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Signal Integrity Analysis of Carbon-Based On-chip Nano-Interconnects

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Outline

- Challenges for nano-interconnects
- Carbon-nanotubes and graphene nanoribbons
- Circuit models for CNT and GNTs interconnects
- Comparative study of electrical performance of on-chip interconnects
- Conclusions

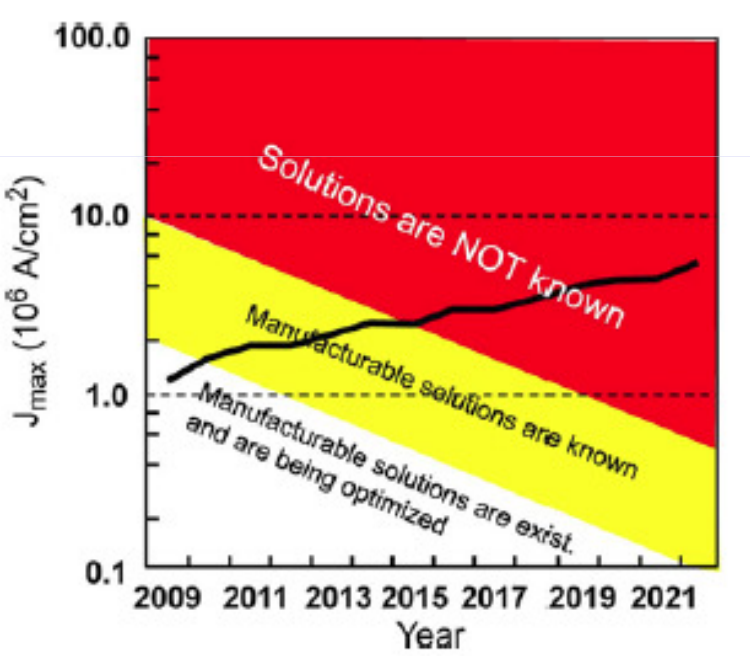
Projects & acknowledgments

- *Nano carbon based components and materials for high frequency electronics* (EU-FP7)
- *Systems of innovative electronic memories for ICT applications, characterized by high data storage capability and low power dissipation, with convergent architectures and micro and nano integration* (EU-PON)

End of the road for Cu interconnects?

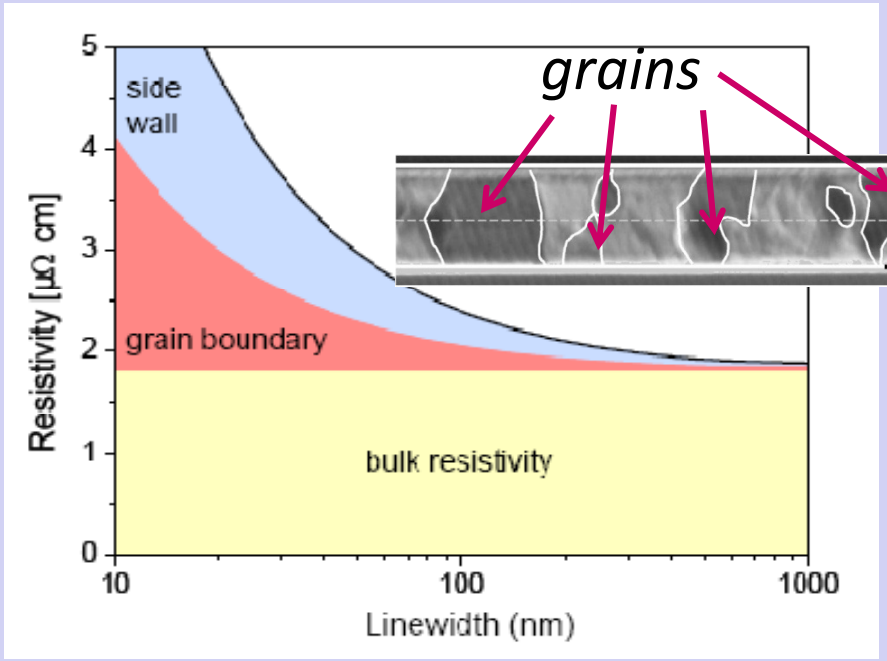
Two "electrical" problems for copper nano-interconnects:

Unadequate **current carrying capability** and **maximum allowed current density**



Y. Awano, et al., Proc. IEEE, 2010.

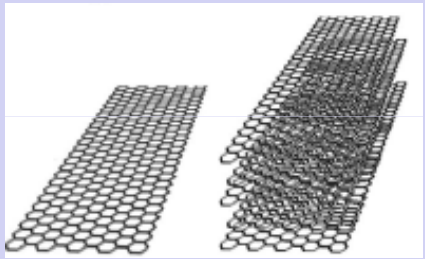
Steep increase of Cu resistivity, due to :
- barrier scattering, grain boundary scattering, finite barrier layer thickness

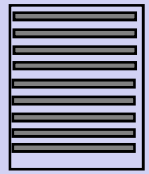


ITRS 2011 Edition

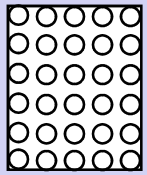
Carbon nanotubes and graphene nanoribbon interconnects

Traditional interconnect scaling will no longer satisfy performance requirements. Defining and finding solutions beyond copper and low κ will require ***material innovation****, combined with accelerated design, packaging and unconventional interconnects"* – **ITRS, 2011**

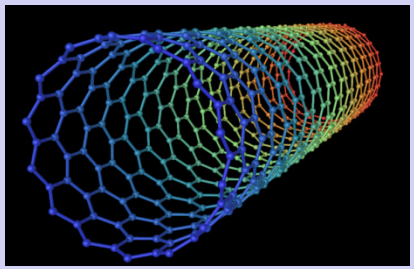




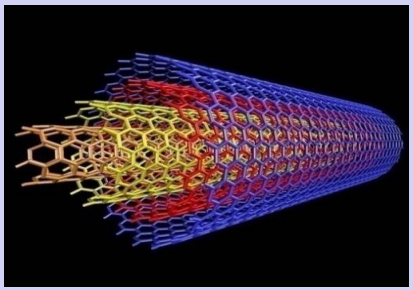
Multi-layer GNR



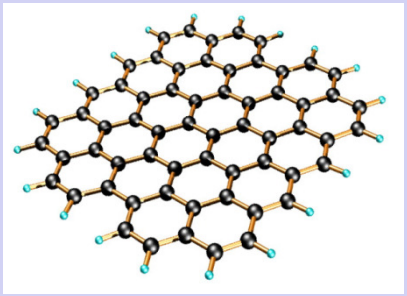
Bundle of CNTs



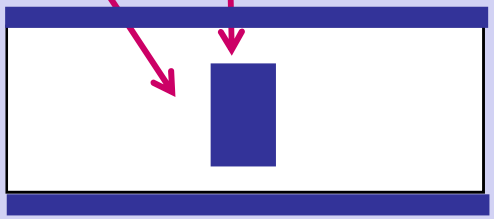
Single-wall CNT (**SWCNT)**
Av. diameter: **1-6 nm**



Multi-wall CNT (**MWCNT)**
Av. external diameter:
20-50 nm



Graphene Nanoribbons



Carbon nanotubes, graphene and copper properties

EXPERIMENTAL EVIDENCES

	Cu	SWCNT	MWCNT	Graphene or GNR
Max current density (A/cm^2)	10^7	$>10^9$	$>10^9$	$>10^8$
Melting point (K)	1356	3800		
Tensile strength (GPa)	0.22	22.2±2.2	11-63	
Thermal conductivity ($\times10^3$ W/m-K)	0.385	1.75-5.8	3	3-5
Temperature Coefficient of Resistance ($\times10^{-3}$/K)	4	<1.1	-1.37	-1.47
Mean free path (nm) @ room temperature	40	$>10^3$	2.5×10^4	1×10^3

higher current density

better heat removal

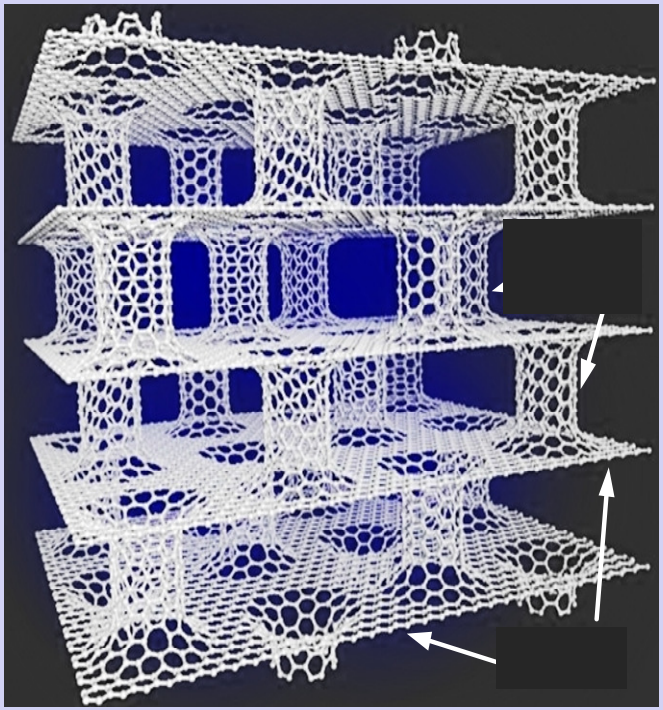
stability of resistance with temperature (TCR may be even <0)

Ballistic transport (zero resistance) for longer distances

CNT bundles vs multi-layer GNR

	CNT	GNR
Vertical interconnects	Easy	Not available
Horizontal interconnects	Difficult	Easy
Control of fabrication process	Easy	Difficult
Fabrication cost	High	Low
Sensitivity of electrical properties to fabrication process	Low	High

Hybrid CNT+graphene interconnecting structure..



D. Kondo, S. Sato, and Y. Awano,

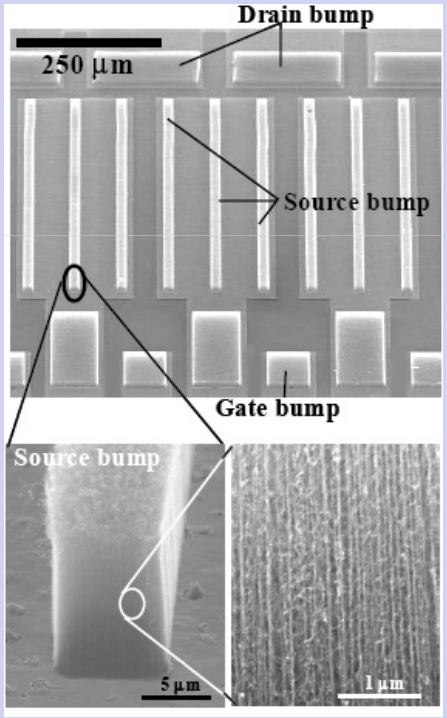
Self-Organization of Novel Carbon Composite Structure: Graphene Multilayers Combined Perpendicularly with Aligned Carbon Nanotubes

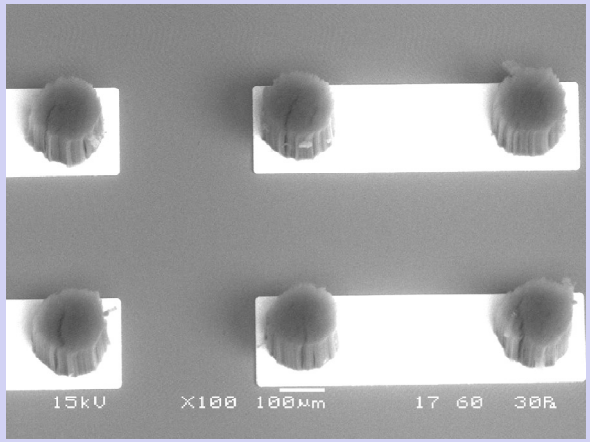
Applied Physics Express, 2008

Real-world examples of successful CMOS-CNT integration..

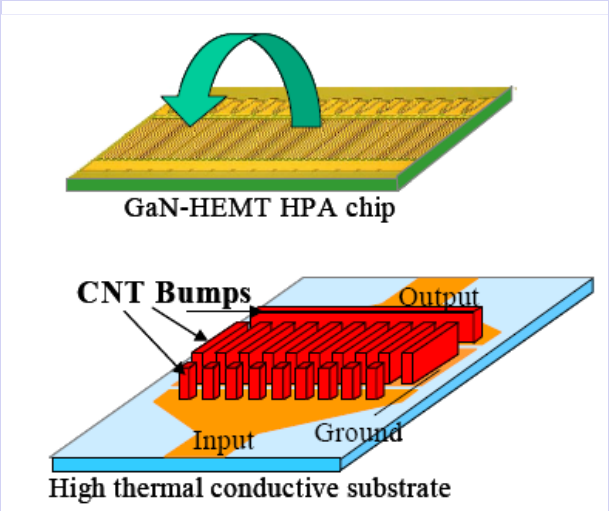
Pillars made by CNTs bundle

CNT pillar bumps for flip-chip high power amplifier





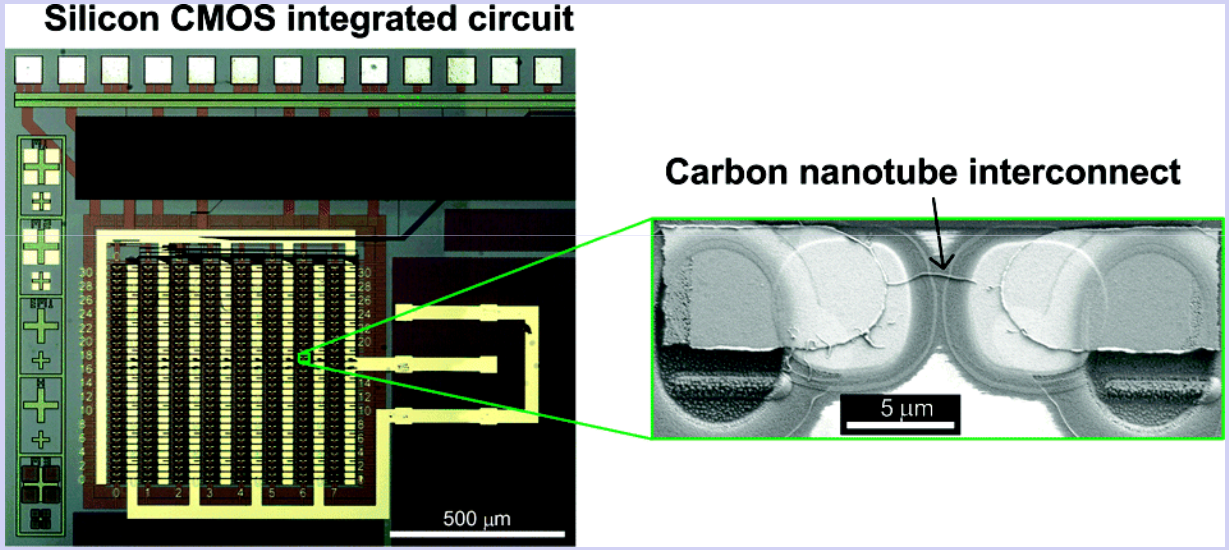
Soga et al.
Proc. ECTC, 2008



Real-world examples of successful CMOS-CNT integration..

Carbon nanotubes as on-chip interconnects:

a 1GHz IC with CNT bundle interconnects wiring CMOS



Close et al.
Nano Letters 2008

Real-world examples of successful CMOS-CNT integration..

Carbon nanotubes and graphene on-chip interconnects:

CMOS ring oscillator

X. Chen, et al., "Fully Integrated Graphene and Carbon Nanotube Interconnects for Gigahertz High-Speed CMOS Electronics," IEEE Trans. Electr. Devices, 2012

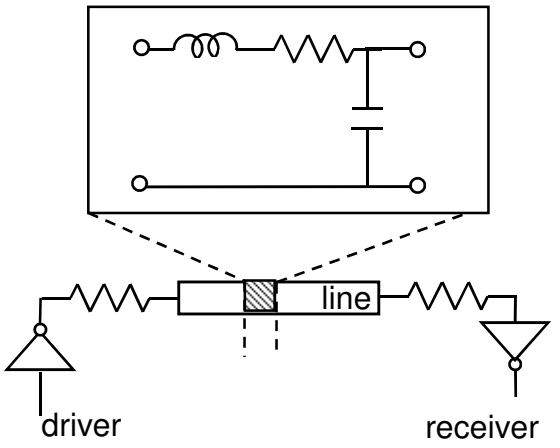
Carbon interconnect modeling: final goal for IC designers

ELECTROMAGNETIC MODEL

Maxwell equations

Carbon interc, electrodynamical model

CIRCUIT MODEL



- **heuristic approaches** (e.g., Luttinger liquid theory)
- **quasi-classical approaches** (e.g., Boltzmann equation, fluid models,..)

The final goal is a **simple** but **physically meaningful** circuit description of the "**channel**":

Non-local Ohm law for a generic CNT shell

Carbon conductor

collision frequency — *current density* — *Fermi velocity* — *charge density* — *longitudinal conductivity* — *longitudinal field*

$$\left(\frac{i\omega}{\nu}+1\right)J_z=\frac{1}{\nu\left(\frac{\nu}{i\omega}+1\right)}v_F^2\frac{\partial\rho_s}{\partial z}+\sigma_c E_z$$

Conventional ohmic conductor

$$J_z=\sigma_c E_z$$

G. Miano, C. Forestiere, A. Maffucci, S.A. Maksimenko, G. Y. Slepyan,
IEEE Trans. on Nanotechnology 2011 and 2012

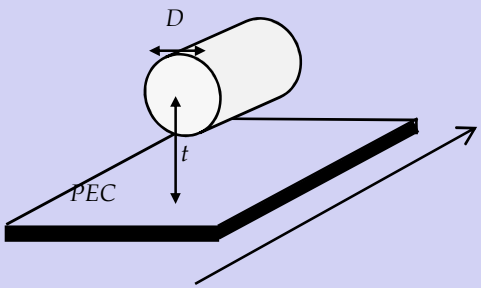
C. Forestiere, A. Maffucci, G. Miano
J. Nanophotonics (2010)

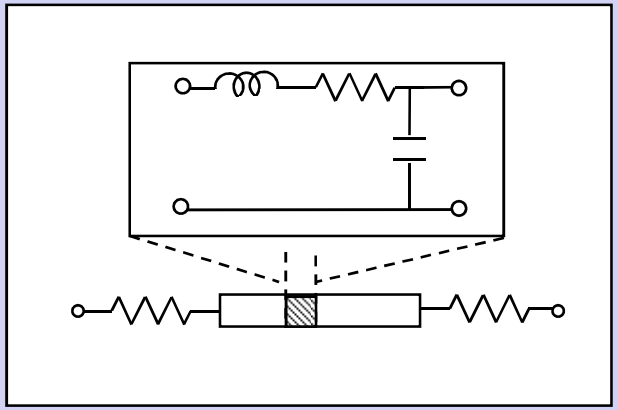
Validity limits:

- **Low bias conditions** $E_z<0.54\,V/\mu m$
- **Low frequency** $f<1\,THz$

Transmission line model for an isolated CNT shell or GNR sheet

CNT





GNR

PUL parameters

$$L' = \frac{L'_m + L'_k}{\alpha_c}$$

$$C' = C'_e$$

$$R' = \frac{v_F}{l_{mfp}} \frac{L'_k}{\alpha_c}$$

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

$$a_C = 1 + \frac{C'_e}{C'_Q}$$

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

$$R_0 = 12.9\text{k}\Omega$$

MODEL PARAMETERS:

Number of conducting channels M

Mean free path l_{mfp}

Transmission line model for CNTs

Typical conditions

$$C'_e \ll C'_Q, \quad L'_m \ll L'_k$$

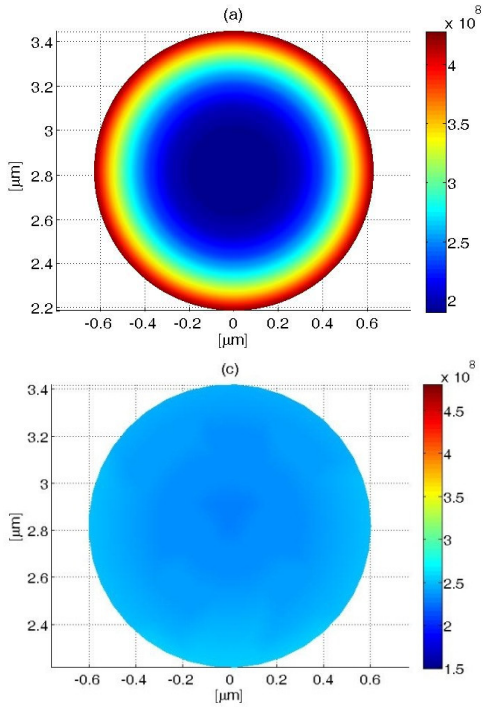
$$a_C \approx 1, \; L' \approx L'_k,$$

$$R' \approx \nu L'_k = \frac{v_F}{l_{mfp}} L'_k$$

The inductance is **dominated** by the kinetic term

NO – low propagation velocity

OK – insensitivity to high-frequency effects (**skin and proximity effect**)

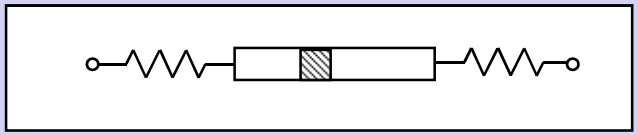


Copper

MWCNT

Impact of the resistance

Resistance model for a single CNT shell or a single GNR



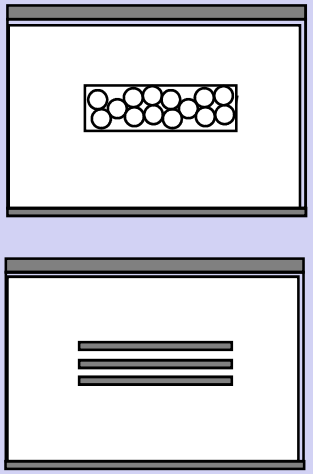
additional resistance

quantum term

Distributed term

$$R_{tot} = \frac{R_0 + R_{con}}{M} + R'l$$

$$R_{\min} = \frac{R_0}{M} = 6.45k\Omega \ \ (for\ M = 2)$$



Bundles of CNTs or arrays of GNRs fed in parallel must be used!!

Circuit model identification: fittings for model parameters

Number of conducting channels:

$$M \approx \begin{cases} 0 & \text{for semicond. SWCNTs} \\ 2 & \text{for metallic SWCNTs} \\ a_1 DT + a_2 & \text{for MWCNTs} \\ \dfrac{M_0(W)}{\alpha - \beta T} & \text{for GNRs} \end{cases}$$

rigorously computed in:

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

→ C. Xu, H. Li, and K. Banerjee, IEEE Trans. Electron Devices, 2009

Mean free path:

$$\frac{1}{l_{mfp}} = \frac{k_1 + k_2 T + k_3 T^2}{D}$$ CNT →

A. Naeemi and J. D. Meindl, IEEE Trans. Electron Devices, 2008

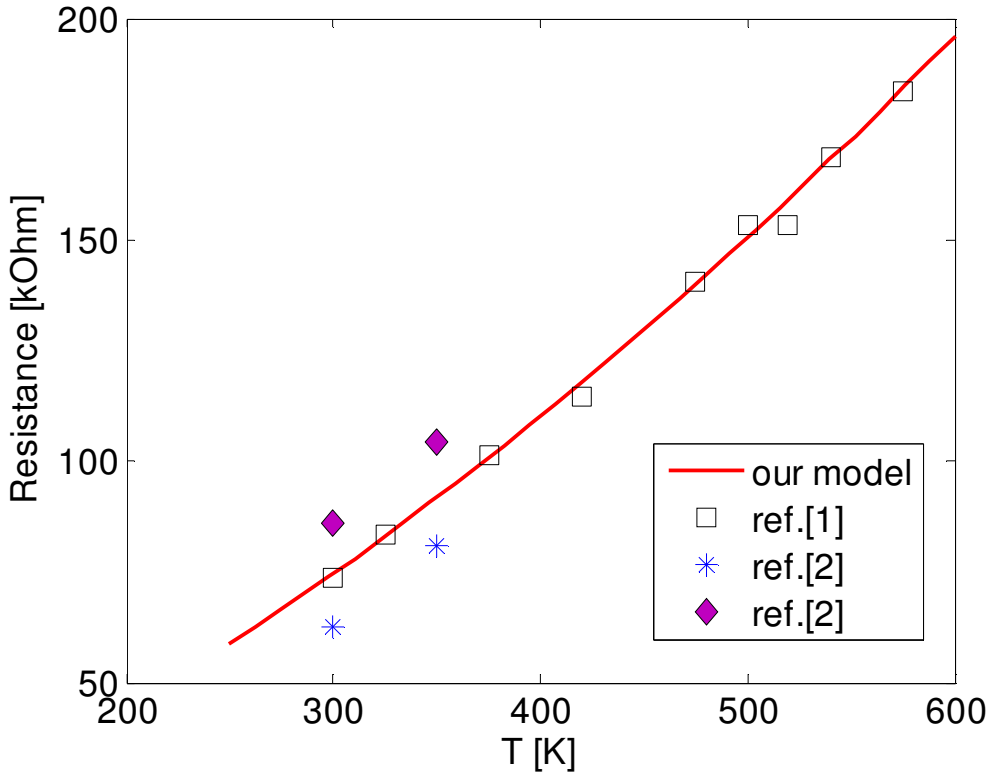
$$\frac{1}{l_{mfp}} = \frac{\gamma}{W}$$ GNR →

A. Naeemi and J. D. Meindl, IEEE Trans. Electron Devices, 2009

The fitting coefficients depend on the temperature and size ranges

Model validation - CNT

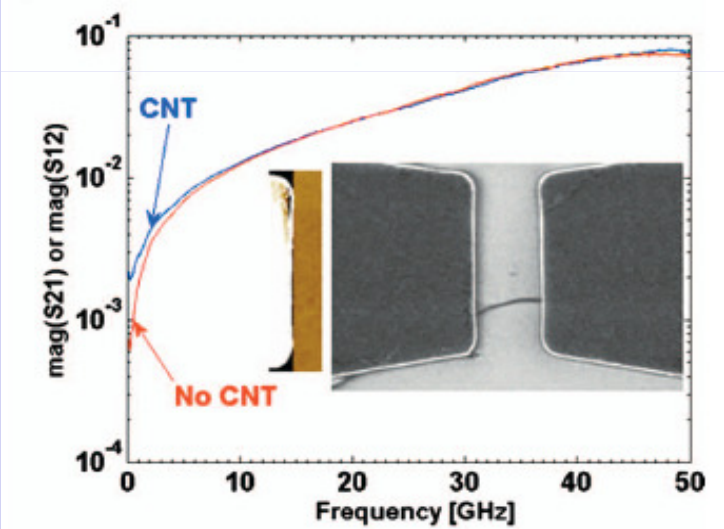
Static parameters (resistance)



[1] Avedisian et al., APL., 2008
[2] E. Pop et al., JAP, 2007

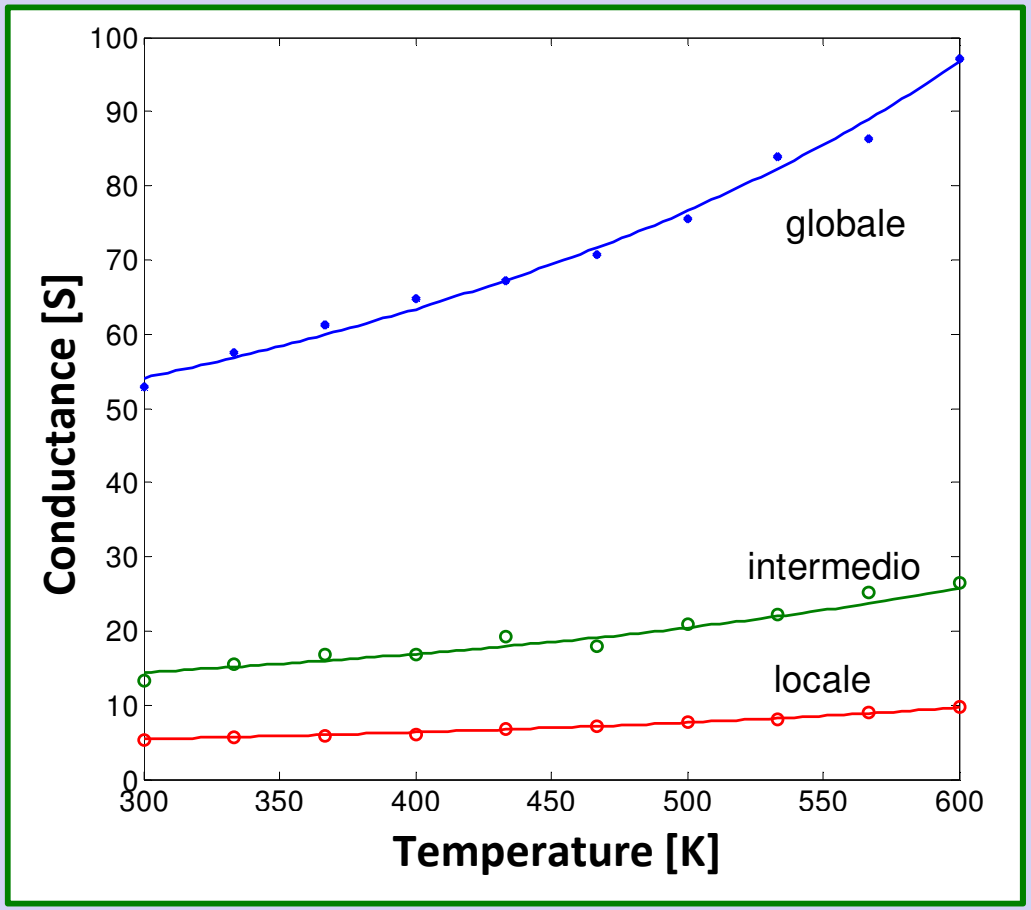
Dynamic parameters (S-param.)

	our model	*measured*
$\|S_{11}\|$	$0.997 \div 0.998$	$0.996 \div 0.998$
$\|S_{21}\|$	$0.0020 \div 0.0034$	$0.0024 \div 0.0026$



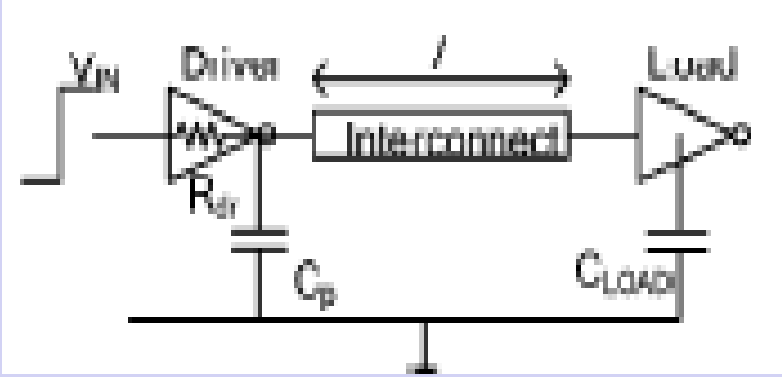
J.J.Plombon et al., APL, 2007

Model validation - GNR



A. Naeemi and J. D. Meindl,
IEEE Trans. Electron Devices, 2009

Signal integrity performance of on-chip CNT interconnects

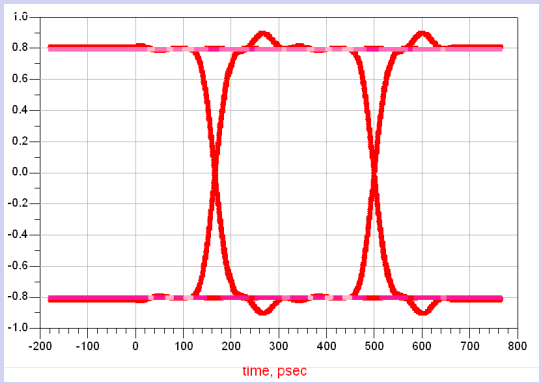


ITRS 2011 Edition

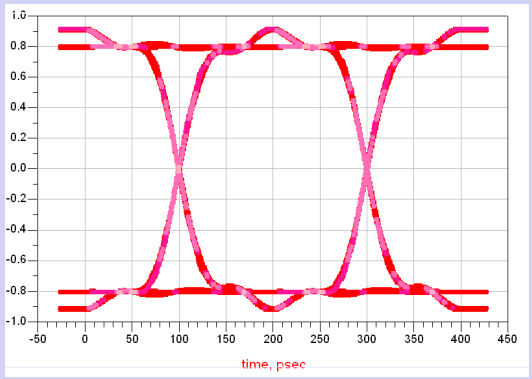
	22 nm node		
	global	interm.	local
W [nm]	160.00	44.00	22.00
H [nm]	96.00	44.00	44.00
Rdr [kΩ]	0.16	0.81	8.09
Cout [fF]	4.90	0.98	0.09
CL [fF]	14.00	2.80	0.28

Local level

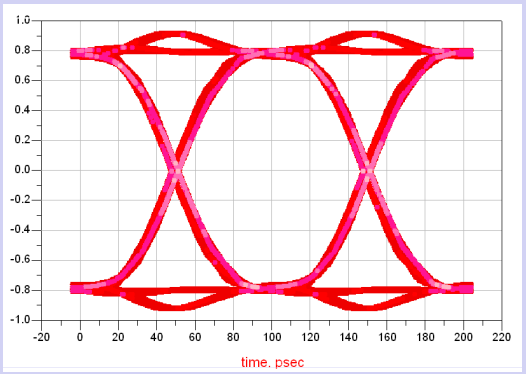
DR=3 GB/s, rs 33 ps



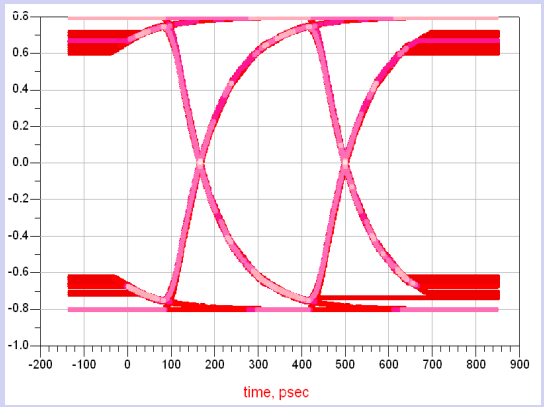
DR=5 GB/s, rs 20 ps

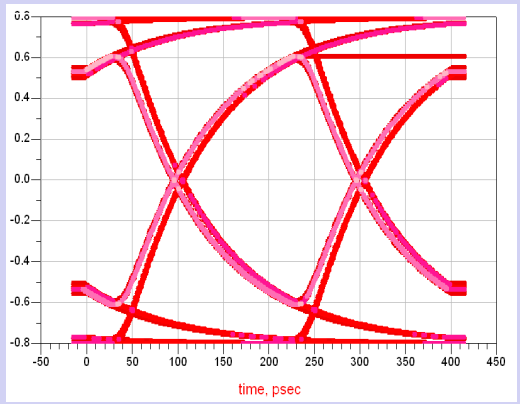


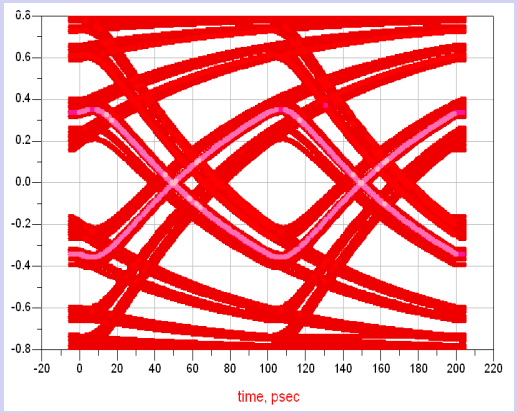
DR=10 GB/s, rs 10 ps



SWCNT

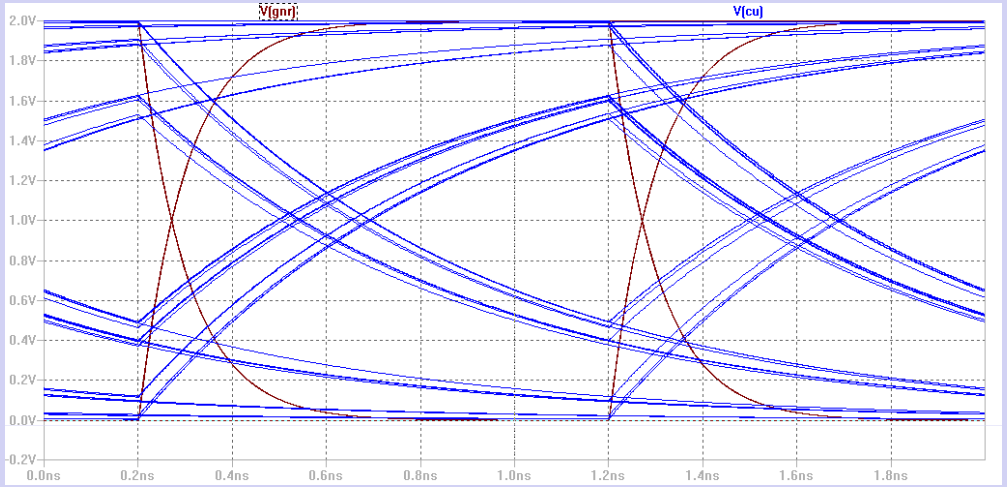






Cu

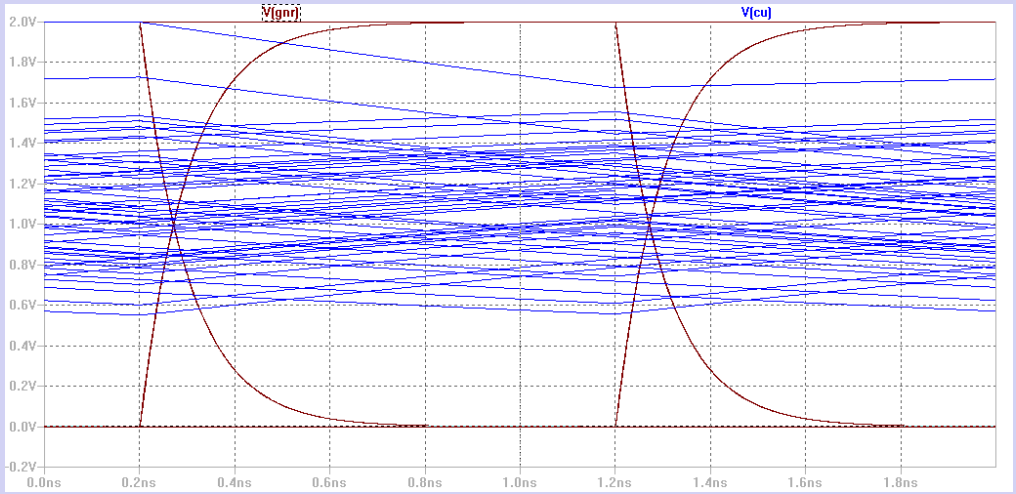
Intermediate level



GNR

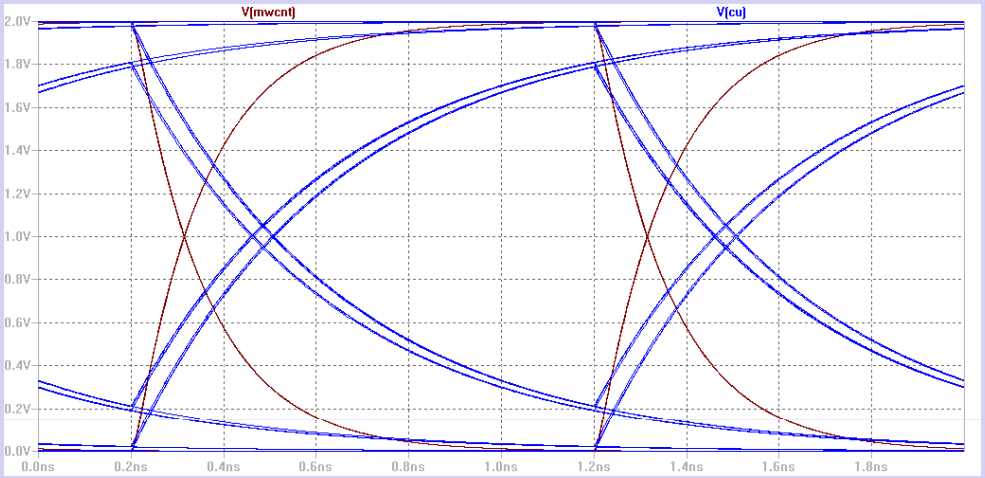
Cu

DR=1 GB/s



DR=10 GB/s

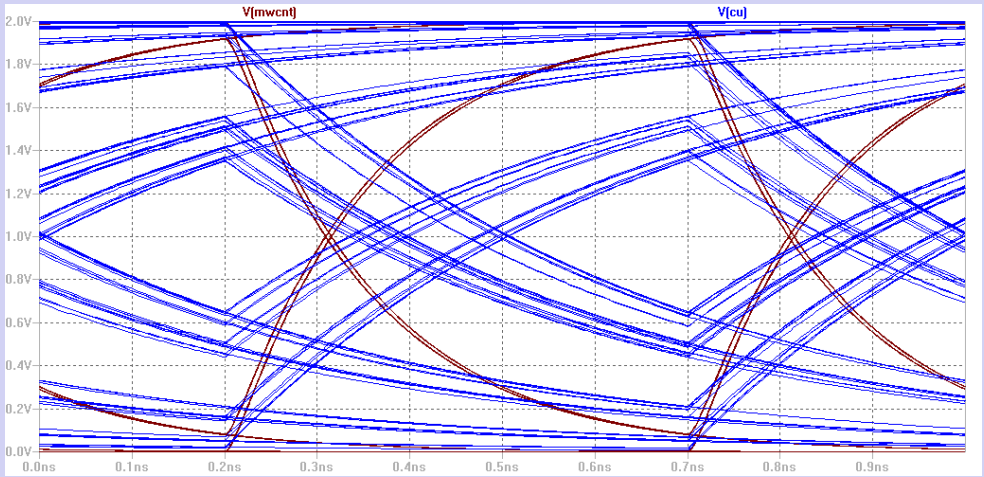
Intermediate level



MWCNT

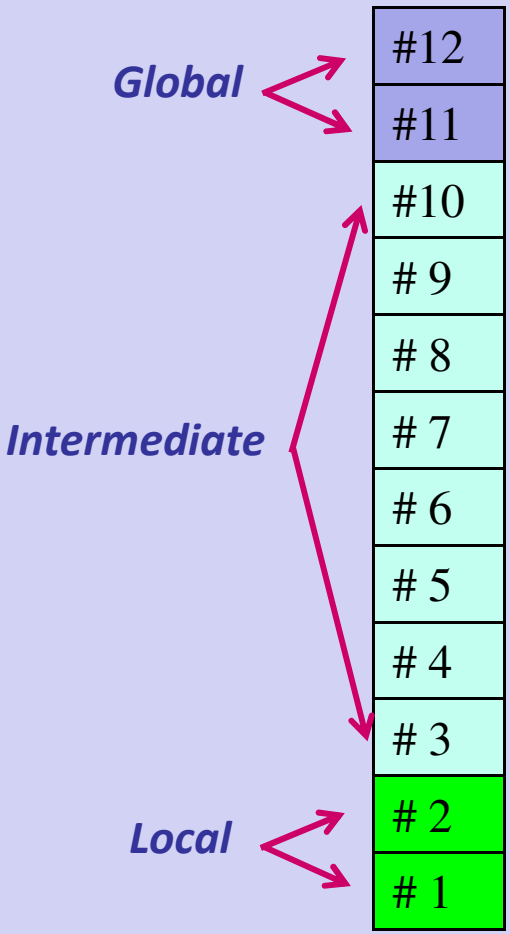
Cu

DR=1 GB/s

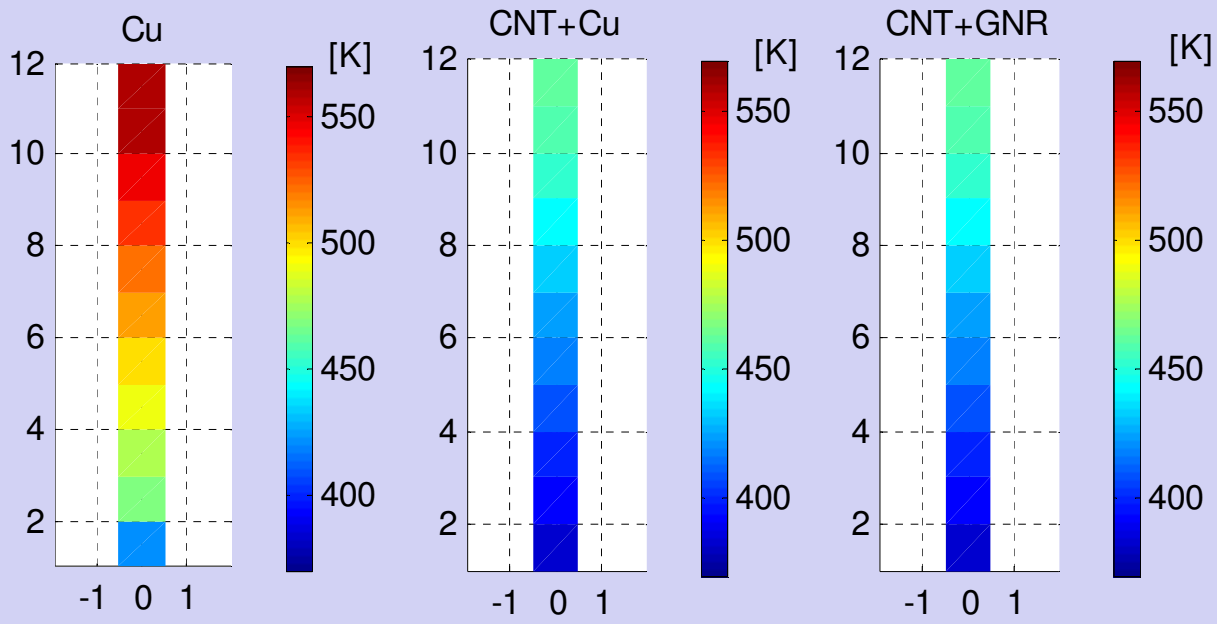


DR=10 GB/s

Hybrid CNT /GNR/Cu on-chip interconnect

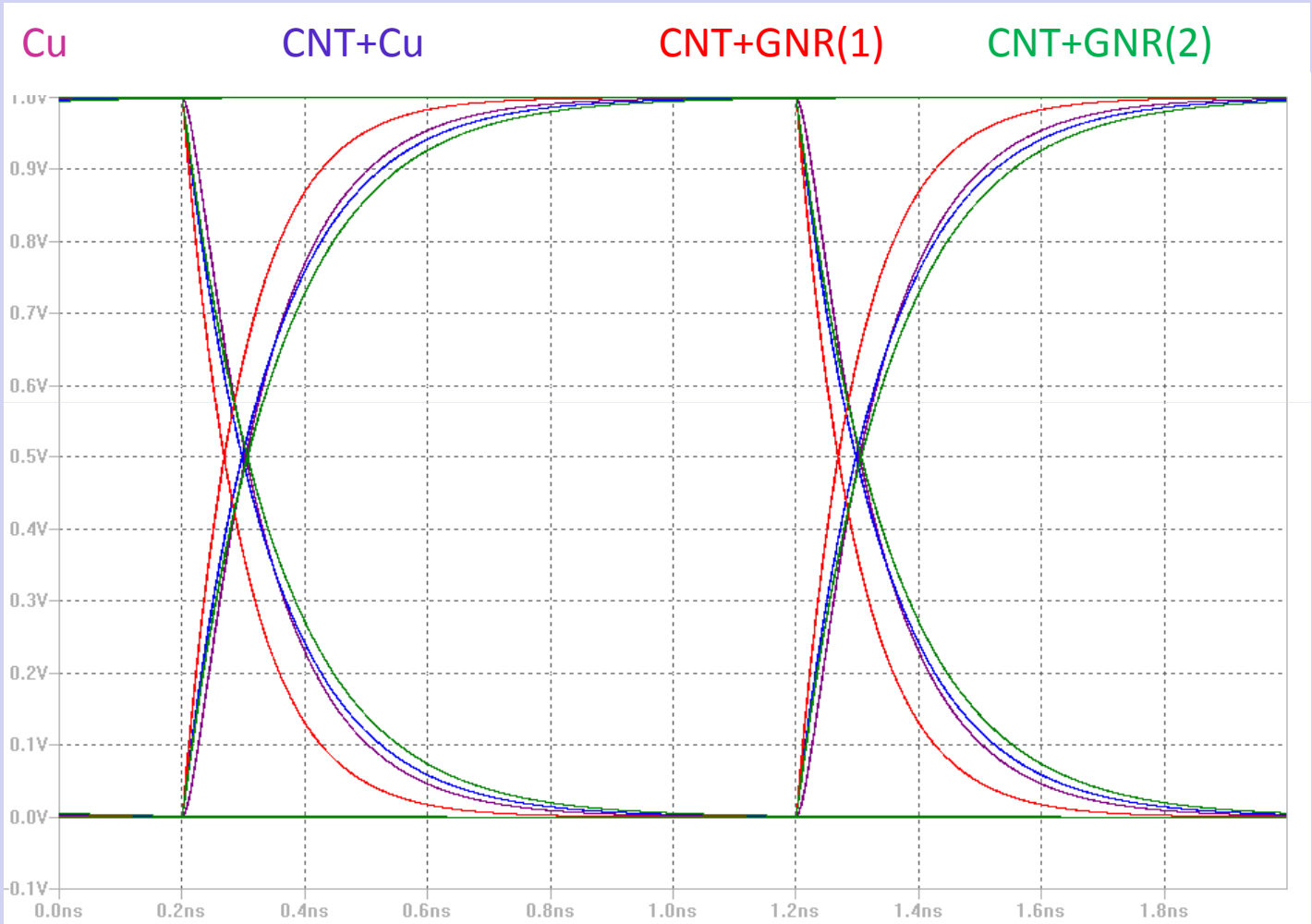


Temperature distribution

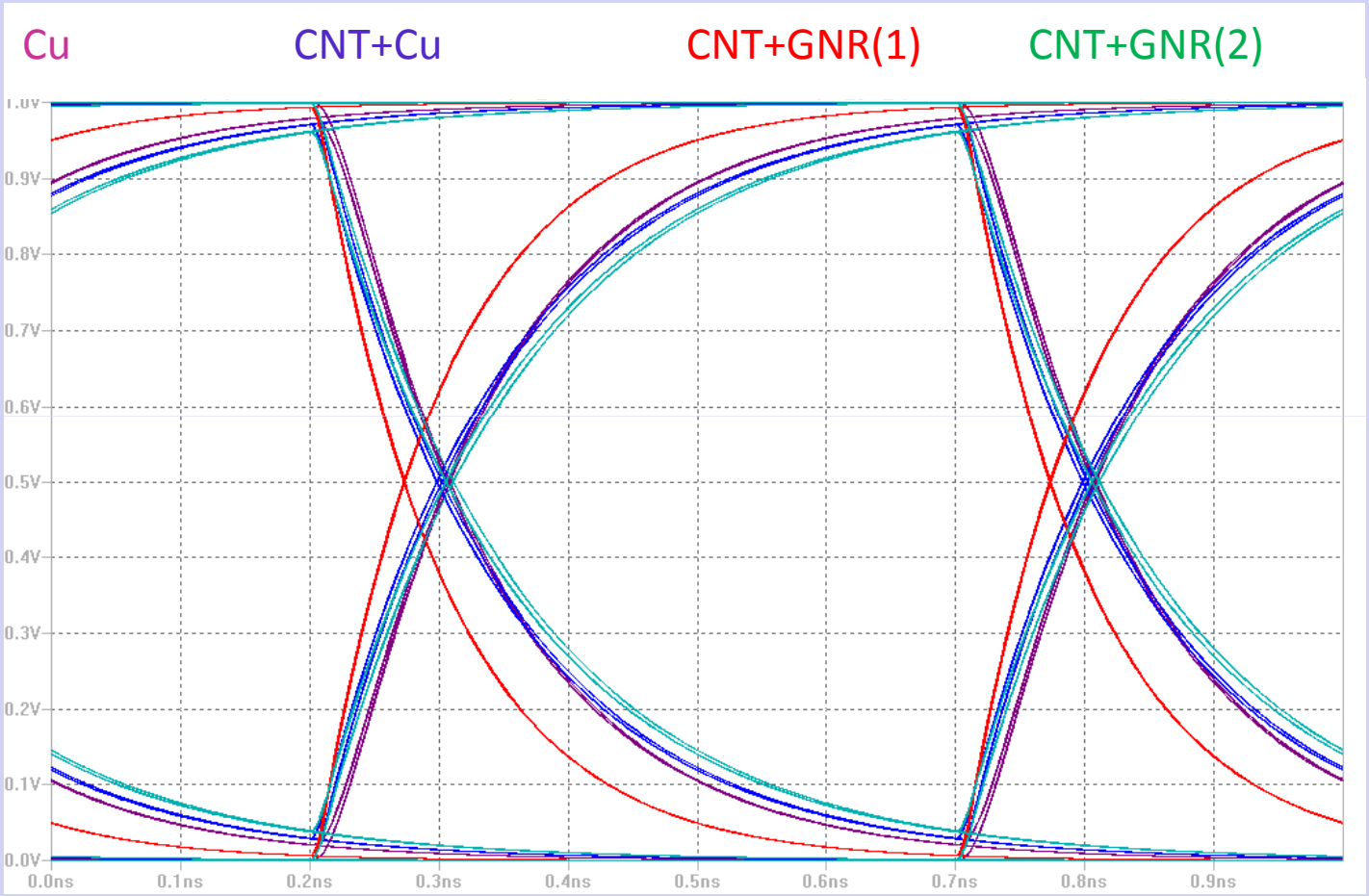


Metal 1 temperature = 378K

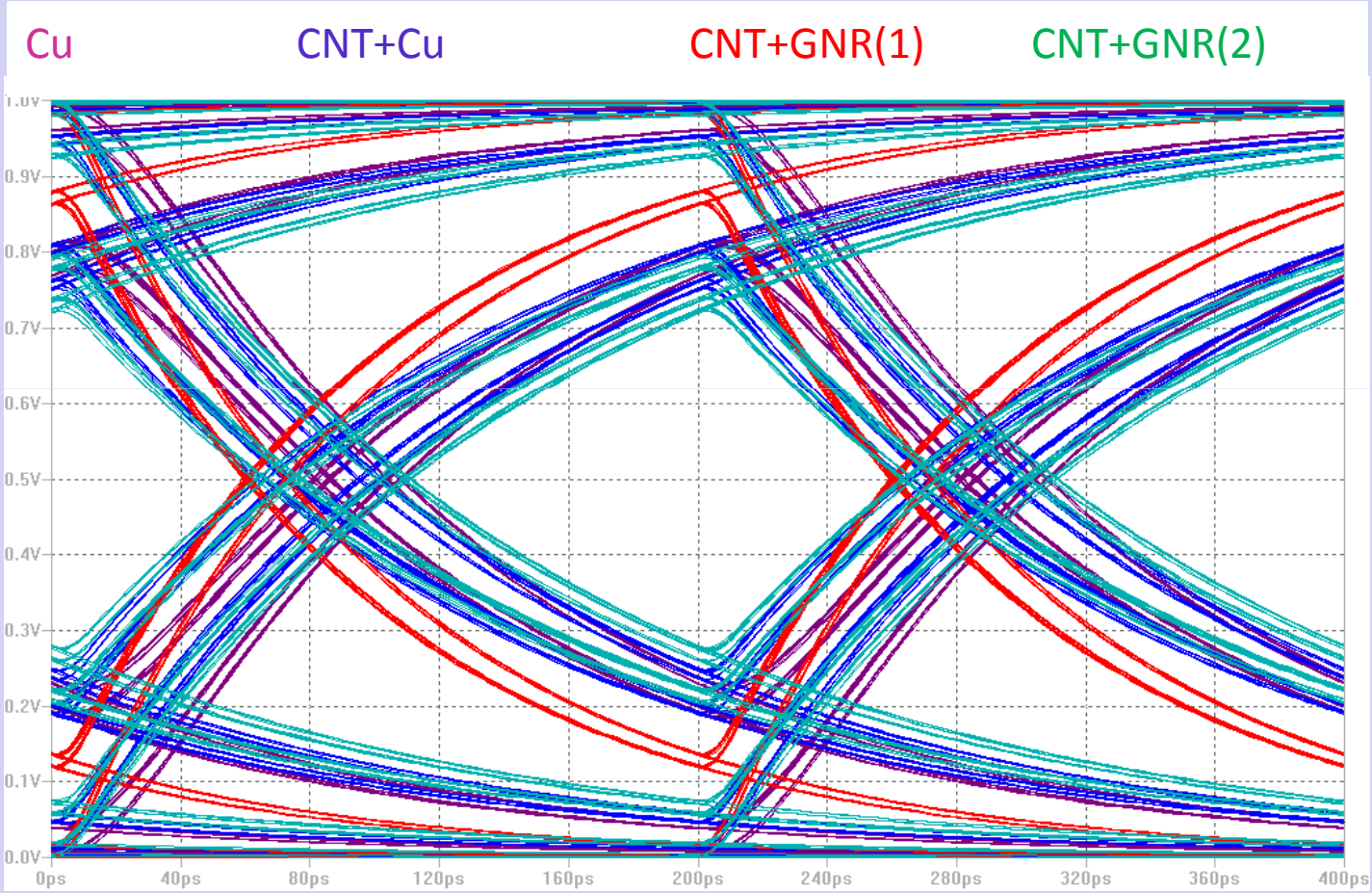
Performance at 1GB/s (400K)



Performance at 5 GB/s (400K)



Performance at 10 GB/s (400K)



Summary: electrical performance vs copper interconnects

	Local interconnects	Global interconnects	On-chip Vias	Chip-to-package interconnects
SWCNT	Comparable or better (depending on the metallic fraction)	Comparable or better (depending on the metallic fraction)	Comparable or better (depending on the metallic fraction)	Comparable or better (depending on the metallic fraction)
MWCNT	comparable	better	worse	better
GNR	comparable	worse or better (stronlgy depending on the edge effect and doping)	Not available	Not available

Conclusions

- **Carbon-based interconnects** are proposed to replace copper for on-chip interconnects for **technology nodes of 22 nm** and below.
- **Carbon nanotubes** and **graphene nanoribbons** are candidate to realize them. First examples of **monolithic CNT/CMOS** and **GNR/CMOS integration.**
- **Circuit models** for carbon interconnects may be derived in the frame of the TL theory. Besides classical parameters, quantistic terms appear (such as **kinetic inductance** and **quantum capacitance**) which strongly affect the electrical behavior.
- **A simple model has been proposed and validated**, based on fittings of the physical parameters. The fitting formulas are function of **temperature and size**
- Signal integrity analysis show the potential electrical performance of the proposed solutions, some of them **strongly influenced** by the possibility to have good control in fabrication process

Thank you