

DMT-core: A Python Toolkit for Semiconductor Device Engineers

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DOI: [DOIunavailable](#)

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Editor: [Pending Editor](#) ↗

Reviewers:

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Submitted: N/A

Published: N/A

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Statement of need

Semiconductor device engineers are faced by a number of non-trivial tasks that can be solved efficiently using software. These tasks include, amongst others, data analysis, visualization and processing, as well as interfacing various circuit and Technology-Computer-Aided-Design (TCAD) simulators. In practice, custom ‘home-made’ scripts of varying quality are employed to solve these tasks. It is often found that fundamental software engineering concepts, such as Test-Driven-Development (Shull et al., 2010), or the use of state-of-the-art version control tools (e.g. Git) and practices (e.g. continuous integration, CI), are not utilised by these scripts. This causes severe inefficiencies with respect to the users cost and time.

The issues inflicted by this practice can be summarized as follows:

- The analysis/visualization/generation of data becomes difficult to reproduce.
- Device engineers work far from their maximum work-efficiency, as they are hindered, instead of empowered, by the employed software infrastructure.
- Knowledge built-up, possibly over decades, may fade away when developers leave a company or institution.

The Device Modeling Toolkit (DMT) presented here aims to solve these issues. DMT provides a Python library that offers:

- classes and methods relevant for day-to-day device engineering tasks
- several abstract base classes for implementing new interfaces to various types of simulators
- concrete implementations of the abstract base classes for open-source simulators such as Ngspice (Vogt, 2022), Xyce (Keiter et al., 2014) or Hdev (Müller et al., 2022).

DMT-based simulations allow data generation, workflow implementation and visualization to be implemented in a single file, allowing for cooperate more effectively and more reproducible research (Stodden et al., 2016). In addition, basic principles of software engineering, such as unit testing, version control, and documentation are adhered to, so that others can also use and contribute to the software.

Summary

DMT is implemented as a toolkit that heavily leverages principles of object-oriented software design. Its Git repository contains documentation, and CI jobs that execute unit and integration tests, and create ready to install wheel files. This enables a large community of engineers (with sufficient Python knowledge) to install, use and contribute to the software.

In DMT data is stored using DataFrame objects. The DataFrame class is a subclass of `pandas.DataFrame` (McKinney, 2010), ideally suited for processing and analyzing large amounts of

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data. DMT extends this class with several data-processing methods that are particularly useful for electrical quantities such as currents, voltages and charges. Some of these methods are based on routines in `scikit-rl` (Arsenovic et al., 2022).

Electrical data comes from diverse sources such as experimental measurements or circuit simulations. A central problem with such data is the naming of variables, which should be consistent throughout the code in order to process data in a unified way. For example, some people might abbreviate the collector current of a bipolar transistor as **I_C**, while others might write **IC** instead. This can lead to major confusion when exchanging data and code with others. DMT implements a bullet-proof grammar for naming electrical quantities for solving this problem. During data import all data columns are translated to this grammar. This solves a big issue when transferring data between engineers or even for a single engineer between different work stations and (proprietary) software.

DMT offers classes and methods which can be used either directly or need to be subclassed, i.e. for creating interfaces to circuit simulators. The base class offered by DMT for representing electrical devices is called `DutView` (Device-Under-Test). This abstract class provides common attributes and methods that represent measurements, circuit simulations or TCAD simulations. There are several subclasses that add logic:

- `DutMeas` adds logic for DUT instances that contain measured data.
- `DutCircuit` is an abstract class that adds logic for DUT instances that represent circuit simulations. The interface is implemented in the DMT-core module for
 - Xyce (Keiter et al., 2014) in `DutXyce` and
 - Ngspice (Vogt, 2022) in `DutNgspice`.
- `DutTCAD` adds logic for DUT instances that represents devices based on TCAD simulations. The interface is implemented for
 - Hdev (Müller et al., 2022) in `DutHdev`.

Interfaces to other simulators, i.e. proprietary ones, are straight forward to implement. All simulators can be used as drop-in replacements for each other. There are only two necessary steps that need to be implemented for each simulator. First, a routine for generating the simulator input file must be implemented. Second, an import routine that returns a `DataFrame` from the simulator output must be provided. This is illustrated in Figure 1.

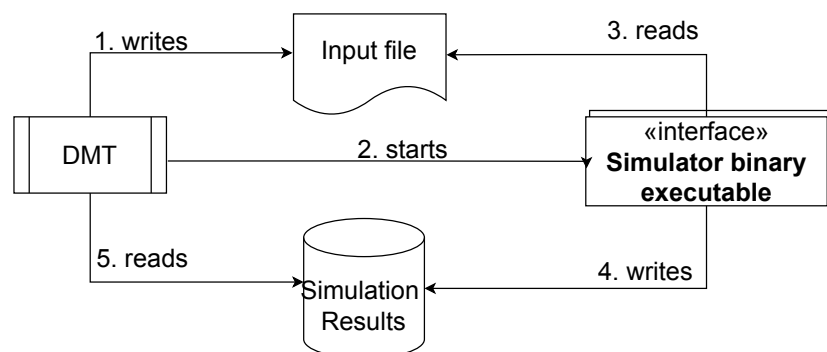


Figure 1: DMT interfacing a circuit simulator and corresponding data flow.

Often one needs to handle many different devices, e.g. transistors with different geometries. For this purpose the `DutLib` class offers a “container” for `DutView` objects, e.g. for storing the measurement data of one wafer. A typical use case is loading measurement data generated for a given technology, including specific test structures and transistors.

Circuit and TCAD simulations are started and controlled by the `SimCon` class. This class enables the user to run many simulations in parallel and utilizes the high core count of modern computers. Each simulation requires one `DutView` object that defines either a circuit or TCAD

simulation, as well as the definition of a sweep for changing the operating point. The definition of sweeps, i.e. the sweep of voltages or currents, is controlled by objects of the `Sweep` class. `SimCon` generates a hash for every simulation so that simulations need not be run when the software is called multiple times, provided the simulation definition (and therefore the hash) have not changed.

Another important class is `MCard`, useful for storing the model parameters of compact models that are defined within Verilog-A files. It implements a container that may store all model parameters, including information on parameter boundaries that is directly obtained from Verilog-A source files. This feature leverages the `VerilogAE` tool (Kuthe et al., 2020). `MCard` can interpret Verilog-A model codes, save and load lists of model parameters and can also be used to define elements in the `Circuit` class used for defining circuit simulations.

Finally, DMT implements the `Plot` class for displaying electrical data using different back-ends:

- `matplotlib` for interactive plots
- `pyqtgraph` for plots to be used in GUI applications
- `LaTeX:pgfplots` for TeX based technical documentation or scientific publications

An example plot of a simulated transistor is shown in [Figure 2](#).

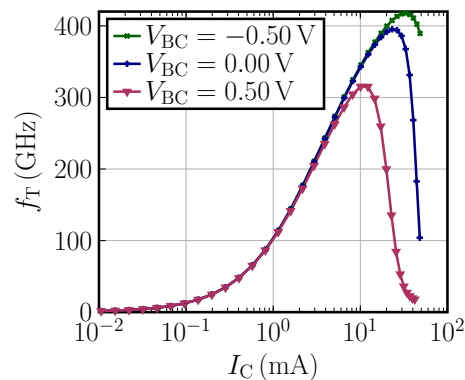


Figure 2: Transit frequency f_T of a Bipolar transistor.

Related Publications

DMT is used internally by CEDIC staff in research and by SemiMod for commercial purposes. It has also been used by cooperating institutions and companies. The project has been used in the following contexts:

- for circuit simulations (Weimer et al., 2022),
- for TCAD simulations and plotting (Markus Muller et al., 2021),
- for circuit and TCAD simulations (M. Muller et al., 2022),
- for model parameter extraction (Müller & Schröter, 2019) and
- for model parameter extraction and TCAD simulation (Phillips et al., 2022).

In addition, DMT has been cited in (Grabinski, 2019; Kuthe et al., 2020; Müller et al., 2019, 2021).

Related Projects

DMT directly uses the [VerilogAE](#) (Kuthe et al., 2020) for accessing all information in Verilog-AMS files. The TCAD simulator [Hdev](#) (Müller et al., 2022) uses the class `DutHdev` as its Python interface.

Acknowledgements

This project would not have been possible without our colleagues Dipl.-Ing. Christoph Weimer and Dr.-Ing. Yves Zimmermann. We particularly acknowledge Wladek Grabinski for his efforts to promote the use of open source software in the semiconductor community.

References

- Arsenovic, A., Hillairet, J., Anderson, J., Forsten, H., Ries, V., Eller, M., Sauber, N., Weikle, R., Barnhart, W., & Forstmayr, F. (2022). Scikit-rf: An Open Source Python Package for Microwave Network Creation, Analysis, and Calibration [Speaker's Corner]. *IEEE Microw. Mag.*, 23(1), 98–105. <https://doi.org/10.1109/MMM.2021.3117139>
- Grabinski, W. (2019). *FOSS TCAD/EDA tools for compact modeling*. Arbeitskreis Bipolar. https://www.see.et.tu-dresden.de/see/eb/forsch/AK-Bipo/2019/7-MOS-AK-Association_wgr_BipAK19.pdf
- Keiter, E. R., Mei, T., Russo, T. V., Schiek, R. L., Sholander, P. E., Thornquist, H. K., Verley, J. C., & Baur, D. G. (2014). *Xyce Parallel Electronic Simulator Reference Guide, Version 6.2* (September). Sandia National Laboratories (SNL). <https://doi.org/10.2172/1826862>
- Kuthe, P., Müller, M., & Schröter, M. (2020). VerilogAE: An open source Verilog-A compiler for compact model parameter extraction. *IEEE J. Electron Devices Soc.*, 8, 1416–1423. <https://doi.org/10.1109/JEDS.2020.3023165>
- Kuthe, P., Müller, M., & Schröter, M. (2020). VerilogAE: An open source Verilog-A compiler for compact model parameter extraction. *IEEE J. Electron Devices Soc.*, 8, 1416–1423. <https://doi.org/10.1109/JEDS.2020.3023165>
- McKinney, W. (2010). Data Structures for Statistical Computing in Python. *Proc. 9th Python Sci. Conf.*, 56–61. <https://doi.org/10.25080/majora-92bf1922-00a>
- Muller, Markus, Dollfus, P., & Schroter, M. (2021). 1-D drift-diffusion simulation of two-valley semiconductors and devices. *IEEE Trans. Electron Devices*, 68(3), 1221–1227. <https://doi.org/10.1109/TED.2021.3051552>
- Muller, M., Schroter, M., Jungemann, C., & Weimer, C. (2022). Augmented Drift-Diffusion Transport for the Simulation of Advanced SiGe HBTs. *2019 IEEE BiCMOS Compd. Semicond. Integr. Circuits Technol. Symp.*, 1–4. <https://doi.org/10.1109/bcicts50416.2021.9682487>
- Müller, M., Krattenmacher, M., & Schröter, M. (2019). *Open license parameter extraction tool - Overview and demo for SiGe HBTs*. HICUM Workshop. https://www.see.et.tu-dresden.de/see/eb/forsch/Models/workshop_2019/contr_2019/dmt.pdf
- Müller, M., Kuthe, P., Krattenmacher, M., & Schröter, M. (2021). *Overview of selected open source tools for compact modeling*. MOS-AK. https://www.mos-ak.org/silicon_valley_2021/presentations/Mueller-MOS-AK_SV_21.pdf
- Müller, M., Mothes, S., Claus, M., & Schröter, M. (2022). Hdev: A 1D and 2D Hydrodynamic/Drift-Diffusion solver for SiGe and III-V HBTs. *J. Open Source Softw.*
- Müller, M., & Schröter, M. (2019). *Selected Results of HICUM Parameter Extraction for InP HBTs*. Arbeitskreis Bipolar. https://www.see.et.tu-dresden.de/see/eb/forsch/AK-Bipo/2019/10-CEDIC_mmu_BipAK19.pdf
- Phillips, S., Preisler, E., Zheng, J., Chaudhry, S., Racanelli, M., Muller, M., Schroter, M., McArthur, W., & Howard, D. (2022). Advances in foundry SiGe HBT BiCMOS processes through modeling and device scaling for ultra-high speed applications. *2021 IEEE BiCMOS*

- Compd. Semicond. Integr. Circuits Technol. Symp.*, 1–5. <https://doi.org/10.1109/bcicts50416.2021.9682485>
- Shull, F., Melnik, G., Turhan, B., Layman, L., Diep, M., & Erdogmus, H. (2010). What do we know about test-driven development? *IEEE Softw.*, 27(6), 16–19. <https://doi.org/10.1109/MS.2010.152>
- Stodden, V., McNutt, M., Bailey, D. H., Deelman, E., Gil, Y., Hanson, B., Heroux, M. A., Ioannidis, J. P. A., & Taufer, M. (2016). Enhancing reproducibility for computational methods. *Science*, 354(6317), 1240–1241. <https://doi.org/10.1126/science.aah6168>
- Vogt, H. (2022). *Ngspice, the open source Spice circuit simulator - Intro*. <http://ngspice.sourceforge.net/>
- Weimer, C., Sakalas, P., Muller, M., Fischer, G. G., & Schroter, M. (2022). An Experimental Load-Pull Based Large-Signal RF Reliability Study of SiGe HBTs. *2021 IEEE BiCMOS Compd. Semicond. Integr. Circuits Technol. Symp.*, 1–4. <https://doi.org/10.1109/bcicts50416.2021.9682473>