Map of China


中国政区
1 : 21 300 000
图 例
北京 首都或首府
西安 省级行政中心
延安 地级行政中心、外国城市
韩城 县（市）级行政中心
国界
省、自治区、直辖市界
特别行政区界
地区界
停火线、军事分界线
河流
湖泊
山峰
新疆维吾尔自治区
西藏自治区
内蒙古自治区
广西壮族自治区
青海
甘肃
四川
云南
贵州
湖南
湖北
河南
安徽
江西
福建
浙江
江苏
山东
山西
陕西
河北
辽宁
吉林
黑龙江
广东
海南
台湾
重庆市
北京
天津
上海
乌鲁木齐
拉萨
西宁
兰州
银川
呼和浩特
哈尔滨
长春
沈阳
石家庄
太原
济南
郑州
西安
成都
重庆
贵阳
昆明
南宁
长沙
武汉
南昌
合肥
南京
杭州
福州
台北
广州
海口
香港
澳门
哈萨克斯坦
俄罗斯
蒙古
乌兰巴托
朝鲜
平壤
韩国
首尔
日本
印度
新德里
尼泊尔
加德满都
不丹
孟加拉国
达卡
缅甸
老挝
越南
河内
太平洋
东海
南海
南海诸岛

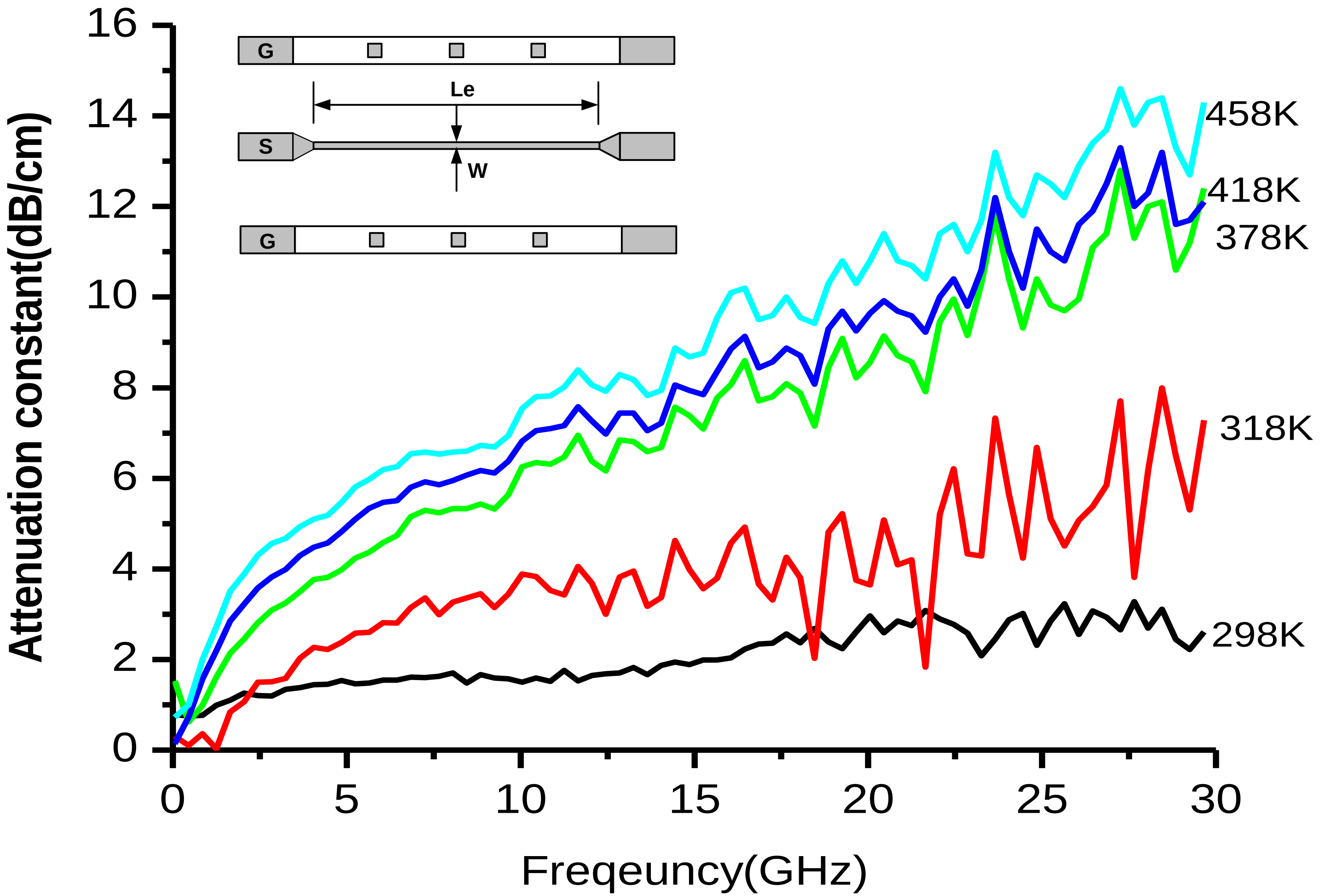
Mulitphysics Solution for Nanoelectronics

Wen-Yan Yin

Center for Optical and EM Research(COER)
Zhejiang University, Hangzhou, China
E-mail: wyyin@zju.edu.cn and wyyin@sjtu.edu.cn
http://coer.zju.edu.cn and http://cmrft.sjtu.edu.cn

Silicon-based Transmission Lines

Electrothermal Effects



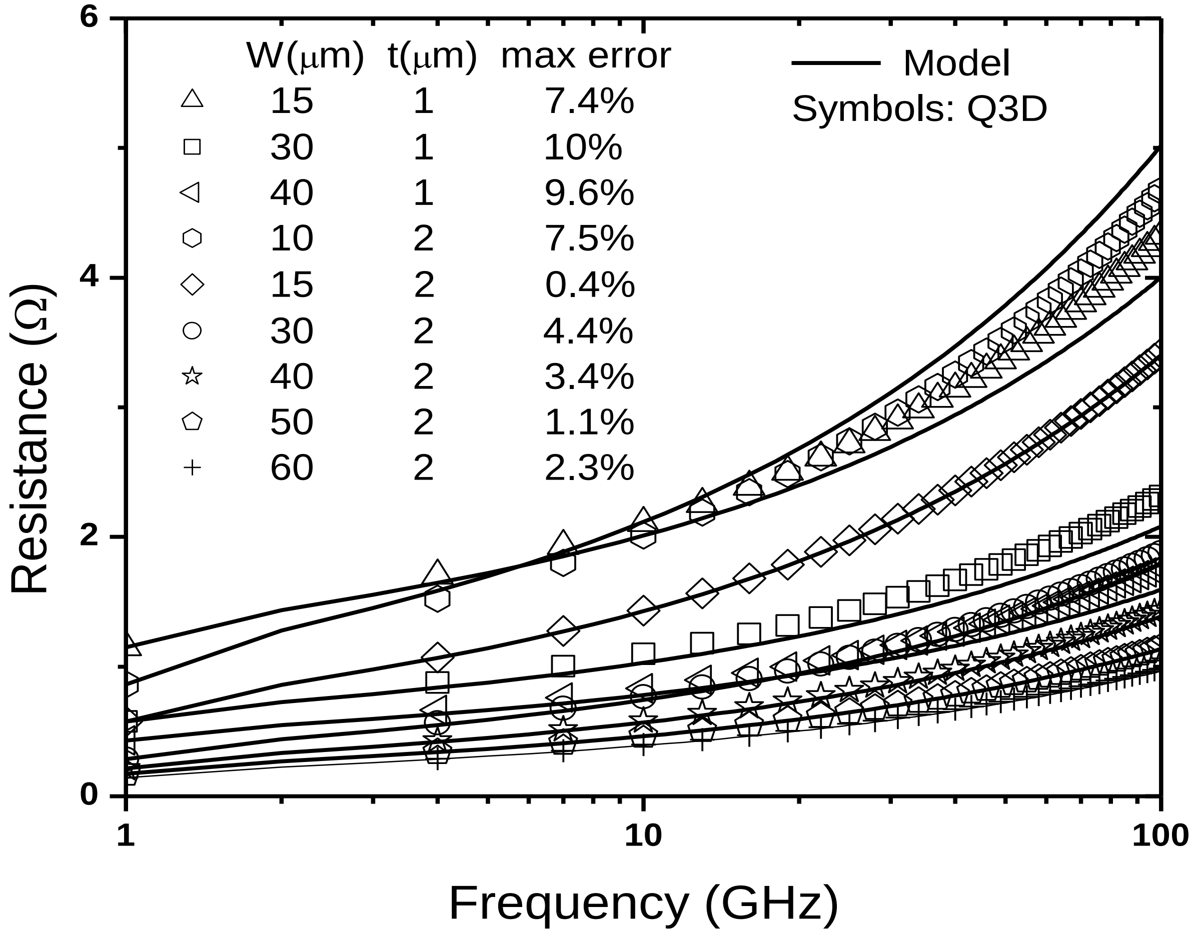
Finite electrical conductivity and semiconducting substrate!

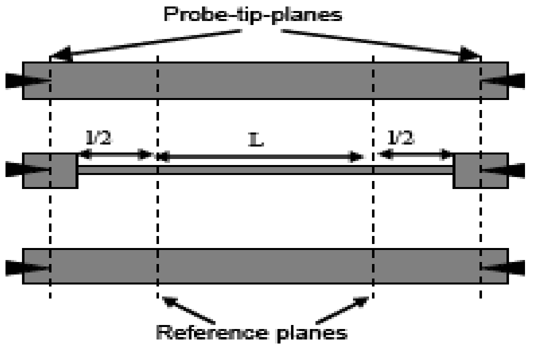
Problems

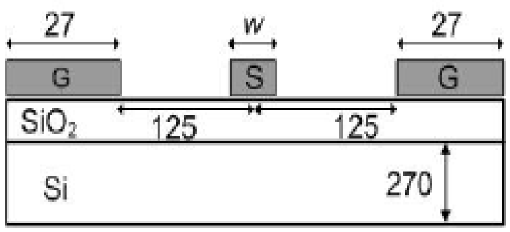
(1) Temperature effects on electrical conductivities of most metal materials?

(2) Temperature effects on thermal conductivities of most semiconducting materials?

Silicon-based Millimeter Wave TLs

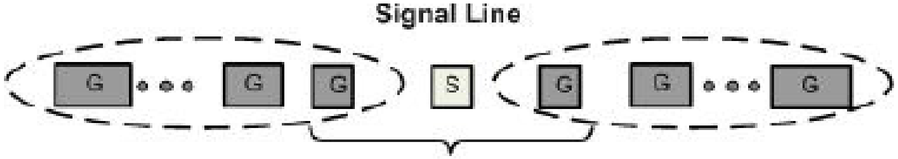


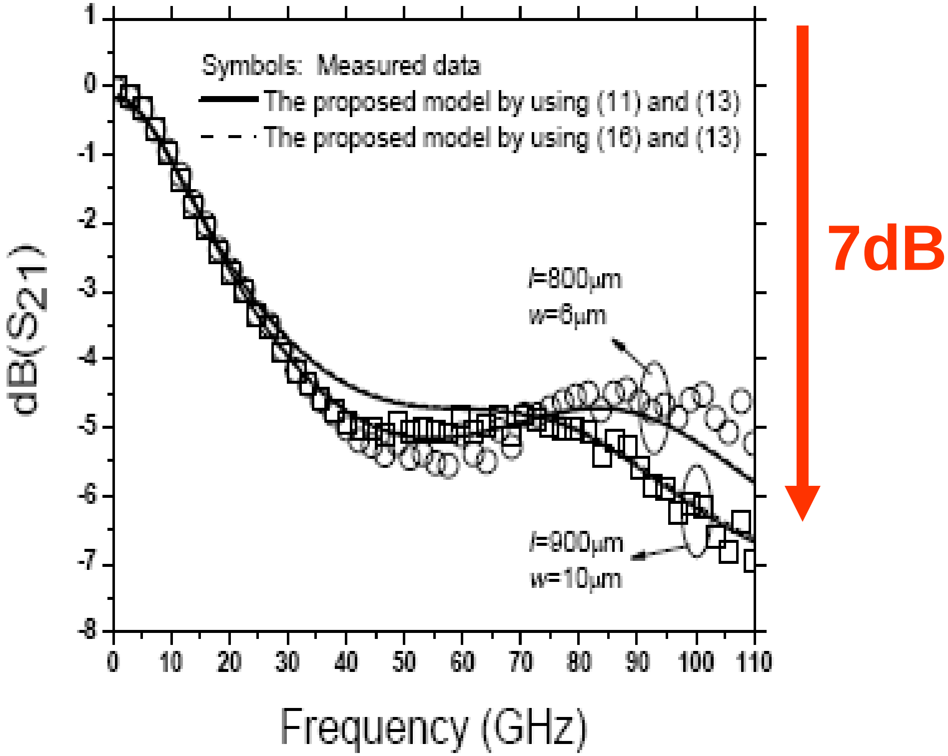


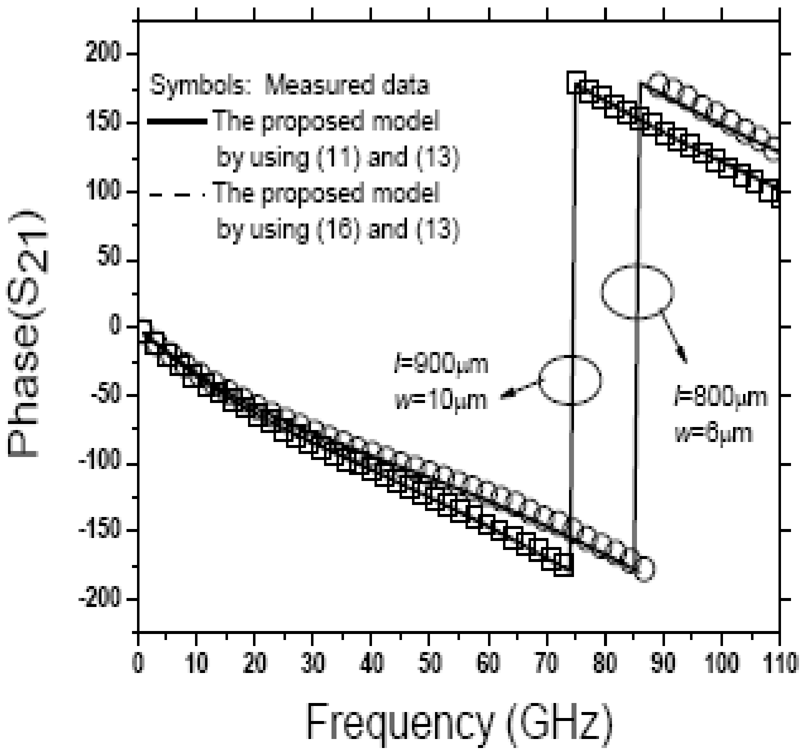


K. Kang, L. Nan, S. C. Rustagi, W. Y. Yin, et al, "A wideband scalable and SPICE-compatible model for on-chip interconnects up to 110 GHz," IEEE Trans. Microwave Theory Tech., 56(4), 942-951, 2008.

Silicon-based Millimeter Wave TLs





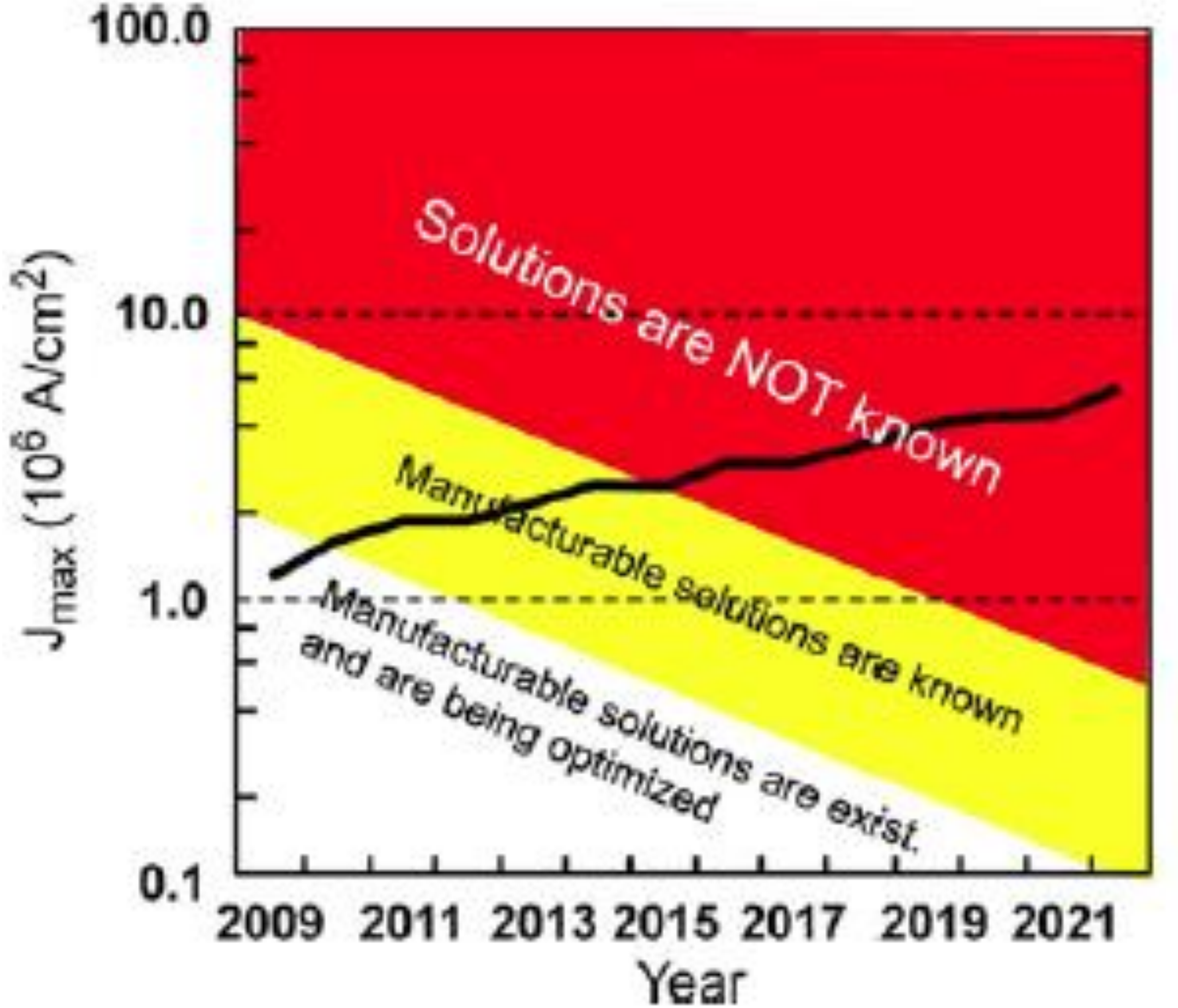


ITRS

Year of Production	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*
DRAM ½ Pitch (nm) (contacted)	*28*	*25*	*22*	*20*	*18*	*16*	*14*
MPU/ASIC Metal 1 ½ Pitch (nm)(contacted)	*28*	*25*	*22*	*20*	*18*	*16*	*14*
MPU Physical Gate Length (nm)	*11*	*10*	*9*	*8*	*7*	*6*	*6*
Number of metal levels	13	13	13	14	14	14	14
Number of optional levels – ground planes/capacitors	4	4	4	4	4	4	4
Total interconnect length (m/cm^2) – Metal 1 and five intermediate levels, active wiring only [1]	3571	4000	4545	5000	5555	6250	7143
FITs/m length/cm^2 × 10^{-3} excluding global levels [2]	1.4	1.3	1.1	1	0.9	0.8	0.7
J_{max} (A/cm^2) – intermediate wire (at 105°C)	1.06E+07	1.14E+07	1.47E+07	1.54E+07	1.80E+07	2.23E+07	2.74E+07
Metal 1 wiring pitch (nm)	56	50	44	40	36	32	28
Conductor effective resistivity (μΩ-cm) Cu intermediate wiring including effect of width-dependent scattering and a conformal barrier of thickness specified below	5.2	5.58	6.01	6.33	6.7	7.34	8.19

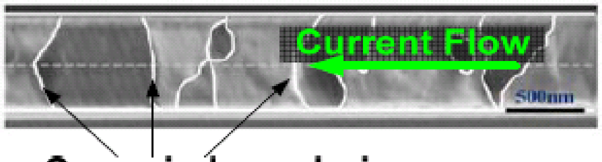
After 2014: J_{max} > 1.06 x 10^7 A/cm2

Final Solutions are not Known

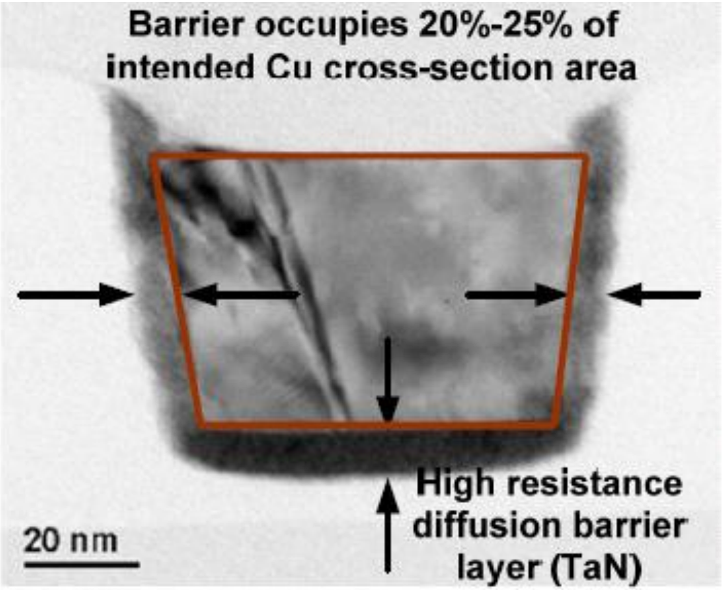


Y. Awano, et al., PIEEE, 98(12), 2015-2031, 2010.

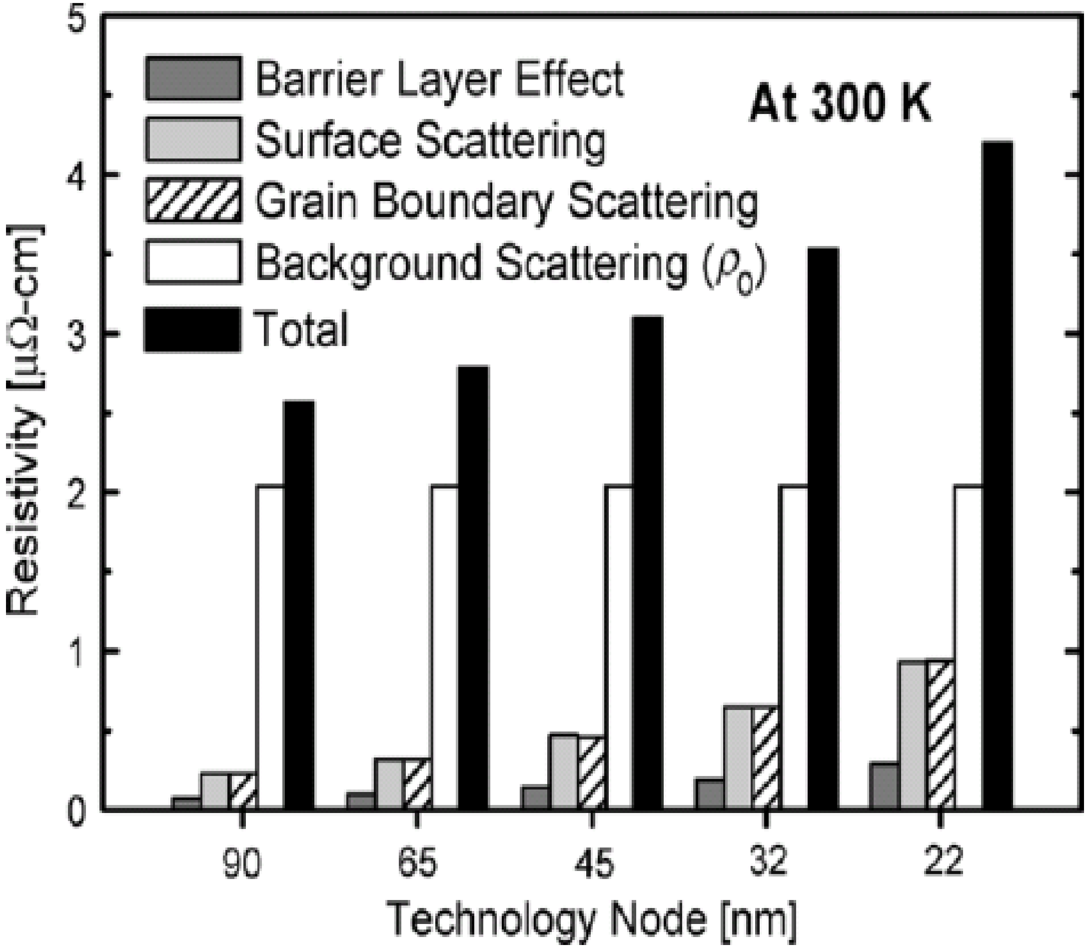
Size Effect in Cu Interconnect



Top-view TEM of Cu interconnect



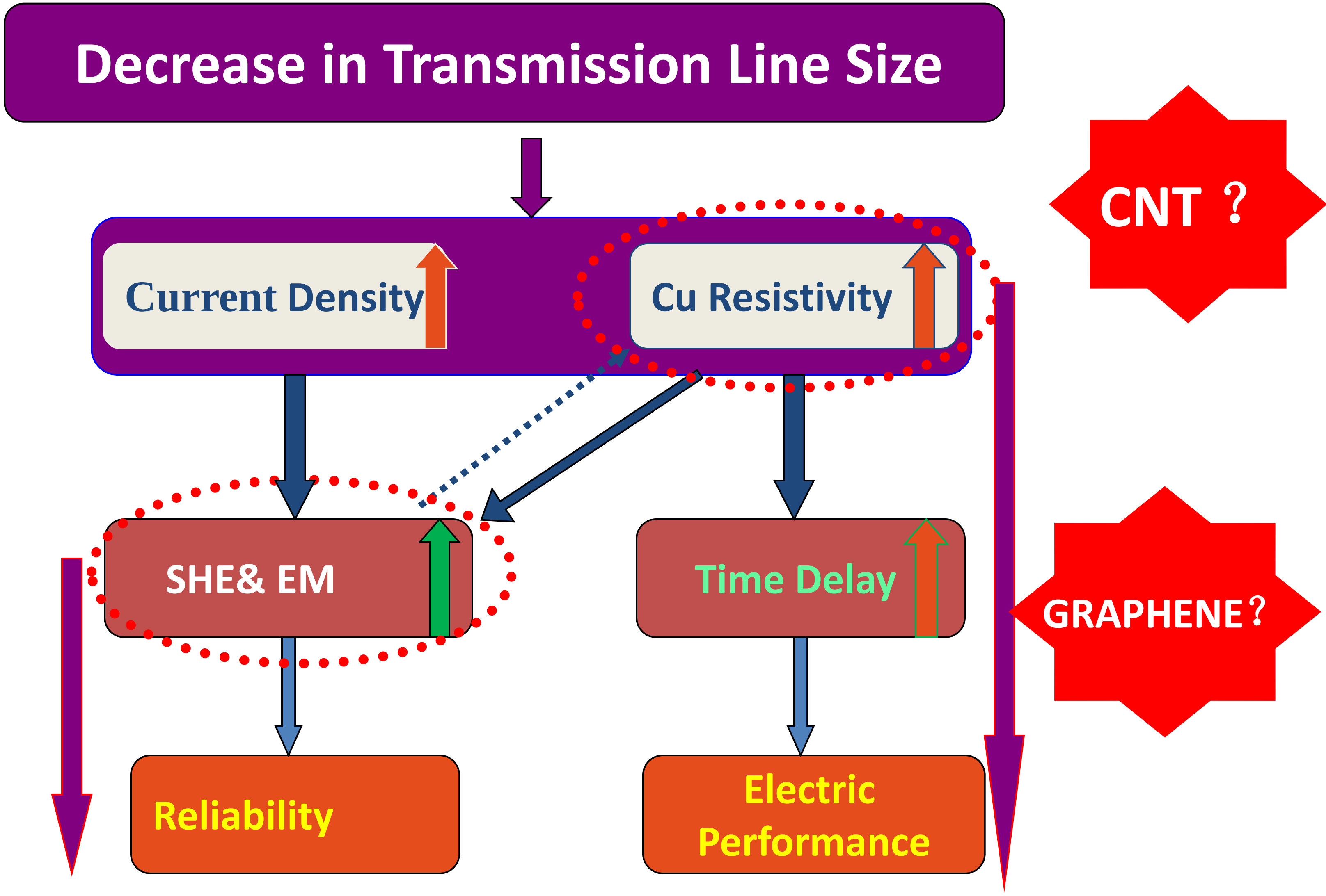
TEM cross-section of narrow Cu interconnect



Steinhogl *et al.*, *JAP*, 2005

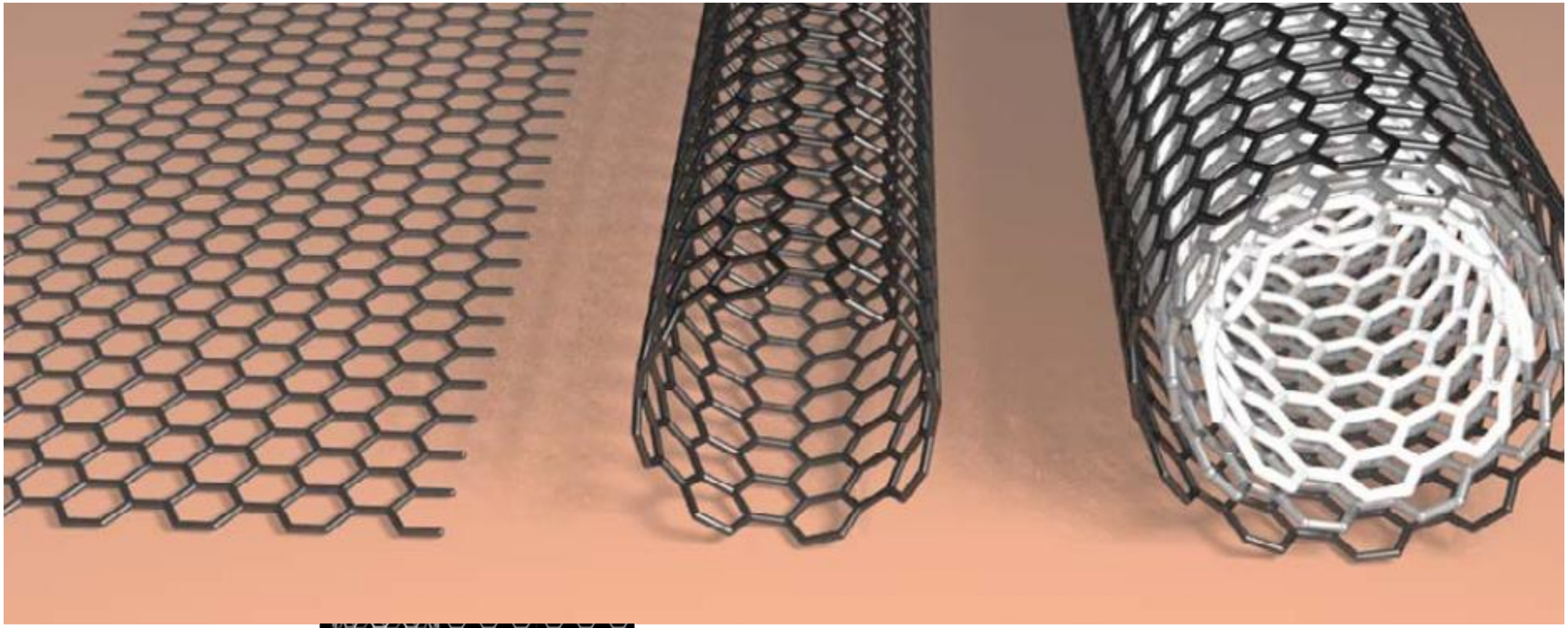
Cu resistivity will be increased rapidly! Electric performance and reliability will be decreased due to self-heating effect !

CNT and GRAPHENE Solutions?

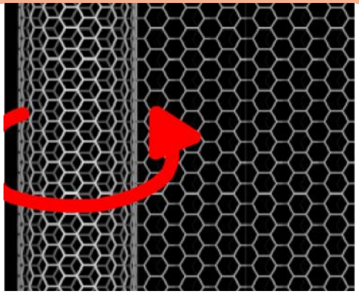


Carbon Nanotube Transmission Lines (CNTL): Beyond Maxwell's Equations

CNT



GR



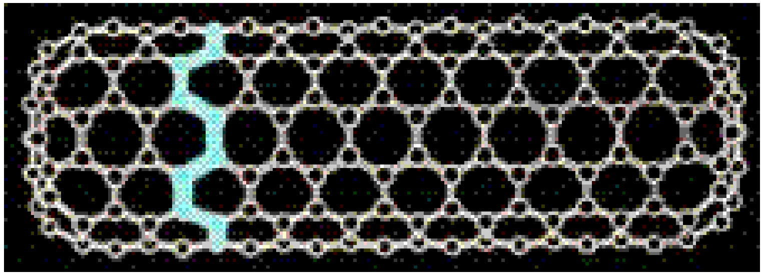
SWCNT

MWCNT

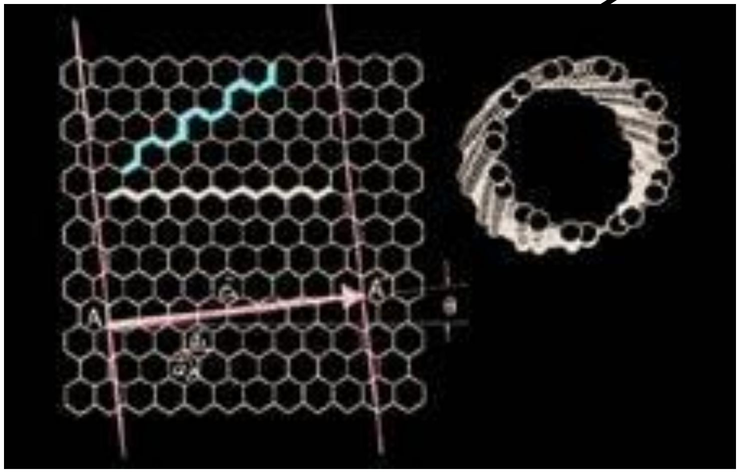
Courtesy: F. Kreupl, Infineon

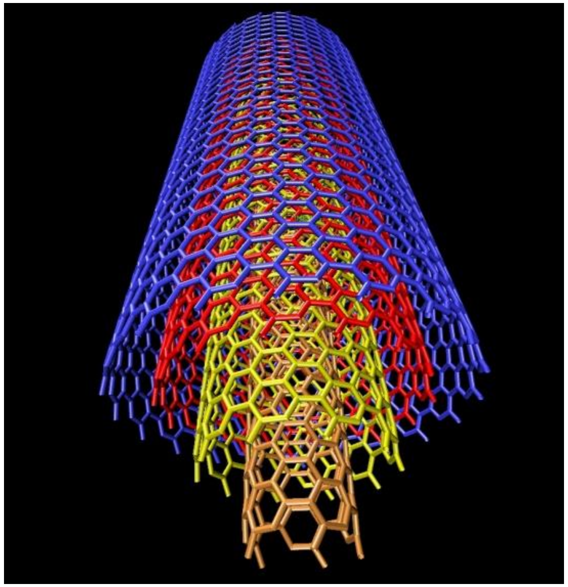
CNT Classification

Arm-Chair CNT(M)



Zig-Zag CNT (M & S)





MWCNT
(each wall can be S or M, most walls are M)

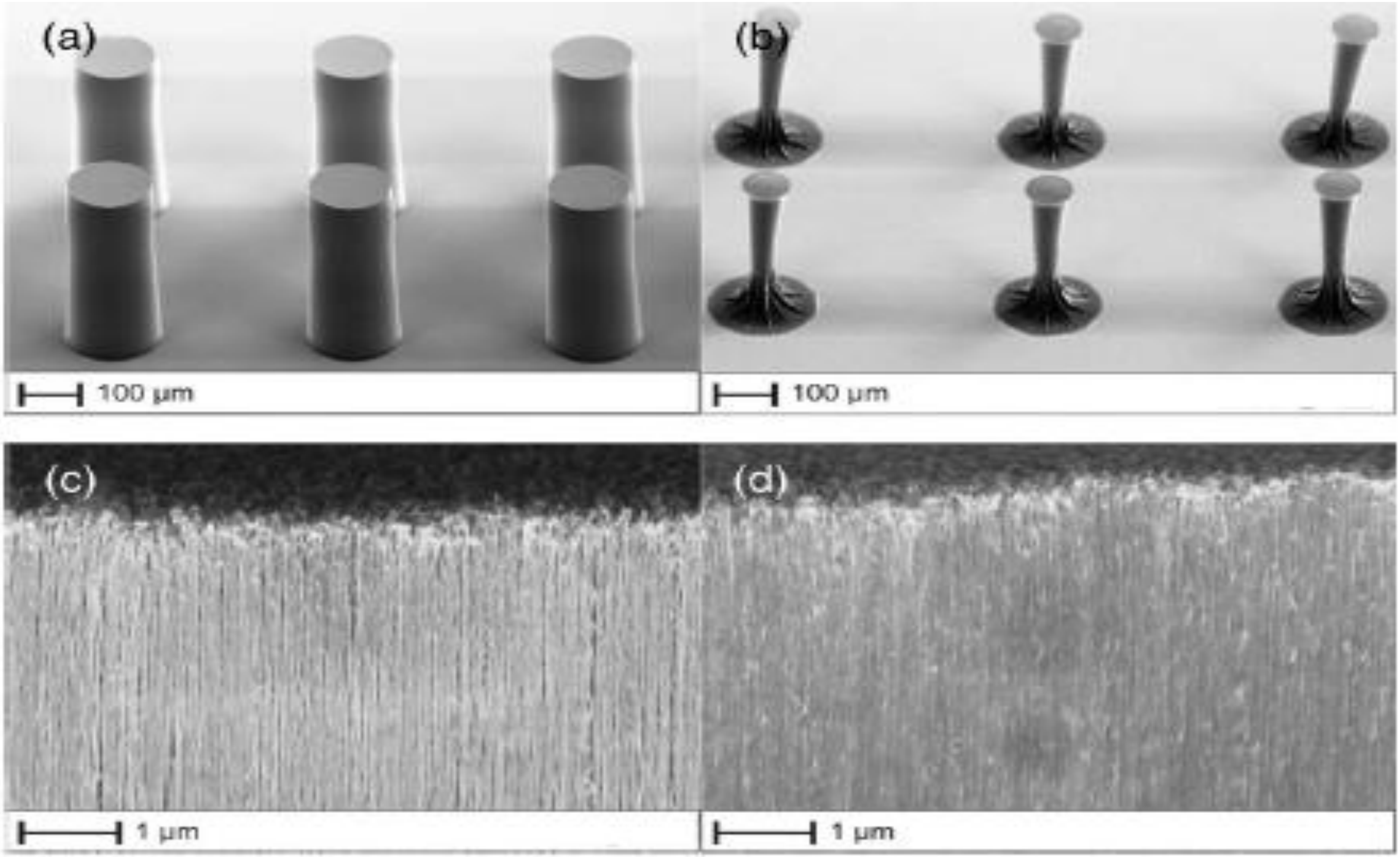
About 1/3 of all SWCNTs are metallic and 2/3 are semiconducting

Metallic SWCNT Properties

- Length: um-mm
- Diameter: 0.4-100nm
- Strength : 45 Tpa! (Steel ~ 2Tpa)
- Thermal stability: operating temperature up to 700 º C.

	CNT	Cu
Maximum current carrying density(A/cm*cm)	$>1X10^9$ Radosavljevic, et al., *Phys. Rev. B*, 2001	$<1X10^7$
Thermal conductivity (W/mK)	5800 Hone, et al., *Phys. Rev. B*, 1999	385
Mean free path（diameter=1nm）	>1000 McEuen, et al., *IEEE Trans. Nano.*, 2002	40

CNT Vias



T. Wang, et al., *IEEE Electronic Devices Lett*., 33(3), 420-422, Mar.2012

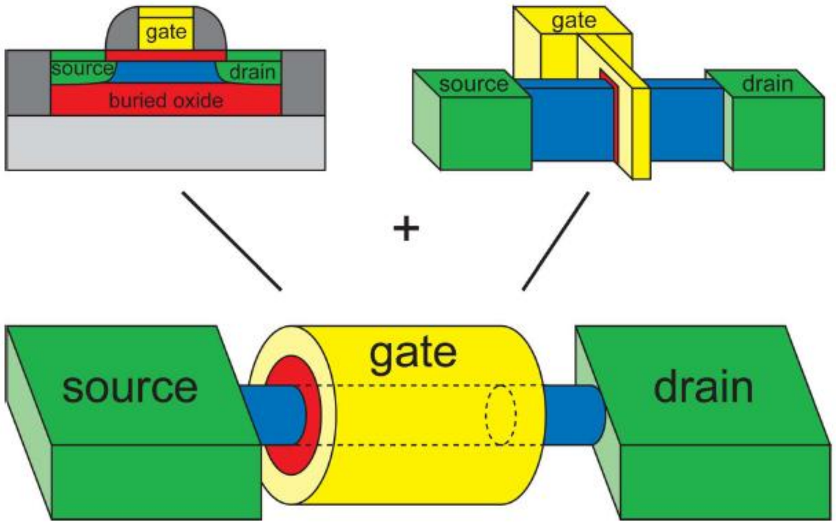
Carbon Nanotubes for Active Nano Devices

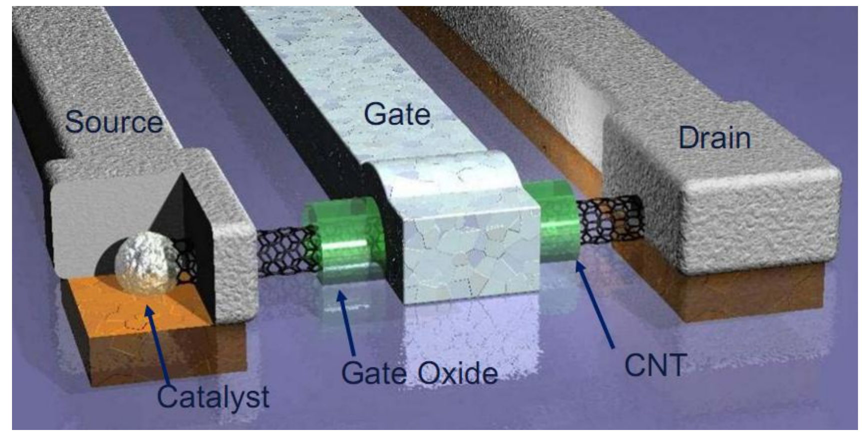
Semiconducting SWCNT Properties

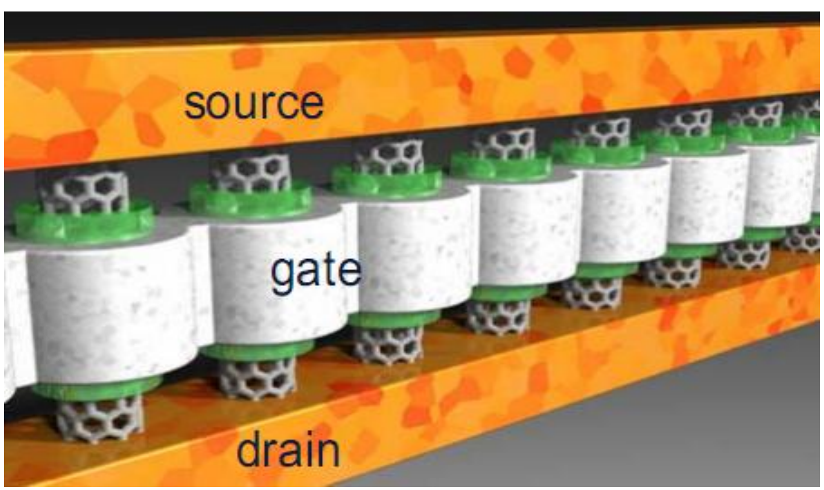
Comparison of CNT properties with other semiconductors.

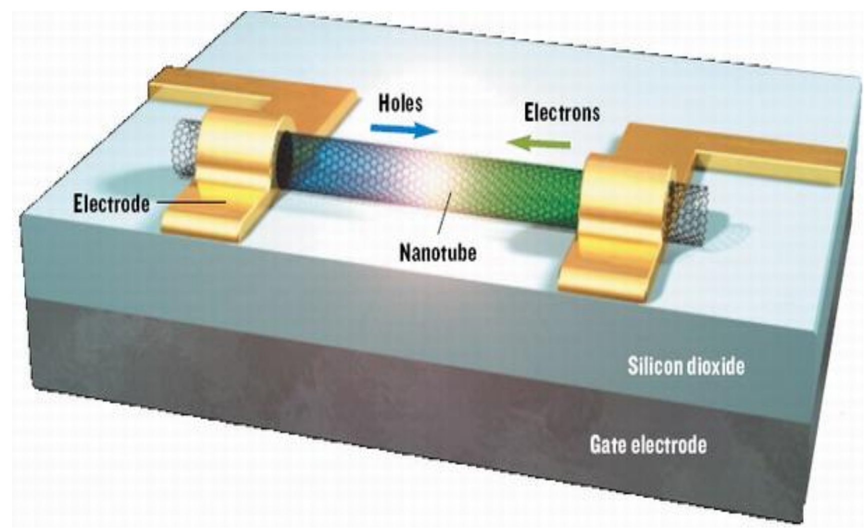
	Bandgap (eV)	Electron Mobility (cm^2/Vs)	Saturated Electron Velocity (107cm/s)	Thermal Conductivity (W/cm-K)
CNT	~0.9	100,000	>10	>30
InAs	0.36	33,000	0.04	0.27
Si	1.1	1,500	0.3	1.5
GaAs	1.42	8,500	0.4	0.5
InP	1.35	5,400	0.5	0.7
4HSiC	3.26	700	2.0	4.5
GaN	3.49	900	3.3	20

CNTFETs

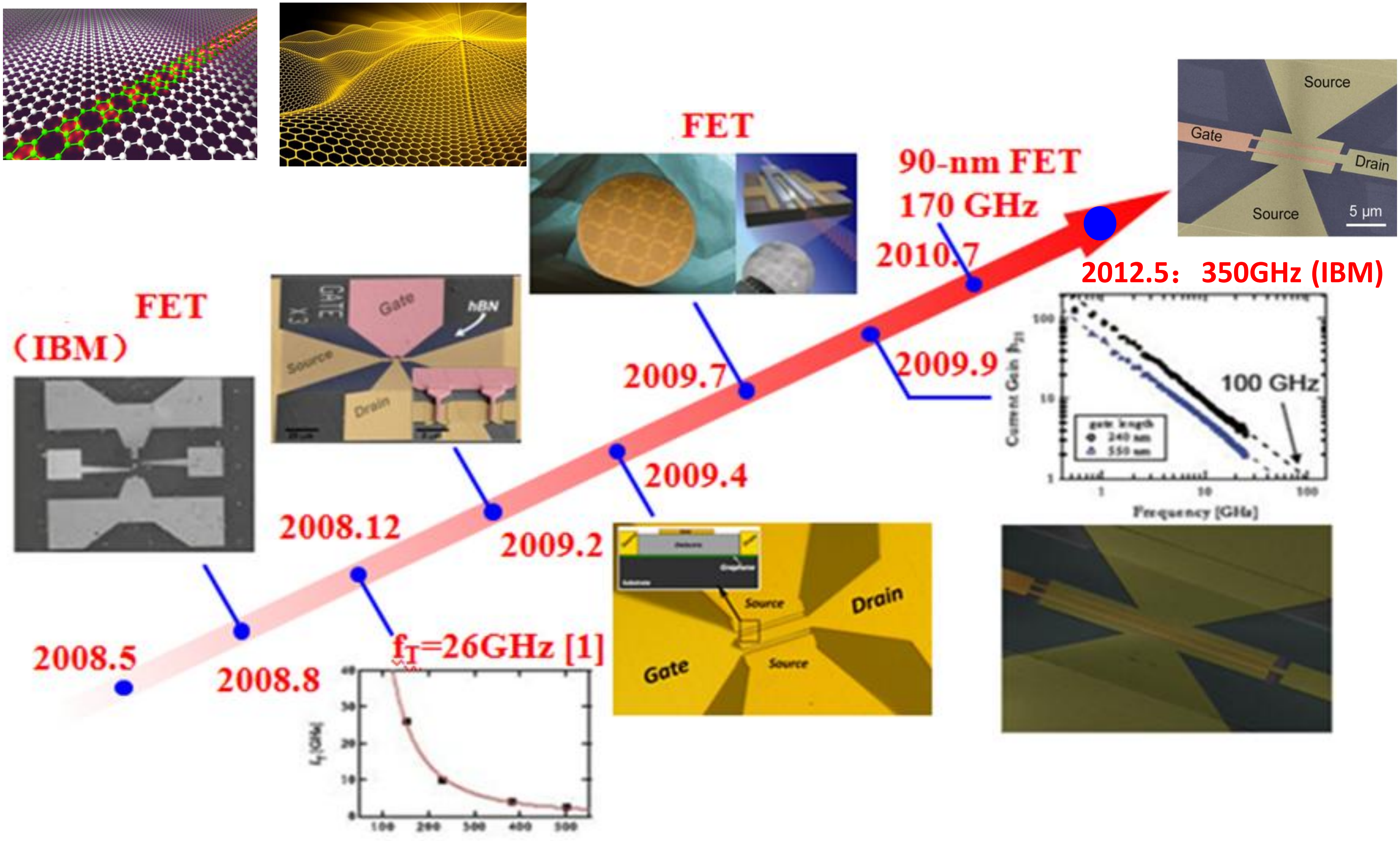

gate
source
drain
buried oxide
gate
source
drain
+
gate
source
drain


Source
Gate
Drain
Catalyst
Gate Oxide
CNT

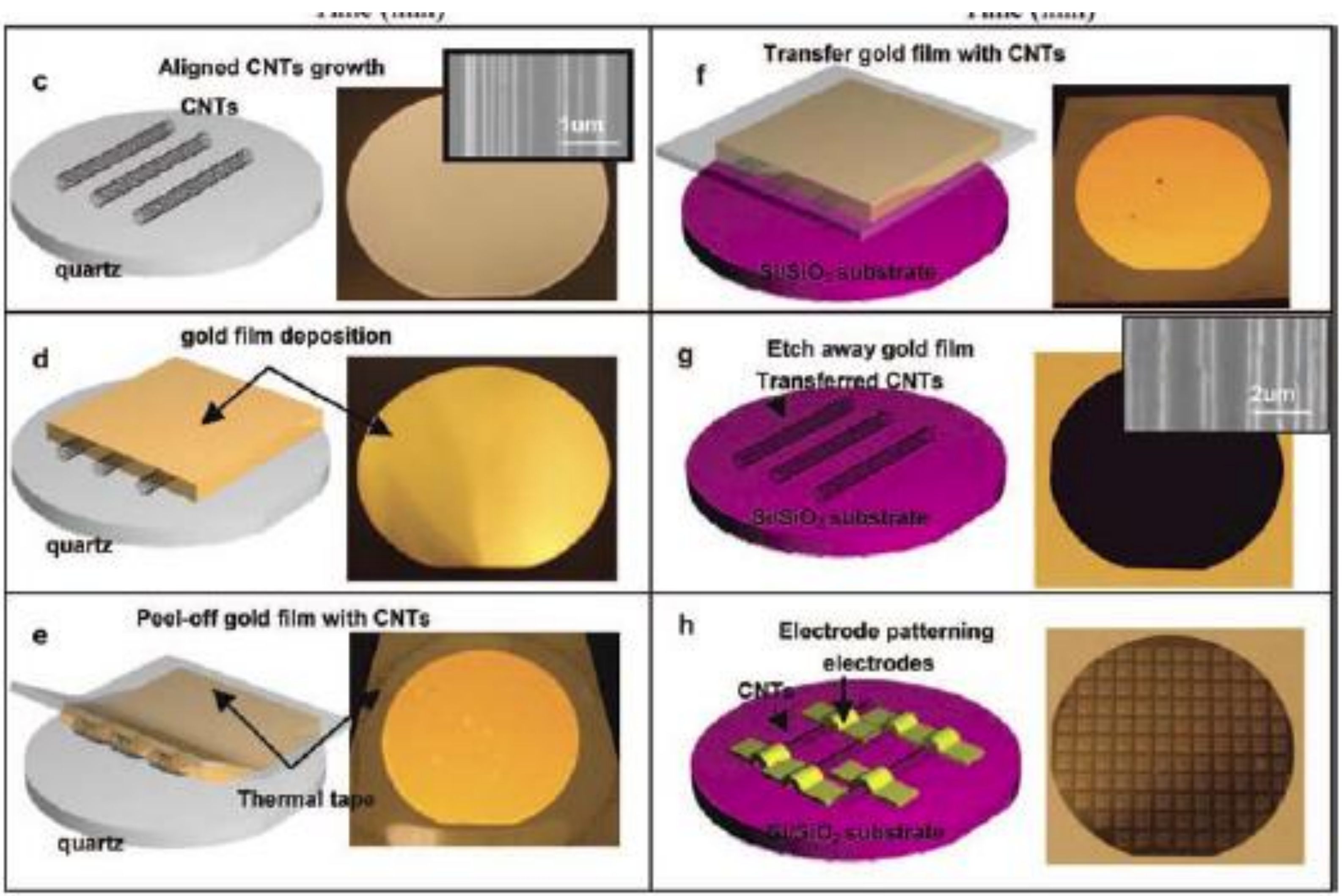

source
gate
drain


Holes
Electrons
Electrode
Nanotube
Silicon dioxide
Gate electrode

GFETs

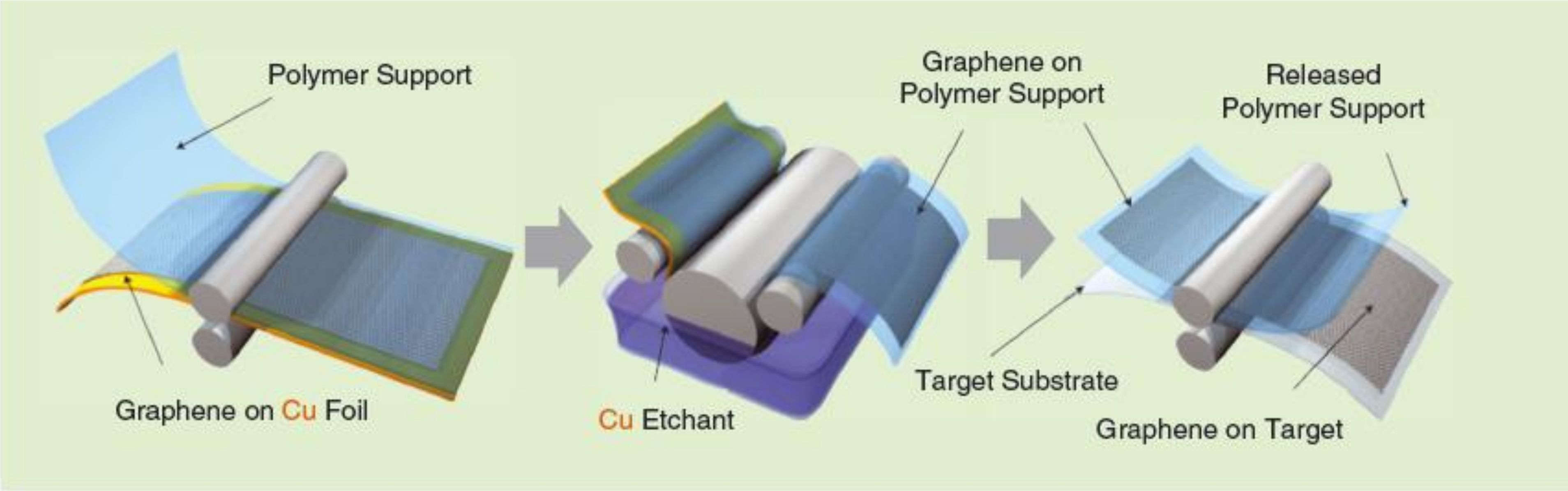

FET
(IBM)
2008.5
2008.8
2008.12
fT=26GHz [1]
Gate
hBN
Source
Drain
2009.2
2009.4
Source
Drain
Gate
Source
FET
2009.7
2009.9
100 GHz
Current Gain h21
Frequency (GHz)
90-nm FET
170 GHz
2010.7
2012.5：350GHz (IBM)
Source
Gate
Drain
Source
5 μm

CNT Fabrication



K. Ryu, and H.S.P. Wong, *et al*., *Nano Lett*., 9(1), 189-197, 2009.

Graphene Fabrication



Han Wang, et al, “Graphene electronics for RF Applications,” IEEE Microwave Magazine, June 2012.

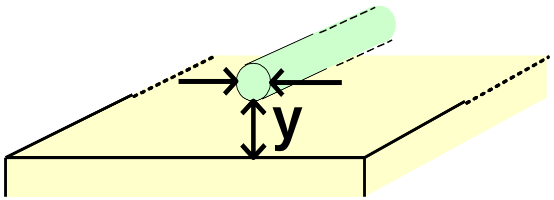
Electromagnetic Capability-Oriented Study on CNTLs

Multiphysics Issues:

Beyond Maxwell's Equations: Quantum Effects

Both Frequency- and Temperature-Dependent

Distributed Parameters of a SWCNT

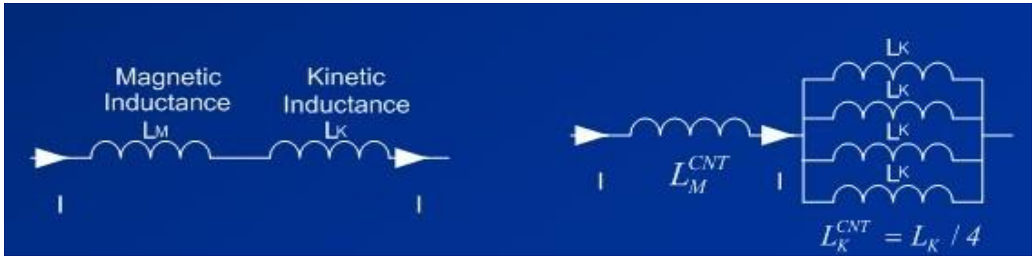


Kinetic Inductance

$$L_{k-CNT} = \frac{h}{2 v_F e^2}$$

$$L_K \approx 16\,nH/\mu m$$

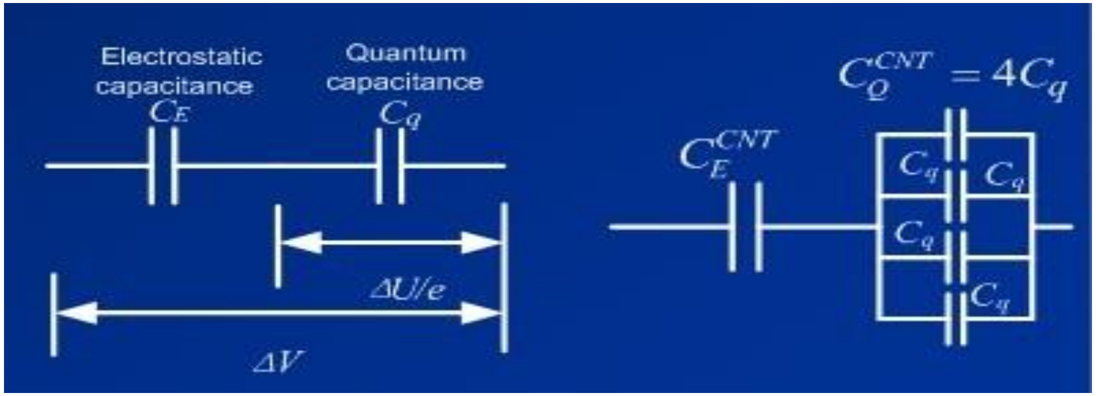
$$L_M^{CNT} = \frac{\mu}{2\pi} \ln\left(\frac{y}{d}\right)$$



Quantum Capacitance

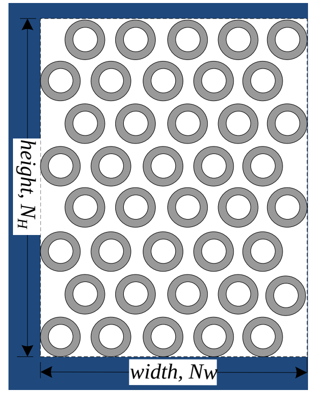
$$C_Q = \frac{\Delta Q}{\Delta V} \sim 96\,aF/\mu m$$

$$C_E = \frac{2\pi\varepsilon}{\ln(2h/d)}$$



SWCNT Bundle

$$R_{CNT} = R_C + R_Q\left(1 + \frac{\ell_{CNT}}{\ell_{mfp}}\right)$$
$$= (R_C + R_Q) + \frac{R_Q}{\ell_{mfp}}\ell_{CNT}$$
$$= R_l + R_d \ell_{CNT};$$



Quantum Resistance

$$R_Q = 6.45K\Omega$$

Contact Resistance

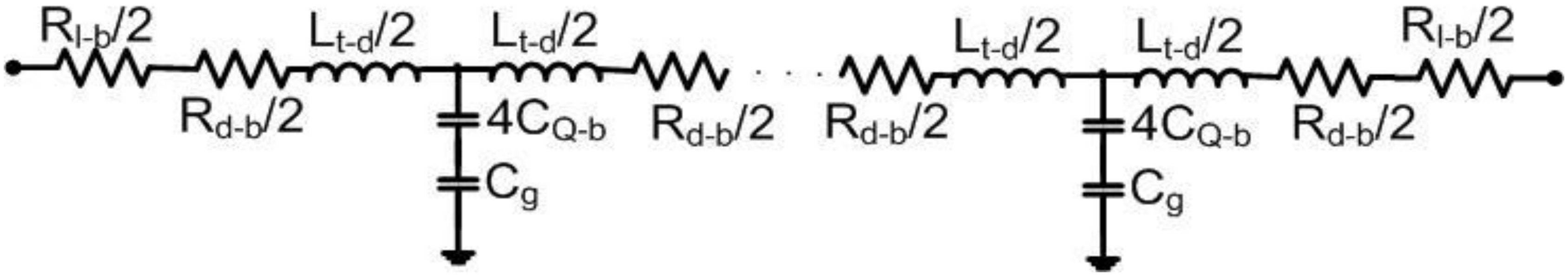
$$R_C$$

$$C_{Q-b} = C_Q \cdot n_{CNT}$$

$$L_{k-b} = \frac{L_{k-CNT}}{4n_{CNT}}$$

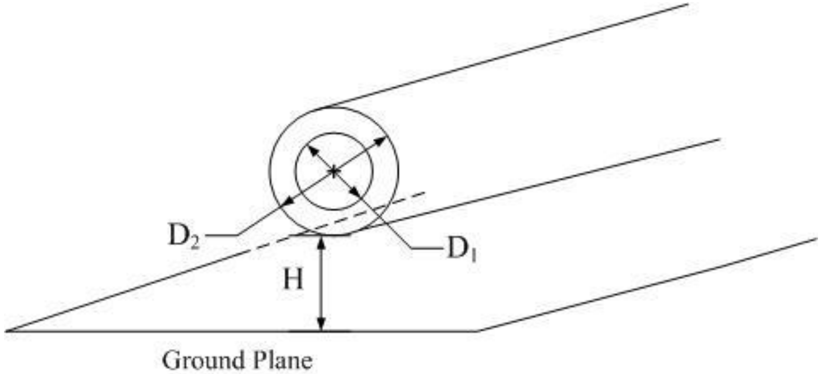
$$R_b = \frac{R_{CNT}}{n_{CNT}} = \frac{(R_C + R_Q)}{n_{CNT}} + \frac{R_Q}{n_{CNT}\ell_{mfp}}\ell_{CNT} = R_{lb} + R_{db}\ell_{CNT};$$

$$L_t = \frac{L_{k-b} + L_{M-b}}{\ell_{CNT}} \cdot \ell_{CNT} = L_{t-d} \cdot \ell_{CNT}.$$



Equivalent circuit model of a SWCNT bundle

DWCNT



$$C_{CM} = \frac{2\pi\varepsilon}{\ln(D_2 / D_1)};$$

$$C_{CM-b} = C_{CM} \cdot n'_{CNT};$$

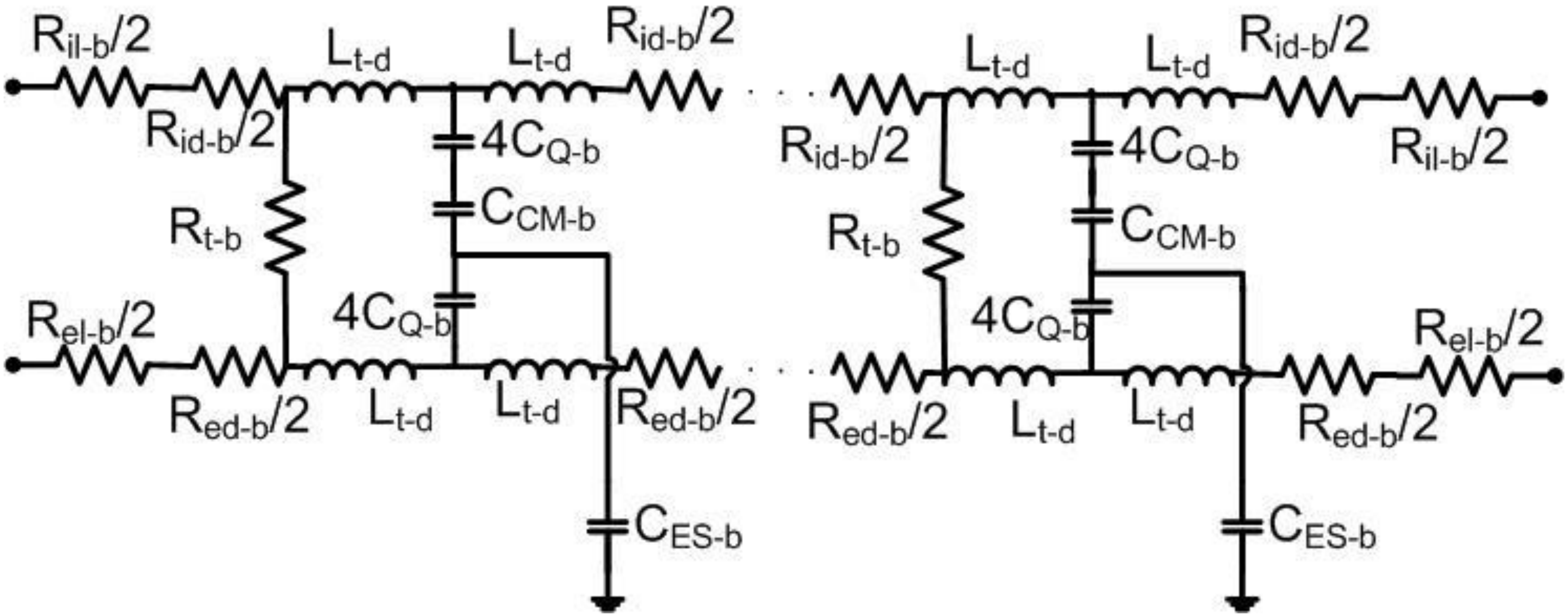
$$C_{ES-b} = C_{ESext} \cdot n'_{CNT};$$

$$C_{Q-b} = C_Q \cdot n'_{CNT}.$$

$$R_{i-b} = \frac{R_{\text{int}}}{n'_{CNT}} = \frac{(R_C + R_{Qi})}{n'_{CNT}} + \frac{R_{Qi}}{n'_{CNT}\,\ell_{mfpi}}\ell_{CNT} = R_{il-b} + R_{id-b}\ell_{CNT};$$

$$R_{e-b} = \frac{R_{ext}}{n'_{CNT}} = \frac{(R_C + R_{Qe})}{n'_{CNT}} + \frac{R_{Qe}}{n'_{CNT}\,\ell_{mfpe}}\ell_{CNT} = R_{el-b} + R_{ed-b}\ell_{CNT}.$$

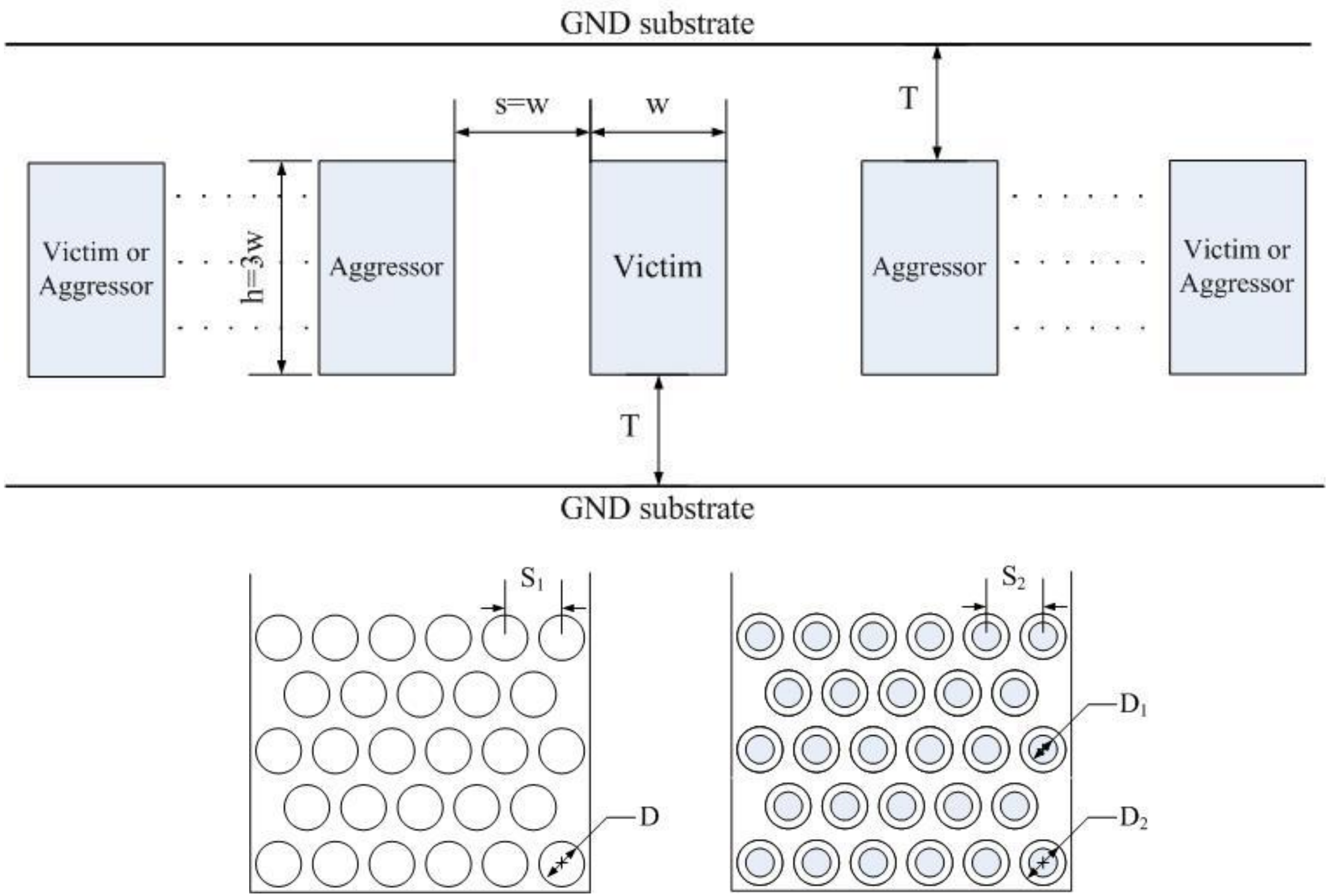
DWCNT Bundle



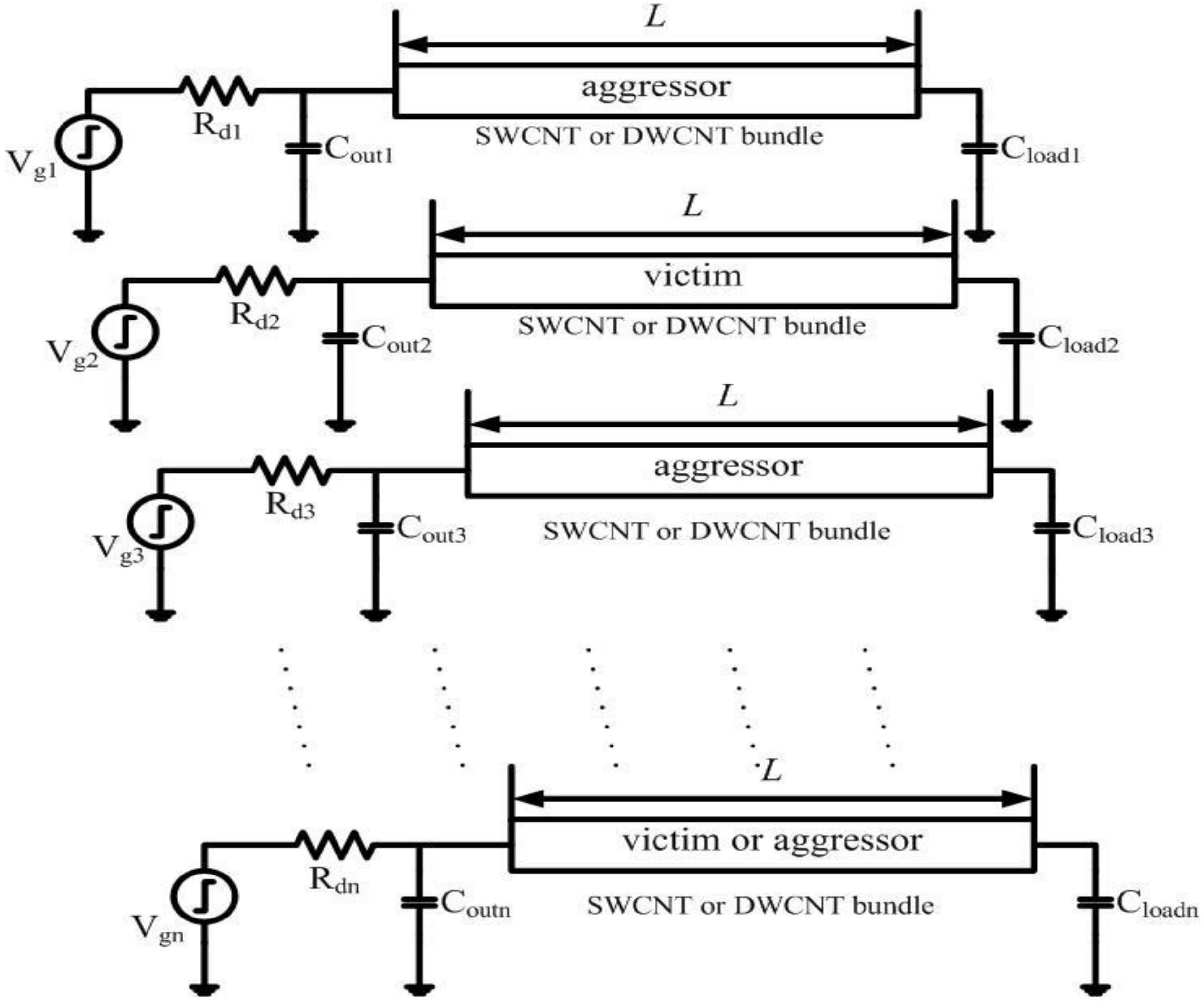
Equivalent circuit model of a DWCNT bundle

S. N. Pu, Wen-Yan Yin, J. F. Mao, *et al.* , "Crosstalk prediction of single and double-walled carbon nanotube(SWCNT/DWCNT) bundle interconnects," *IEEE Trans. Electron Devices,* 56(4), 560-568, 2009

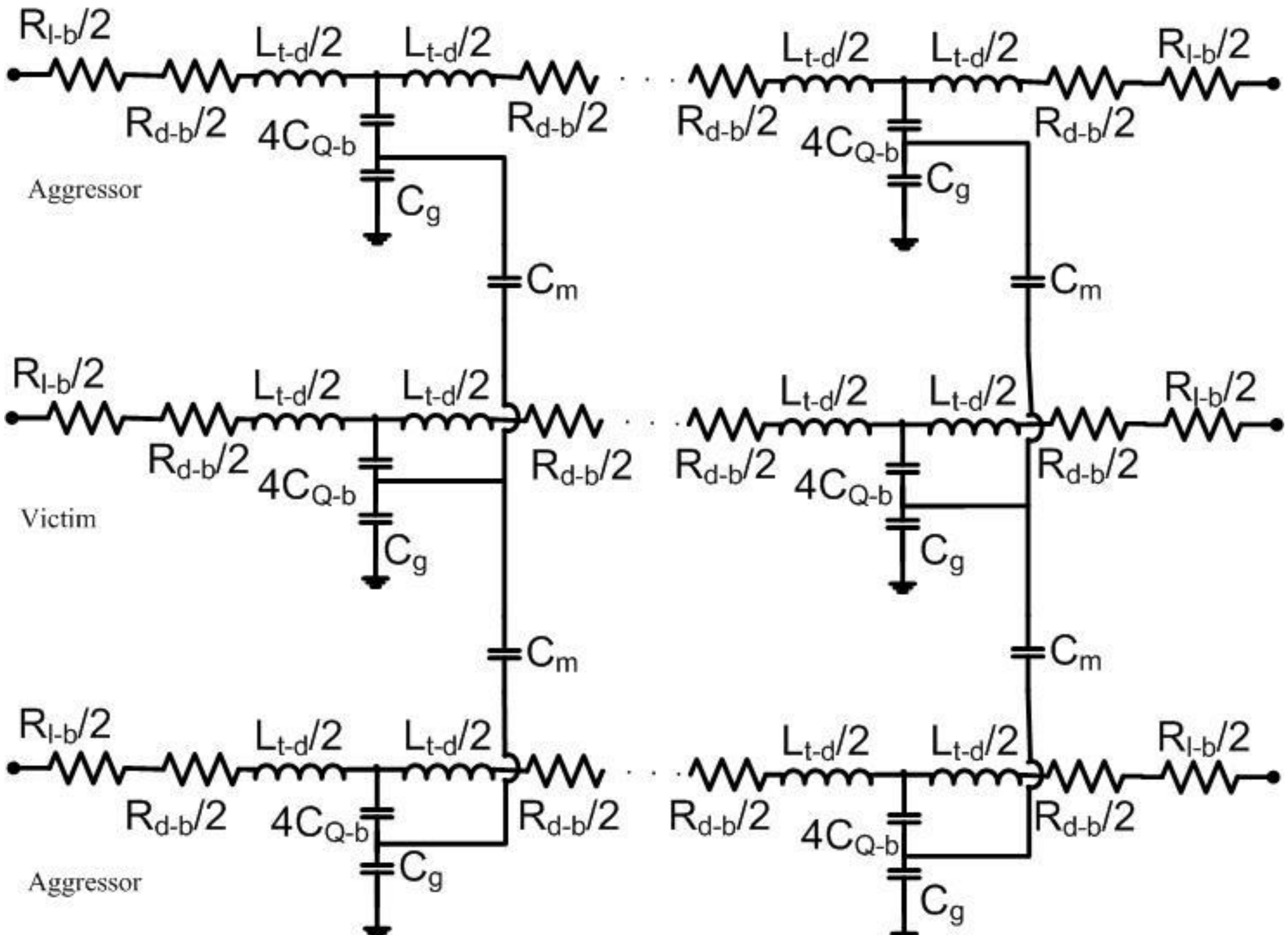
DWCNT Bundle TL



Multi-SWCNT/DWCNT Bundle TL

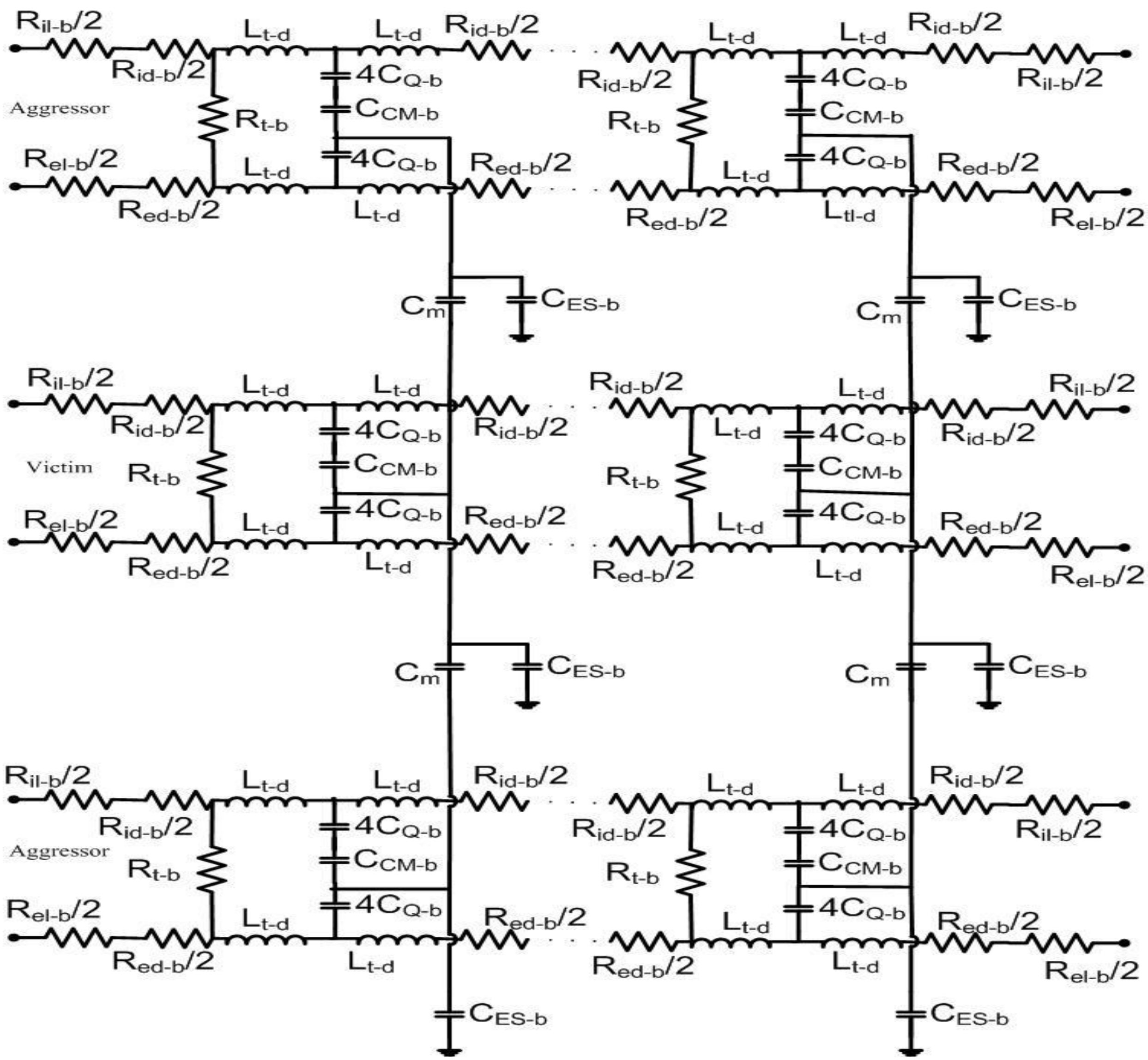


Tri-SWCNT Bundle TL



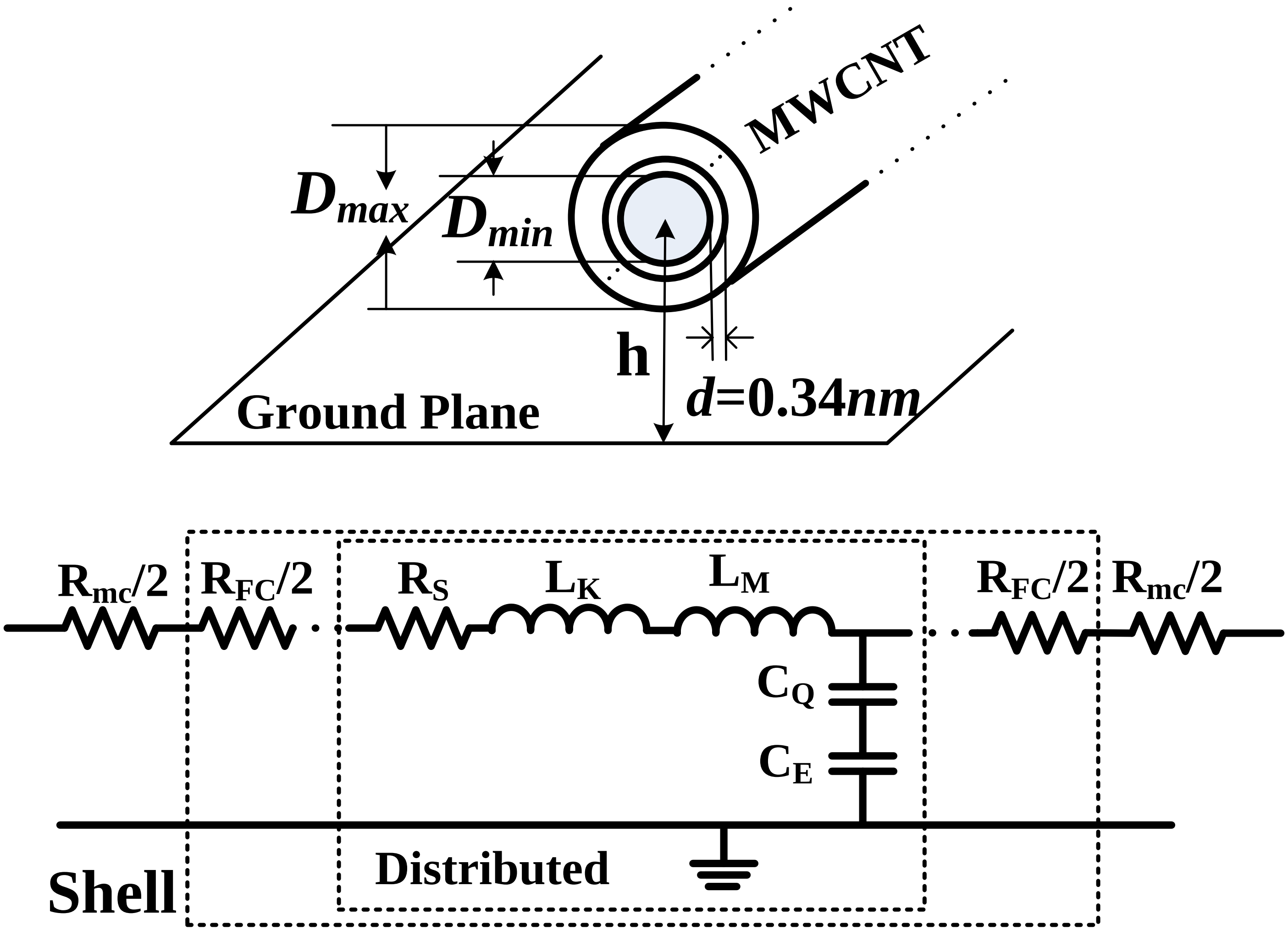
Equivalent circuit model of a tri-SWCNT bundle interconnect.

Tri-DWCNT Bundle TL



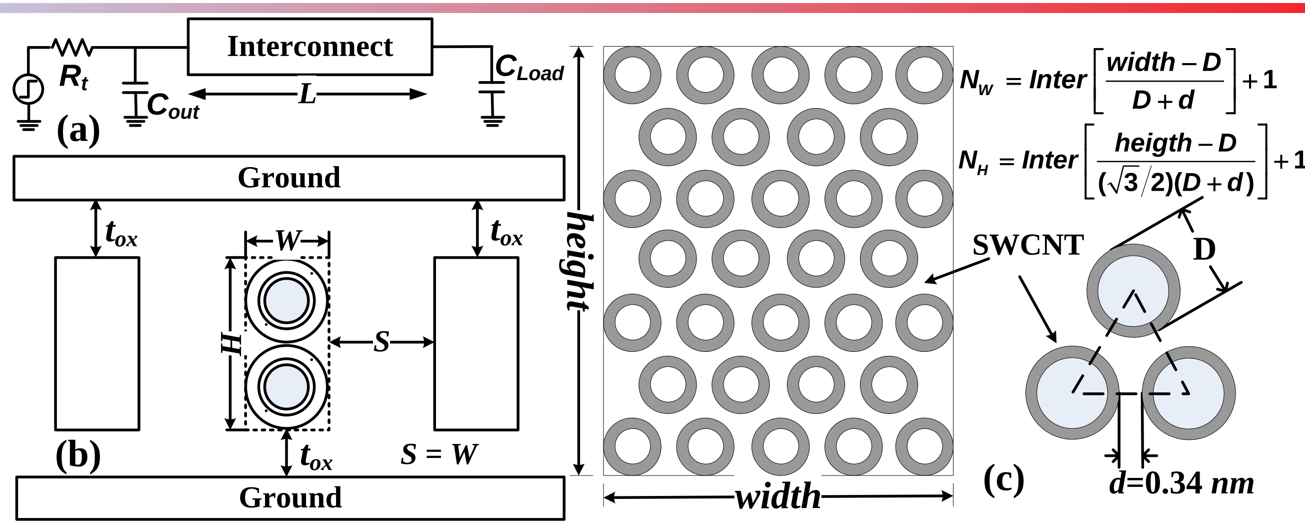
Equivalent circuit model of a tri-DWCNT bundle interconnect.

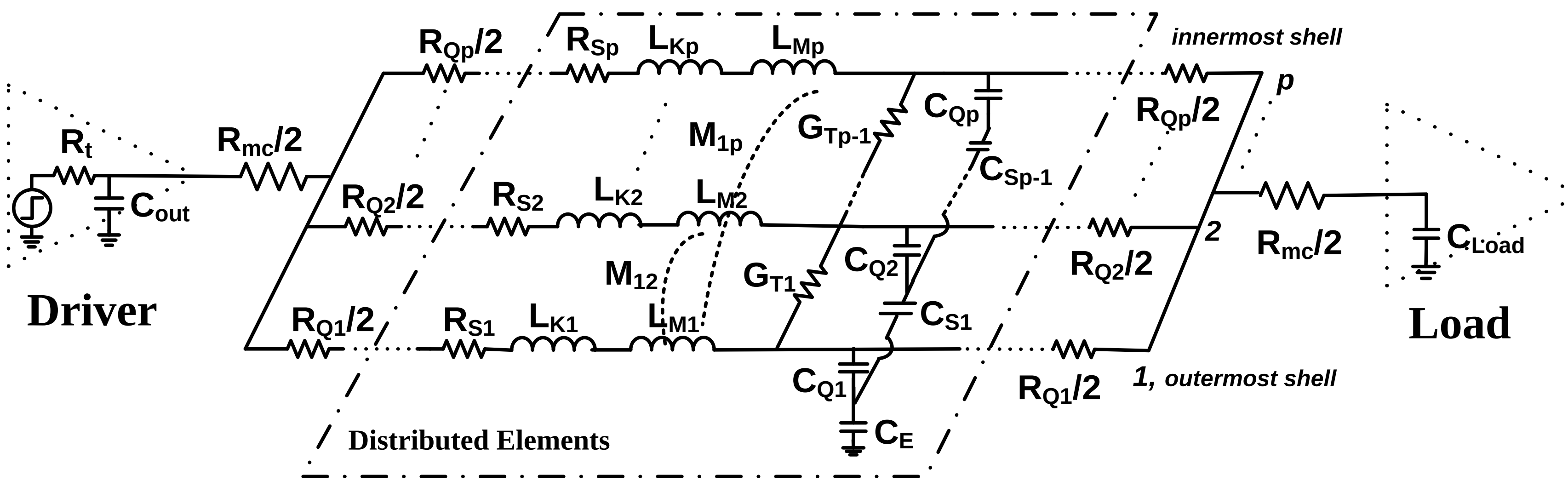
MWCNT TL



MWCNT
Dmax
Dmin
h
d=0.34nm
Ground Plane
Rmc/2
RFC/2
RS
LK
LM
CQ
CE
RFC/2
Rmc/2
Shell
Distributed

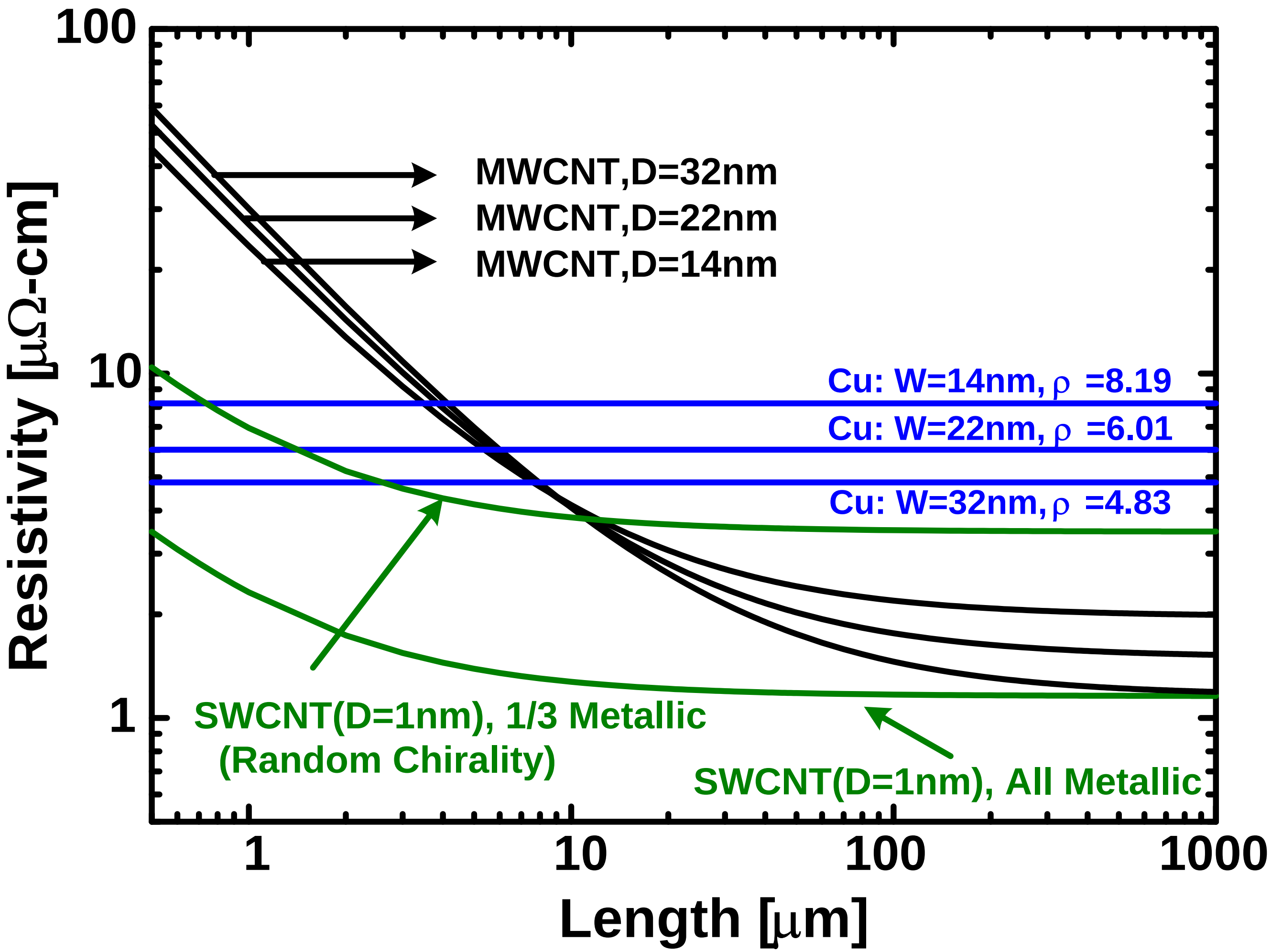
MWCNT Bundle TL





•H. Li, W. Y. Yin, J. F. Mao, and K. Banerjee, "Circuit modeling and performance analysis of multi-walled carbn nanotube(MWCNT)
•interconnects," *IEEE Trans. Electron Devices,* 55(6), 1328-1337, 2008.

Resistivity Comparison



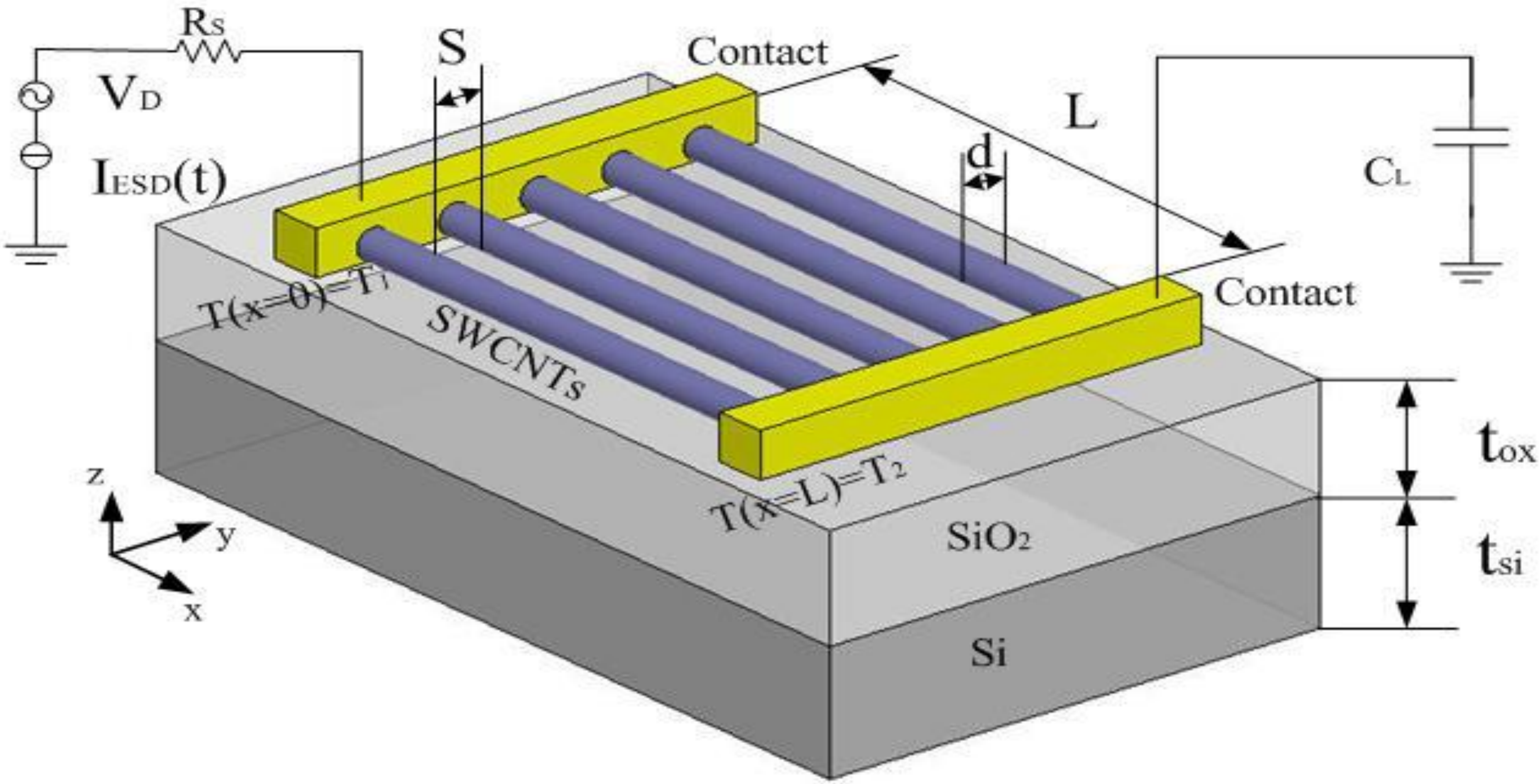
Comparison of resistivity among MWCNTs with various diameters, Cu wires with different dimensions, and SWNCT bundles with different chiralities. Dimension of Cu wires are adopted from ITRS. SWCNT bundles are assumed to be densely packed.

Problems

(1) How to get the breakdown voltage of a SWCNT?

(2) How to get the peak power handling capability of a SWCNT?

SWCNT ARRAY



Rs
VD
IESD(t)
S
Contact
L
d
CL
Contact
T(x=0)=T1
SWCNTs
T(x=L)=T2
tox
tsi
SiO2
Si
z
y
x

1-D Heat Conducting Equation

$$\begin{cases} \rho(T)c(T)\dfrac{dT(V,L,t)}{dt} = A\dfrac{d}{dx}[\kappa(T,L)\dfrac{d}{dx}T(V,L,t)] + p' - g(T-T_0) \\ T(x=0) = T_1 \\ T(x=L) = T_2 \end{cases}$$

$$p'(V,T(x),L) = I^2(V,T,L)\frac{dR(V,T(x),L)}{dx}\frac{h}{4q^2}\frac{1}{\lambda_{eff}(V,T(x),L)}$$

$$R(V,T,L) = R_C + \frac{h}{4q^2}\left[1 + \int_{-L/2}^{L/2}\frac{dx}{\lambda_{eff}(V,T(x),L)}\right]$$

elastic electron scattering of acoustic phonon

inelastic electron scattering caused by optical phonon emission

$$\lambda_{eff}(V,T(x),L) = \left(\lambda_{AC}^{-1} + \lambda_{OP,ems}^{-1} + \lambda_{OP,abs}^{-1}\right)^{-1}$$

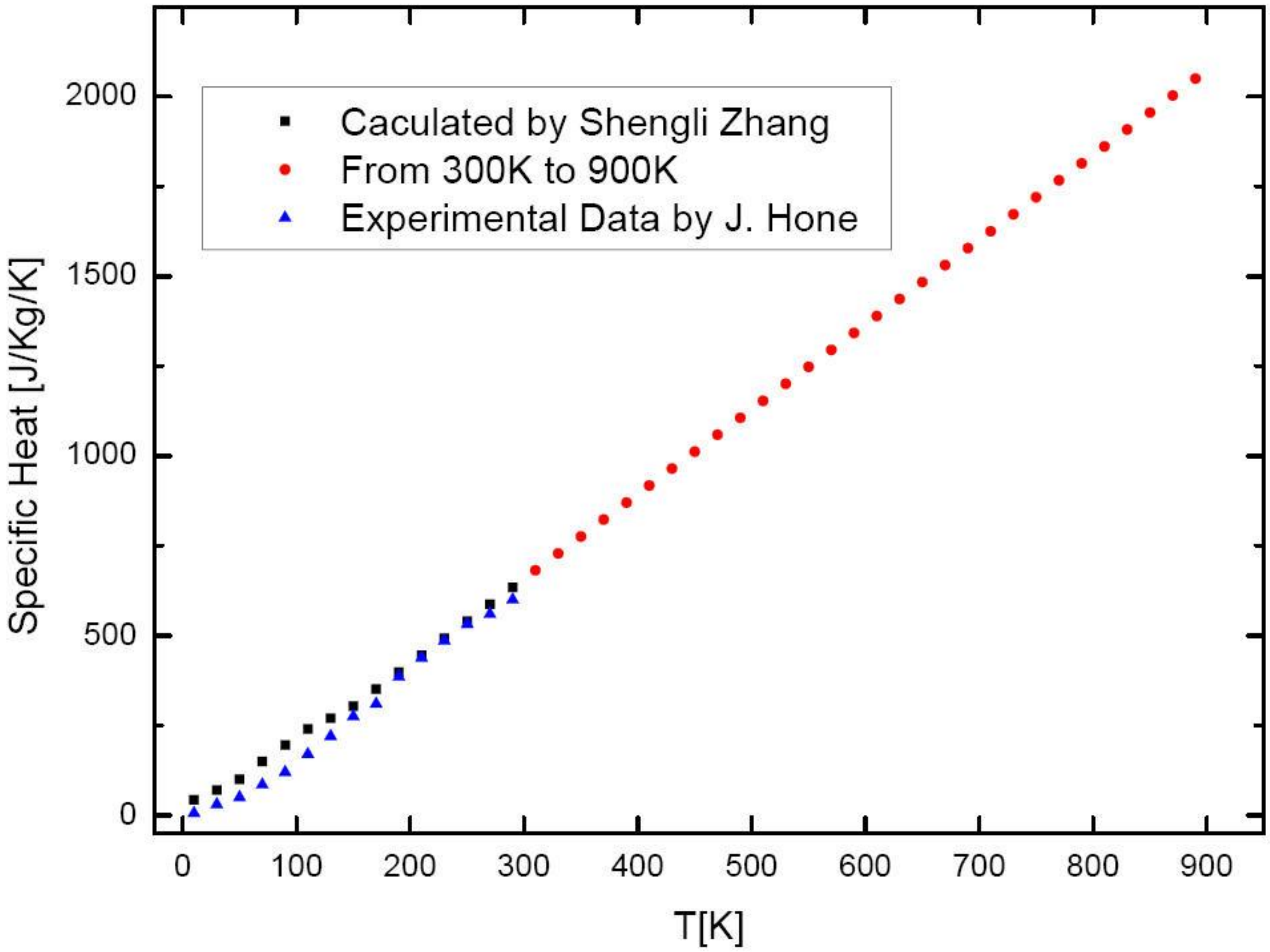
inelastic electron scattering caused by optical phonon absorption

$$\lambda_{AC} = \lambda_{AC,300}\left(\frac{300}{T}\right)$$

$$\lambda_{OP,ems} = \left(1/\lambda_{OP,ems}^{fld} + 1/\lambda_{OP,ems}^{abs}\right)^{-1}$$

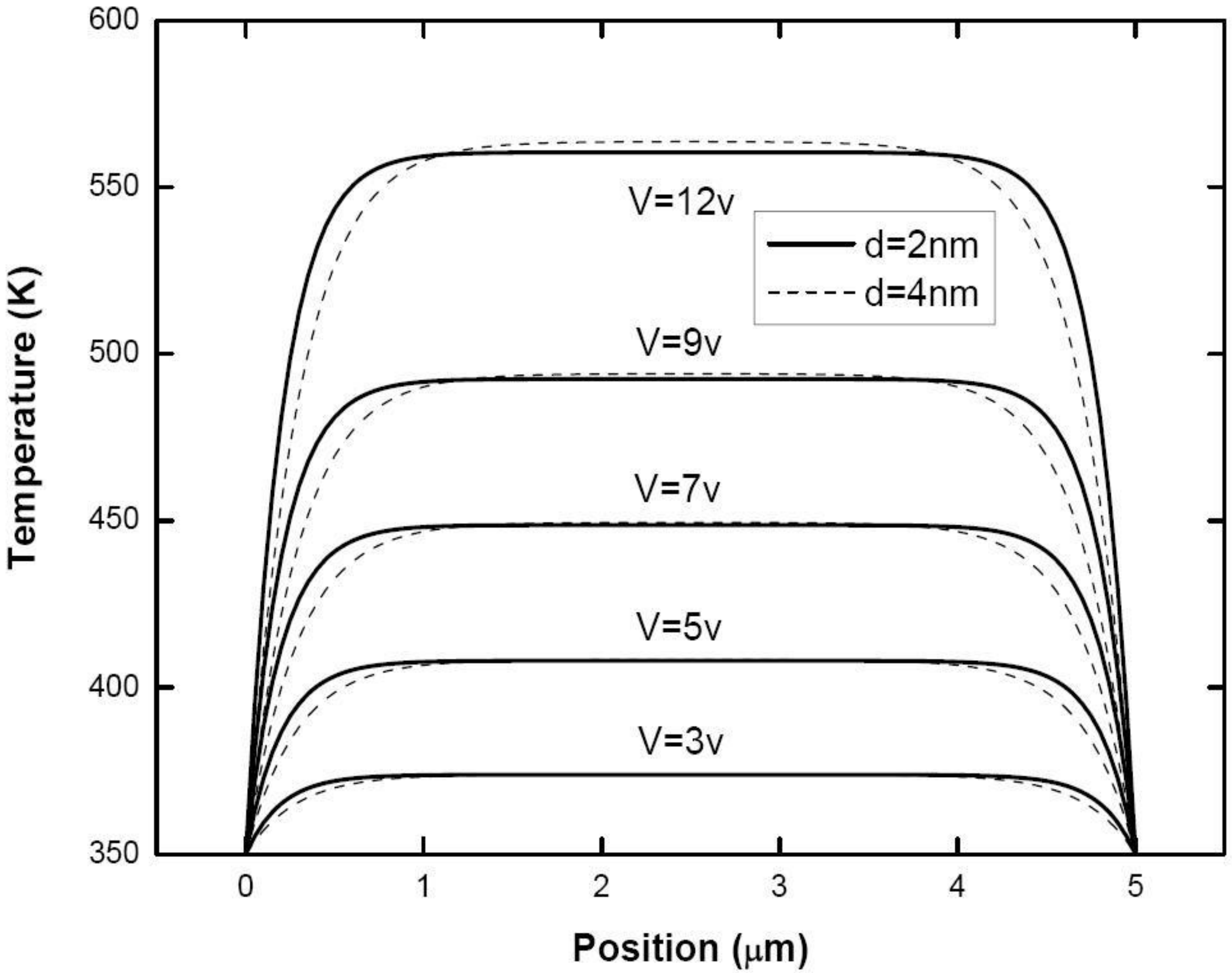
$$\kappa(T,L) = [3.7\times10^{-7}T + 9.7\times10^{-10}T^2 + 9.3(1+0.5/L)T^{-2}]^{-1}$$

Specific Heat



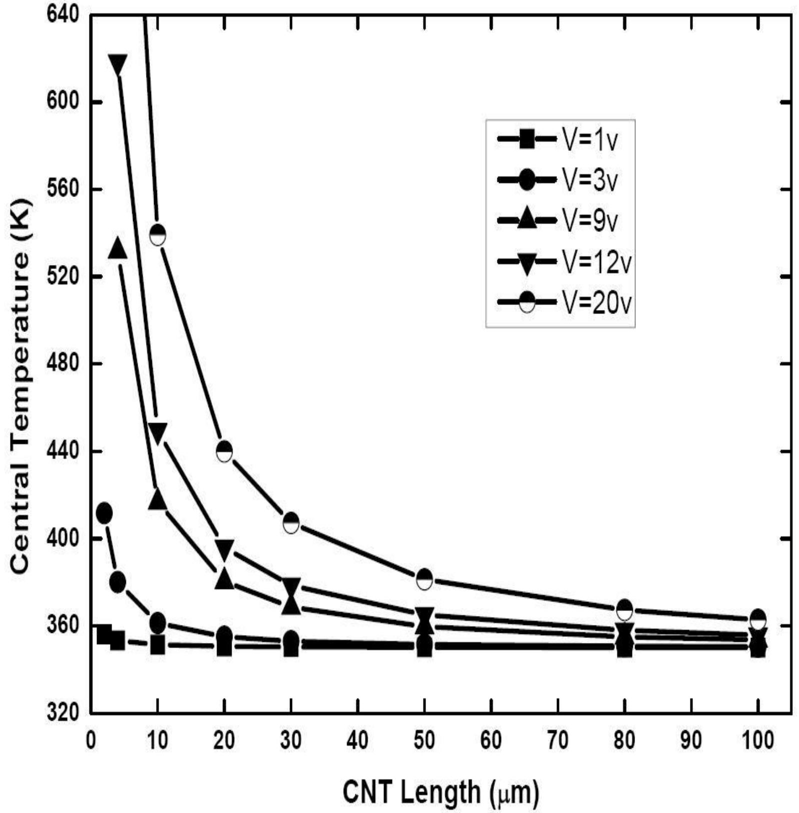
Specific heat of a SWCNT as a function of temperature

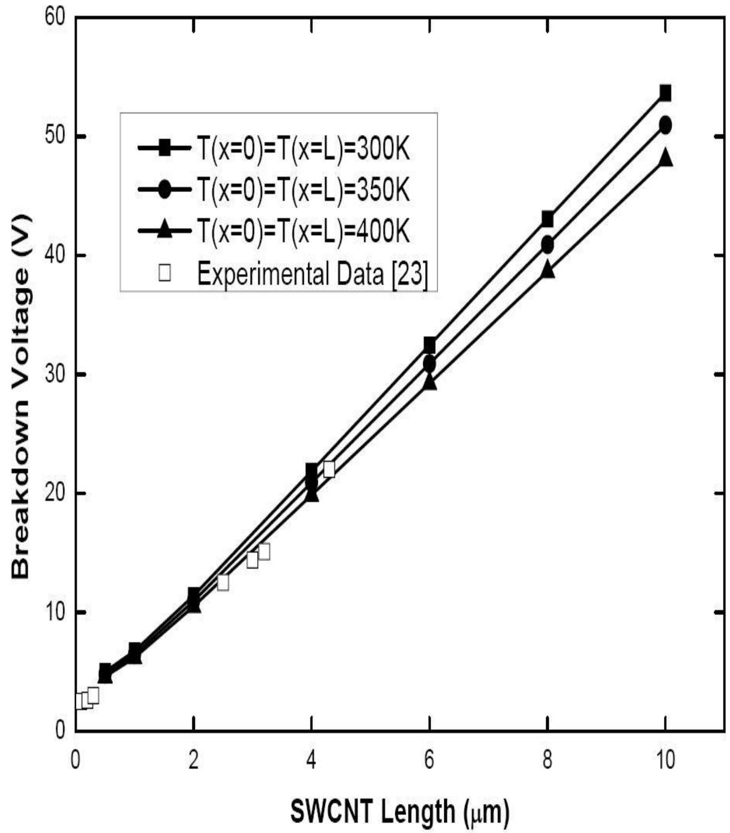
Temperature Distribution



Longitudinal temperature distribution along single SWCNT in a SWCNT array biased by different voltages, respectively, where the total contact resistance is assumed to be 100Kohm.

Breakdown Voltage

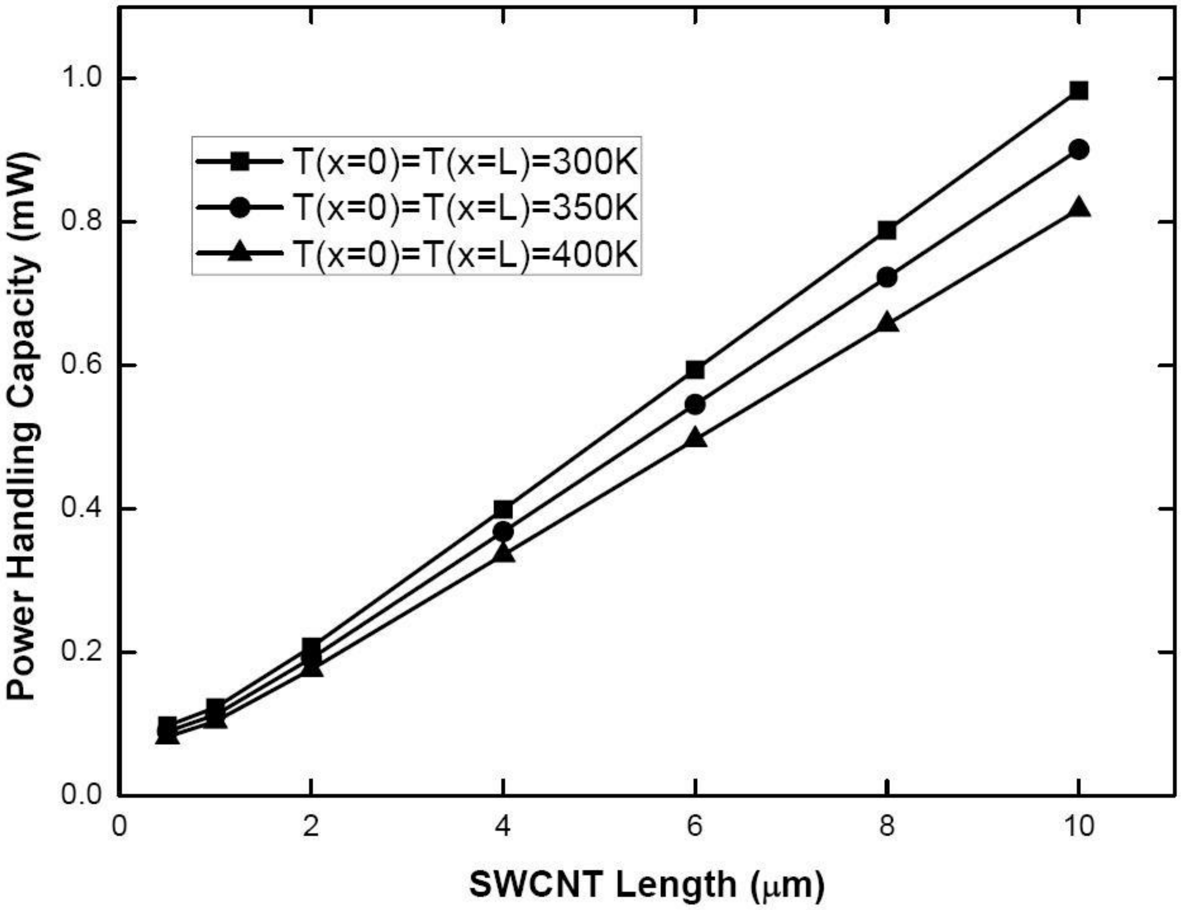




The highest central temperature of the SWCNTs in the array as a function of length biased by different voltage, respectively.

Breakdown voltage of the SWNCT local interconnect as a function of its length for different ambient temperatures at the input and output of the array, respectively.

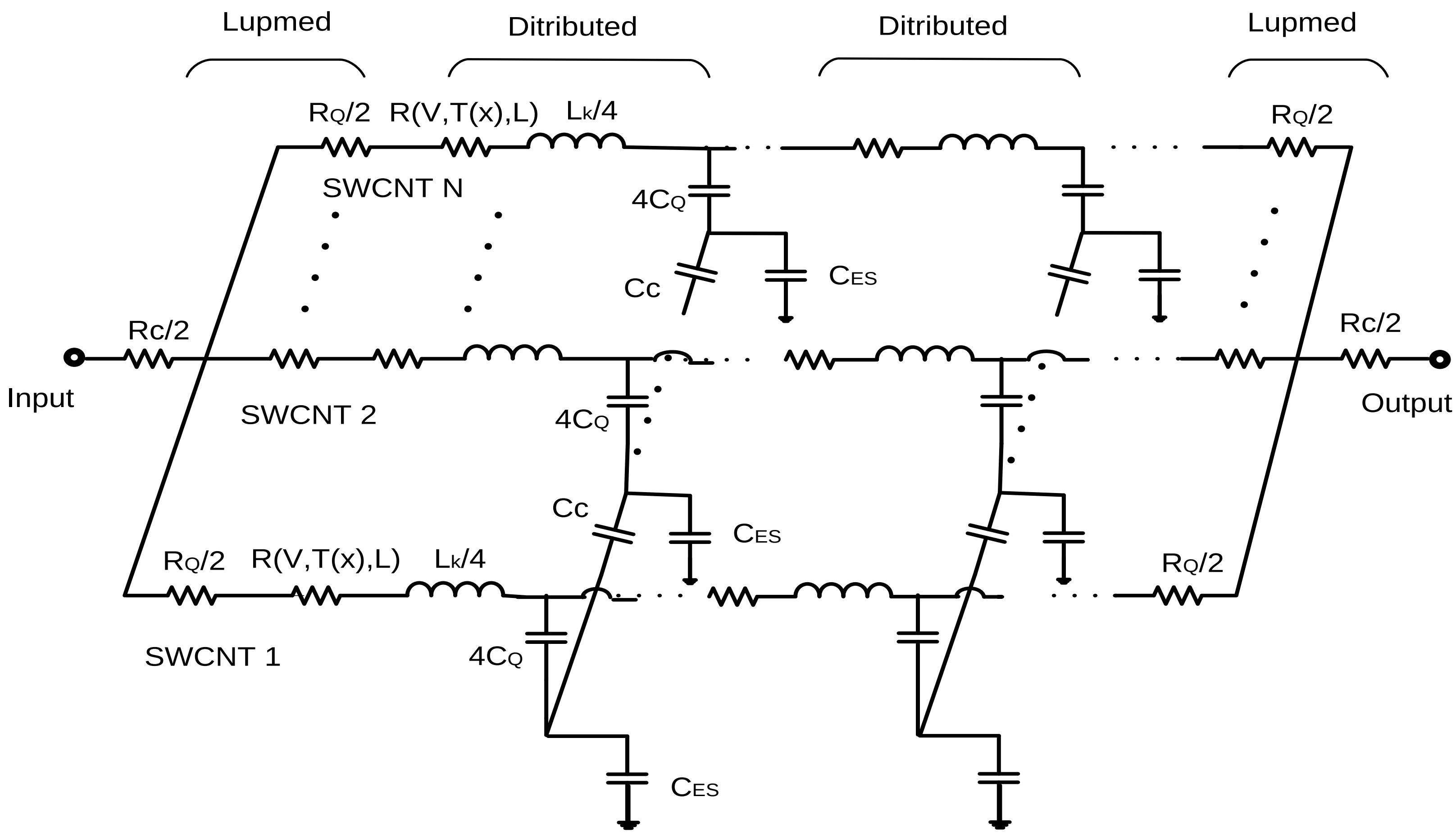
Power Handling Capability



Power handling capacity of the SWNCT local interconnect as a function of its length for different ambient temperatures at the input and output of the array, respectively.

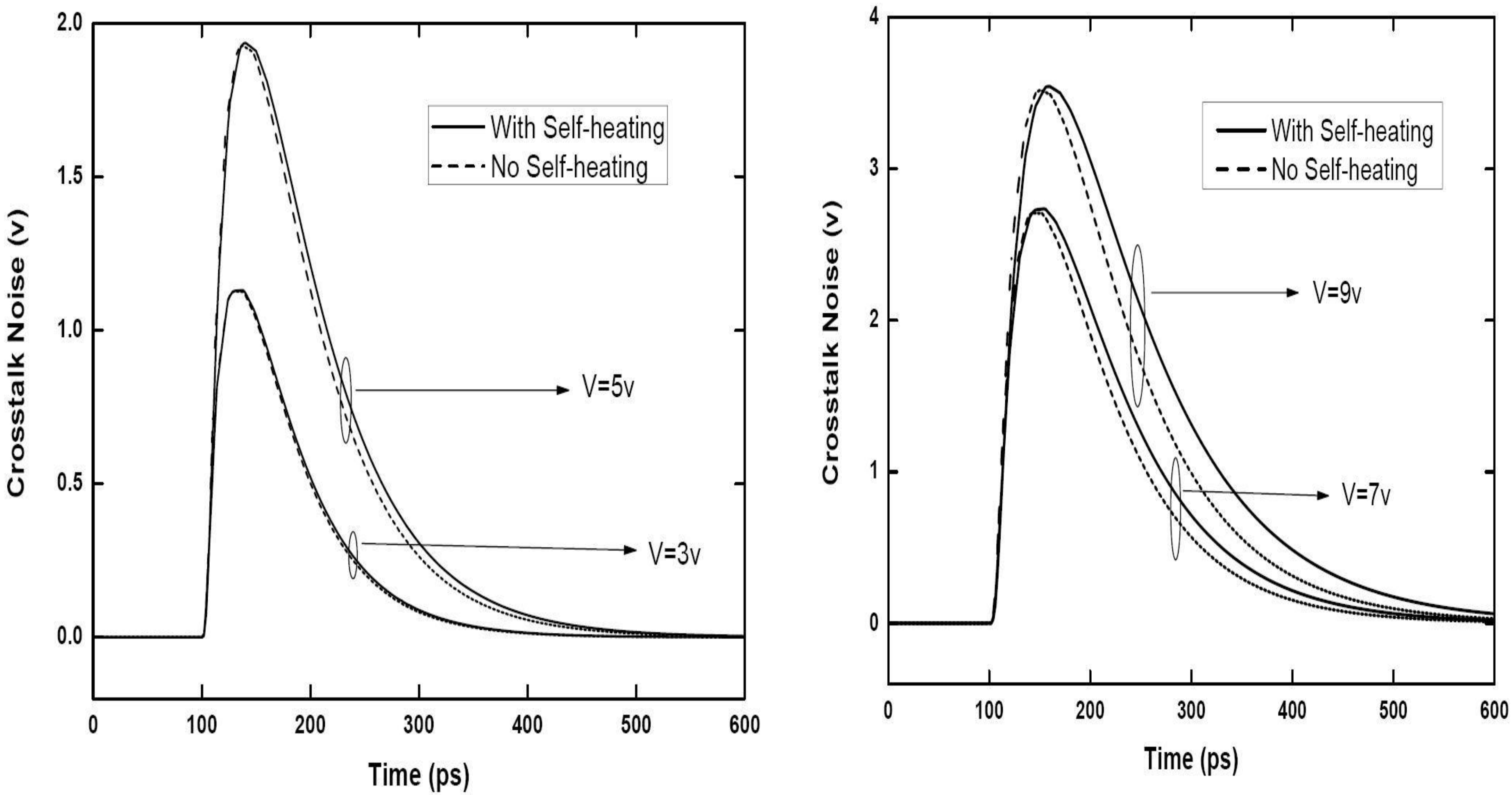
W. C. Chen, W. Y. Yin, *et al*., "Electrothermal characterization of single-walled carbon nanotube (SWCNT) interconnect arrays," *IEEE Trans. Nanotechnology*, 8(6), 718-728, 2009.

Electro-thermal Equivalent Circuit Model



Electro-thermal equivalent circuit model of a metallic SWCNT N-array.

Self-heating Effect



Crosstalk noise on the victim line in various biasing conditions with SWCNT length of 5 um.