Device design parameters for carbon nanotube field-effect transistors

Aníbal Pacheco-Sánchez[1], Michael Schröter[1,2]
Anibal.Pacheco-Sanchez@tu-dresden.de

[1]Chair for Electron Devices and Integrated Circuits,
Technische Universität Dresden, Germany.
[2]Electrical and Computer Engineering Department,
University of California, San Diego, CA, U.S.A.

NanoSpain 2018
Bilbao, Spain, March 13-15, 2018

Motivation

Claims about CNTFETs [1]

1. Analog HF applications are the most suitable entry point for carbon nanotube field-effect transistors (CNTFETs).
2. Device linearity is most valuable for HF applications.

[1] M. Schröter et al., "Carbon nanotube FET technology for radio-frequency electronics: State-of-the-art overview (invited)", IEEE J. Electron Dev. Soc., 1(1), 2013.

Motivation

Claims about CNTFETs [1]

1. Analog HF applications are the most suitable entry point for carbon nanotube field-effect transistors (CNTFETs).
2. Device linearity is most valuable for HF applications.

Challenges

1. Provide access to intrinsic material properties in fabricated devices, i.e., characterize metal-CNT interfaces and transport properties.
2. Use CNTFETs for applications

[1] M. Schröter et al., "Carbon nanotube FET technology for radio-frequency electronics: State-of-the-art overview (invited)", IEEE J. Electron Dev. Soc., 1(1), 2013.

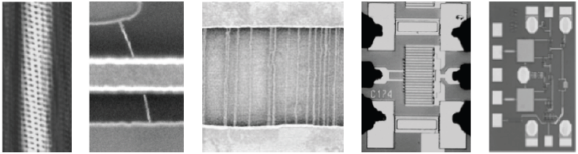
Motivation

Claims about CNTFETs [1]

1. Analog HF applications are the most suitable entry point for carbon nanotube field-effect transistors (CNTFETs).
2. Device linearity is most valuable for HF applications.

Challenges

1. Provide access to intrinsic material properties in fabricated devices, i.e., characterize metal-CNT interfaces and transport properties.
2. Use CNTFETs for applications



from materials science to system engineering!

[1] M. Schröter et al., "Carbon nanotube FET technology for radio-frequency electronics: State-of-the-art overview (invited)", IEEE J. Electron Dev. Soc., 1(1), 2013.

Agenda

- Schottky barrier height
- Contact resistance
- Mobility
- Summary

Agenda

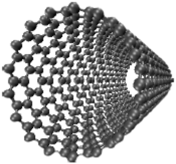
- Schottky barrier height
- Contact resistance
- Mobility
- Summary

others for offline discussion:

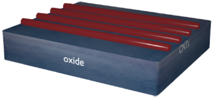
- Modeling tools: compact models and numerical device simulator
- Device modeling
- Current status of CNTFET technology for HF applications
- Electrical characterization: issues and challenges

CNTFETs in general

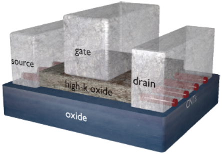
Transistor characteristics are affected by...



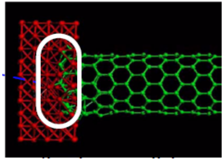
intrinsic properties



channel morphology



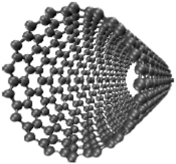
device architecture



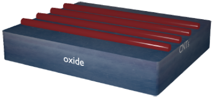
interface properties

CNTFETs in general

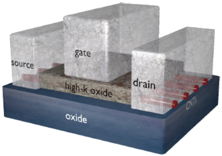
...and can be electrically characterized by



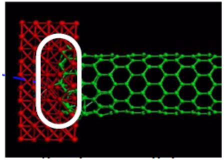
intrinsic properties
ballistic mobility, channel resistance



channel morphology
apparent mobility, channel resistance

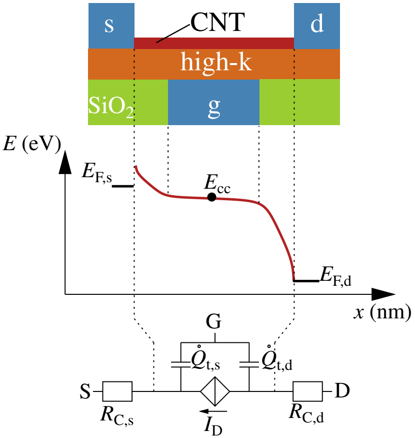


device architecture
extrinsic mobility, Schottky barrier height, contact and channel resistance



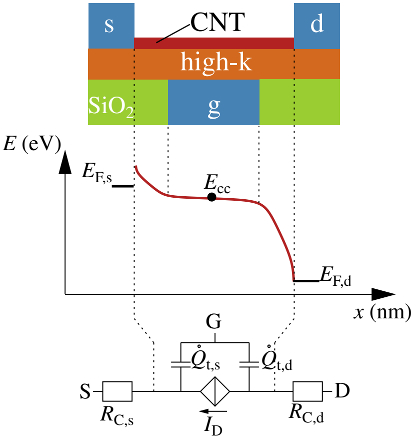
interface properties
Schottky barrier height, contact resistance

Schottky barrier CNTFETs (I)



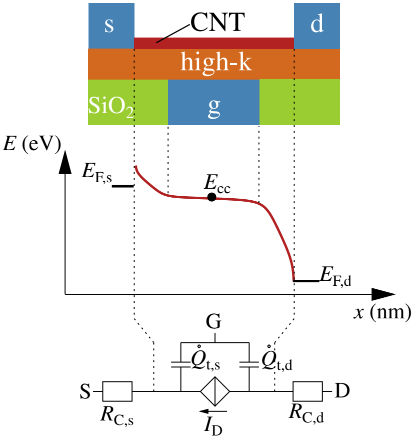
- SB CNTFETs are the most common devices

Schottky barrier CNTFETs (I)



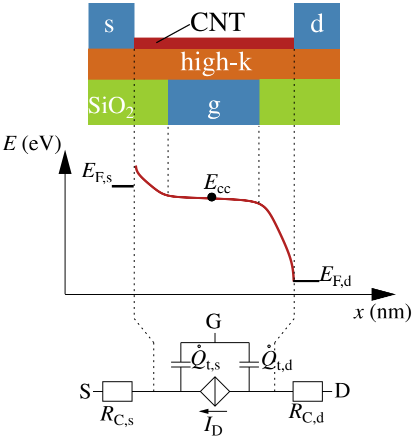
- SB CNTFETs are the most common devices
- different energies lead to potential barrier dominated by Schottky barrier (SB)

Schottky barrier CNTFETs (I)



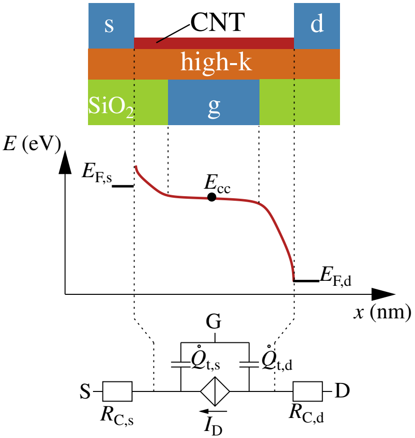
- SB CNTFETs are the most common devices
- different energies lead to potential barrier dominated by Schottky barrier (SB)
- thermionic and tunneling current depend on SB properties

Schottky barrier CNTFETs (I)



- SB CNTFETs are the most common devices
- different energies lead to potential barrier dominated by Schottky barrier (SB)
- thermionic and tunneling current depend on SB properties
- metal-CNT interface characterized by
  - Schottky barrier height Φ_{SB}
  - contact resistance $R_C = R_{C,s} + R_{C,d}$

Schottky barrier CNTFETs (I)

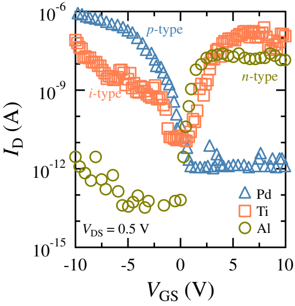


- SB CNTFETs are the most common devices
- different energies lead to potential barrier dominated by Schottky barrier (SB)
- thermionic and tunneling current depend on SB properties
- metal-CNT interface characterized by
  - Schottky barrier height Φ_{SB}
  - contact resistance $R_C = R_{C,s} + R_{C,d}$

$\Rightarrow$ values of Φ_{SB} and R_C are essential for technology development, model verification and circuit design studies

Schottky barrier CNTFETs (II)

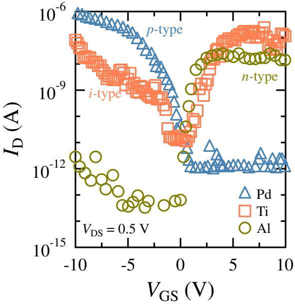
- Metal-CNT interface properties impact on the device behaviour [2]

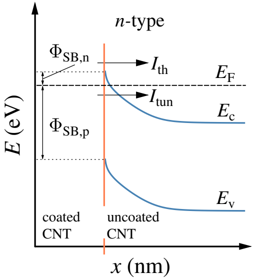


[2] M. H. Yang et al., "Carbon nanotube Schottky diode and directionally dependent field-effect transistor using asymmetrical contacts", Appl. Phys. Lett., 87, 2005.
[3] A. Fediai et al., "Towards an optimal contact metal for CNTFETs", Nanoscale, 8, 2016.

Schottky barrier CNTFETs (II)

- Metal-CNT interface properties impact on the device behaviour [2]

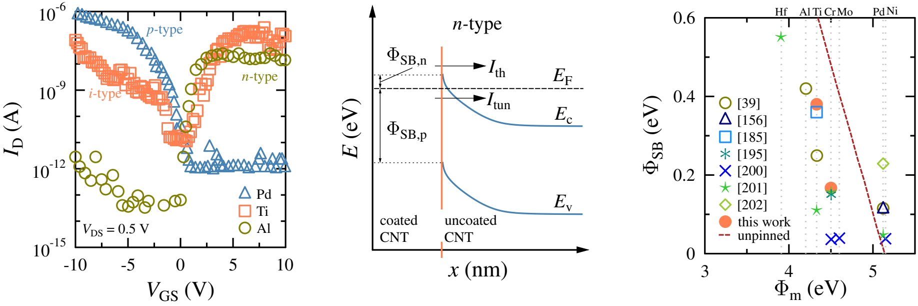




[2] M. H. Yang et al., "Carbon nanotube Schottky diode and directionally dependent field-effect transistor using asymmetrical contacts", Appl. Phys. Lett., 87, 2005.
[3] A. Fediai et al., "Towards an optimal contact metal for CNTFETs", Nanoscale, 8, 2016.

Schottky barrier CNTFETs (II)

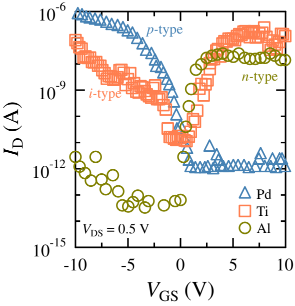
- Metal-CNT interface properties impact on the device behaviour [2]

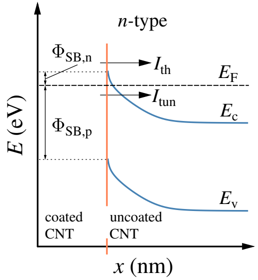


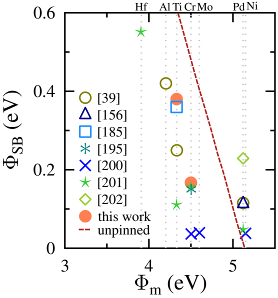
[2] M. H. Yang et al., "Carbon nanotube Schottky diode and directionally dependent field-effect transistor using asymmetrical contacts", Appl. Phys. Lett., 87, 2005.
[3] A. Fediai et al., "Towards an optimal contact metal for CNTFETs", Nanoscale, 8, 2016.

Schottky barrier CNTFETs (II)

- Metal-CNT interface properties impact on the device behaviour [2]





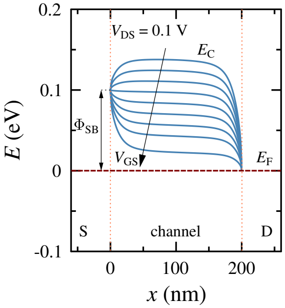


- Schottky-Mott theory predicts only contact type [3]
- extraction methods for Φ_{SB} are then required

[2] M. H. Yang et al., "Carbon nanotube Schottky diode and directionally dependent field-effect transistor using asymmetrical contacts", Appl. Phys. Lett., 87, 2005.
[3] A. Fediai et al., "Towards an optimal contact metal for CNTFETs", Nanoscale, 8, 2016.

Φ_{SB} extraction method

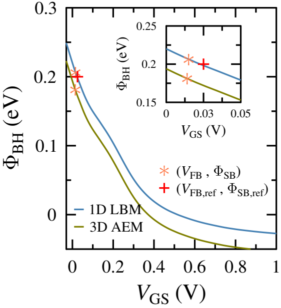
conventional 3D AEM vs. novel 1D LBM [4]



[4] A. Pacheco-Sanchez et al., "Device design-enabled Schottky barrier height extraction for nanoFETs based on the 1D Landauer-Büttiker equation", Appl. Phys. Lett., 111, 2017.

Φ_{SB} extraction method

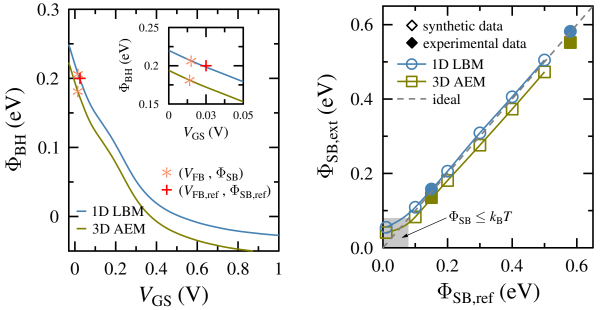
conventional 3D AEM vs. novel 1D LBM [4]



[4] A. Pacheco-Sanchez et al., "Device design-enabled Schottky barrier height extraction for nanoFETs based on the 1D Landauer-Büttiker equation", Appl. Phys. Lett., 111, 2017.

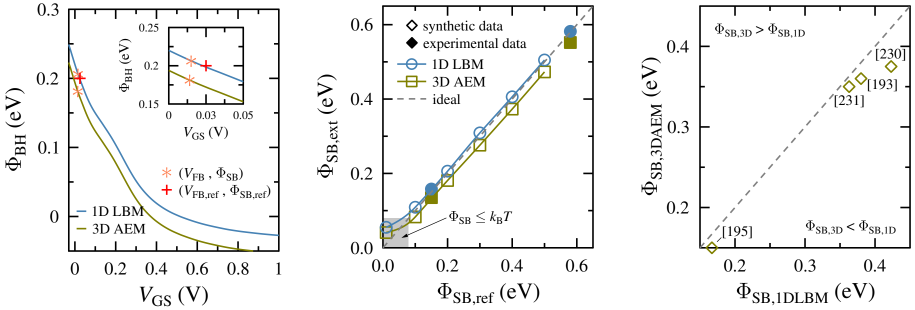
Φ_{SB} extraction method

conventional 3D AEM vs. novel 1D LBM [4]



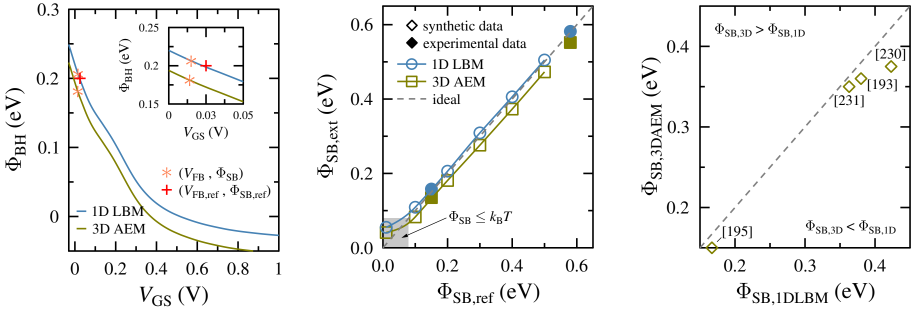
[4] A. Pacheco-Sanchez et al., "Device design-enabled Schottky barrier height extraction for nanoFETs based on the 1D Landauer-Büttiker equation", Appl. Phys. Lett., 111, 2017.

conventional 3D AEM vs. novel 1D LBM [4]



[4] A. Pacheco-Sanchez et al., "Device design-enabled Schottky barrier height extraction for nanoFETs based on the 1D Landauer-Büttiker equation", Appl. Phys. Lett., 111, 2017.

conventional 3D AEM vs. novel 1D LBM [4]



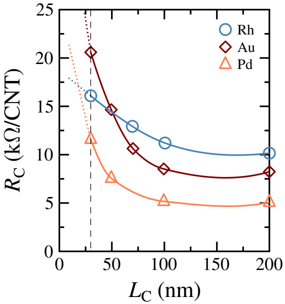
⇒ Superior reliability of 1D LBM over 3D AEM shown for synthetic and experimental data of nanoFETs with different gate architectures and channel materials

[4] A. Pacheco-Sanchez et al., "Device design-enabled Schottky barrier height extraction for nanoFETs based on the 1D Landauer-Büttiker equation", Appl. Phys. Lett., 111, 2017.

Contact resistance in CNTFETs

R_C is a convenient electrical representation of physical phenomenon at the metal-CNT interfaces indicating contact quality

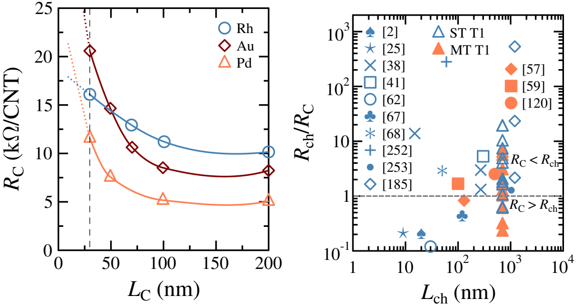
$$R_T = R_C$$



[5] A. D. Franklin et al., "Defining and Overcoming the Contact Resistance Challenge in Scaled Carbon Nanotube Transistors", ACS Nano, 8(7), 2014.
[6] A. Pacheco-Sanchez et al., "Contact resistance extraction methods for CNTFETs", ESSDERC, Graz, Austria, 2015.

R_C is a convenient electrical representation of physical phenomenon at the metal-CNT interfaces indicating contact quality

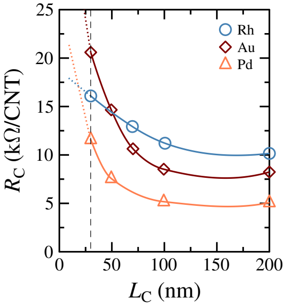
$$R_T = R_C \ (?)$$

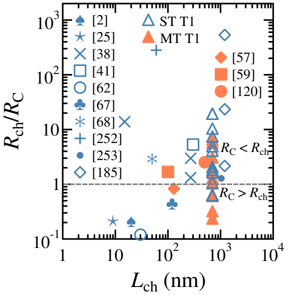


[5] A. D. Franklin et al., "Defining and Overcoming the Contact Resistance Challenge in Scaled Carbon Nanotube Transistors", ACS Nano, 8(7), 2014.
[6] A. Pacheco-Sanchez et al., "Contact resistance extraction methods for CNTFETs", ESSDERC, Graz, Austria, 2015.

R_C is a convenient electrical representation of physical phenomenon at the metal-CNT interfaces indicating contact quality

$$R_T \neq R_C$$
$$R_T = R_C + R_{ch}$$



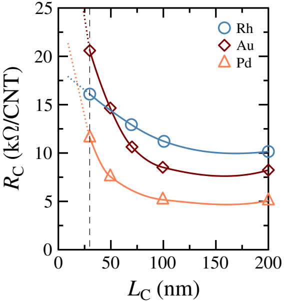


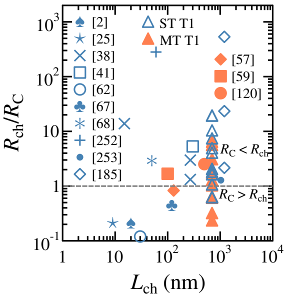
[5] A. D. Franklin et al., "Defining and Overcoming the Contact Resistance Challenge in Scaled Carbon Nanotube Transistors", ACS Nano, 8(7), 2014.
[6] A. Pacheco-Sanchez et al., "Contact resistance extraction methods for CNTFETs", ESSDERC, Graz, Austria, 2015.

R_C is a convenient electrical representation of physical phenomenon at the metal-CNT interfaces indicating contact quality

$$R_T \neq R_C$$
$$R_T = R_C + R_{ch}$$

- different trends in short and long contact [5] and channel [6] limits possible



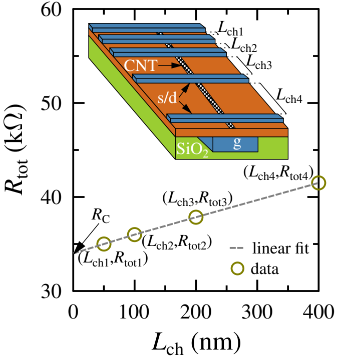


⇒ R_C extraction method for short- and long- ST/MT CNTFETs is needed

[5] A. D. Franklin et al., "Defining and Overcoming the Contact Resistance Challenge in Scaled Carbon Nanotube Transistors", ACS Nano, 8(7), 2014.
[6] A. Pacheco-Sanchez et al., "Contact resistance extraction methods for CNTFETs", ESSDERC, Graz, Austria, 2015.

R_C extraction methods in CNTFETs (I)

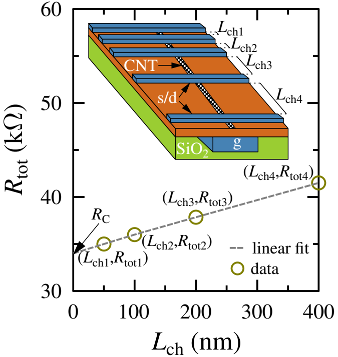
Transfer length method (TLM)



- Test structure with very long CNTs

R_C extraction methods in CNTFETs (I)

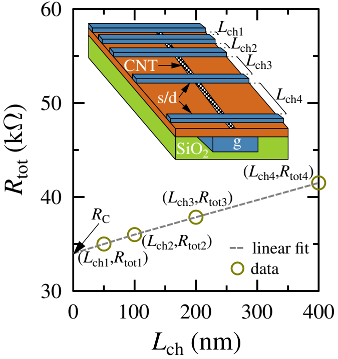
Transfer length method (TLM)



- Test structure with very long CNTs
  - challenging for DEP technologies

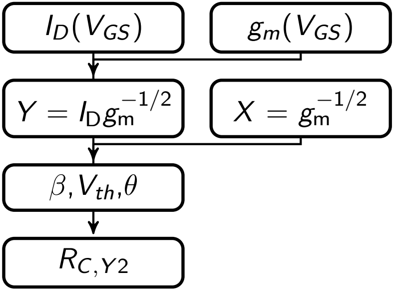
R_C extraction methods in CNTFETs (I)

Transfer length method (TLM)



- Test structure with very long CNTs
  - challenging for DEP technologies

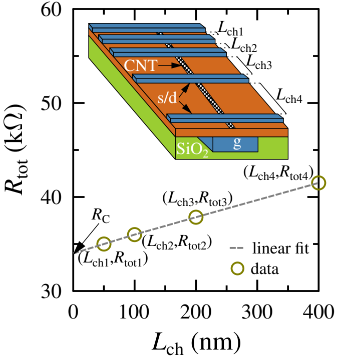
Y-function methods (YFM)



- Adapted from drift-diffusion
  - linear region
  - low drain voltages

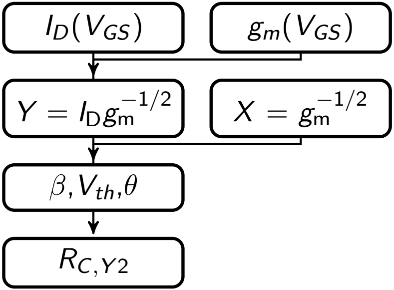
R_C extraction methods in CNTFETs (I)

Transfer length method (TLM)



- Test structure with very long CNTs
  - challenging for DEP technologies

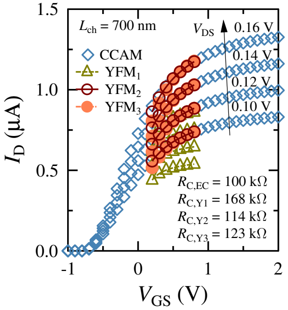
Y-function methods (YFM)



- Adapted from drift-diffusion
  - linear region
  - low drain voltages
  - there is no need of test structures!

R_C extraction methods for CNTFETs (II)

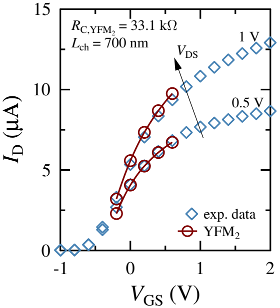
YFMs applied and verified by synthetic and experimental data of ST, MT, short- and long-channel CNTFETs [7].



[7] A. Pacheco-Sanchez et al., "Contact resistance extraction methods for short- and long-channel carbon nanotube field-effect transistors", Solid-State Electron., 125, 2016.

R_C extraction methods for CNTFETs (II)

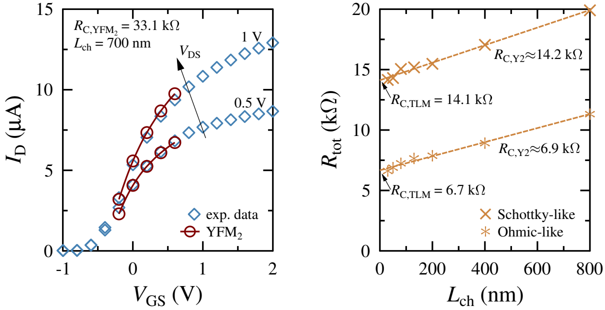
YFMs applied and verified by synthetic and experimental data of ST, MT, short- and long-channel CNTFETs [7].



[7] A. Pacheco-Sanchez et al., "Contact resistance extraction methods for short- and long-channel carbon nanotube field-effect transistors", Solid-State Electron., 125, 2016.

R_C extraction methods for CNTFETs (II)

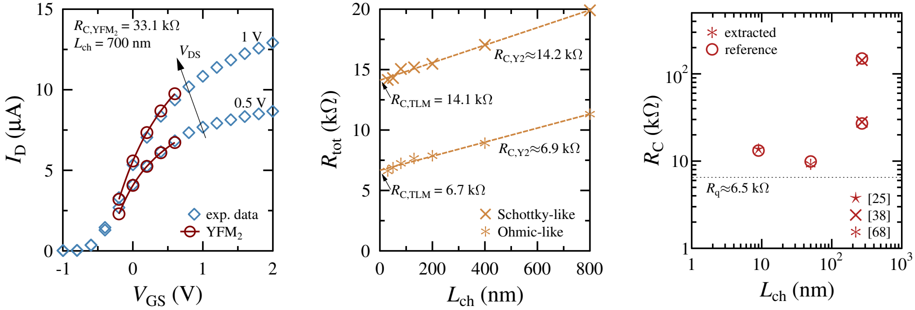
YFMs applied and verified by synthetic and experimental data of ST, MT, short- and long-channel CNTFETs [7].



[7] A. Pacheco-Sanchez et al., "Contact resistance extraction methods for short- and long-channel carbon nanotube field-effect transistors", Solid-State Electron., 125, 2016.

R_C extraction methods for CNTFETs (II)

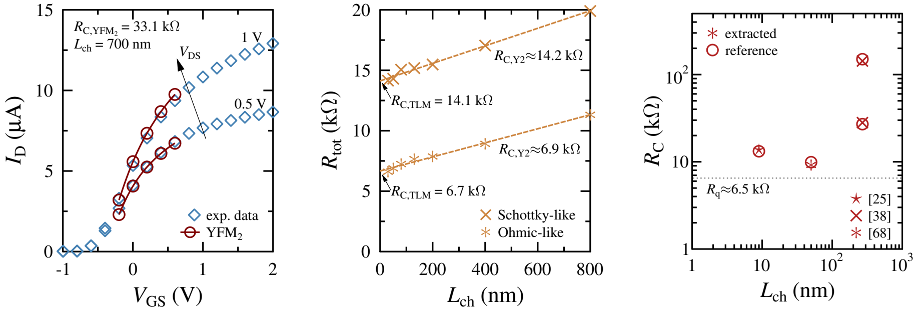
YFMs applied and verified by synthetic and experimental data of ST, MT, short- and long-channel CNTFETs [7].



[7] A. Pacheco-Sanchez et al., "Contact resistance extraction methods for short- and long-channel carbon nanotube field-effect transistors", Solid-State Electron., 125, 2016.

R_C extraction methods for CNTFETs (II)

YFMs applied and verified by synthetic and experimental data of ST, MT, short- and long-channel CNTFETs [7].



→ YFM$_2$ extracts a value close to reference contact resistances set in compact model and obtained with TLM and with more sophisticated physics-based models.

[7] A. Pacheco-Sanchez et al., "Contact resistance extraction methods for short- and long-channel carbon nanotube field-effect transistors", Solid-State Electron., 125, 2016.

Mobility in CNTFETs

Mobility μ characterize the transport of carriers in a semiconductor.

1D-channel transistors:

$$\mu = \frac{v}{E} = \frac{L}{C_G} \frac{I_D / V_{DS}}{V_{GS} - V_{th}}$$

μ	R_C	R_q

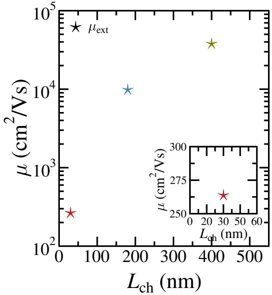
Mobility in CNTFETs

Mobility μ characterize the transport of carriers in a semiconductor.

extrinsic mobility

$$\mu_{\text{ext}} = \frac{L}{C_G} \frac{I_D / V_{DS,\text{ext}}}{V_{GS,\text{ext}} - V_{\text{th}}}$$

μ	R_C	R_q
μ_{ext}	✓	✓



Mobility in CNTFETs

Mobility μ characterize the transport of carriers in a semiconductor.

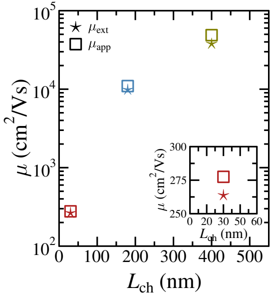
apparent mobility [8]

$$\mu_{\text{app}} = \frac{L}{C_G} \frac{I_D / V_{\text{DS,int}}}{V_{\text{GS,int}} - V_{\text{th}}}$$

$$V_{\text{DS,int}} = V_{\text{DS,ext}} - I_D R_C$$

$$V_{\text{GS,int}} = V_{\text{DS,ext}} - \frac{I_D R_C}{2}$$

μ	R_C	R_q
μ_{ext}	✓	✓
μ_{app}	✓	✗



Mobility in CNTFETs

Mobility μ characterize the transport of carriers in a semiconductor.

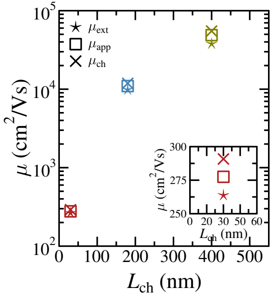
channel mobility

$$\mu_{ch} = \frac{L}{C_G} \frac{I_D / V_{DS,int}}{V_{GS,int} - V_{th}}$$

$$V_{DS,int} = V_{DS,ext} - I_D(R_C - R_q)$$

$$V_{GS,int} = V_{DS,ext} - \frac{I_D(R_C - R_q)}{2}$$

μ	R_C	R_q
μ_{ext}	✓	✓
μ_{app}	✓	✗
μ_{ch}	✗	✗



Mobility in CNTFETs

Mobility μ characterize the transport of carriers in a semiconductor.

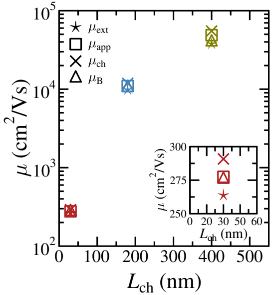
ballistic mobility

$$\mu_B = \frac{L}{C_G} \frac{I_D / V_{DS,int}}{V_{GS,int} - V_{th}}$$

$$V_{DS,int} = V_{DS,ext} - I_D R_q$$

$$V_{GS,int} = V_{DS,ext} - \frac{I_D R_q}{2}$$

μ	R_C	R_q
μ_{ext}	✓	✓
μ_{app}	✓	✗
μ_{ch}	✗	✗
μ_B	✗	✓



Mobility μ characterize the transport of carriers in a semiconductor.

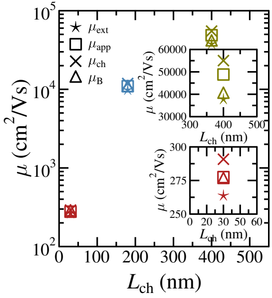
ballistic mobility

$$\mu_B = \frac{L}{C_G} \frac{I_D / V_{DS,int}}{V_{GS,int} - V_{th}}$$

$$V_{DS,int} = V_{DS,ext} - I_D R_q$$

$$V_{GS,int} = V_{DS,ext} - \frac{I_D R_q}{2}$$

μ	R_C	R_q
μ_{ext}	✓	✓
μ_{app}[8]	✓	✗
μ_{ch}	✗	✗
μ_B[8]	✗	✓



→ Detailed mobility definitions are proposed for technology comparison

[8] M. Lundstrom et al., "Compact models and the physics of nanoscale FETs", IEEE TED, 61(2), 2014.

Summary

- reliable quantification of internal phenomenon in CNTFETs is given by Φ_{SB}, R_{C} and μ
- novel and straightforward extraction methods have been presented
- 1D LBM: verified by experimental-based synthetic simulations; valid for ST devices; applied to NWFETs
  - next step: extend method to MT and 2D devices
- YFM_2: verified by compact model, TLM, and sophisticated atomic models; applied to organic FETs
- careful mobility definitions are presented

$\Rightarrow$ extraction methods and device engineering techniques involved in this project are used in the framework of achieving a suitable and reproducible HF CNTFET technology

Refs. in figures (I)

[2] A. Franklin et al., "Length scaling of Carbon Nanotube Transistors", Nat. Nanotech., 5, 2010.
[25] A. Franklin et al., "Sub-10 nm Carbon Nanotube Transistor", Nano Lett., 12(2), 2012.
[38] S-J. Choi et al., "Short-Channel Transistors Constructed with Solution-Processed Carbon Nanotubes", ACS Nano, 7(1), 2013.
[39] Z. Chen et al., "The role of metal-nanotube contact in the performance of carbon nanotube field-effect transistors", Nano Lett., 5(7), 2005.
[41] M. H. Yang et al., "Carbon nanotube Schottky diode and directionally dependent field-effect transistor using asymmetrical contacts", App. Phys. Lett., 87, 2005.
[62] A. Franklin et al., "Carbon Nanotube Complementary Wrap-Gate Transistors", Nano Lett., 13, 2013.
[67] Z. Zhang et al., "Self-Aligned Ballistic n-Type Single-Walled Carbon Nanotube Field-Effect Transistors with Adjustable Threshold Voltage", 8(11), 2008.
[68] A. Javey et al., "Self-Aligned Ballistic Molecular Transistors and Electrically Parallel Nanotube Arrays", Nano Lett., 4(7), 2004.
[156] J. Svensson et al., "The dependence of the Schottky barrier height on carbon nanotube diameter for Pd-carbon nanotube contacts", Nanotechnology, 20(17), 2009.
[185] J. Appenzeller, et al., "Multimode Transport in Schottky-Barrier Carbon-Nanotube Field-Effect Transistors", Phys. Rev. Lett., 92(22), 2004.
[193] J. Appenzeller et al., "Tunneling Versus Thermionic Emission in One-Dimensional Semiconductors", Phys. Rev. Lett., 92, 2004.
[195] Y-F. Chen et al., "Tuning from Thermionic Emission to Ohmic Tunnel Contacts via Doping in Schottky-Barrier Nanotube Transistors", Nano Lett., 6, 2006.

Refs. in figures (II)

[200] D. Perello et al., "Quantitative Experimental Analysis of Schottky Barriers and Poole-Frenkel Emission in Carbon Nanotube Devices", IEEE TNANO, 8, 2009.
[201] D. Perello et al., "Anomalous Schottky Barriers and Contact Band-to-Band Tunneling in Carbon Nanotube Transistors", ACS Nano, 4(6), 2010.
[202] S. Jejurikar et al., "Anomalous n-type electrical behaviour of Pd-contacted CNTFET fabricated onsmall-diameter nanotube", Nanotechnology, 21, 2010.
[230] M. Tamaoki et al., "Electrical properties of the graphitic carbon contacts on carbon nanotube field effect transistors", App. Phys. Lett., 101, 2012.
[231] J. Trommer et al., "Enabling Energy Effciency and Polarity Control in Germanium Nanowire Transistors by Individually Gated Nanojunctions", ACS Nano, 11(2), 2017.
[252] Q. Cao et al., "End-bonded contacts for carbon nanotube transistors with low, size-independent resistance", Science, 35(12), 2015.
[253] Ph. Avouris et al., "Molecular Electronics with Carbon Nanotubes", Acc. Chem. Res., 35(12), 2002.