A Quick User Guide on

Stanford University
Carbon Nanotube Field Effect Transistors (CNFET)
HSPICE Model

v. 2.2.1

Patent Pending.

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09/09/2008

Carbon Nanotube Field Effect Transistors HSPICE implementation based on "A Circuit-Compatible SPICE model for Enhancement Mode Carbon Nanotube Field Effect Transistors" by Jie Deng and H.-S. Philip Wong.

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1. Model Files

Table 1. Summary of Model Files

File Name	Description
CNFET.lib	CNFET Models.
PARAMETERS.lib	Global parameters for the model.

Additional Files

File Name	Description
User Guide	
Stanford CNFET Model Quick User Guide.doc	This User Guide in Word format.
Stanford CNFET Model Quick User Guide.pdf	This User Guide in PDF format.
References/Publications	
CNFET Model Part1.pdf	Describes the core of this model.
CNFET Model Part2.pdf	Describes the complete model.
Gate Cap 1D FET.pdf	Describes in detail inter-CNT charge screening as implemented in this model.
Jie Deng Thesis.pdf	Thesis work describing this model.
Sample Decks	
cnfet_sample.sp	Example HSPICE deck using this model.

This documentation pertains to the model files in the Carbon Nanotube Field Effect Transistor (CNFET) HSPICE Model package. A brief summary and description of the model files included in the package are shown in Table 1.

The package should include all and only these files, plus this User Guide document. A summary of the model scope is in 2. *Scope of the Model*; details regarding model usage and instantiation can be found in 3. *Model Usage*; lastly, 4. *Global Parameters* describes the various global parameters that can be adjusted.

2. Scope of the Model

Table 2 below summarizes the scope of the model.

Table 2. Summary of the Scope of the CNFET Model

Device Types	n-type/p-type CNFET
Device Dimensions:	
Channel Length (Minimum)	~10nm
Channel Length (Maximum)	Unlimited
Channel Width (Minimum)	4nm
Channel Width (Maximum)	Unlimited
Number of CNTs / device (Minimum)	1[1]
Number of CNTs / device (Maximum)	Unlimited
Additional Effects / Practical Non-idealities:	
Schottky Barrier Effects	Yes: requires CNT source/drain degenerate doping
Parasitics	CNT, Source/Drain, and Gate resistances and capacitances
CNT Charge Screening Effects	Standard Model: Yes; Uniform Model: Limited
Metallic Chiralities	No

This model was designed for unipolar, MOSFET-like CNFET devices, where each device may have one or more carbon nanotubes (CNTs). The minimum channel length is ~10nm, as various complex quantum mechanisms which describe the sub-10nm regime are not modeled here. In principle, this model has no limitations on the maximum channel length of the CNFET. For channel lengths longer than 100 nm, the device is treated as a long-channel device. The transition from the short channel model (10 nm < Lg < 100 nm) to the long channel model (Lg > 100 nm) is continuous and is automatically handled by the model.

Schottky Barrier (SB) effects are modeled and can be observed using this model. The SB model incorporated in this model requires that the doping level in the doped source/drain extension region be above the first conduction band of the carbon nanotube; otherwise the model may yield inaccurate results.

[1] For a single-CNT device *(tubes*=1), set *Pitch* to the default value of 20nm or greater.

3. Model Usage

The model is implemented in HSPICE. This section illustrates how to instantiate the model in HSPICE.

3.1 Model Variants – Standard Model vs Uniform Model

Two model variants are available:

1) Standard CNFET Model [Recommended]
2) Uniform-tubes CNFET Model

In both cases, multiple carbon nanotubes are allowed under the same gate (i.e. multiple tubes per device). In the Standard Model, charge screening effects between multiple nanotubes in the same device are handled by the model. In the Uniform Model, charge screening effects are approximated to be uniform for all CNTs in the device.

In the Standard CNFET Model (Standard Model), the nanotubes in a given device are automatically grouped into two groups: the two CNTs at two ends (with only one neighboring nanotube) and the other *n-2* CNTs in between (each with two neighbors to the sides). The CNTs at the ends observe less charge screening effects than those in the middle. Thus, this model accounts for charge screening effects on drive current and device performance more accurately and is thus the standard model. See Section 3.3 for details on instantiation.

On the other hand, the Uniform-tubes CNFET Model (Uniform Model) is an approximation to the Standard Model to speed up runtime. It simplifies the modeling of charge screening effects by considering uniform tubes, that is, all tubes are identical and experience the degree of same charge screening. Tubes can be set to either all have charge screening from 1 neighboring CNT or charge screening from two neighboring CNTs. Naturally, due to the approximation, this model is less accurate than the Standard Model, but can improve runtime up to 2x faster. See Section 3.3 for details on instantiation.

The Standard Model is recommended as it is most accurate and already quite fast. The Uniform Model is provided for those who find the Standard Model runtime too long or who do not need high accuracy. Note that the Uniform Model and the Standard Model converge in two cases: i) when the number of CNTs / device is two, and ii) when the number of CNTs goes to infinity (or realistically, just much greater than 2). Thus in either of these cases, using the Uniform Model should yield identical or similar results as the Standard Model.

3.2 Convergence and Settings

For improved convergence and run times, include the following lines of code at the beginning of the SPICE deck:

```
**************************************************
.options POST
.options AUTOSTOP
.options INGOLD=2      DCON=1
.options GSHUNT=1e-12  RMIN=1e-15
.options ABSTOL=1e-5   ABSVDC=1e-4
.options RELTOL=1e-2   RELVDC=1e-2
.options NUMDGT=4      PIVOT=13

.param   TEMP=27
**************************************************
```

3.3 Model Instantiation

To instantiate the devices in the model, the library must be included at the beginning of the SPICE deck:

```
.lib 'CNFET.lib' CNFET
```

This will allow you to instantiate any of the following models:

NCNFET	Standard n-type CNFET model.
PCNFET	Standard p-type CNFET model.
NCNFET_uniform	Uniform-tubes n-type CNFET model.
PCNFET_uniform	Uniform-tubes p-type CNFET model.

The other model file (PARAMETERS.lib) included in the package is automatically referenced by the top level model files; thus, it should never be instantiated directly in the SPICE deck.

The only file that should ever be modified is the PARAMETERS.lib file, which holds the global device parameters. The main model file (CNFET.lib) should never be modified (and you should find no need to ever modify it).

Then to instantiate a CNFET device, use the appropriate syntax below. The usage of this model is similar to that of the Si CMOS model.

*Top level n-CNFET Standard Model:
XDevice ***Drain Gate Source Sub*** **NCNFET** **<** Lch=L_channel Lgeff=Lceff Lss=L_sd Ldd=L_sd Efi=Efo Kgate=Kox Tox=4.0e-9 Csub=20.0e-12 Ccsd=Ccsd CoupleRatio=CoupleRatio Vfbn=0.0 Dout=1.0 Sout=0.0 Pitch=20e-9 Wgate=sub_pitch n1=19 n2=0 tubes=1 **>**

*Top level n-CNFET Uniform Model:
XDevice ***Drain Gate Source Sub*** **NCNFET_uniform** **<** Lch=L_channel Lgeff=Lceff Lss=L_sd Ldd=L_sd Efi=Efo Kgate=Kox Tox=4.0e-9 Csub=20.0e-12 Ccsd=Ccsd CoupleRatio=CoupleRatio Vfbn=0.0 Dout=1.0 Sout=0.0 Pitch=20e-9 Wgate=sub_pitch CNTPos=1.0 n1=19 n2=0 tubes=1.0 **>**

*Top level p-CNFET Standard Model:
XDevice ***Drain Gate Source Sub*** **PCNFET** **<** Lch=L_channel Lgeff=Lceff Lss=L_sd Ldd=L_sd Efi=Efo Kgate=Kox Tox=4.0e-9 Csub=20.0e-12 Ccsd=Ccsd CoupleRatio=CoupleRatio Vfbp=0.0 Dout=1.0 Sout=0 Pitch=20.0e-9 Wgate=sub_pitch n1=19 n2=0 tubes=1 **>**

*Top level p-CNFET Uniform Model:
XDevice ***Drain Gate Source Sub*** **PCNFET_uniform** **<** Lch=L_channel Lgeff=Lceff Lss=L_sd Ldd=L_sd Efi=Efo Kgate=Kox Tox=4.0e-9 Csub=20.0e-12 Ccsd=Ccsd CoupleRatio=CoupleRatio Vfbp=0.0 Dout=1.0 Sout=0 Pitch=20.0e-9 Wgate=sub_pitch CNTPos=1.0 n1=19 n2=0 tubes=1 **>**

The ports definitions *Drain*, *Gate*, *Source*, *Sub* for the CNFET are the same as that for a CMOS device. The ports *Drain* and *Source* are not interchangeable in this model due to implementation details. Since the CNFET sits on an insulator, the port *Sub* can also act as a backgate in some applications, e.g. for a double gate CNFET. But the dominant driving gate should always be connected to the *Gate* port since the model utilizes a few approximations for the substrate.

The device parameters indicated in the < … > are optional and can be set differently for each device instance. If omitted, default or global values set in the parameter definition file are used. The syntax for setting a parameter is:
parameter_name = value or parameter

The assigned values shown in the code above are the default values (or global parameter value) for the parameters. See Table 3 for the definitions and default values of the device parameters (Figure 1 illustrates some of these parameters).

Table 3. Device Parameter Definitions and Default Values

Device Parameter	Description	Default Value
Lch	Physical channel length[2].	32.0nm (Set by global parameter *L_channel*)
Lgeff	The mean free path in the intrinsic CNT channel region due to non-ideal elastic scattering.	200.0nm (Set by global parameter *Lceff*)
Lss	The length of doped CNT source-side extension region.	32.0nm (Set by global parameter *L_sd*)
Ldd	The length of doped CNT drain-side extension region.	32.0nm (Set by global parameter *L_sd*)
Efi	The Fermi level of the doped S/D tube.	0.6 eV (Set by global parameter *Efo*)
Kgate	The dielectric constant of high-k top gate dielectric material (planer gate).	16.0 (Set by global parameter *Kox*)
Tox	The thickness of high-k top gate dielectric material (planer gate).	4.0nm
Csub	The coupling capacitance between the channel region and the substrate (backgate effect).	20.0pF/m (for a 10μm thick SiO_2)
Ccsd	The coupling capacitance between channel region and source/drain region.	0.0pF/m (Set by global parameter *Ccsd*)
CoupleRatio	The percentage of Ccsd that corresponds to the coupling capacitance between the channel and drain.	0.0 (Set by global parameter *CoupleRatio*)
Vfbn, Vfbp	Flatband voltage for n-CNFET and p-CNFET, respectively.	0.0eV, 0.0eV
Dout	The property of the drain-side output: 0: the drain output is connected to metal contact, 1: the drain output is connected to another CNFET directly.	0
Sout	The property of the source-side output: 0: the source output is connected to metal contact, 1: the source output is connected to another CNFET directly.	0
Pitch	The distance between the centers of two adjacent CNTs within the same device[3].	20.0nm
Wgate	The width of metal gate[4].	6.4nm (set by global parameter *sub_pitch*)

[2] This model may not be valid for channel lengths below 10nm where other quantum mechanical effects may need to be considered.

[3] This parameter is used to model the charge screening effects.

[4] This parameter is used to include interconnect capacitance, approximated as 0.213 fF/μm, assuming a G/S/D contact height of 64nm and contact spacing of 32nm.

CNTPos	The position of CNT under the gate (only for Uniform Models): 0: the tube is in the middle and sees two adjacent neighbors, 1: the tube is at edge of the device and sees only 1 neighboring CNT.	1
(n1, n2)	The chirality of tube[5].	(19, 0)
tubes	The number of tubes in the device.	1

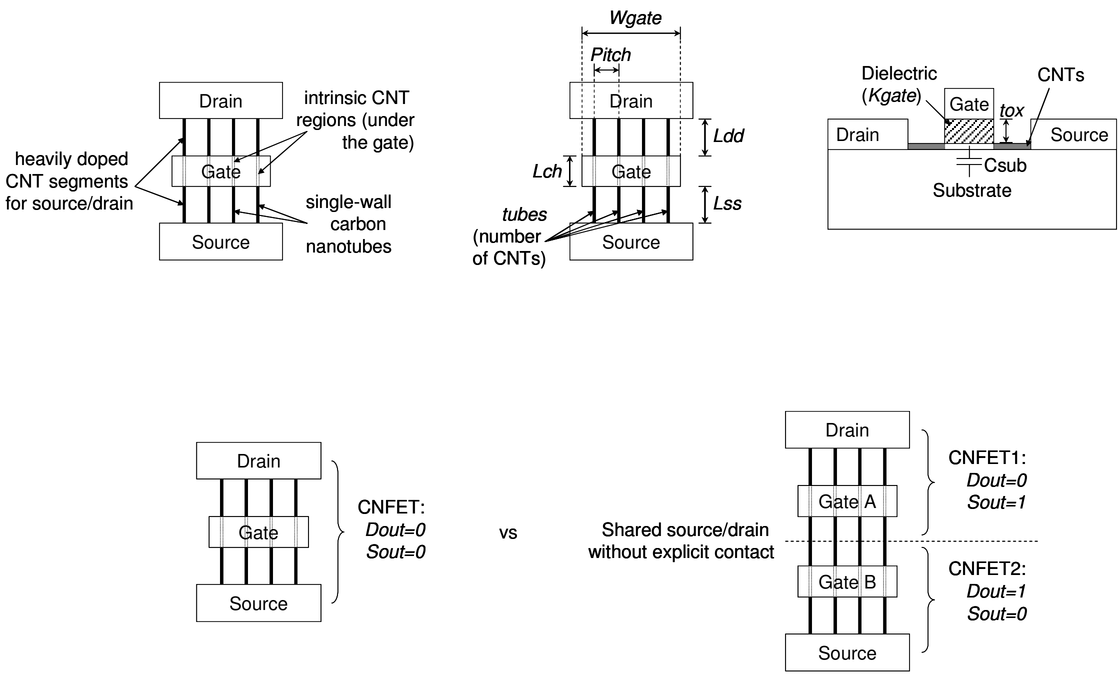

Figure 1. Illustration of Modeled CNFET Device and Relevant Parameters.

[5] The CNT chirality should be that of a semiconducting CNT. The model does not model metallic chilarities and will not report an error if a metallic chirality if given.

4. Global Parameters

In addition to the device parameters which can be individually set for each device instance, there are some global parameters in the "PARAMETERS.lib" file which can be modified to change the default values for device parameters or values used in model calculations[6]. The definition and values of those global parameters are summarized in Table 4.

Table 4. Global Parameter Definitions and Values[6]

Global Parameters	Description	Default Value
L_channel	Physical gate length.	32.0nm
Lceff	The mean free path in intrinsic CNT.	200.0nm
L_sd	The length of doped CNT source/drain extension region.	32.0nm
Efo	The Fermi level of n+/p+ doped source/drain CNT regions. This parameter is internally limited to be above the first conduction band.	0.6eV (~0.8% doping level)
Kox	The dielectric constant of high-k gate oxide material.	16.0
Ccsd	The coupling capacitance between channel region and source/drain region.	0.0pF/m
CoupleRatio	The percentage of Ccsd that corresponds to the coupling capacitance between the channel and drain.	0.0
sub_pitch	Sub-lithographic (e.g. CNT gate width) pitch	6.4nm
Klowk	The dielectric constant of low-k oxide material.	2.0
Ksub	The dielectric constant of back gate (substrate) dielectric material.	4.0
lambda_op	The Optical Phonon backscattering mean-free-path in Metallic CNTs[7].	15.0nm
lambda_ap	The Acoustic Phonon backscattering mean-free-path in Metallic CNTs.	500.0nm
photon	The optical phonon energy.	0.16eV
L_relax	Fitting parameter. Carrier relaxation range at drain side, used to match band-to-band tunneling current.	40.0nm
Leff	The mean free path in p+/n+ doped CNT.	15.0nm
phi_M	The work function of Source/Drain metal contact	4.6eV
phi_S	CNT work function	4.5eV

6 Several other global parameters are also defined in the PARAMETERS.lib model file but should not be changed, such as natural constants and model critical values.

7 These parameters are used by the model to derive related semiconducting CNT parameters and do not imply metallic CNTs are handled by the model.

5. References

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