emit** signals below the limits imposed by the technical Norms

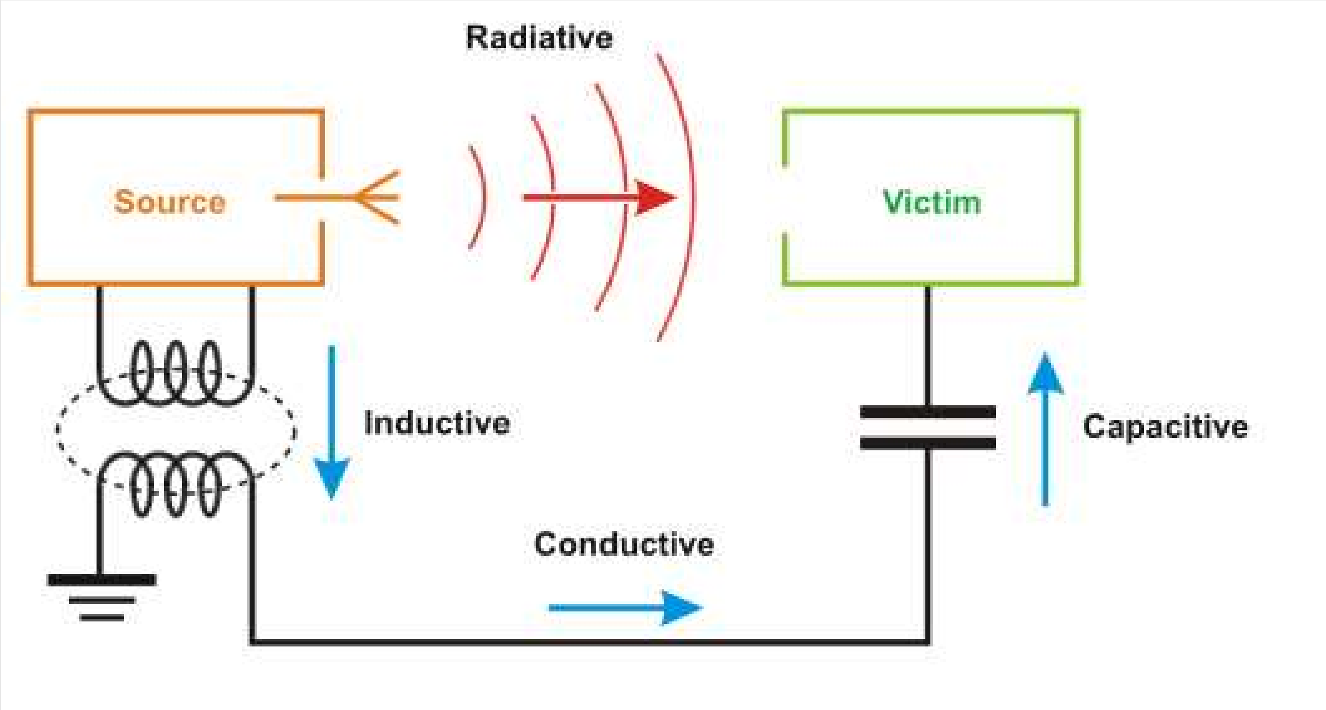
2) to exhibit a given grade of **robustness** to external disturbances

3) To guarantee the **internal compatibility** between subparts

EMC compliance

Paths and coupling mechanisms

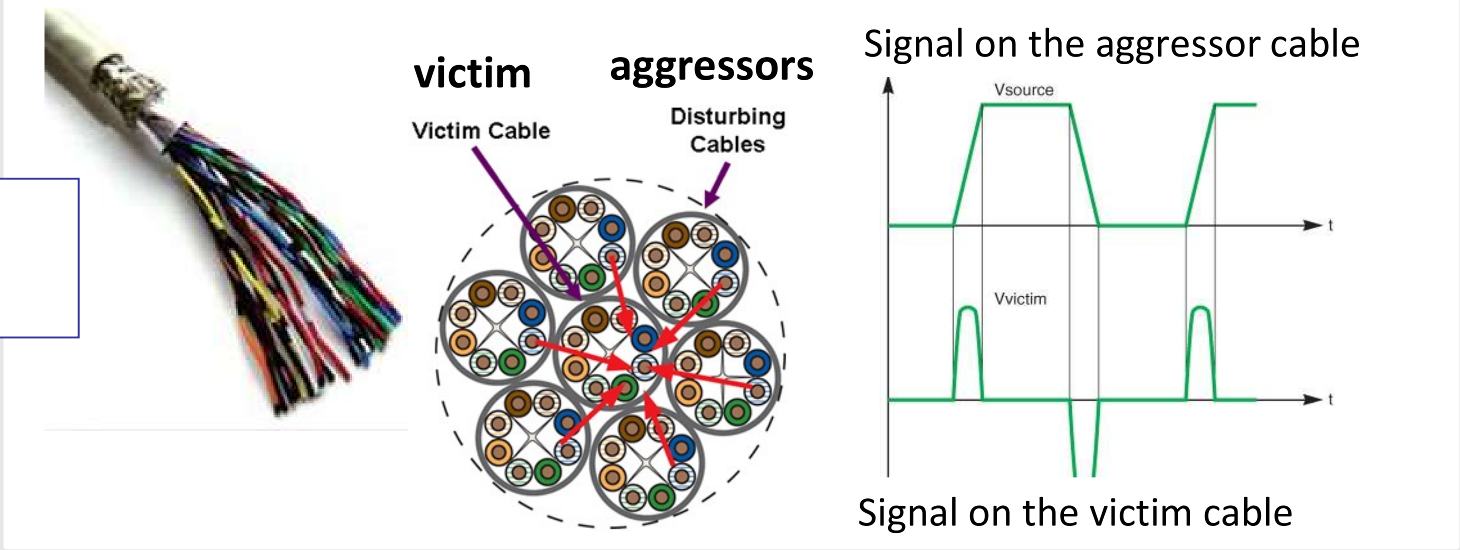
They strongly drive the design choices



Examples of «classical» EMC problems and «classical» solutions

CROSSTALK

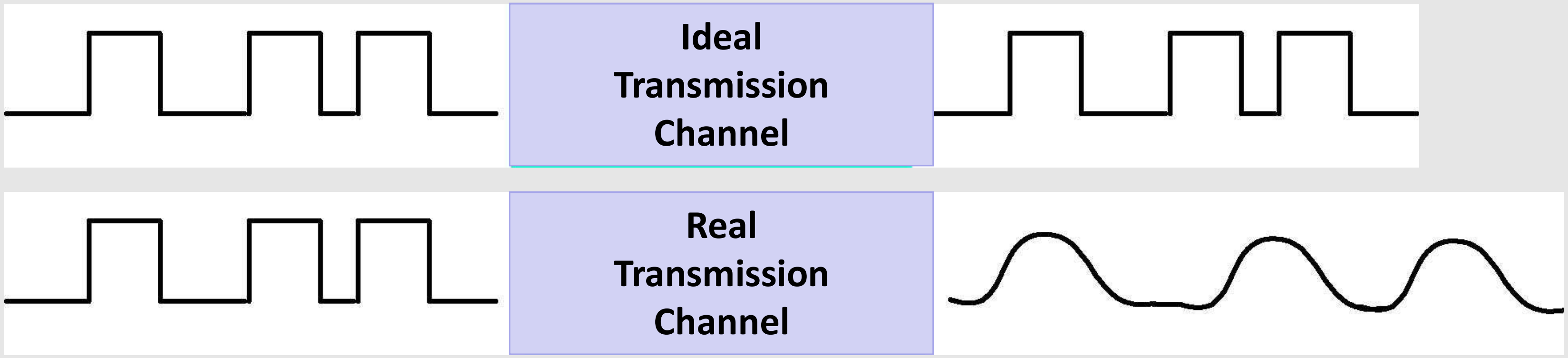
NOISE



CROSSTALK	Coupling	Possible solution
	capacitive	Shielded cables
	inductive	Twisted cables

An EMC problem for electronic circuit: signal integrity

- **Quality and timing of the received signal**

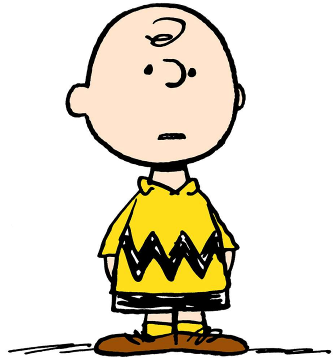


Problems	Classical solutions	Impact on design
• Delay	→ shorten lengths or insert repeaters	→ layout level (architecture)
• Reflections	→ matching loads	→ component level (materials)
• Losses	→ signal amplification	→ component level (materials)
• Skin-effect	→ reduced cross-section	→ component level (materials)
• crosstalk	→ wide separation, shielding, twisting	→ layout level (architecture)

Classical EMC concepts

Current trends and challenges for nanoscale circuits

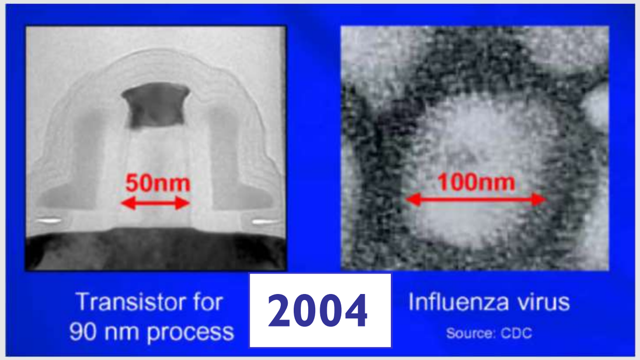
- **Miniaturization**
- **New fabrication concepts**
- **New materials**
- **New architectures and management**
- **New operating conditions**

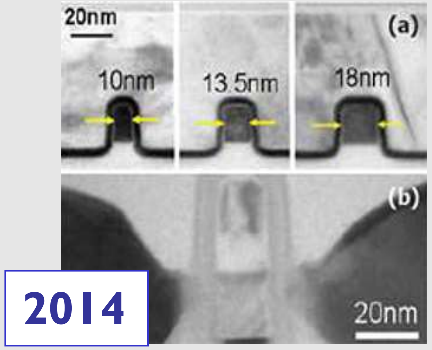


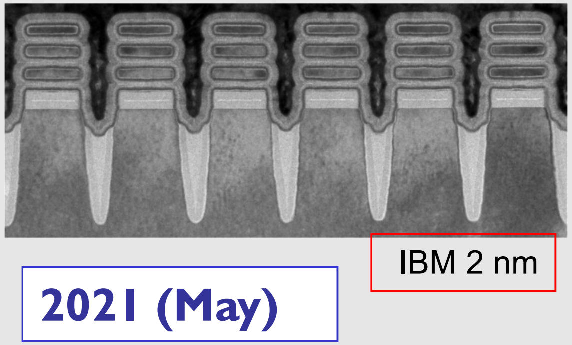
Novel EMC concepts at nanoscale

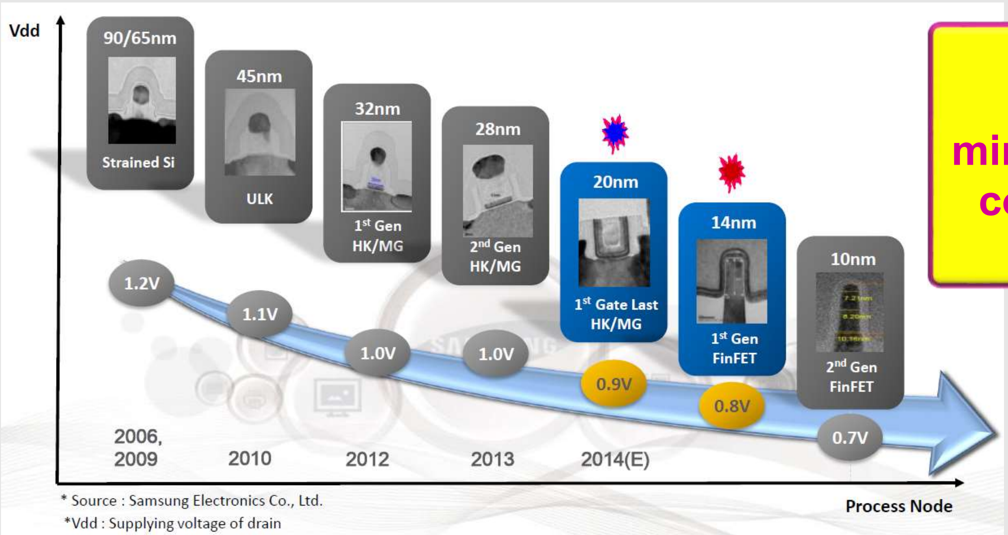
Carbon-based materials to enable nanoelectronics

Current trends - miniaturization (example: transistors)









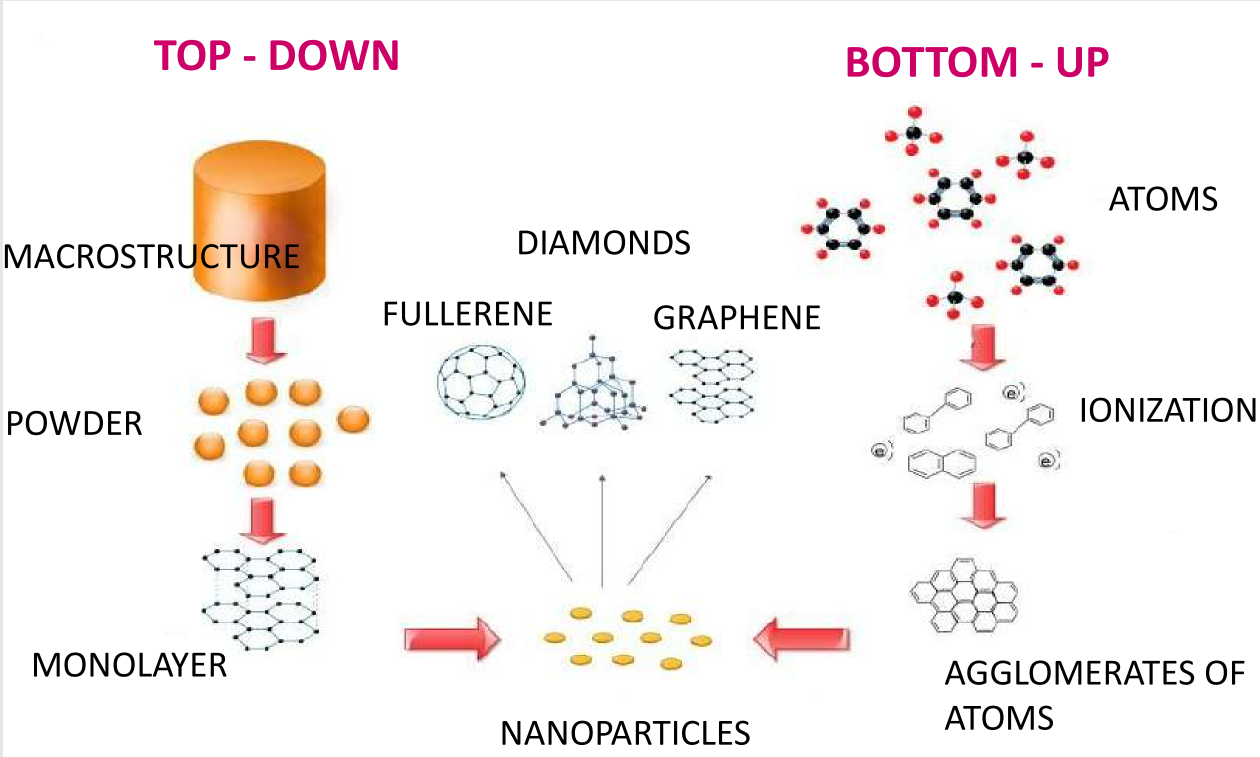
Transistor roadmap: miniaturization and power consumption reduction

Source: SAMSUNG LTD

Current trends - new fabrication concepts (example: bottom-up)

End of the road for top-down approaches?

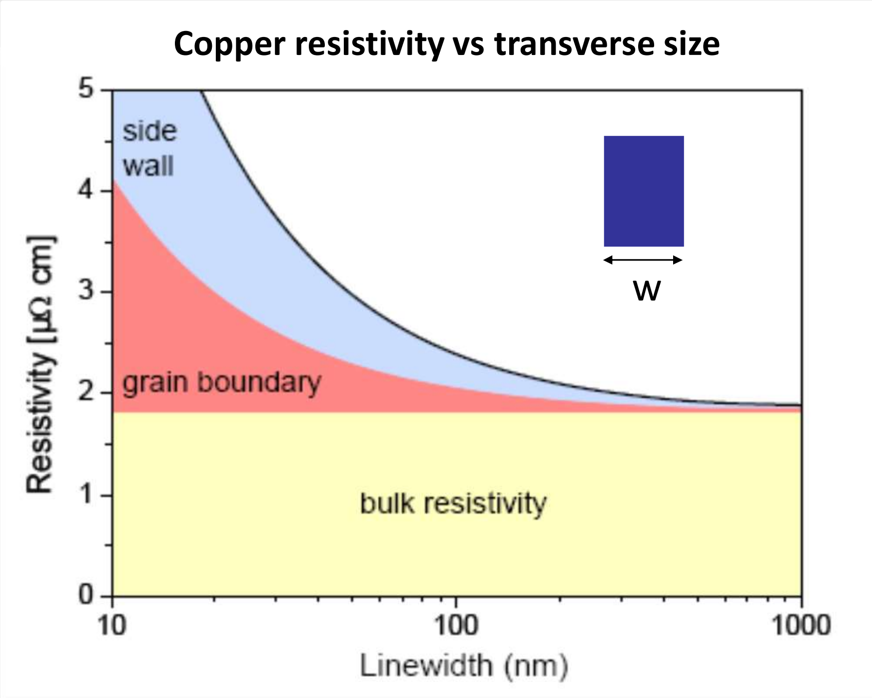
MICRO-
ELECTRONICS



NANO-
ELECTRONICS

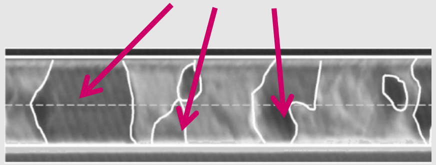
Current trends: re-think conventional materials (example: copper)

End of the road for conventional copper conductors?



Transverse dimensions comparable to grain size:

grains



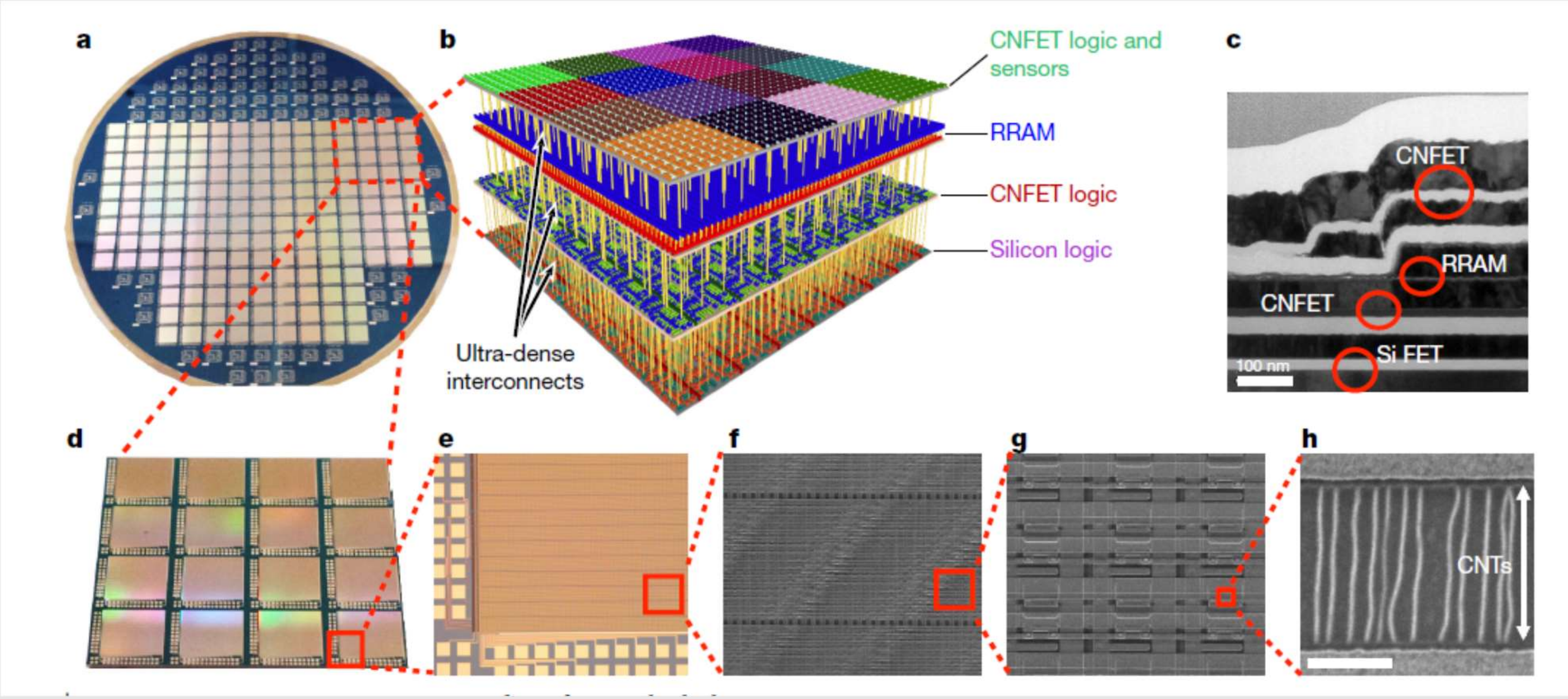
Steep increase of resistivity, due to :

- *barrier scattering*
- *grain boundary scattering*
- *finite barrier layer thickness*

Conventional materials are inadequate: looking for innovative conducting and dielectric materials!

Current trends - novel architectures (example: 3D integration)

Monolithically integrated layers



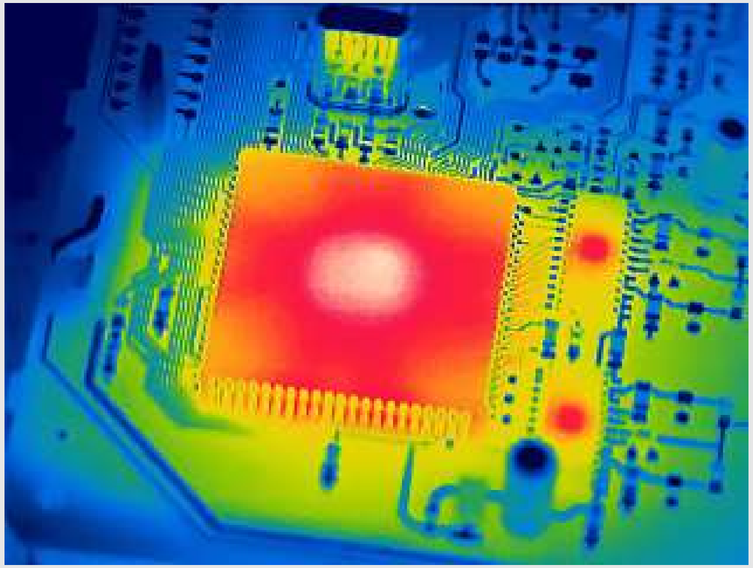
M. M. Shulaker, et al,. Nature, Jul. 2017

Current trends: power and thermal management

Interconnects for ultrascaled technology nodes are required to carry on **current densities** of the order of **MA/cm^2**, leading to a volumetric **heat production** of the order of **10^3-10^4 W/mm**

MAIN ISSUES:

- **Limited performance**: operating frequency must be lowered to reduce heat production
- **Limited capability:** heat introduces electromigration and limits the amount of current carrying capacity to ensure reliability (e.g. for Copper, maximum current density is **10^7 A/cm^2**)



Current trends - new frequency ranges (example: THz)

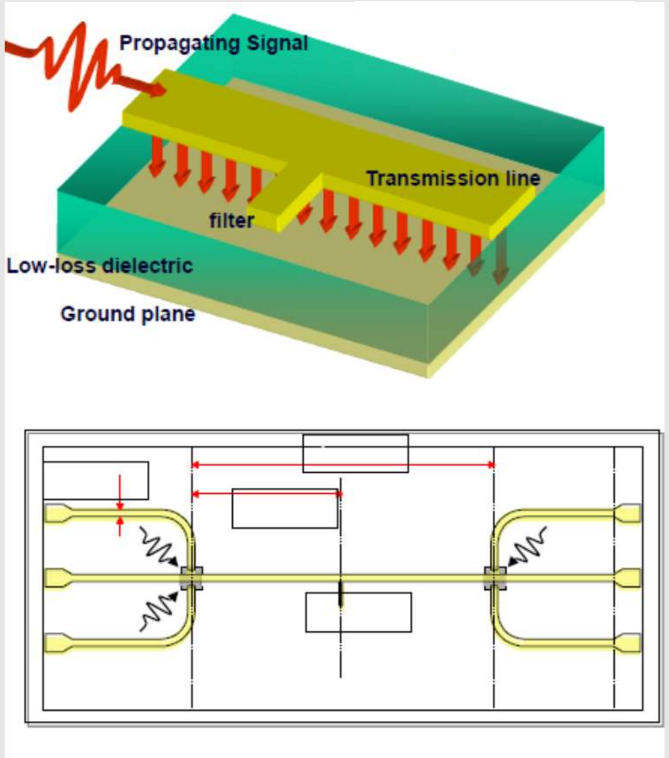
ADVANTAGES

- Small sample volume
- Simplified preparation
- Low cost

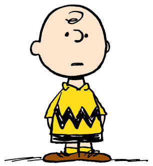
CHALLENGES

- Power Sources
- Detectors
- Interconnects

THz circuit modules realized with conventional materials result in **too large dimensions**, hard suitable for compact low-cost THz systems.



Classical EMC concepts



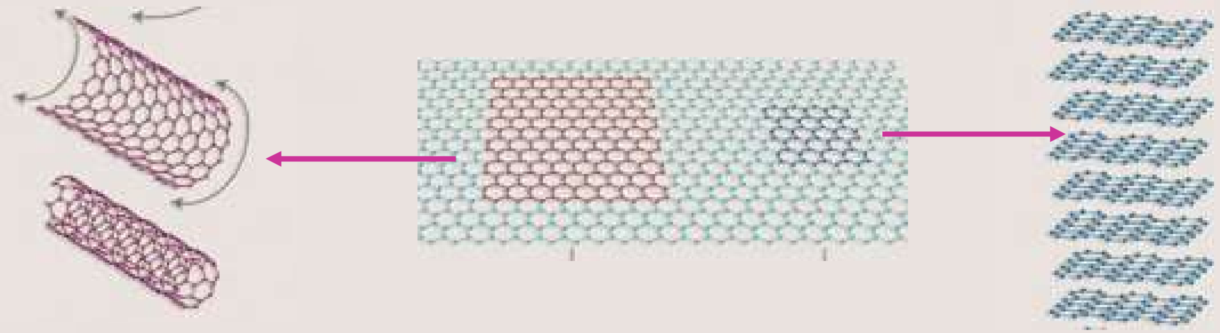
Current trends and challenges for nanoscale circuits

Novel EMC concepts at nanoscale

Carbon-based materials to enable nanoelectronics

- **New materials and new applications**
- **Modelling nanoscale circuits**
- **«Generalized» equivalent electrical parameters**

Carbon based materials for enabling nanoelectronics: CNT and GNRs

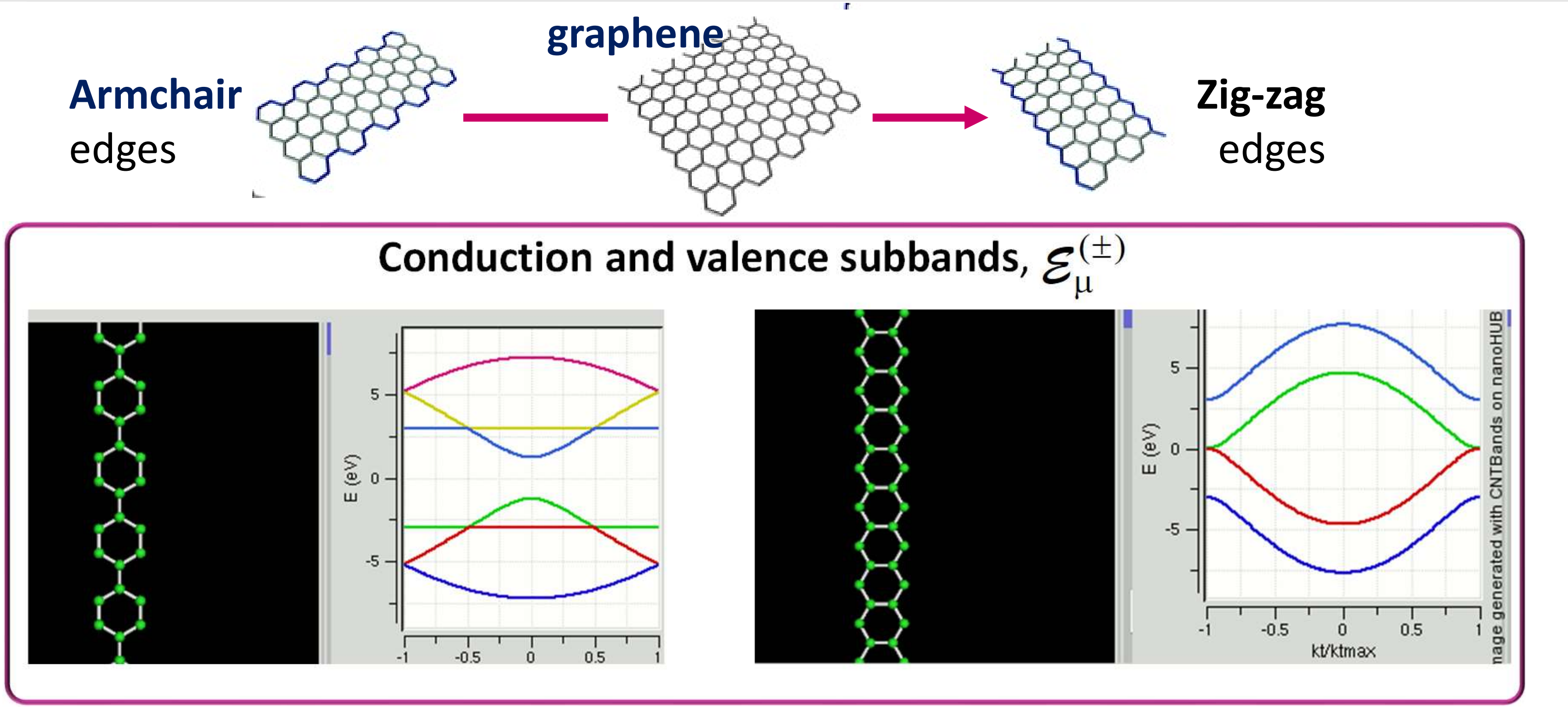


Carbon nanotubes (CNT) | graphene sheet (2D carbon) | Graphene Nanoribbons (GNR)

	Cu	CNT	GNR
Max current density [A/cm^2]	10^7	> 10^9	>10^8
Thermal conductivity [kW/mK]	0.38	1.7 ÷ 5.8	3.0 ÷ 5.0
Mean free path at 20 °C [nm]	40	$10^3 \div 25\text{x}10^3$	~ 10^3
Temperature coefficient of the resistance [10^{-3}K^{-1}]	3.7	-1.37 ÷ 1.1	- 1.47
Tensile strength [GPa]	0.22	11 ÷ 63	---

Graphene nanoribbon electronic band structure (π-electrons)

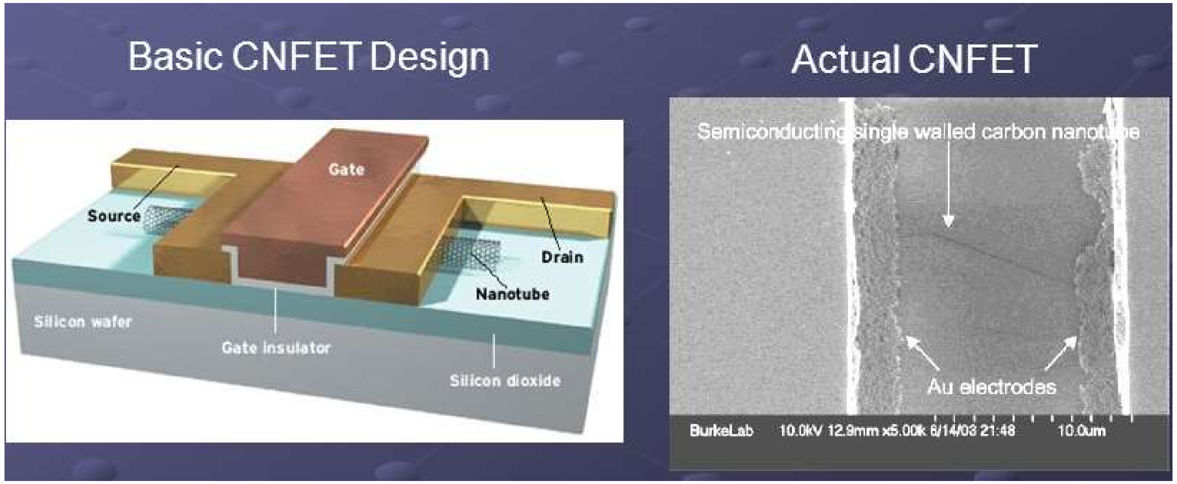
Depending on its chirality (hence, on the way it is cut), the GNR may be either **metallic** or **semiconducting.**
The same happens for **CNTs.**



Source: www.nanoHUB.org

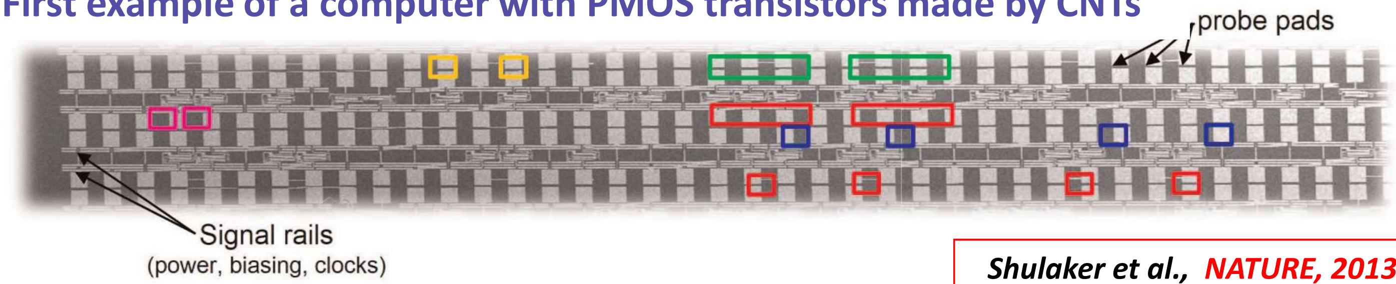
Carbon-based transistors and computers

CNFET: a carbon nanotube Field Effect Transistor



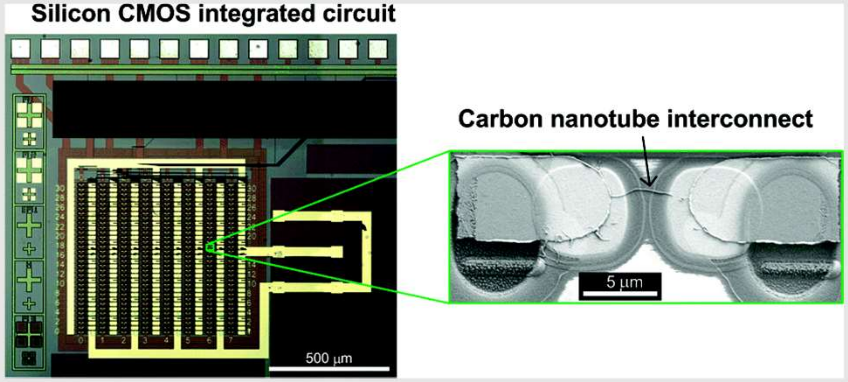
BURKE Lab, 2005

First example of a computer with PMOS transistors made by CNTs



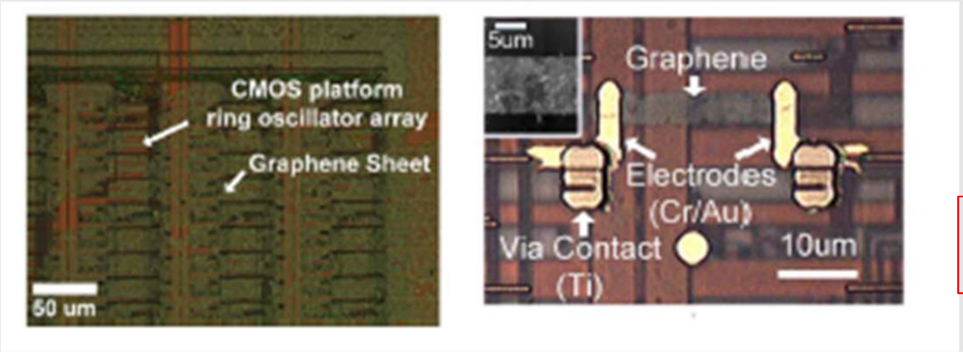
Shulaker et al., NATURE, 2013

Integrated circuits with CNT or graphene interconnects



A 1GHz IC with CNT bundle interconnects wiring CMOS

H.-S. Philip Wong et al.
Nano Letters 2008

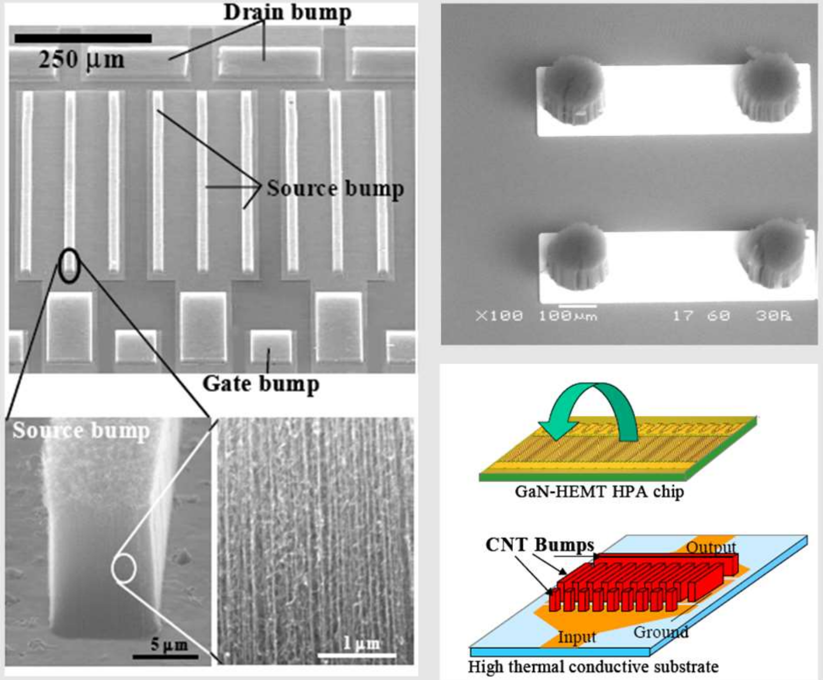


CMOS ring oscillator with GNR interconnects

H.-S. Philip Wong et al.
IEEE T- Electr. Devices 2010

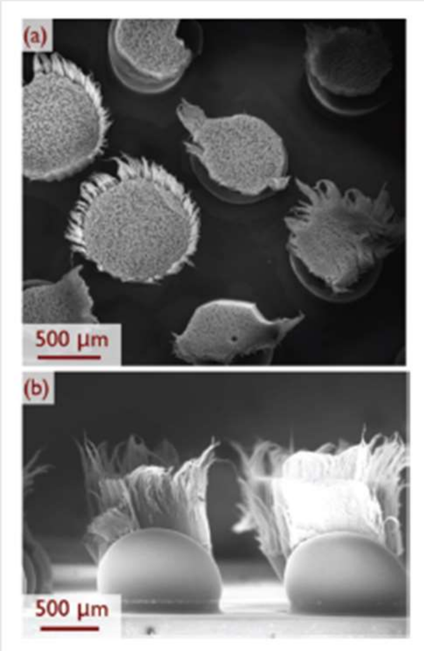
CNT and graphene for electronic packaging

CNT pillar bumps for flip-chip high power amplifier



Soga et al.
Proc. ECTC, 2008

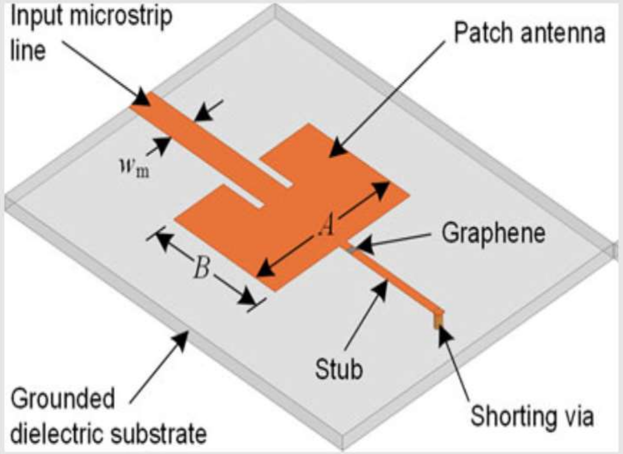
CNT bumps extracted by BGA

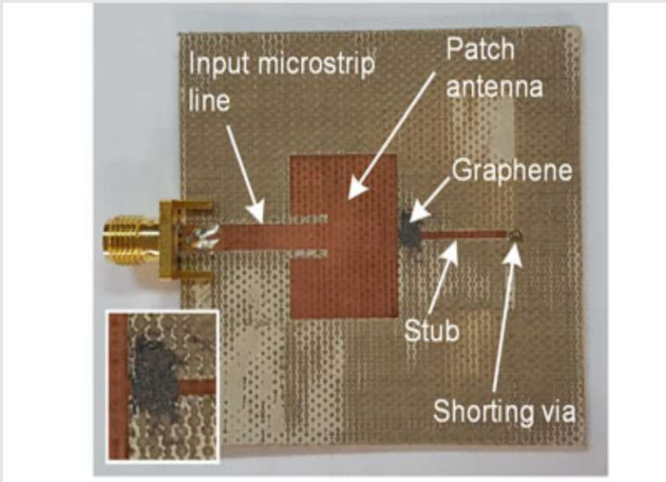


C. P. Wong et al.
Proc. ECTC, 2009

CNT and graphene for antennas

Tunable patch antenna with a graphene flakes film embedded





Yasir, Bellucci, et al.,
IEEE Antennas and Wireless Propagation Letters, 2017

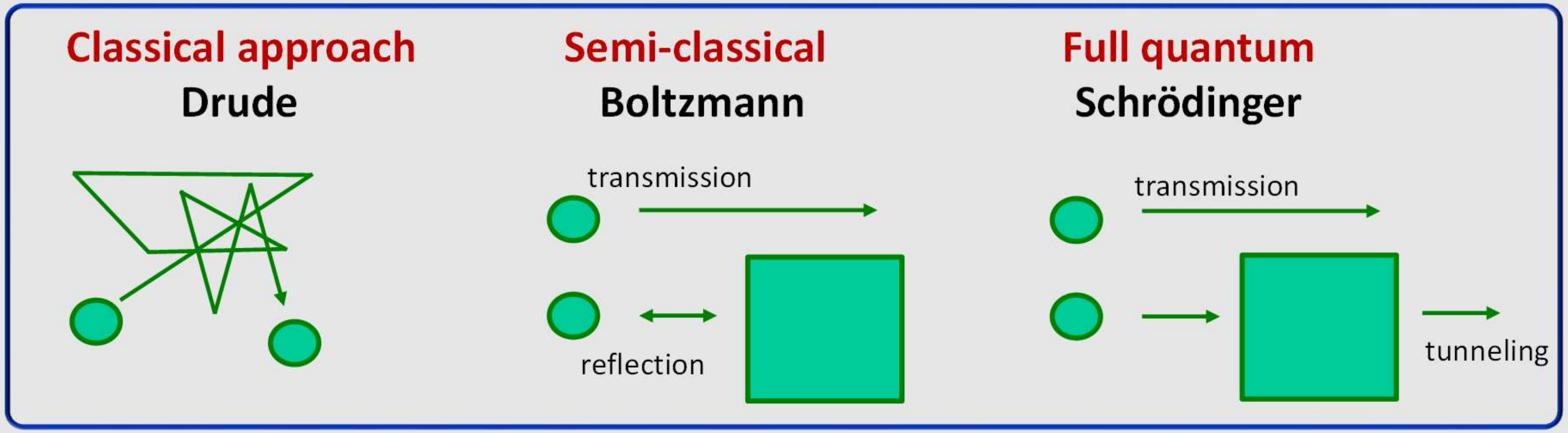
Integrating graphene into electronics: currently only prototypes

Requirements for a mass production process

GOAL	STATUS
Low cost	The use of graphene or CNTs will be costly. Low cost solutions like GNPs are investigated
Reliable	Controlling the quality is an issue (defects, impurities, density, edges, contacts)
High yield and monolithic integration	Not possible at the moment. Techniques with high yield (e.g., CVD) requires growth conditions not compatible with CMOS technology

Mass production of carbon-based nanoelectronics is still far away!

Modeling the electrodynamics of the conduction electrons



Macroscopic scale | **Nanoscale** | **Atomic scale**

Electrical transport at macroscopic scale: Drude model

Applying an external electrical field (DC)

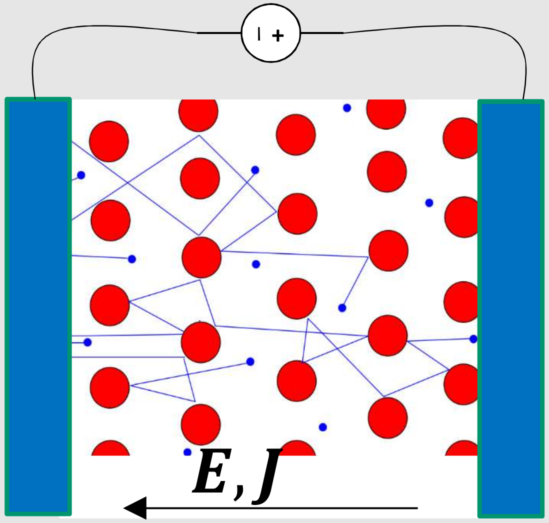
- $\boldsymbol{F}_E = -e\boldsymbol{E}$: force acting on the electrons
- $\boldsymbol{J} = -en\boldsymbol{v}_D$: density of electrical current
- $\boldsymbol{v}_D$: drift velocity (collective velocity)
- $\boldsymbol{F}_v = -m_e\boldsymbol{v}_D/\tau$: viscous friction due to collisions

Ohm's law (DC):

- $\boldsymbol{F}_E + \boldsymbol{F}_v = 0 \;\rightarrow\; \boldsymbol{E} = \frac{m_e}{e^2 n\tau}\boldsymbol{J} = \rho\boldsymbol{J}$

electrical resistivity or conductivity

$\rho = \frac{m_e}{e^2 n\tau} \qquad \sigma = \frac{e^2 n\tau}{m_e} \qquad (\boldsymbol{J} = \sigma\boldsymbol{E})$



Applying an external electrical field (AC)

- $\boldsymbol{E} = Ee^{i\omega t}$ harmonic field

Dynamic equation:

- $\boldsymbol{F}_E + \boldsymbol{F}_v = m_e\frac{d\boldsymbol{v}_D}{dt}$
- $-eE - \frac{m_e\boldsymbol{v}_D}{\tau} = i\omega m_e\boldsymbol{v}_D$
- $-eE = \frac{m_e\boldsymbol{v}_D}{\tau}(1 + i\omega\tau)$

Generalized Ohm's law (AC)

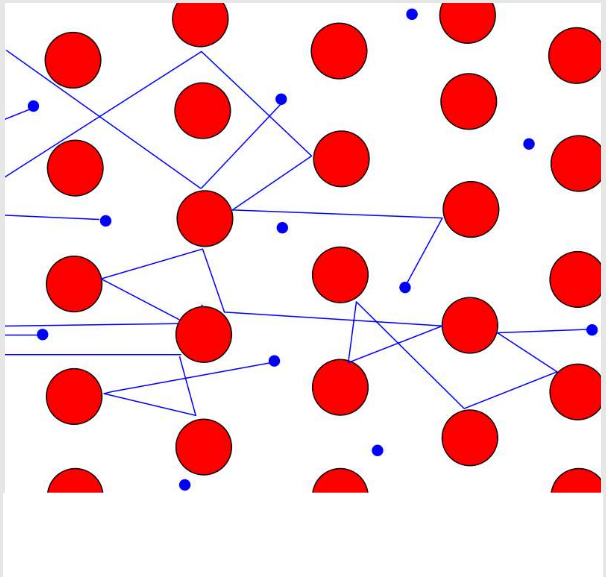
- $\boldsymbol{E} = \rho(\omega)\boldsymbol{J},\;\; with\;\; \rho(\omega) = \rho_0(1 + i\omega\tau) \qquad \rho_0 = \rho_{DC} = \frac{m_e}{e^2 n\tau}$
- $\boldsymbol{J} = \sigma(\omega)\boldsymbol{E} \quad with\; \sigma(\omega) = \frac{\sigma_0}{(1+i\omega\tau)} \qquad \sigma_0 = \sigma_{DC} = \frac{e^2 n\tau}{m_e}$

Electrical transport at atomic scale: Schrödinger model

The electrons are associated to waves, characterized by a wavefunction $\Psi(r,t)$ which describes the probability of the states

Schrödinger equation:

$$i\hbar\frac{\partial\Psi(\boldsymbol{r},t)}{\partial t}=\hat{H}\Psi(\boldsymbol{r},t)$$



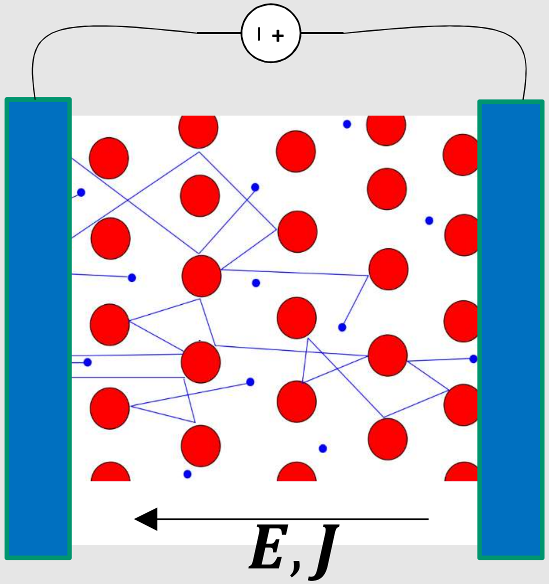
The transport is governed by the solution of the above equation under the given condition.

The macroscopic quantities (e.g., velocity, energy, momentum) are averaged values of the so-called observable quantities

Electrical transport at nanoscale: Boltzmann semi-classical model

Three components of the electric field:

- **atomic** ($\boldsymbol{E}_{at}$) generated by ions and valence electrons
- **collective** ($\boldsymbol{E}_{co}$) generated by free electrons
- **external** ($\boldsymbol{E}$), applied macroscopic electric field

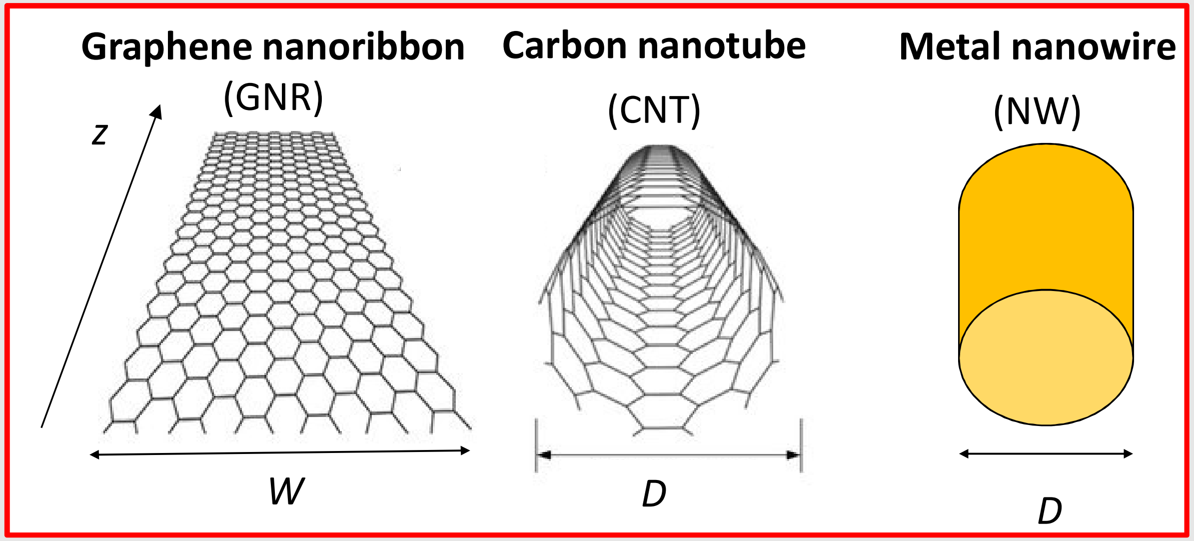


Assumptions:

- $|\boldsymbol{E} + \boldsymbol{E}_{co}| \ll |\boldsymbol{E}_{at}|$
- the free electrons behave as **quasi-classical particles**, hence they are unable to tunnel barriers
- These quasi-particles have **effective mass** and **velocity** that can be derived from the **energy dispersion relation**

$$m_{eff} = \left(\frac{1}{\hbar^2} \frac{d^2 E(k)}{dk^2} \right)^{-1} \qquad v_{eff} = \frac{1}{\hbar} \frac{dE(k)}{dk}$$

Electrical transport at nanoscale: Boltzmann semi-classical model



Assumptions for using the semi-classical approach:

- Transverse dimensions (*D*, *W*) below 100 nm
- Low bias conditions: $E_z < 0.54\, V/\mu m$
- Operating frequency below 100 THz

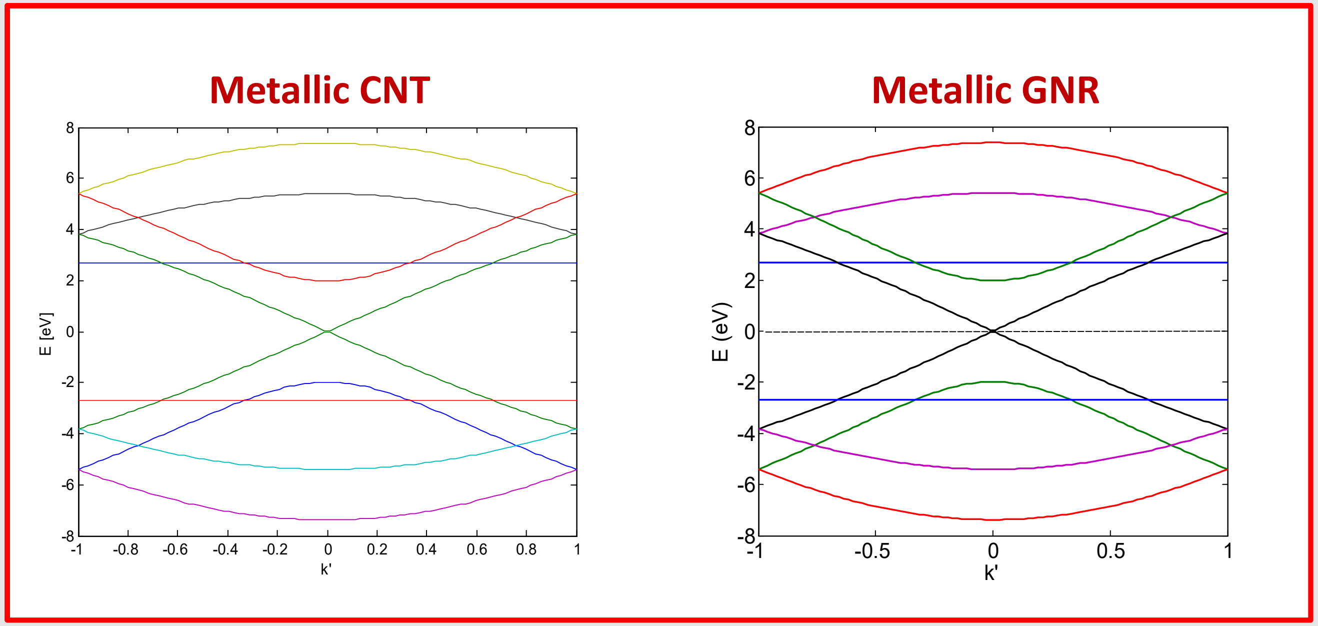
Electrical transport at nanoscale: Boltzmann semi-classical model

STEP 1: From the energy subbands *E*(*k*), evaluate effective mass and velocity

Example of subbands:

$E_{\mu}^{\pm}(k)$

$\mu = 1 \ldots . N$
+ = conduction
- = valence



For each subband

effective velocity: $v_{\mu}^{\pm} = \dfrac{1}{\hbar}\dfrac{dE_{\mu}^{\pm}(k)}{dk}$ *effective mass:* $m_{eff}^{\pm} = \left(\dfrac{1}{\hbar^2}\dfrac{d^2E_{\mu}^{\pm}(k)}{dk^2}\right)^{-1}$

Electrical transport at nanoscale: Boltzmann semi-classical model

STEP 2: In each subband the transport is modeled by the Boltzmann equation

$$\frac{\partial f_\mu^{(\pm)}}{\partial t} + v_\mu^{(\pm)} \frac{\partial f_\mu^{(\pm)}}{\partial z} + \frac{e}{\hbar} E_z \frac{\partial f_\mu^{(\pm)}}{\partial k} = -\nu\left(f_\mu^{(\pm)} - f_{0,\mu}^{(\pm)}\right)$$

distribution function

Longitudinal component of the external electric field

collision term (a small perturbation)

$f_\mu^{\pm}(k)$ function describing the distribution of the electrons in the subband

$f_{0,\mu}^{\pm}(k) = F\left[E_\mu^{\pm}(k)\right]/X$ distribution function at equilibrium $X = \begin{cases} \pi D & CNT \\ \pi W & GNR \\ \pi (D/2)^2 & NW \end{cases}$

$$F[E] = \frac{1}{e^{E/k_B T} + 1}$$ Dirac-Fermi function

Electrical transport at nanoscale: Boltzmann semi-classical model

STEP 3: write the equation in frequency domain and sum over all the *N* subbands

$$\hat{J}_z(k,\omega) = \frac{\sigma_0}{1+i\omega\tau}\frac{1}{1-\psi(\omega)k^2}\hat{E}_z(k,\omega)$$

Generalised dispersive OHM's Law

Parameters

$$\sigma_0 = \frac{2v_F M}{\upsilon R_0 X} \qquad \psi(\omega) = \frac{\alpha(\omega)v_F^2}{\upsilon^2(1+i\omega\tau)^2}$$

v_F Fermi velocity

$R_0 = 12.9\mathrm{k}\Omega$ Quantum resistance

M Equivalent number of conducting channels

$\upsilon = \frac{1}{\tau} = \frac{v_F}{l_{mfp}}$ Collision frequency

Materials

$$X = \begin{cases} \pi D & CNT \\ \pi W & GNR \\ \pi(D/2)^2 & NW \end{cases}$$

$$\alpha(\omega) = \begin{cases} 1 & CNT \\ \frac{1}{3}\frac{1+1.8i\omega\tau}{1+i\omega\tau} & NW \end{cases}$$

$\alpha(\omega)$ Numerically computed for GNR

For CNTs:

G. Miano, C. Forestiere, A. Maffucci, S.A. Maksimenko, G. Y. Slepyan, IEEE Trans. on Nanotechnology 2011

A. Todri-Sanial, J. Dijon, A. Maffucci Carbon Nanotubes for Interconnects: Process, Design and Applications, Springer, 2016.

For GNRs and NW:

C. Forestiere, A. Maffucci, G. Miano, IEEE Trans. CPMT, 2013.

Electrical transport at nanoscale: Boltzmann semi-classical model

Ohm's law in frequency and wavenumber domain:

$$\hat{J}_z(k,\omega) = \frac{\sigma_0}{1+i\omega\tau}\,\frac{1}{1-\psi(\omega)k^2}\,\hat{E}_z(k,\omega)$$

Time dispersion

negligible for $\omega\tau \ll 1$ (low frequency)

Spatial and time dispersion

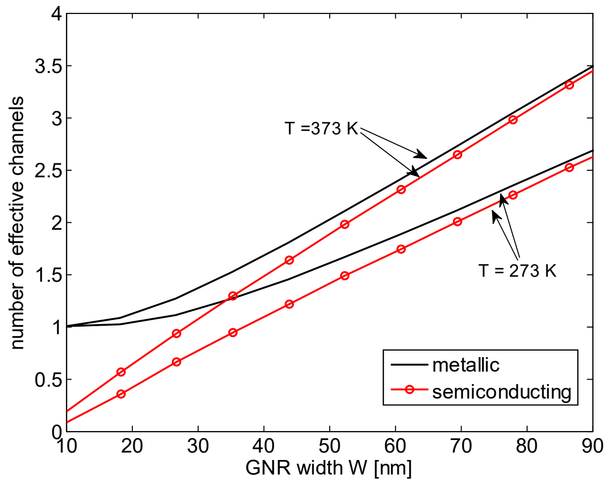
negligible for $\psi(\omega)k^2 \ll 1$ (low spatial frequency)

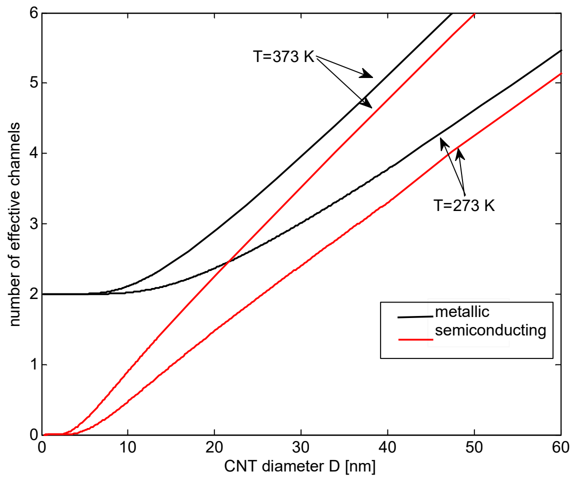
Ohm's law in frequency domain:

$$J_z(\omega) = \frac{\sigma_0}{1+i\omega\tau} E_z(k,\omega) \quad \text{for } \psi(\omega)k^2 \ll 1$$

$$J_z(\omega) = \sigma_0 E_z(k,\omega) \qquad \sigma_0 = \frac{2v_F M}{\upsilon R_0 X}$$

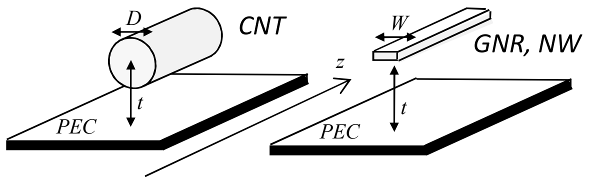
for $\omega\tau \ll 1$ *low frequency and spatial frequency*



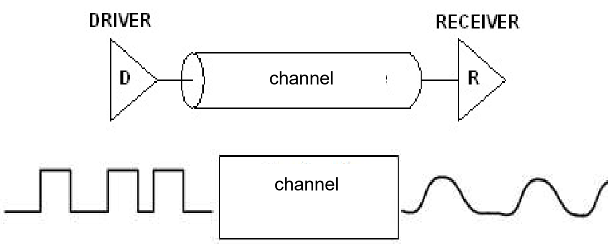


A key-parameter: effective number of conducting channels

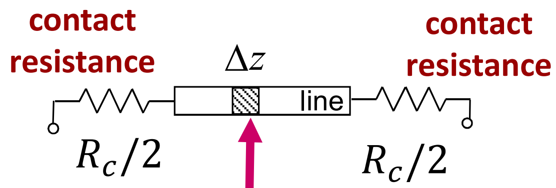
Equivalent circuit for a nano-interconnect



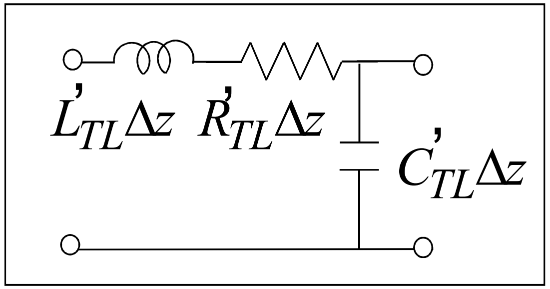
Nano-interconnect
as a «**channel**»



Maxwell equations
+
generalized Ohm law



Distributed element: **RLC cell**



Equivalent circuit for a nano-interconnect

Transmission line equations

$$-\frac{\partial v(z,t)}{\partial z} = \left(R_{TL} + L_{TL} \frac{\partial}{\partial t} \right) i(z,t)$$

$$-\frac{\partial i(z,t)}{\partial z} = C_{TL} \frac{\partial}{\partial t} v(z,t)$$

$$R'_{TL} = \upsilon L'_k$$

$$L'_{TL} = L'_k + L'_m$$

$$(C'_{TL})^{-1} = (C'_e)^{-1} + (C'_q)^{-1}$$

$L'_k = \frac{R_0}{2v_F} \frac{1}{M}$ Kinetic inductance

$C'_q = \frac{2}{R_0 v_F} M$ Quantum capacitance

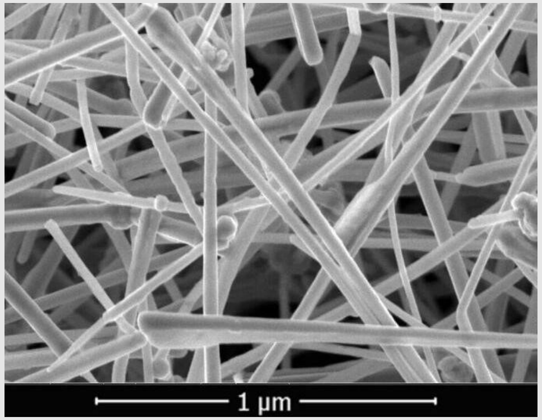
C'_e Electrostatic capacitance

L'_m Magnetic inductance

Classical parameters are "corrected" by quantum ones

Consistency with macroscale circuit model: example of a Cu nanowire

Number of conducting channels M (T = 273 K)			
Size	**Cu – NW**	**Metallic CNT**	**Metallic GNR**
14 nm	808	2.15	1
1 nm	3.12	2	1



Ex.: copper wire (bulk 3D interconnect)

D=200nm $\quad M \approx 3.1 \cdot 10^5 \quad \sigma_0 \approx 6 \cdot 10^7$ S/m

$$L'_k \ll L'_m, \quad C'_q \gg C'_e \longrightarrow L'_{TL} \approx L'_m, \quad C'_{TL} \approx C'_e$$

$$R'_{TL} = \frac{1}{\sigma_0 X}, \quad L_{TL} = L_m, \quad C_{TL} = C_e,$$

The **general model for nanowire** reduces to the **classical model for bulk 3D structures** for large values of M

Classical EMC concepts

Current trends and challenges for nanoscale circuit

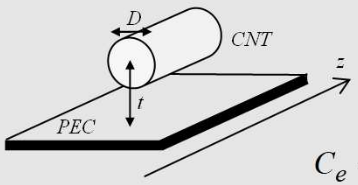
Novel EMC concepts at nanoscale

- **Electronic circuits**
- **Electromagnetic systems**
- **Quantum circuits**

Carbon-based materials to enable nanoelectronics

EMC issue on signals: the propagation delay

Example: a CNT line



$D = 5.4$ nm
$t = 20$ nm

$$C_e = 2\pi\varepsilon\left[\ln\left(\frac{2t}{D}\right)\right]^{-1}$$

$$L_m = \frac{\mu}{2\pi}\ln\left(\frac{2t}{D}\right)$$

Propagation Velocity	
v_{CNT} [m/s]	v_0 [m/s]
~3·10^6	~3·10^8

P.u.l. inductance and capacitance			
L_m [µH/m]	L_k [mH/m]	C_e [pF/m]	C_q [pF/m]
0.4	3.6	0.5	27.7

Typical conditions

$$C_e << C_Q, \quad L_m << L_k \quad \Rightarrow L_{TL} \approx L_k, C_{TL} \approx C_e$$

inductance **dominated** by the kinetic term

low propagation velocity, large delay

$$v_{ph} \approx \frac{1}{\sqrt{L_k C_e}} \qquad T = l / v_{ph}$$

This worsen the signal timing and shorten the useful lengths

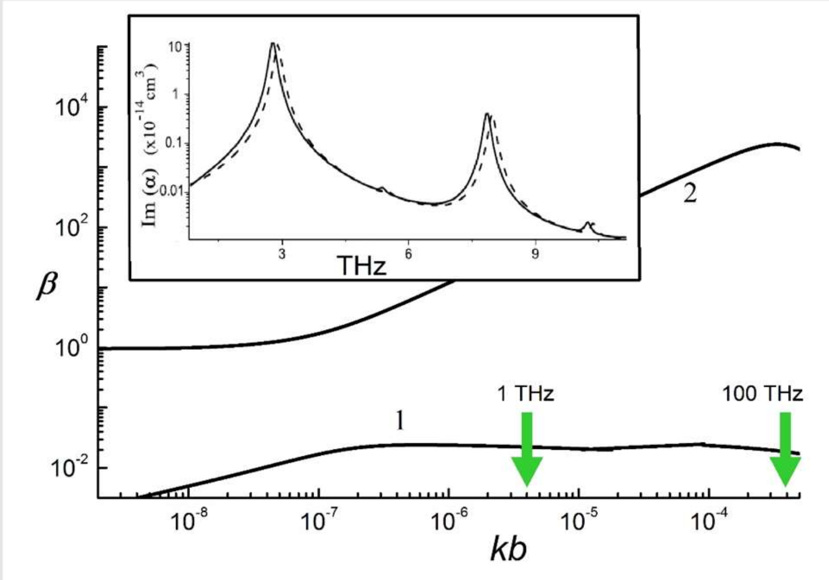
Slow wave and antenna resonances in the THz range

Smaller electrical length:

$$v \approx \left(\sqrt{L_k C_e}\right)^{-1} \rightarrow \lambda = v / f$$

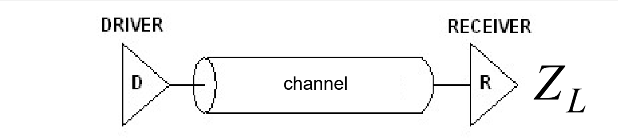
Resonance frequency modulated by the CNT **length**.

Favourable behavior in the THz range: antenna resonances



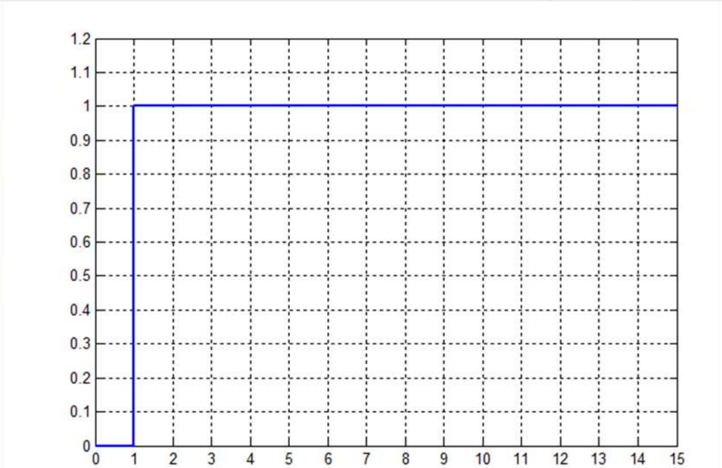
G. Slepyan, M. Shuba, S. Maksimenko, A Lakhtakia
PRB 2006, 2012

EMC issue on signals: mismatching

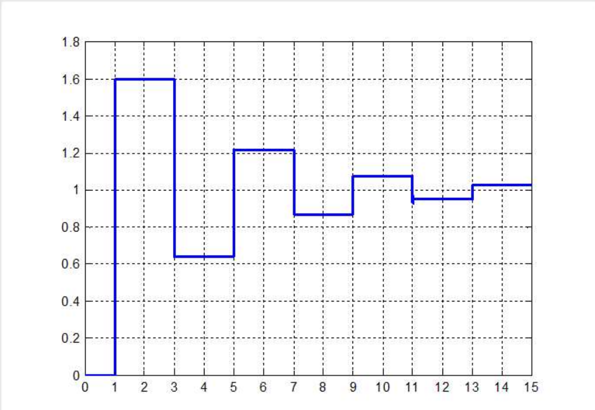


characteristic impedance $$Z_C(\omega)=\sqrt{\frac{R_{TL}+i\omega L_{TL}}{i\omega C_{TL}}}$$

matching condition $Z_L = Z_c$

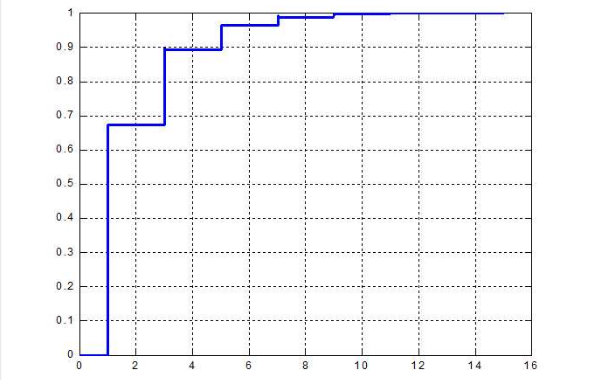


mismatch



overvoltages

$Z_L > Z_c$



undervoltages

$Z_L < Z_c$

A novel concept of matching at nanoscale: broadband matching

Classical condition

$$Z_L = Z_0 \qquad Z_0 = \lim_{R\to 0}\left[Z_C(\omega)\right] = \sqrt{\frac{L_{TL}}{C_{TL}}}$$

A **broadband matching is impossible**, since Z_C is frequency-dependent.
An approximated condition is imposed on the lossless case, Z_0

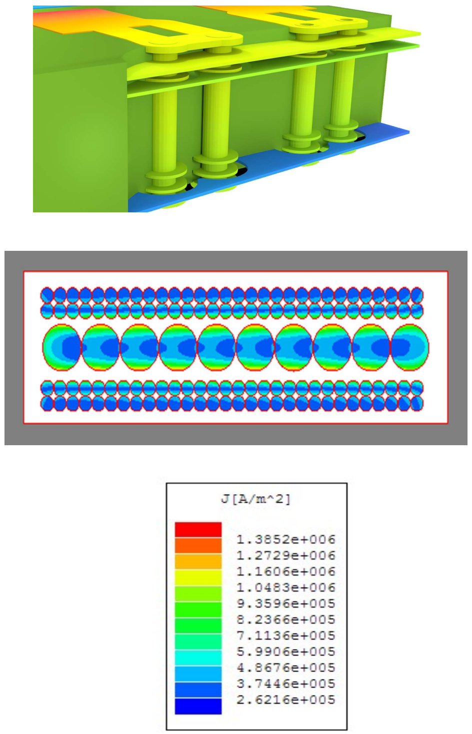
Nanoscale condition

$$Z_C(\omega) = \sqrt{\frac{R_{TL} + i\omega L_{TL}}{i\omega C_{TL}}} \approx \sqrt{\frac{(\nu + i\omega)L_k}{i\omega C_{TL}}} \approx \sqrt{\frac{L_k}{C_{TL}}} \quad \omega >> \nu$$

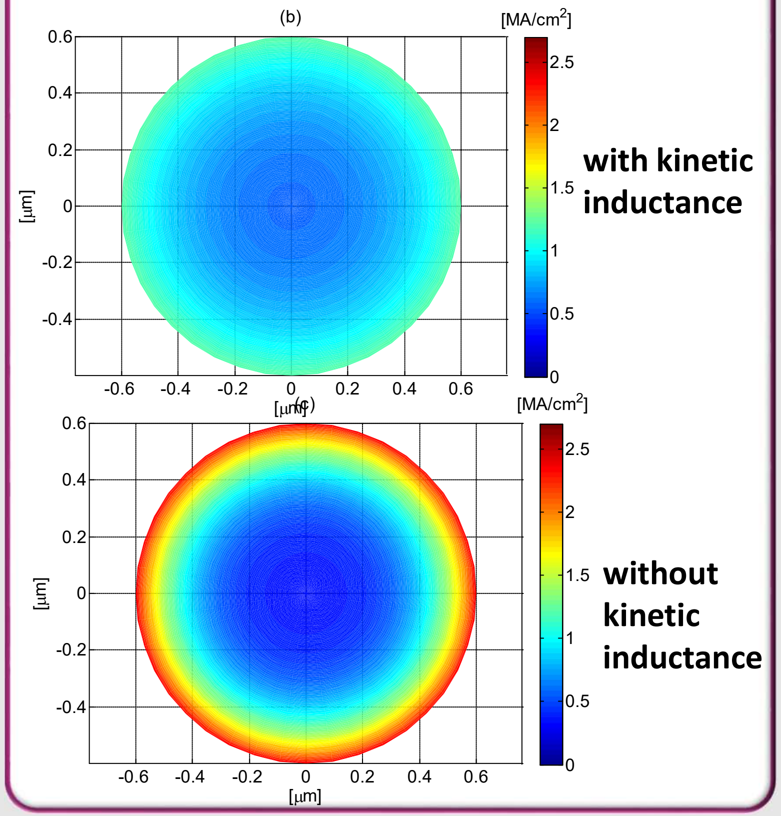
A **broadband matching is possible**, since Z_C becomes a constant at high-frequency

EMC issues on signals: Skin effect and proximity effect

Current density in a conventional via array

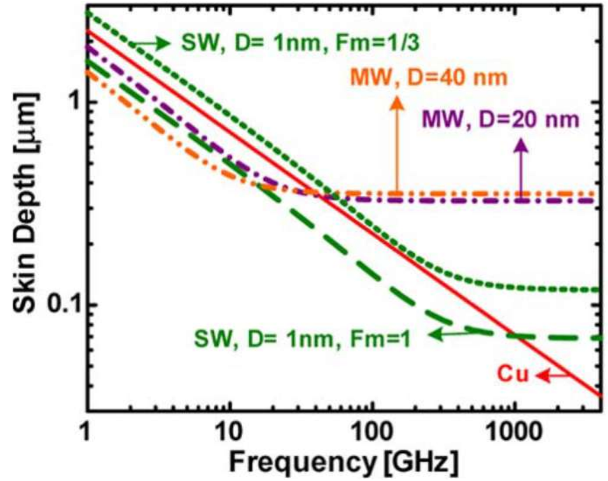


Current density in a via made by a bundle of MWCNTs



Skin depth model

$$\delta = \sqrt{\frac{2}{\sigma_0 \omega \mu}} \sqrt{\left[\left(\frac{\omega}{\nu}\right)^2 + 1\right]\left(\sqrt{\left(\frac{\omega}{\nu}\right)^2 + 1} - \frac{\omega}{\nu}\right)}.$$

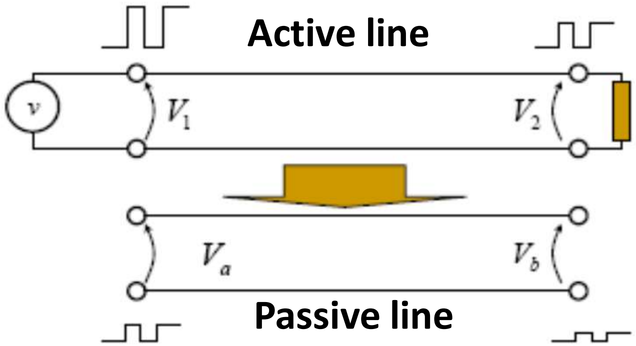


K. Banerjee, IEEE, TED, 2009.

Poor sensitivity to skin effect due to the dominance of kinetic inductance

EMC issues on signals: crosstalk noise (far-field coupling)

EM coupling between lines



Crosstalk noise:

Signals at the passive line ends

Classical solutions:

- **Shielding** (capacitive coupling)
- **Twisting** (inductive coupling)

Novel solution at nanoscale: crosstalk reduction via load impedance control

If the crosstalk is mainly **capacitive** (**inductive**) we can reduce it by using a **low** (**high**) impedance load, namely:

$$|Z_L| << |Z_c| \quad \left(|Z_L| >> |Z_c|\right)$$

$$Z_c \approx \sqrt{\frac{L_k}{C_e}} \quad (\omega >> \nu)$$

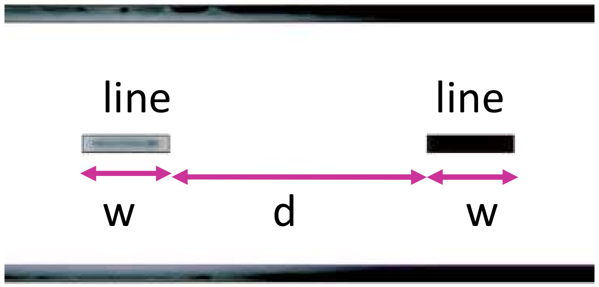
A frequency-independent characteristic impedance changes makes more promising this approach

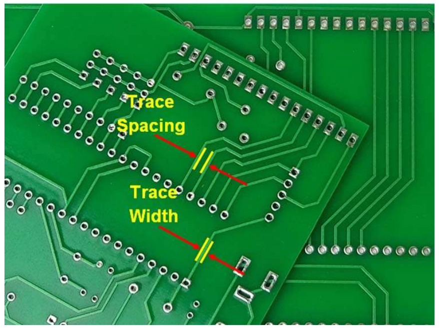
EMC issues on signals: crosstalk noise

Alternative classical solution to reduce crosstalk:

Separation rule: when shielding and twisting are not possible

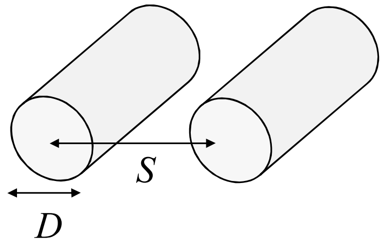
"3W spacing rule" *d=3w*





Crosstalk reduction via separation: new scaling rules at nanoscale

The design **scaling rules** change for the presence of quantum terms



macroscale

$$L_{TL} = L_m = \frac{\mu_0}{\pi} \ln\left(\frac{S}{D/2}\right)$$

$$C_{TL} = C_e = \pi\varepsilon \ln\left(\frac{D/2}{S}\right)^{-1}$$

nanoscale

$$L_{TL} = L_m + L_k$$

$$C_{TL} = \frac{C_e C_q}{C_e + C_q}$$

Other EMC issues at nanoscale

New emission mechanisms (EMI problems):

- **Spontaneous emission** by Plasmon resonances
- **Spontaneous emission** by tunable hot electrons
- **Spontaneous emission** by Rabi-Bloch waves

G.W. Hanson, IEEE T-AP, 2005

M. Portnoi et al., Nano Letters, 2007

G. Slepyan et al., Applied Sciences, 2017

Novel shielding concepts:

- **absorbing features of NANOCOMPOSITES**

P. Khuzhir al., J. Appl.Physics, 2016

Interaction with quantum circuits:

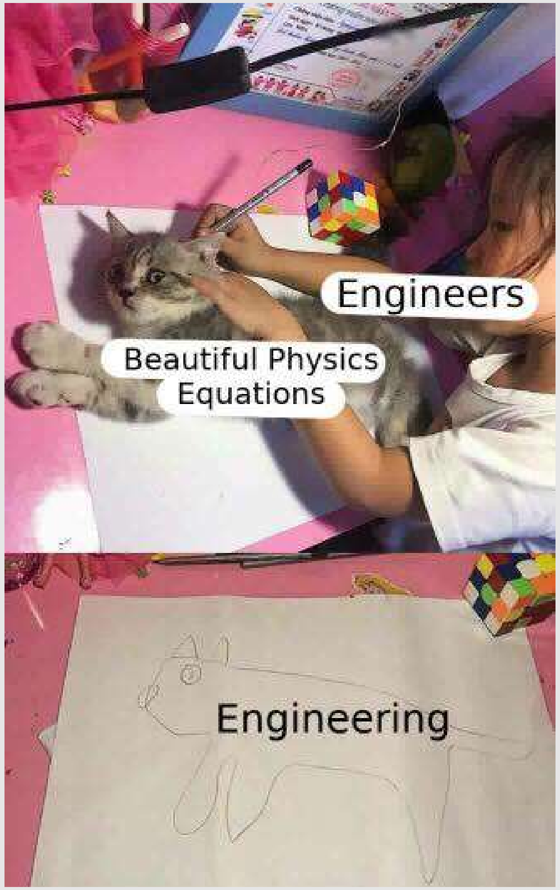
- **Novel crosstalk mechanism:** (e.g., via entanglement)
- **Novel concept of matching**

G. Slepyan, A. Maffucci, et al.
New Journal of Physics, 2017

G. Slepyan, P. Kuzhir,
S. Maksimenko, A Maffucci et al.
IEEE Trans. on EMC, Dec. 2015

Conclusions

- Nanoscale electronics systems are characterized by novel features, due to the quantum nature of the electrical transport
- At nanoscale **a semi-classical modelling approach is suitable**, leading to **generalized constitutive laws** for nanostructured materials. In the derived model, **the quantum effects appear as corrections terms** to classical electromagnetic ones
- EMC concepts and solution must be revisited in view of **new mechanisms** imposed by these quantum terms
- **Advantages in nanoscale EMC**: possibility of broadband matching, crosstalk reduction via load control, low sensitivity to skin effect, stability with temperature
- **Disadvantages in nanoscale EMC**: slow propagation (high delay), high losses, novel design scaling rules

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