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A User Guide on the

Graphene Nano-Ribbon Field-Effect Transistor (GNRFET) HSPICE Model

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GNRFET HSPICE implementation based on the work of [1]-[2].

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1. Model Files

Table 1. Summary of Files

File Name		Description
MOS-GNRFET/	gnrfet.lib	MOS-GNRFET model definition.
	gnrfet_sample.sp	Example HSPICE netlist using the above model.
	parameters.lib	Global parameters for the model.
	technology.lib	Suggested design parameters.
SB-GNRFET/	parameters.lib	Global parameters for the model.
	sbgnrfet-DG.lib	Double-Gate SB-GNRFET model definition.
	sbgnrfet-DG_sample.sp	Example HSPICE netlist using the above model.
	sbgnrfet-SG.lib	Single-Gate SB-GNRFET model definition.
	sbgnrfet-SG_sample.sp	Example HSPICE netlist using the above model.
	technology.lib	Suggested design parameters.
subband/	define_const.m	Global parameters.
	get_subbands.m	MATLAB file to compute subbands.
	printsbbd.m	MATLAB file to generate subband info used in the models.
	subbands.txt	Example output file generated by printsbbd.m.
references/	GNRFET-DATE2013.pdf	Publication the MOS-GNRFET model is based on.
	SBGNRFET-DATE14.pdf	Publication the SB-GNRFET model is based on.
GNRFET_userguide_v1.4.pdf		This file.

This manual provides a basic outline of the GNRFET model and the input definitions needed for HSPICE simulations.

2. Scope of the Model

Table 2 below summarizes the scope of the model.

Table 2. Summary of the Scope of the GNRFET Model

Device Types	n-type/p-type GNRFET
Device Dimensions:	
Channel Length (Minimum)	~10nm
Channel Length (Maximum)	~100nm
Channel Width (Minimum) per GNR	~0.873nm (N=6)
Channel Width (Maximum) per GNR	~6.36nm (N=50)
Number of GNRs / device (Minimum)	1
Number of GNRs / device (Maximum)	Unlimited
Oxide Thickness (Minimum)	0.5nm
Oxide Thickness (Maximum)	2.5nm
Line Edge Roughness (Minimum)	0%
Line Edge Roughness (Maximum)	20%
Doping Fraction (Minimum)	0.001
Doping Fraction (Maximum)	0.015

This model was designed for GNRFET devices, where each device may have one or more Graphene Nano-Ribbons (GNRs) (See Figure 1). The minimum channel length is ~10nm, as various complex quantum mechanisms which describe the sub-10nm regime are not modeled here. Also, the model is based on the assumption of ballistic transport, which is only accurate in a short-channel GNRFET. As a result, we do not recommend setting channel length above 100nm. The channel width is defined through the number of dimer lines N in the GNR lattice by $W_{CH} = \sqrt{3}d_{cc}\,(N+1)/2$, where d_{cc} = 0.142 nm refers to the carbon–carbon bond distance. In principle, channel width is unlimited. However, as the band gap of GNRs is inversely proportional to the width, a wide GNR would have a low I_{on}/I_{off} ratio and would no longer be suitable for digital circuits. Therefore, we only recommend widths up to N=50. The other parameters oxide thickness, line edge roughness, and doping fractions (for MOS-GNRFET only) were thoroughly tested in the ranges given in Table 2, and we recommend setting these parameters within these ranges.

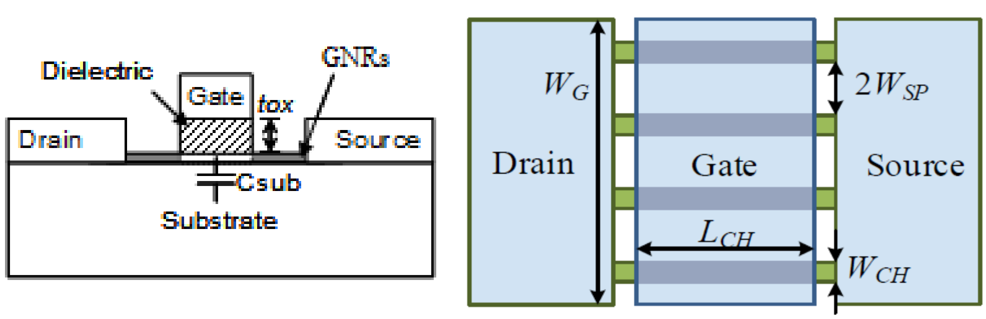

Figure 1. Illustration of Modeled GNRFET Device.

3. Model Usage

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

3.1 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

****************************************************
```

3.2 Model Instantiation

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

MOS-GNRFET:

```
.lib 'gnrfet.lib' GNRFET
```

Double-Gate SB-GNRFET:

```
.lib 'sbgnrfet-DG.lib' GNRFET
```

Single-Gate SB-GNRFET:

```
.lib 'sbgnrfet-SG.lib' GNRFET
```

The above library file contains the following models:

gnrfetnmos	n-type GNRFET model.
gnrfetpmos	p-type GNRFET model.

Modifications should not be done in the model definition files (i.e. gnrfet.lib, sbgnrfet-DG.lib, and sbgnrfet-SG.lib). All changes in device and global parameters should be done in the "parameters.lib" and "technology.lib," which are also provided with the model definition files.

The syntax to instantiate a GNRFET is given below.

*Top level n-MOS-GNRFET Standard Model:

XDevice ***Drain Gate Source Sub*** **gnrfetnmos** < *nRib*=6 *N*=12 *L*=15n *Tox*=1n *sp*=2n *dop*=5e-3 *p*=0 *Tox2*= 20n *gates_tied*='0'>

*Top level n-DG-SB-GNRFET Standard Model:

XDevice ***Drain Gate Source Sub*** **gnrfetnmos** < *nRib*=6 *N*=12 *L*=15n *Tox*=1n *sp*=2n *p*=0>

*Top level n-SG-SB-GNRFET Standard Model:

XDevice ***Drain Gate Source Sub*** **gnrfetnmos** < *nRib*=6 *N*=12 *L*=15n *Tox*=1n *sp*=2n *p*=0 *Tox2*= 20n *gates_tied*='0'>

*Top level p-MOS-GNRFET Standard Model:

XDevice ***Drain Gate Source Sub*** **gnrfetpmos** < *nRib*=6 *N*=12 *L*=15n *Tox*=1n *sp*=2n *dop*=5e-3 *p*=0 *Tox2*= 20n *gates_tied*='0'>

*Top level p-DG-SB-GNRFET Standard Model:

XDevice ***Drain Gate Source Sub*** **gnrfetpmos** < *nRib*=6 *N*=12 *L*=15n *Tox*=1n *sp*=2n *p*=0>

*Top level p-SG-SB-GNRFET Standard Model:

XDevice ***Drain Gate Source Sub*** **gnrfetpmos** < *nRib*=6 *N*=12 *L*=15n *Tox*=1n *sp*=2n *p*=0 *Tox2*= 20n *gates_tied*='0'>

The GNRFET model definitions *Drain, Gate, Source and Sub* are same as that of standard MOSFET HSPICE models and also Predictive Technology Models (PTM). For MOS-GNRFETs, *Drain* and *Source* port definition are not interchangeable due to the equation definitions in the model. The assumption is that the drain voltage V_D is always greater or equal to the source voltage V_S. For SB-GNRFETs, *Drain* and *Source* are interchangeable. The *Substrate* (*Sub)* can also be used as the second gate or back gate in transistor models such as double gated GNRFET. By default, we set the substrate oxide thickness *Tox2*=20nm, and set the variable *gates_tied*='0'. If using as a double-gated GNRFET with the same top gate and bottom gate voltages, *gates_tied* can be set to '1' to indicate connected top and bottom gates. The dominant driving gate should always be connected to the *Gate* port since more approximations take place for the substrate.

The model assumes default parameter values when the parameters are not defined during usage. Table 3 contains the default values of parameter and their definitions.

Table 3. Device Parameter Definitions and Default Values

Device Parameter	Description	Default Value
L	Physical channel length.	15.0nm (Set by global parameter *L*)
Tox	The thickness of top gate dielectric material (planer gate).	0.95nm
2*sp	The spacing between the edges of two adjacent GNRs within the same device.	2.0nm
nRib	The number of GNRs in the device.	6
N	The number of dimer lines in the GNR lattice	12
p	The edge roughness percentage of the device	0
dop	Source and Drain reservoirs doping fraction	0.001
Tox2	Oxide Thickness between channel and substrate/bottom gate	20nm
gates_tied	Whether *Gate* or *Sub* hold the same voltage	0

3.3 Computation of Gate width for GNRFET

The channel width W_{CH} is defined through the number of dimer lines *N* in the GNR lattice as

$$W_{CH} = \sqrt{3}d_{cc}\,(N+1)/2$$

where d_{cc} = 0.142 nm refers to the carbon–carbon bond distance. The gate width W_G is then computed based on W_{CH} as follows:

$$W_G = (2W_{sp} + W_{CH}) \times n_{Rib}$$

where $2W_{sp}$ is the spacing between ribbons and n_{Rib} is the number of ribbons.

3.4 Computation of Graphene Metal Junction

For MOS-GNRFET circuits, graphene-based drain/source terminals need to connect to metal-based gate terminals, forming graphene-metal junctions. The graphene-metal junction can be simulated in HSPICE by using a resistor of 10kΩ or 20kΩ. This resistor should be placed between the graphene terminal and the local interconnect composed of metal. A 2-input NAND gate and the corresponding Graphene-metal junctions are shown as an example below.

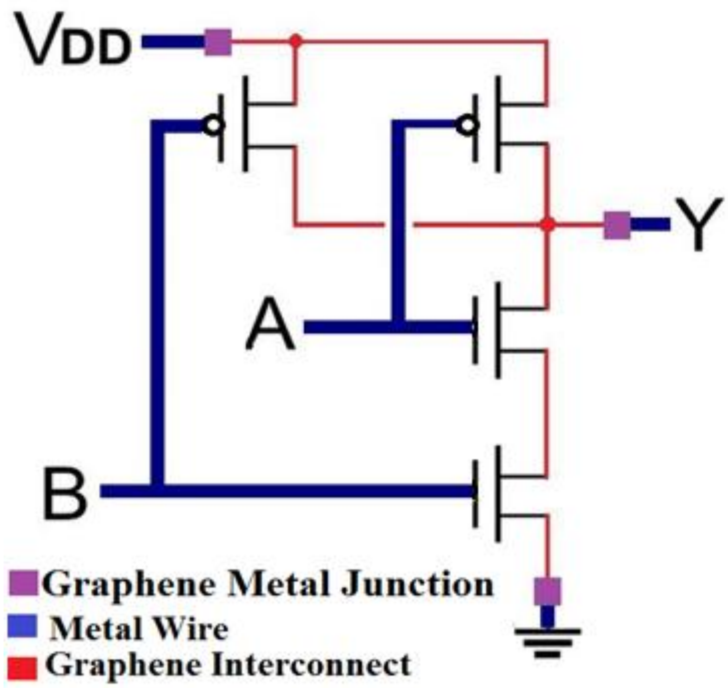

Figure 2. Illustration of Graphene Metal Junction in 2 input NAND Gate

3.5 Extending the Range of N

The model definition files contain pre-computed subband information from N=6 to N=20, which is sufficient in most situations. If one needs to simulate a GNRFET with N out of this range, the subband information can be generated by running the MATLAB script file *printsbbd.m* in the *subband* folder. The range of N can be set in *printsbbd.m.* A text file *subbands.txt* is generated once *printsbbd.m* is ran, which can be pasted into the model definition files.

4. Global Parameters

The definition and values of those global parameters are summarized in Table 4. These parameters are used for internal computations in the model and can be changed by the user if so desired. These parameters cannot be modified for each GNRFET defined in the circuit.

Table 4. Global Parameter Definitions and Values

Global Parameters	Description	Default Value
P__q	Electron Charge in Coulomb	1.60217646e-19
P__h	Planck's constant in eV.s	4.135667516e-15
P__k	Boltzmann's constant in eV/K	8.6173324e-15
P__pi	Value of π	3.14159265
P__epsSi	Relative Permittivity of SiO_2	3.9
P__T	Temperature in K	300
Vthm	Thermal Voltage	0.0259
P_qkT_h	Current Equation Constant (qkT/h)	1e-6

5. References

[1] Y-Y. Chen, A. Rogachev, A. Sangai, G. Iannaccone, G. Fiori, and D. Chen (2013). A SPICE-Compatible Model of Graphene Nano-Ribbon Field-Effect Transistors Enabling Circuit-Level Delay and Power Analysis Under Process Variation. IEEE/ACM Design, Automation & Test in Europe, pp. 1789-1794.

[2] M. Gholipour, Y-Y. Chen, A. Sangai, and D. Chen, (2014). Highly Accurate SPICE-Compatible Modeling for Single- and Double-Gate GNRFETs with Studies on Technology Scaling. IEEE/ACM Design, Automation & Test in Europe, to appear.

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