The deployment and evolution of the first NEEDS-certified model

MIT virtual source compact model for silicon nanotransistors

Shaloo Rakheja

Email: shaloo.rakheja@nyu.edu

Electrical and Computer Engineering, New York University

Thanks: Prof. Dimitri Antoniadis, MIT

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NEEDS has a vision for a new era of electronics that couples the power of billion-transistor CMOS technology with the new capabilities of emerging nano-devices and a charter to create high-quality models and a complete development environment that enables a community of compact model developers.

NEEDS Team: Purdue, MIT, U.C. Berkeley, and Stanford.

REGISTER NOW for the May 11-12 NEEDS annual meeting and workshop.

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NEEDS announces the public release of Berkeley MAPP, a MATLAB-based platform for prototyping compact models and simulation algorithms.

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For presentations on these device technologies by experts in the field, see the NEEDS Seminar Series on "Emerging Transistor Technologies."

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NEEDS compact model development

Compact models

NEEDS is charged to develop compact models for a very wide variety of novel nanodevices. A set of carefully chosen compact models that encompass a wide variet of nanodevice physics is being developed to provide concrete guidelines for how compact models can be grounded in fundamental physics and detailed simulations ar then carefully validated by experiments. Developing these models also provides a "laboratory" for addressing formulational, numerical, and convergence issues that aris for compact models. The models developed will provide the community with a library high-quality and tested models, provide NEEDS with a set of case studies and examp and drive the development of the NEEDS compact model development platform.

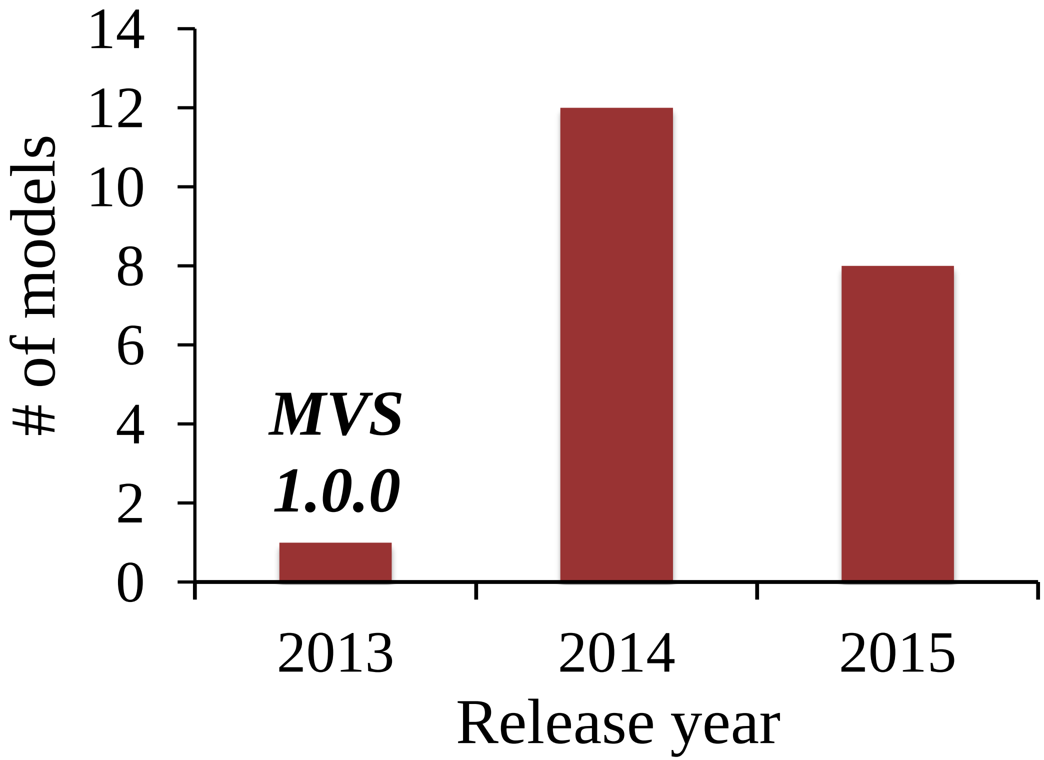
NEEDS models are licensed with the Compact Model Council (CMC) Standard licens as described in the following document – CMC_Standard_license.pdf (155 KB) and follow the CMC recommendations for versioning.

NEEDS model releases will include:

- Matlab version for downloading
- Verilog-A version for downloading
- Manual (with a complete list of equations used and procedures to calibrate the

- A list of compact models for nanoscale devices available to download.
- Total number of models till date: 20
- Models from NEEDS member universities: 12/20 (60%)

NEEDS model release history

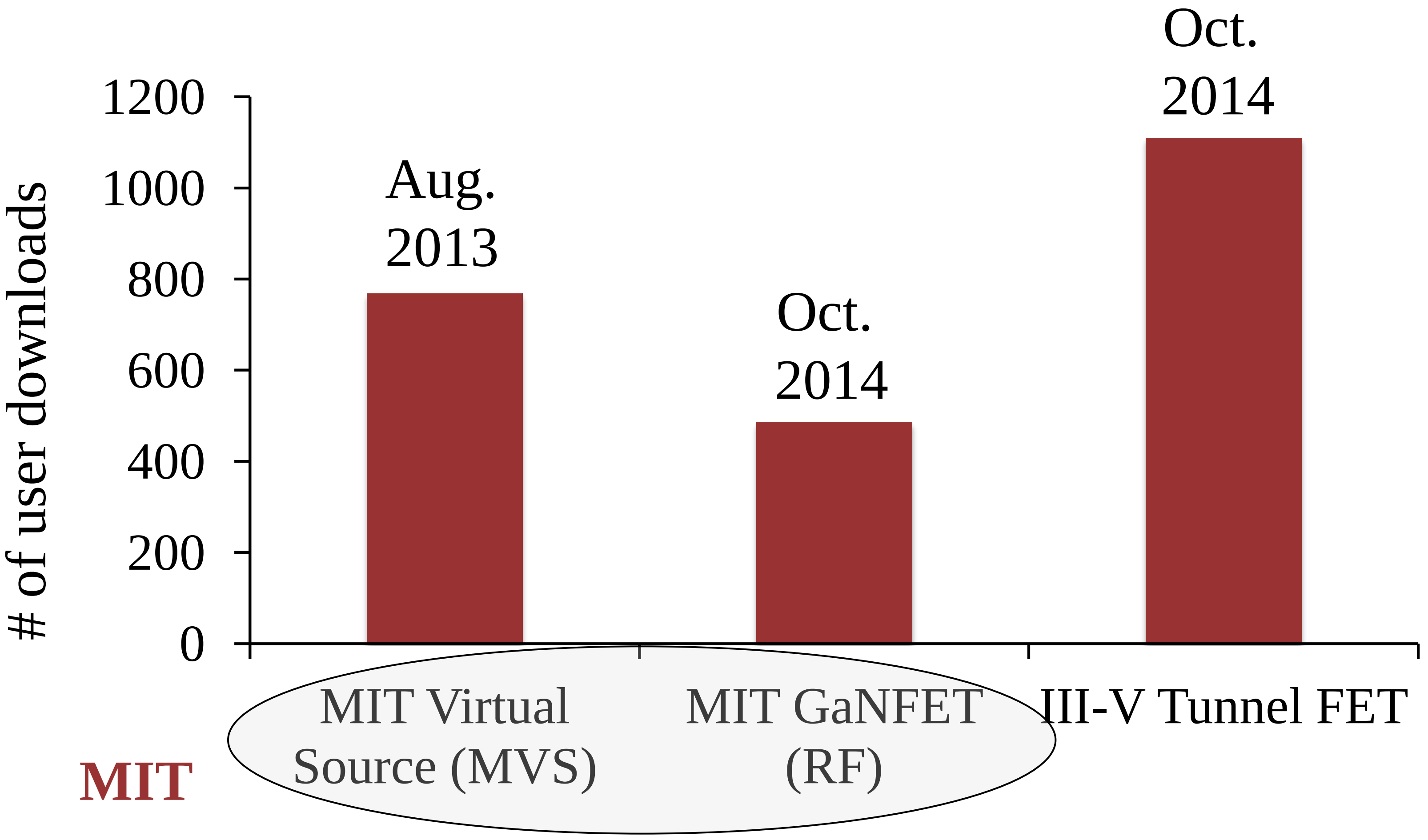


Upcoming models

- Thermoelectric device
- Phase change memory
- Steep Subthreshold FETs
- NEMS Relay
- Optical modulator
- 45 nm CMOS SOI RF

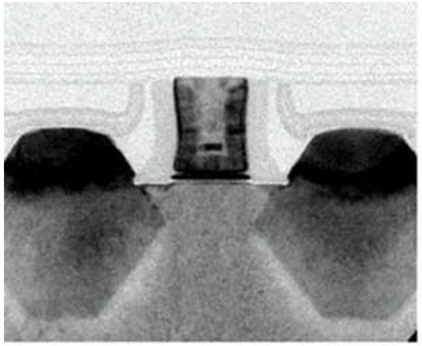
Data current as of 08/28/2015

NEEDS compact models: top user downloads



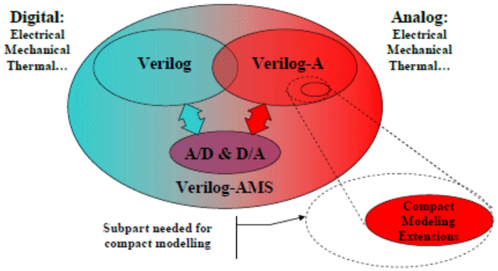
MIT

This presentation focuses on



I. **MVS model**
- Nanotransistor basics
- Model formulation
- Experimental verification
- Mathematical issues

12 min

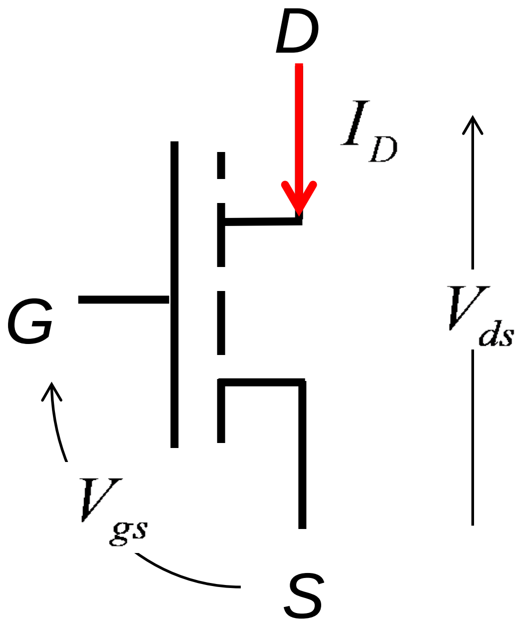


II. **Model deployment on nanoHUB**
- Process and requirements
- Current status
- Future goals

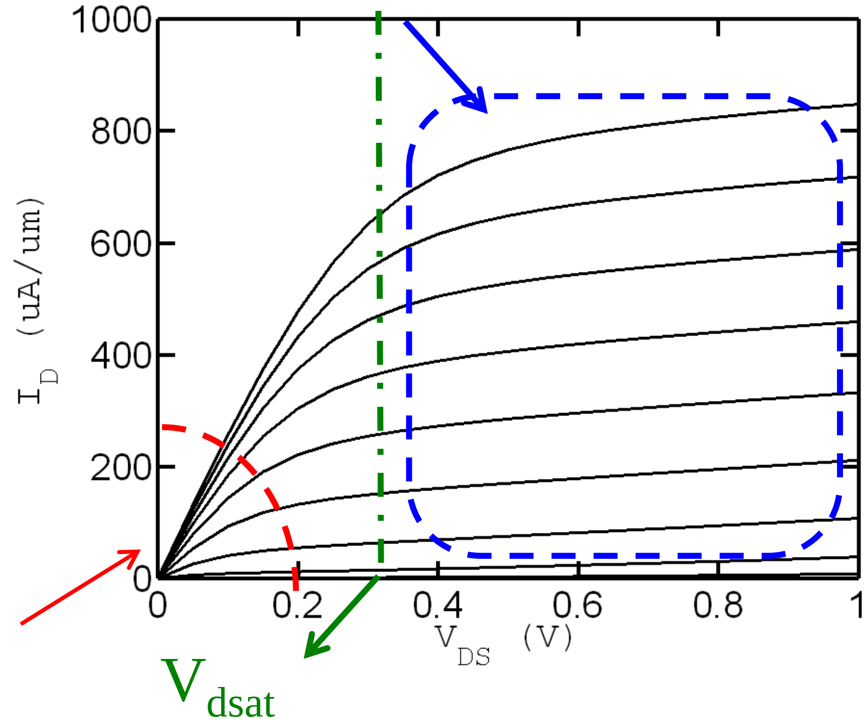
8 min

PART I
MIT Virtual Source Model For Nanotransistors

Textbook MOSFET *I-V* theory

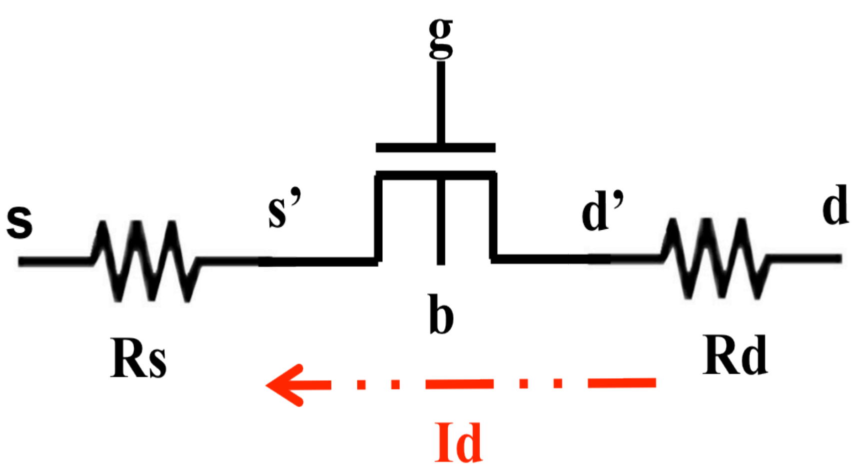


gate-voltage controlled
current source
a.k.a. saturation



gate-voltage controlled
Resistor
a.k.a. linear region

What is MVS model?



MIT **V**irtual **S**ource (MVS) nanotransistor model gives *currents* and *charges* as functions of terminal voltages.

Currents

Id = f(Vg,Vd,Vs,Vb)

Ig = Ib = 0

Charges

Qs = f1(Vg,Vd,Vs,Vb)

Qd = f2(Vg,Vd,Vs,Vb)

Qb = f3(Vg,Vd,Vs,Vb)

Qg = -(Qs+Qd+Qb)

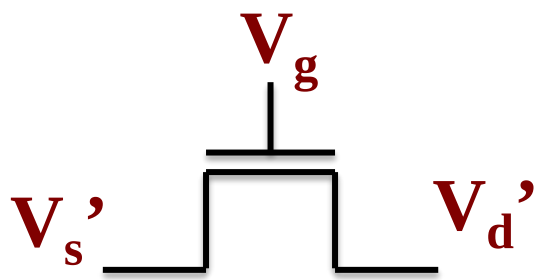
MVS model: I-V characteristics

$$\frac{I_D}{W} = Q_{x0} v_{x0} \, F_{sat}$$

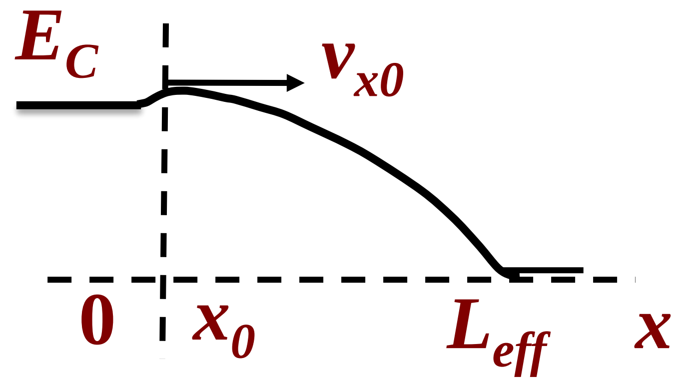
F_{sat} → Empirical function

Q_{x0}: Charge at VS

v_{x0}: Velocity at VS



- → 10 fitting parameters.
- → most of the parameters are physical and can easily be obtained through device characterization.
- → describes quasi-ballistic **silicon, III-V and graphene devices.**



MVS 1.0.0 model formulation

1) $I_{DS} = WQ_{x0}\left(V_{GS},V_{DS}\right)F_{SAT}\left(V_{DS}\right)\upsilon_{x0}$

2) $Q_{x0}\left(V_{GS}\right) = -C_{inv}m\left(k_B T/q\right)\ln\left(1+e^{q\left(V_{GS}-V_T+\alpha\left(k_B T_L/q\right)F_f\right)/mk_B T}\right)$

$$V_T = V_{T0} - \delta V_{DS}$$

3) $F_{SAT}\left(V_{DS}\right) = \dfrac{V_{DS}/V_{DSAT}}{\left[1+\left(V_{DS}/V_{DSAT}\right)^{\beta}\right]^{1/\beta}}$

4) $V_{DSAT} = \dfrac{\upsilon_{x0}L}{\mu_{app}}$

Only 10 parameters in this model:

$C_{inv}, V_T, \delta, m, \upsilon_{x0}, \mu_{app}, L,$

$R_{SD0} = R_{S0} + R_{D0},$

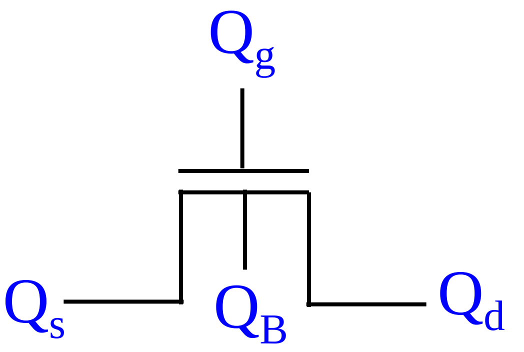
α, β

Charge partitioning/ Dynamic model

- Charge partitioning tells us the charge associated with the various terminals in the transistor.

- **Transient analysis needs charges and inter-nodal capacitances.**

- In MVS, dynamic model is obtained self-consistently with the static transport model → **no additional fitting parameters.**



$$C_{ij} = -\frac{\partial Q_i}{\partial V_j} (i \neq j)$$

$$C_{jj} = \frac{\partial Q_j}{\partial V_j}$$

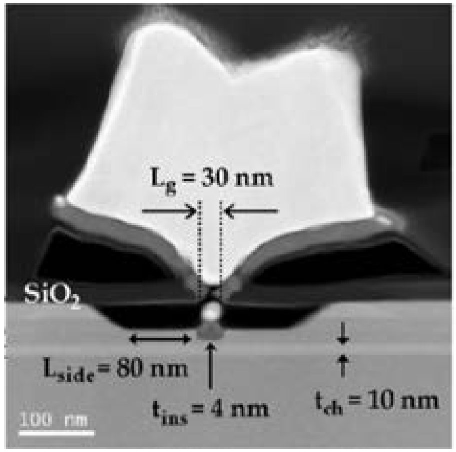
References for MVS model equations

1. A. Khakifirooz et al., “A simple semi-empirical short-channel MOSFET current-voltage model continuous across all regions of operation and employing only physical parameters,” IEEE Trans. Electron Devices, vol. 56, no. 8, **July 2009**.

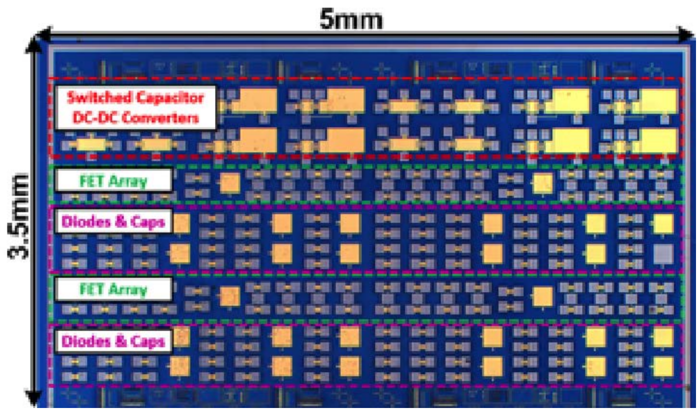
2. L. Wei et al., “ Virtual-source-based self-consistent current and charge FET models: from ballistic to drift-diffusion velocity-saturation operation,” IEEE Trans. Electron Devices, vol. 59, no. 5, **May 2012**.

3. S. Rakheja and D. Antoniadis, “MVS 1.0.1 Nanotransistor Model (Silicon),” https://nanohub.org/resources/19684 (**Nov. 2013**)

MVS model verification with experiments

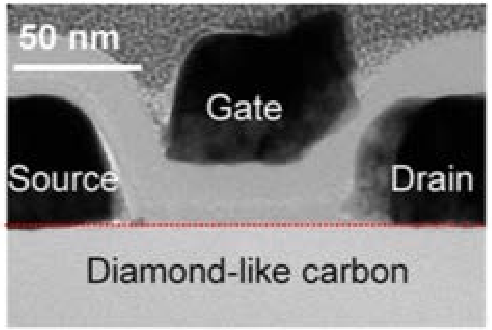


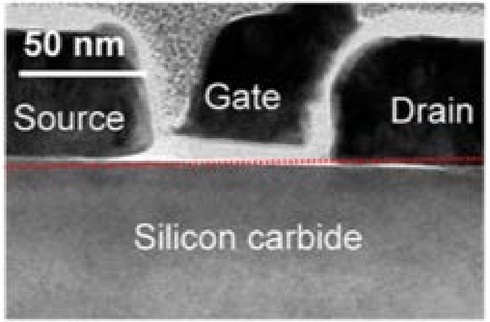
III-V HEMT
(Intel & MIT)

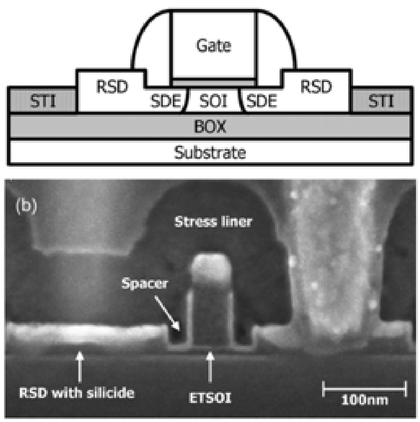


(MIT) Test chip fabricated using CVD grown MoS_2

Graphene
(IBM, Columbia, MIT)



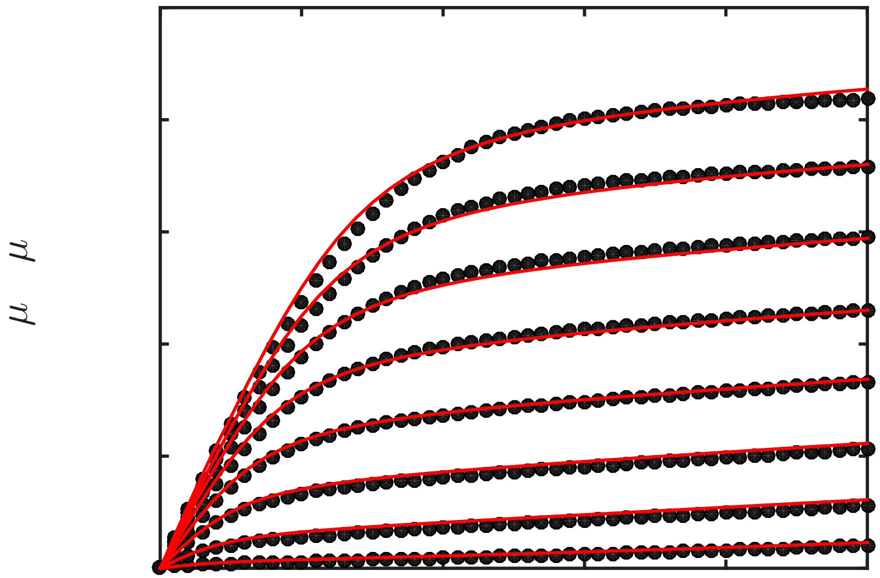




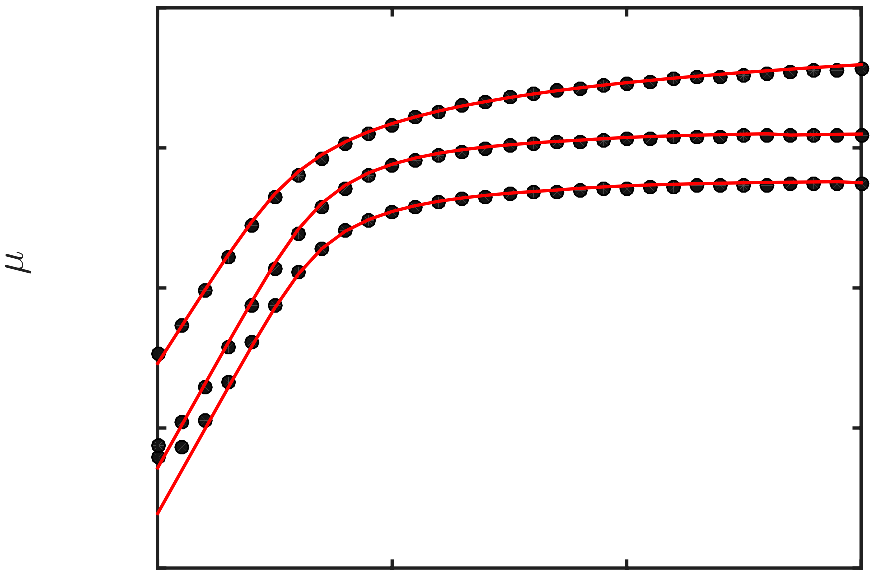
Si ETSOI
(IBM)

Extremely thin silicon-on-insulator (SOI) (IBM, 2014)

Output characteristics



Transfer characteristics



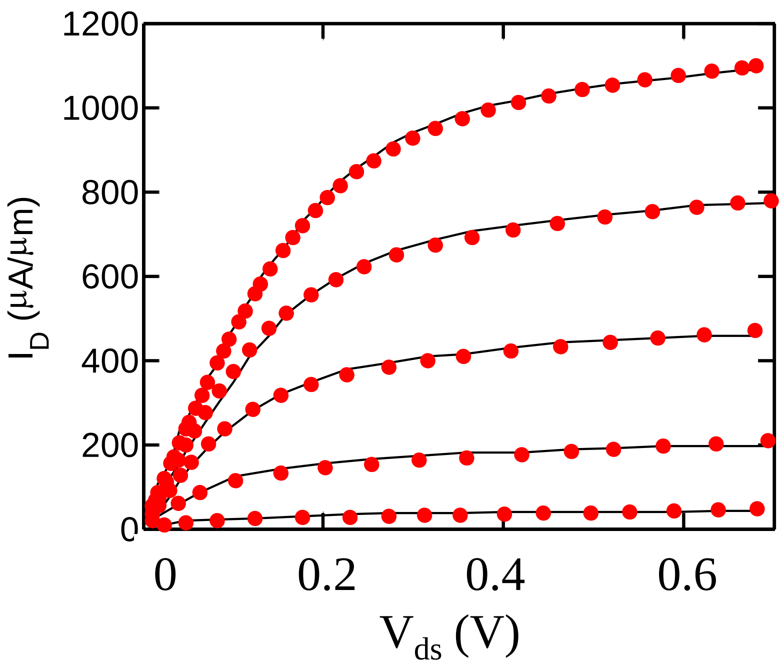
$L_{eff} = 30\ nm$

Symbols → experiment

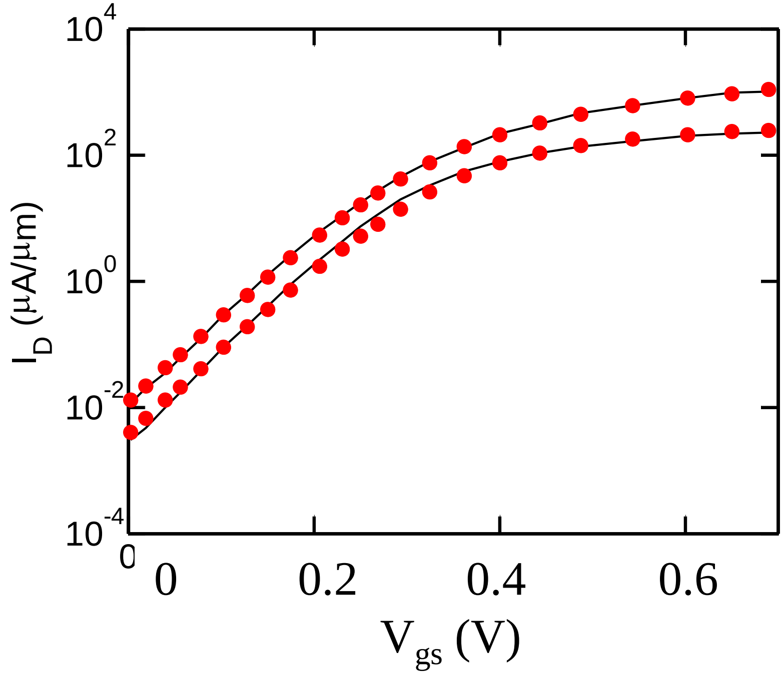
Solid lines → model

FinFET CMOS technology (Intel, 2014)

Output characteristics



Transfer characteristics

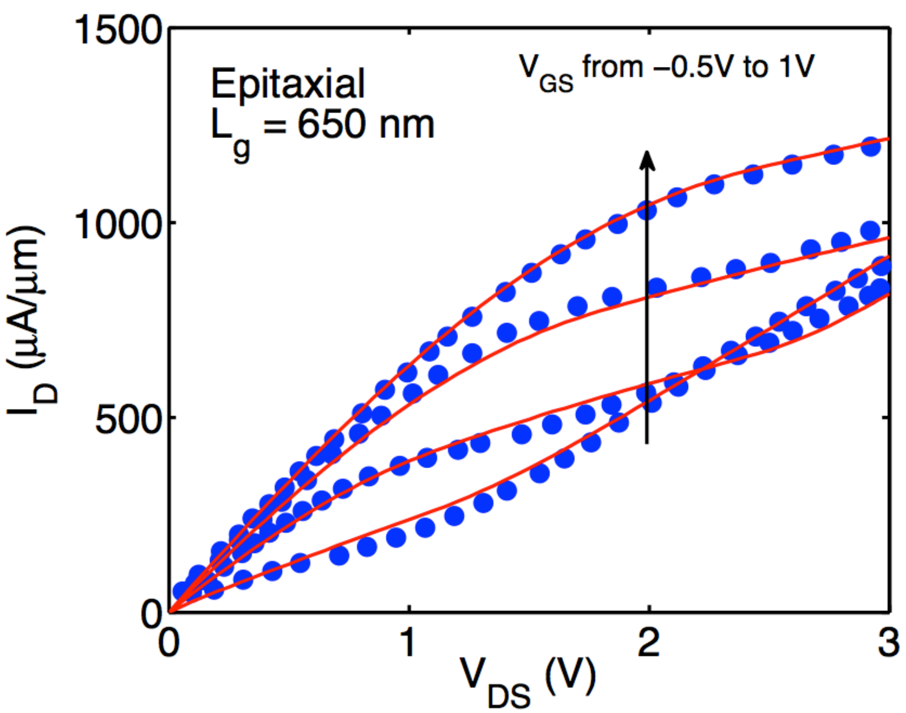


L_{eff} = 20 nm

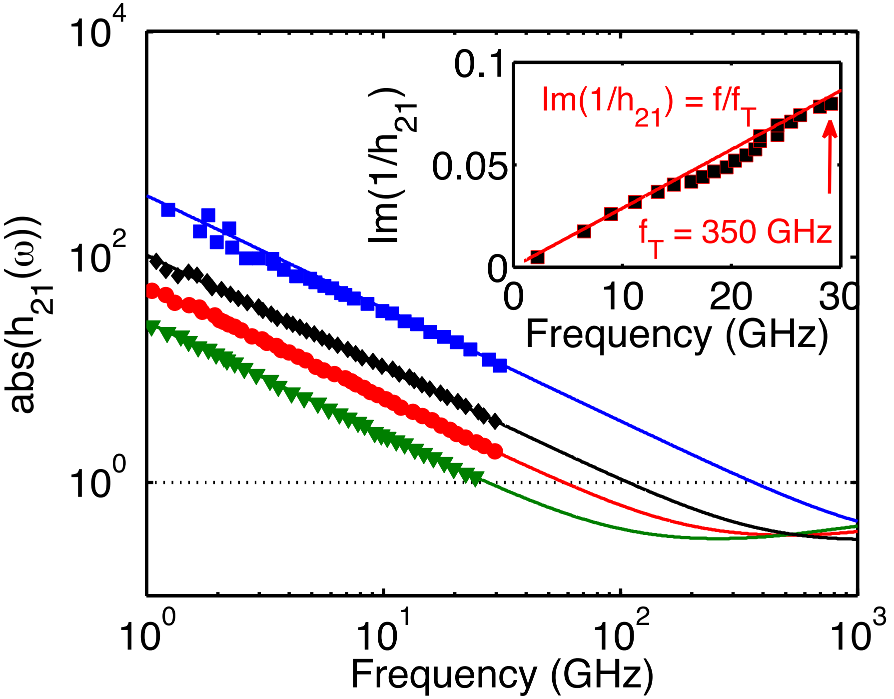
Symbols → experiment
Solid lines → model

Ambipolar graphene RF FETs

<u>*Output characteristics*</u>



<u>*Current gain versus freq.*</u>



Epitaxial GFETs fabricated at IBM, 2013.

Symbols → experiment
Solid lines → model

Mathematical issues in writing compact models: "smoothness" is key

Need for smoothness in model functions and their slopes

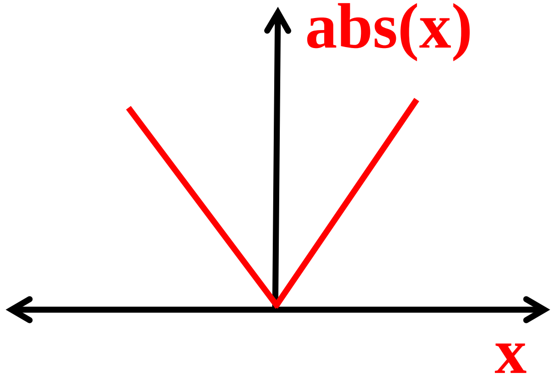
DC/transient/AC analysis of circuits

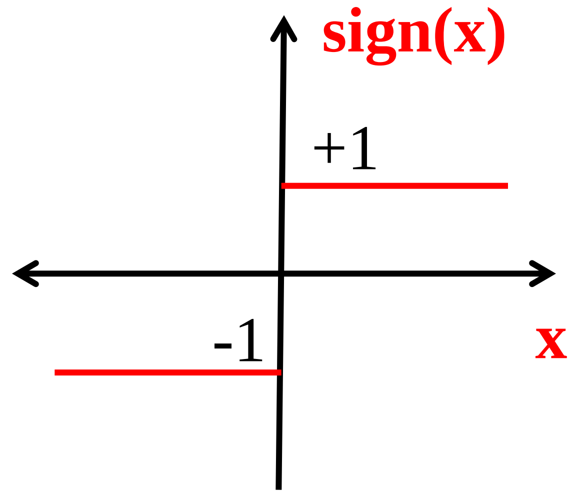
Small-signal resistance /capacitance/inductance

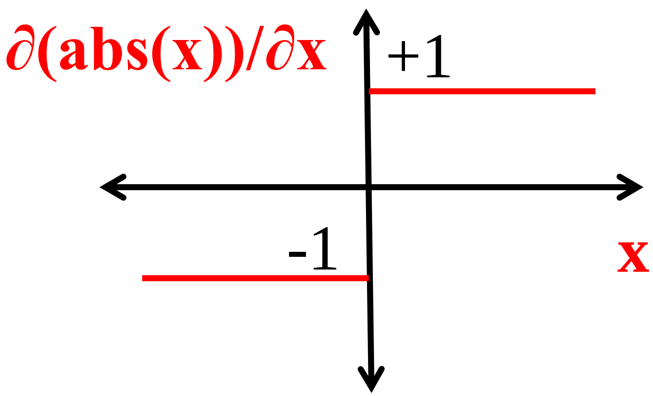
Physical systems are smooth at fine enough resolution

"A quick circuit simulation primer" https://nanohub.org/resources/20610

Example of non-smooth functions







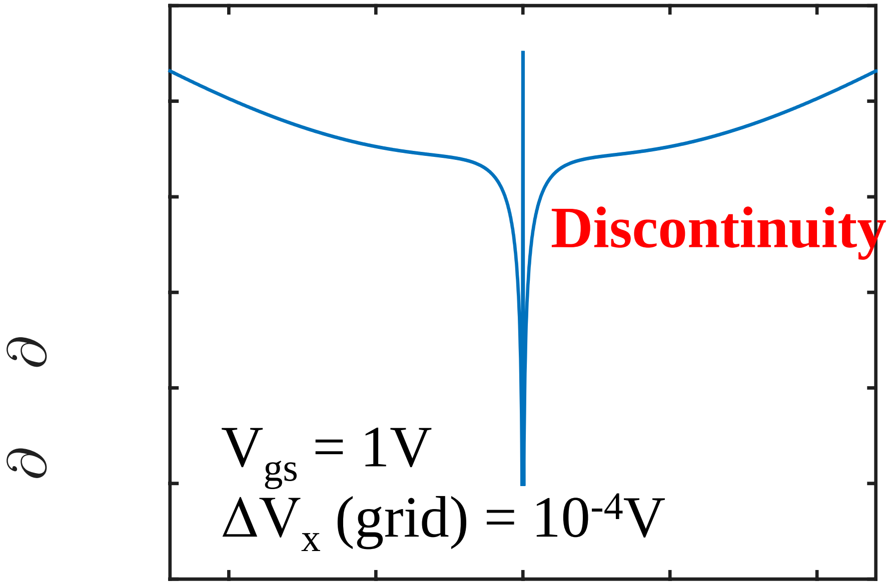
$$I_d = type \times dir \times \left(Q_{x0} v_{x0} F_{sat}\right)$$

$$dir = type \times sign\left(V_d - V_s\right)$$

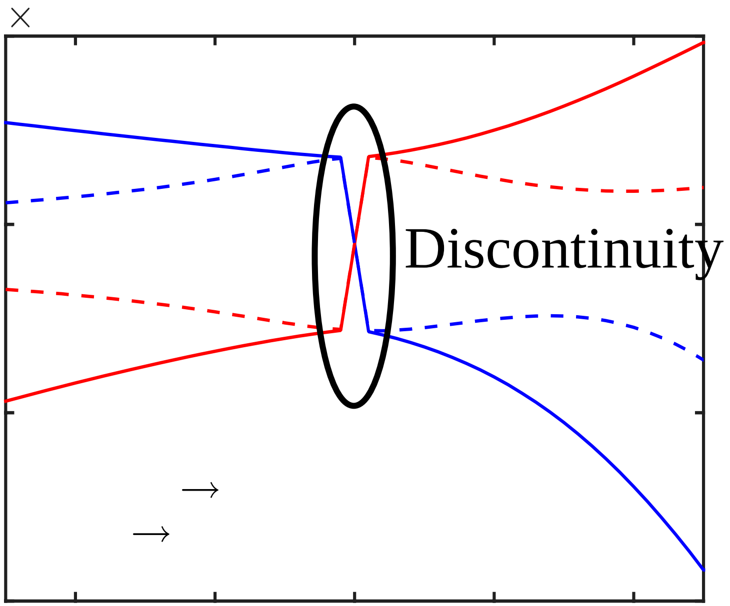
$$V_{ds} = abs\,(V_d - V_s)$$

Problem areas in MVS model

Third derivative of current

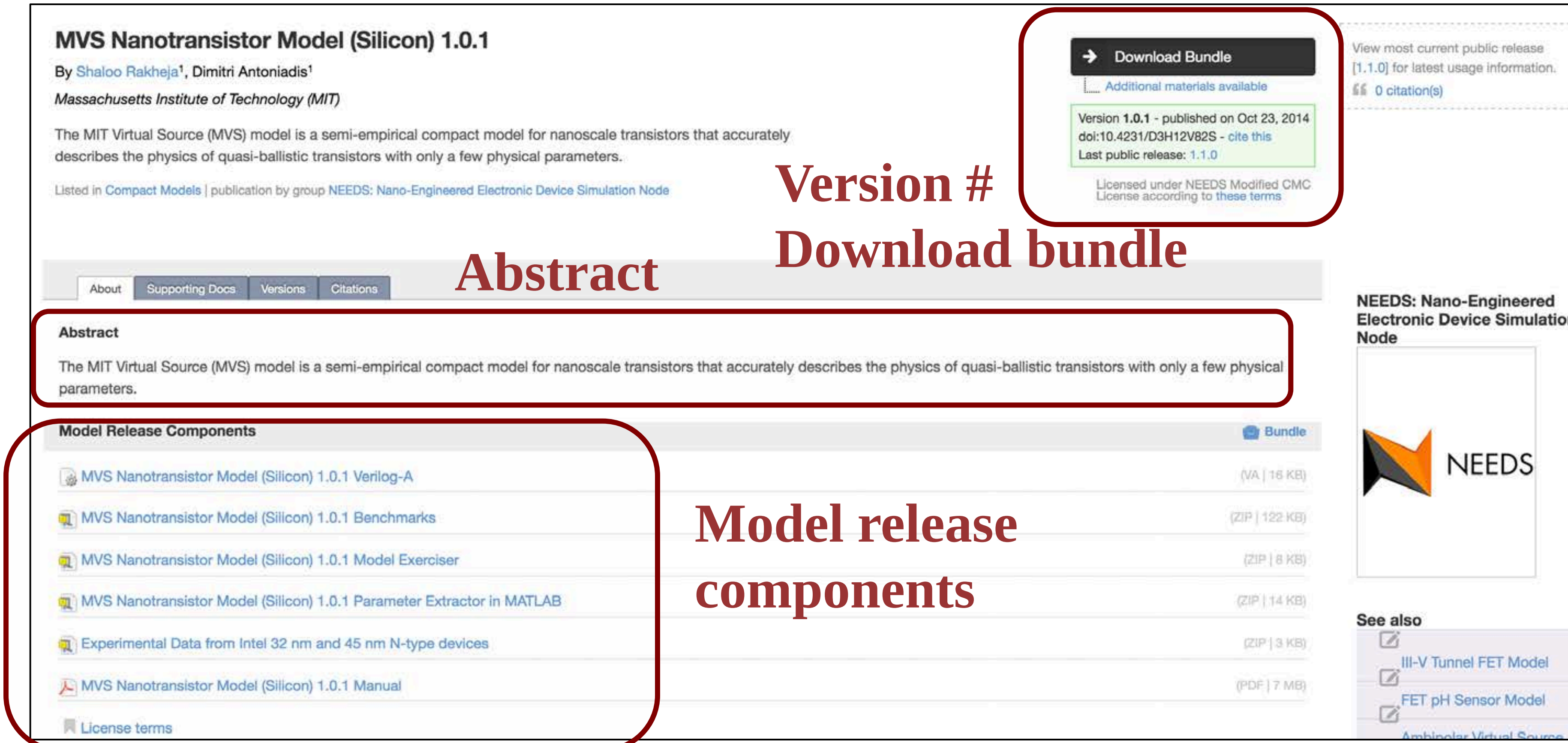


Capacitance versus V_{ds}



PART II
MVS model deployment on nanoHUB

MVS 1.0.1 package release snapshot



MVS 1.0.1 release package contents on nanoHUB: 1/2

1. **MATLAB-related**
   i. Model implementation
   ii. Model exerciser
   iii. Numerical parameter extractor
2. **Verilog-related**
   i. Model implementation
   ii. Test-benches for simple circuits
3. **Experimental data for model calibration**
4. **Model manual**

4

MVS 1.0.0 release package contents on nanoHUB: 2/2

5. **Update log (when a new version is released)**
6. **License agreement**

Link to the model on nanohub:
https://nanohub.org/publications/15

Wiki for model-release checklist:
NEEDS → For Developers → First item on Resources

Quick checklist for model release

Component	Associated files and/or requirements
MATLAB	• Model file Model exerciser • Parameter extraction (analytical/non-linear) • Readme file
Verilog-A	• Model file • SPECTRE/HSPICE netlists for simple circuits Readme file
Experimental data	• Readme file for data format and references
Model manual	• Explaining all of the model equations • Simulation results • Extraction methodology • Proper references

CMC license agreement

+

Update log (if needed)

MVS-related seminars on nanoHUB

- NEEDS Compact Model Release – Lessons Learned from MVS 1.0.0

  https://nanohub.org/resources/20139

Steps to follow when releasing your own compact model

- The MVS Nanotransistor Model: A Case Study in Compact Modeling

  https://nanohub.org/resources/21712

Dealing with mathematical issues in compact models

MVS model evolution

MIT Virtual Source (MVS)

Aug. 2013

MVS 1.0.0

Nov. 2013

MVS 1.0.1

Aug. 2015

MVS 1.1.0

Aug. 2015

MVS 1.2.0

- Targeted toward III-V HEMTs.
- Core formulation is same as MVS 1.1.0

Aug. 2015

MVS 2.0.0

- More physical
- /less empiricism than previous versions.
- Does not have dynamic model.

MVS model evolution

MIT Virtual Source (MVS)

Aug. 2013

MVS 1.0.0

Nov. 2013

MVS 1.0.1

Aug. 2015

MVS 1.1.0

Original MVS model [2009, 2012]

MVS 1.0.0 model evolution

MVS 1.0.0
Aug. 2013
→
MVS 1.0.1
Nov. 2013
→
MVS 1.1.0
Aug. 2015

Issues:
- Unused variables
- Hidden states
- Parameter range
- Indentation

Issues:
- **Capacitance discontinuity**
- Better ways needed to fix some other numerical issues in VA

- While we fixed some existing bugs in MVS 1.0.1, the mathematical issues still exist.

MVS model evolution

MIT Virtual Source (MVS)

Aug. 2015

MVS 2.0.0

Based on Landauer transmission theory

Accounts for non-equilibrium conditions in the channel

Non-linearity of access region resistances

- More physical
- /less empiricism than previous versions.
- Does not have dynamic model.

MVS 2.0.0

<u>MVS 2.0.0 provides two implementations:</u>

- For **[III-V HEMTs]** which have degeneracy and gm-reduction under high drain current

- For **[Si ETSOI]** devices which operate under non degeneracy and do not have any gm-reduction.

MVS 2.0.0 provides **only static transport model**.

https://nanohub.org/publications/74	Contains links to all other versions of MVS

https://nanohub.org/publications/74

MVS Nanotransistor Model 2.0.0

By Shaloo Rakheja[1], Dimitri Antoniadis[1]

Massachusetts Institute of Technology (MIT)

The MIT Virtual Source (MVS) model is a semi-empirical compact model for nanoscale transistors that accurately describes the physics of quasi-ballistic transistors with only a few physical parameters.

Listed in Compact Models | publication by group NEEDS: Nano-Engineered Electronic Device Simulation Node

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Abstract

MVS 2.0.0 is an improved physics-based virtual source (VS) model to describe transport in quasi- ballistic transistors. The model is based on Landauer scattering t
(i) degeneracy on thermal velocity and mean free path of carriers in the channel, (ii) drain-bias dependence of gate capacitance and VS charge including the effects
non-linear resistance of the extrinsic device region on gm-degradation at high drain currents in the channel.

Other MIT Virtual Source Models:

- **MVS 1.2 HEMT**

  This version of the MVS model is specifically targeted toward III-V HEMT devices that show a reduction in the transconductance at high drain currents.The r
  mechanical correction to the gate-channel capacitance.

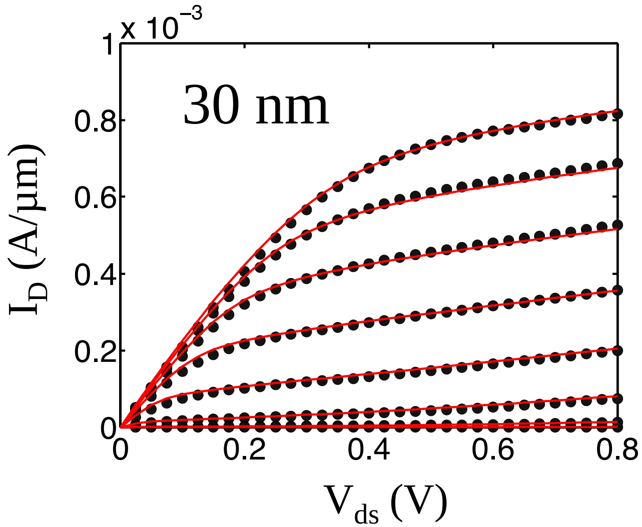
  Finally, the static transport model is supplemented with a charge partioning model. As in the previous MVS model versions, we provide the drift-diffusion no
  NVSAT) and blended quasi-ballistic charge model.

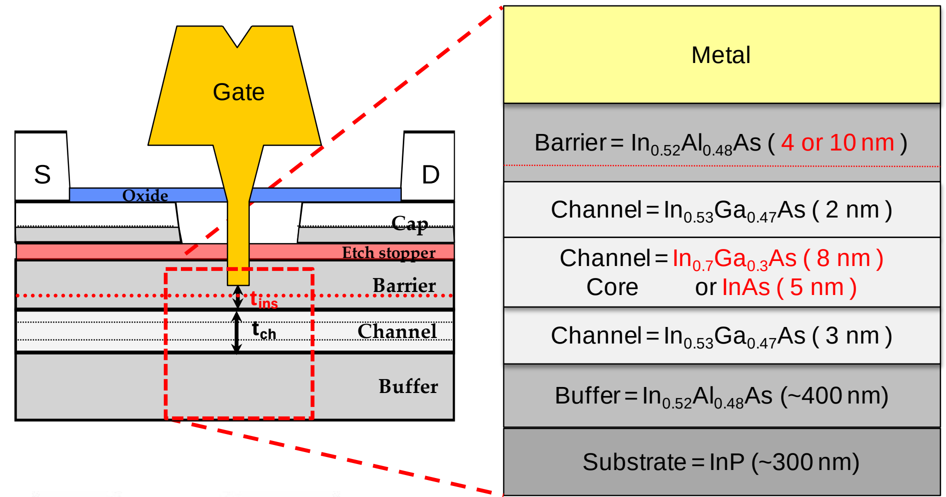
- **MVS 1.1 Silicon**

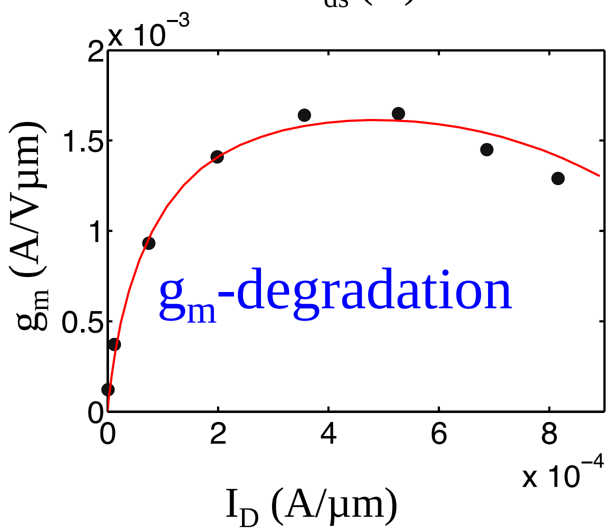
  This version of the MVS model is specifically targeted toward silicon devices. It contains slightly more empiricism than the more detailed MVS 2.0, and it is b
  models.

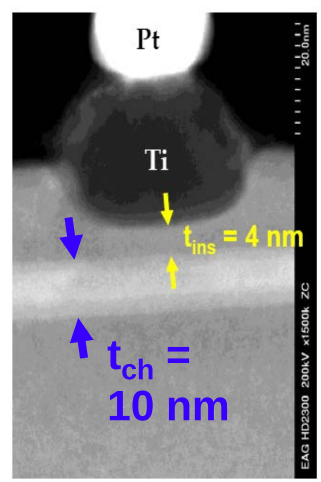
Links to all MVS versions available on the same page

InGaAs HEMTs with MVS 2.0.0









- L_{eff} = [30, 40, 60, 80, 130] nm
- Fabricated at MIT, 2009.

Key references for MVS 2.0.0

- S. Rakheja, M. Lundstrom, D. Antoniadis, “An Improved Virtual-Source-Based Transport Model for Quasi-Ballistic Transistors – Part I: Capturing Effects of Carrier Degeneracy, Drain-Bias Dependence of Gate Capacitance, and Non-linear Channel-Access Resistance,” **IEEE Transactions on Electron Devices, vol. 62, no. 9, pp. 2786-2793, Sep. 2015.**

- S. Rakheja, M. Lundstrom, D. Antoniadis, "An Improved Virtual-Source-Based Transport Model for Quasi-Ballistic Transistors – Part II: Experimental Verification,” **IEEE Transactions on Electron Devices, vol. 62, no. 9, pp. 2794-2801, Sep. 2015.**

Summary- MVS nanotransistor models

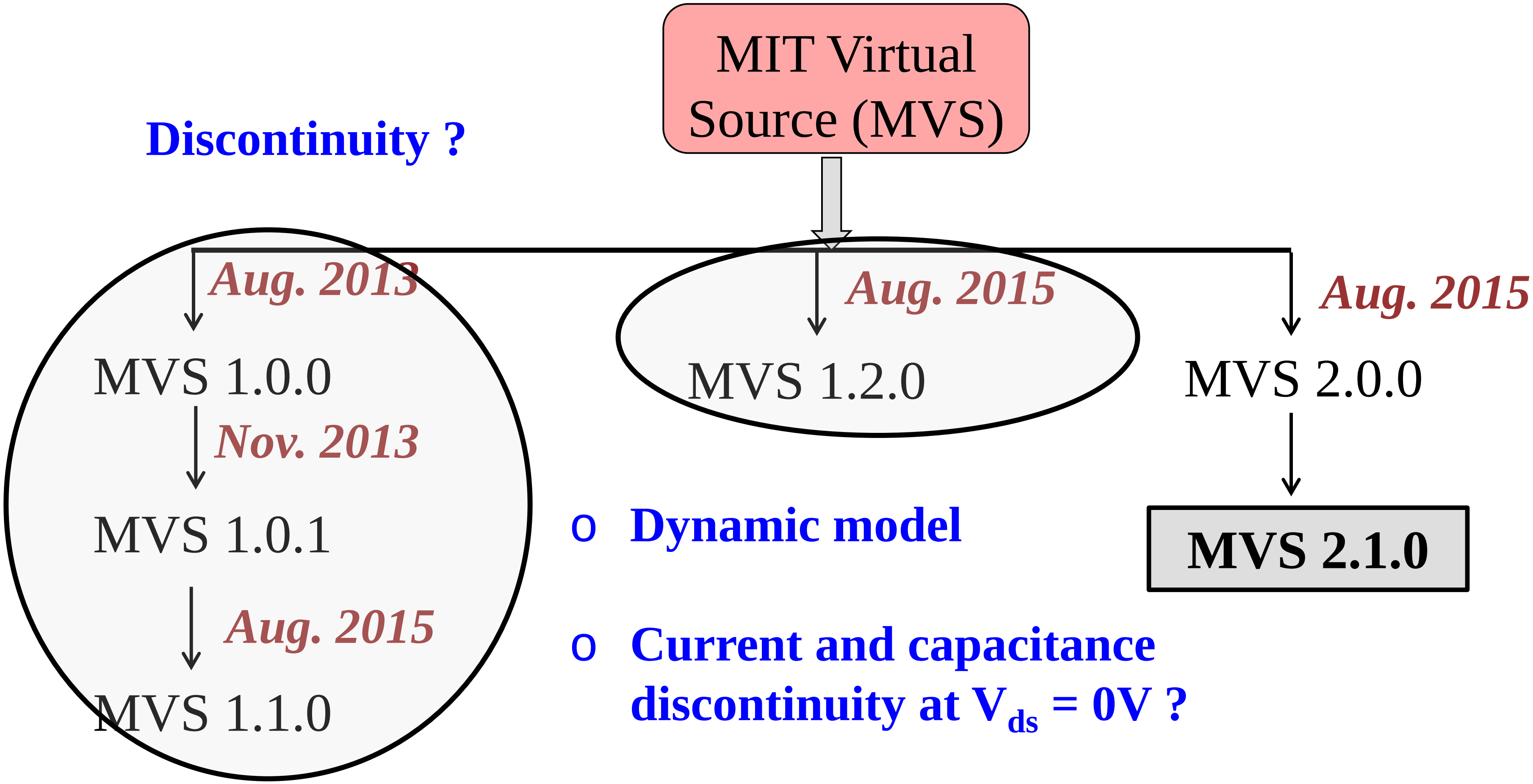
- Two VS Models **(MVS-1 and 2)** provide a progression of approximation accuracy to the Transmission Model suitable for any FET structure.

- Despite its simplicity MVS-1 provides a suitable tool for FET carrier transport benchmarking for technology assessment.

- MVS-2 is based on physically sound charge-control and transport models to allow quantitative analysis of band-structure characteristics.

MVS future plans

Discontinuity ?



- **Dynamic model**
- **Current and capacitance discontinuity at V_{ds} = 0V ?**