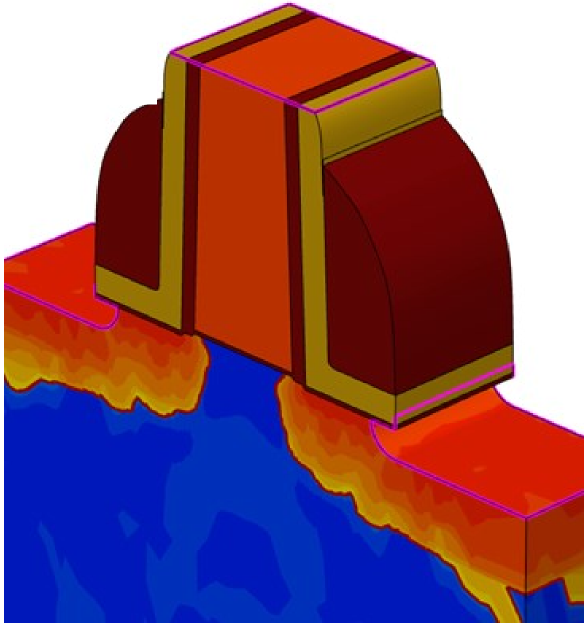
Technology Computer Aided Design (TCAD) Laboratory

Lecture 1, Introduction



[Source: Synopsys]

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Advanced Research Center on Electronic Systems (ARCES)

University of Bologna, Italy

About the course 1/2

- The main part of the course will be devoted to the practical use of a commercial TCAD software. The activities will be held in the *ARCES Lab (room Ex. 3.2).*
- The two fundamental questions *What is TCAD? Why TCAD?* will be answered in this lecture.
- Some theoretical background will be introduced as well to provide a mathematical and physical foundation to support the TCAD activities. The theoretical lessons will be delivered by Prof. M. Rudan.
- The **exam** consists in two tests:
  – A TCAD design project strictly related to the content of the course. The project will be carried out by the students during the last week of the course, *directly during the course class,* in the *ARCES Lab (room Ex. 3.2).*
  – A questionnaire about the theoretical background part
  – No mark will be given, the outcome will be either ‘passed’ or ‘not passed’

About the course 2/2

- Course notes can be downloaded from following website

www.micro.deis.unibo.it/~rudan/MATERIALE_DIDATTICO/diapositive/TCAD/diapo_TCAD_index.html

- The days before the class, please check the page “Notices” (“Avvisi”, in the Italian version) of my UniBo website for possible last minute communications (rescheduled lessons, change of agenda, etc.), see

people.unibo.it/it/giovanni.betti2

Outline

- Physical Modeling
- What is TCAD?
- Why TCAD?
- A link to the context
- In this class
- To probe further

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- ✓ ***Physical Modeling***
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Physical modeling: definitions

Physical Modeling

Representation of the physical behavior of a system (device) by an abstract mathematical model which approximates this behavior. Such a model may either be a closed-form expression (analytical model), or, in general, a system of coupled (differential) equations to be solved numerically.

Analytical Modeling vs. Numerical Modeling

Analytical modeling basically means the representation of a physical property or law in terms of approximate closed-form expressions using “lumped” parameters. It is also called “compact” modeling.

Numerical modeling: modeling of the device behavior through the numerical solution of the differential equations describing the device physics on a given geometrical domain.

Note: In the literature, the word “**modeling**” usually implies analytical/compact modeling, while “**simulation**” is much used for numerical modeling.

Examples

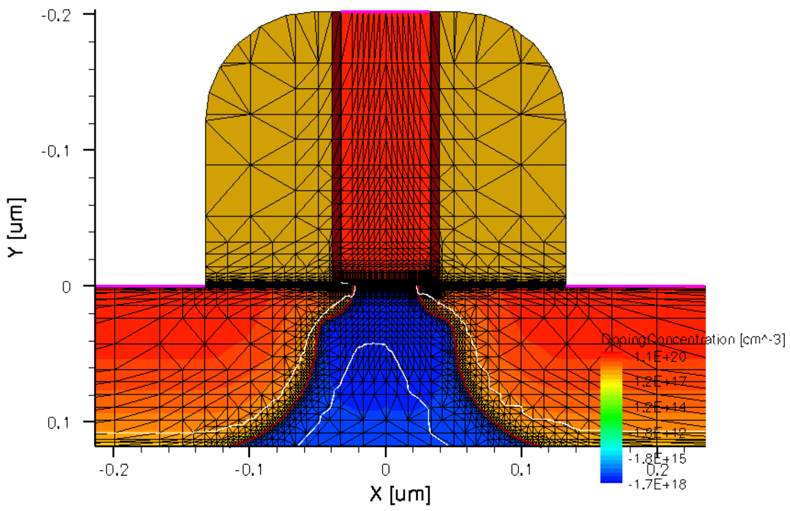
- Analytical modeling
  - I_{DS}-V_{DS} curve of a MOS transistor

$$I_D = \mu_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_{TH}) V_{DS} - \frac{1}{2} V_{DS}^2 \right]$$

- Numerical modeling
  - Drift-Diffusion numerical model

$$\begin{cases} \nabla \cdot \mathscr{E} = \rho / K_S \varepsilon_0 \\ \dfrac{\partial n}{\partial t} = \dfrac{1}{q} \nabla \cdot \mathbf{J}_N - r_N + g_N \\ \dfrac{\partial p}{\partial t} = -\dfrac{1}{q} \nabla \cdot \mathbf{J}_P - r_P + g_P \\ \mathbf{J}_N = q \mu_n n \mathscr{E} + q D_N \nabla n \\ \mathbf{J}_P = q \mu_p p \mathscr{E} - q D_P \nabla p \end{cases}$$

solved at each node of a discretized domain



Physical modeling: Pros & Cons

- Analytical Modeling
  - 🙂 Captures the essential concepts of device physics.
  - 🙂 Very effective to single out the most important aspects of a problem.
  - 🙂 Computationally efficient. Statistical analysis can be afforded.
  - 🙁 Limited applicability: hard to describe problems with complex geometry or very rich physics (e.g., “multiphysical” problem, i.e. coupled equations).
  - 🙁 New, physical models need significant a-priori understanding of the problem and long developing times.
- Numerical Modeling
  - 🙂 Allows for the description of more complex phenomena (physics & geometry).
  - 🙂 Addresses also problems that do not have a closed-form solution.
  - 🙂 More flexible, does not always need a depth a-priori understanding of the problem.
  - 🙂 More reliable from a quantitative point of view.
  - 🙁 High computational burden. Statistical analysis hard to be afforded.
  - 🙁 More difficult framework to interpret the results and to single out essential points.
  - 🙁 Require complex software architectures or expensive licenses of commercial tools.

Physical modeling of semiconductor devices

- Analytical and numerical modeling are *complementary techniques*, that are often used together in both industry and academia, with different specific aims. In the semiconductor device field, compact models and numerical simulation are expected to interact with each other in the semiconductor chip design flow (see next).
- Nowadays, in the semiconductor industry compact models are mainly used for circuit-device interaction (circuit simulators), statistical analysis and on-the-fly screening of experimental results.
- Numerical simulation is much used to understand advanced device physics, for device design, scaling analyses & interaction with process manufacturing.
- Of course, any kind of modeling should always be validated (or, in some cases, *calibrated*) with respect to the available experimental data.
- This course will be about *numerical modeling* of semiconductor devices, usually named as TCAD, which stands for "Technology Computer-Aided Design" (see next).

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✓ ***What is TCAD?***

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What is TCAD?

- TCAD = Technology Computer-Aided Design

TCAD is a branch of Electronic Design Automation (EDA) that models semiconductor fabrication and semiconductor device operation. The modeling of the fabrication is termed *Process TCAD*, while the modeling of the device operation is termed *Device TCAD.* The aim of TCAD is the design of semiconductor processes and devices to fulfill some given specifications.

- Process TCAD: modeling of semiconductor-chip process-manufacturing steps like lithography, deposition, etching, ion implantation, diffusion, oxidation, silicidation, mechanical stress, etc..

➢ It requires detailed modeling of the *physical principles of manufacturing*, and usually also the modeling of the *specific equipments* used. Calibration of models needs expensive experiments (ad-hoc wafer fabrication, physical-chemical investigations).

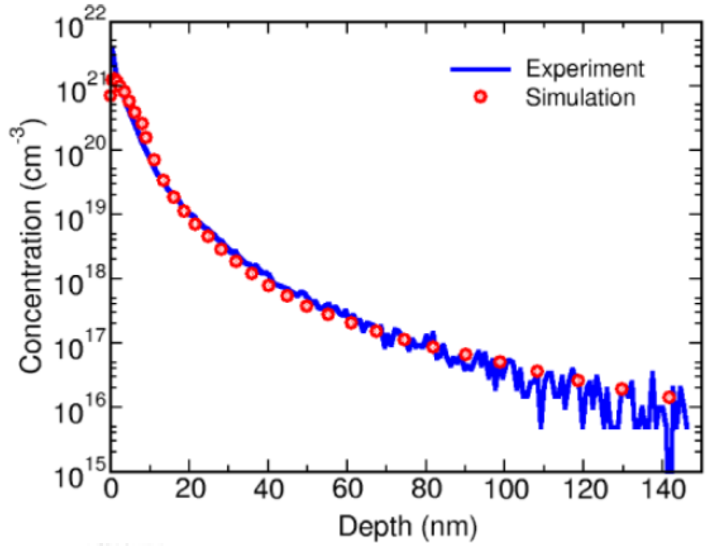
- Device TCAD: modeling of electrical, thermal, optical and mechanical behavior of semiconductor devices (e.g., diode, BJT, MOSFET, solar cell,…).

➢ It focuses on the physical principles at the basis of *carrier transport* and of *optical generation* in semiconductor devices. Models are more easily generalized than for process physics. In addition, they do not need moving boundaries/moving meshes, as instead process simulations need, i.e. convergence is in general easier. Calibration of models usually needs only electrical characterization of fabricated samples.

What is TCAD? – Examples

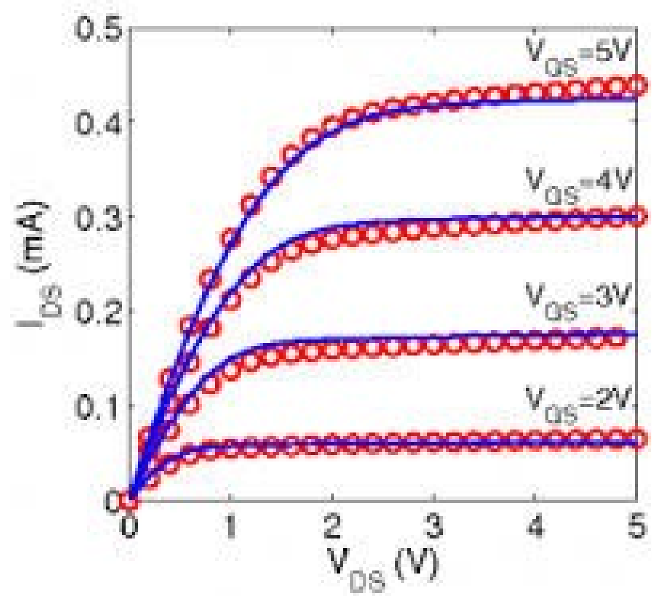
- Process simulations

  Simulate doping profiles obtained by specific processing techniques, calibrate the model with experimental data and then optimize the process to obtain the desired profile.



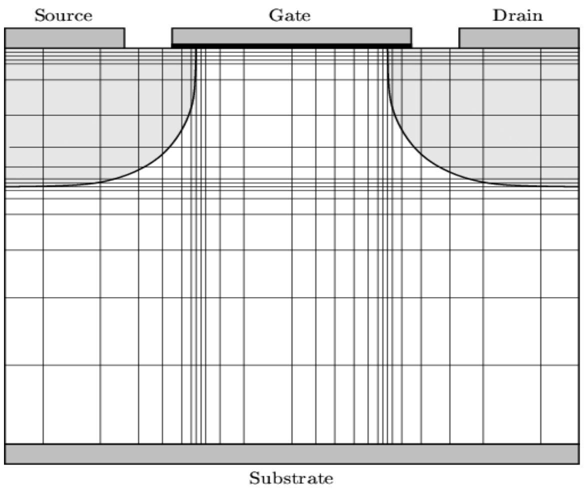
- Device simulations

  Simulate the output characteristics of a MOSFET device and calibrate the device architecture to fine-tune the device performance.

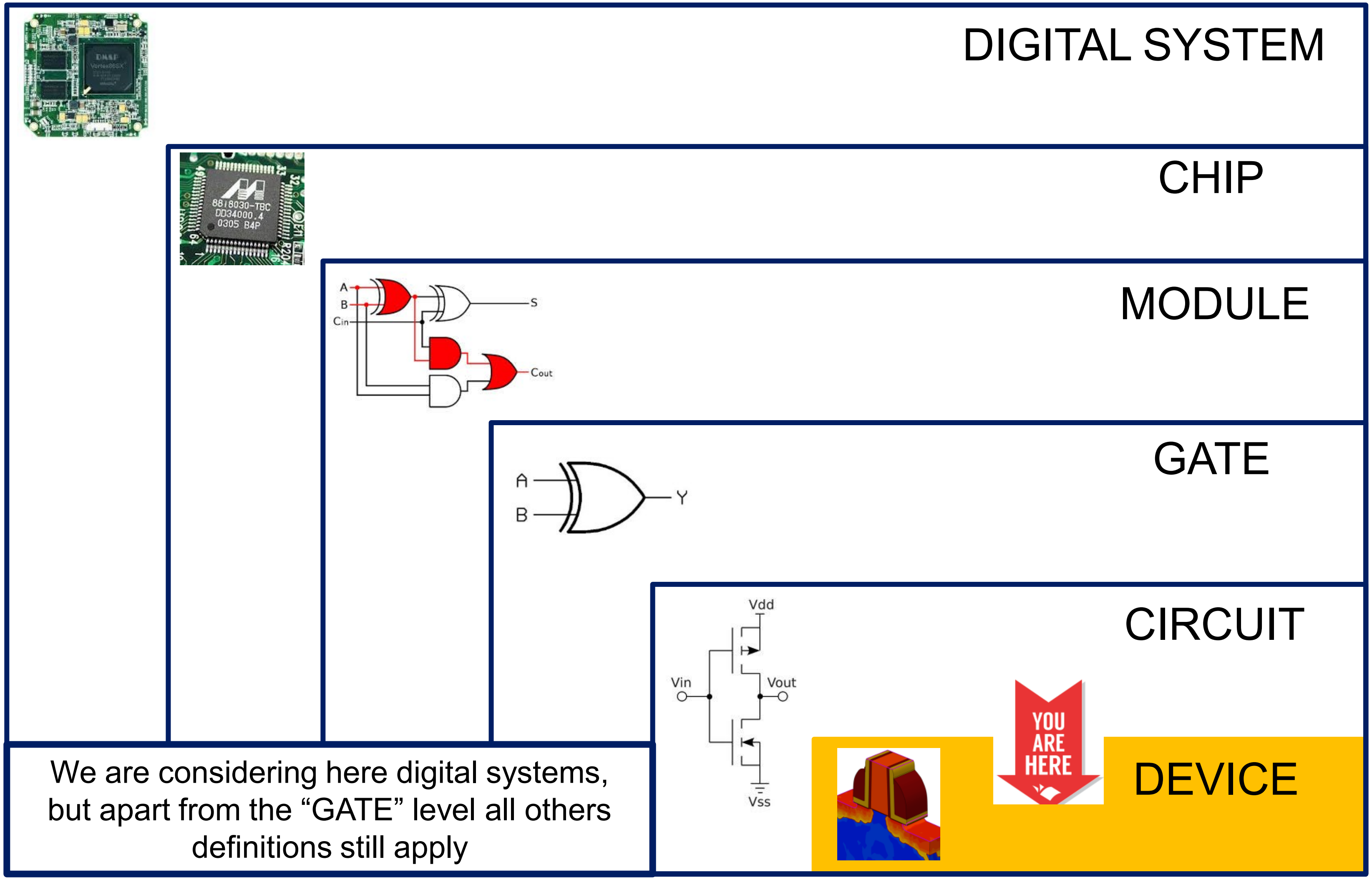


What is TCAD? – Device Simulation

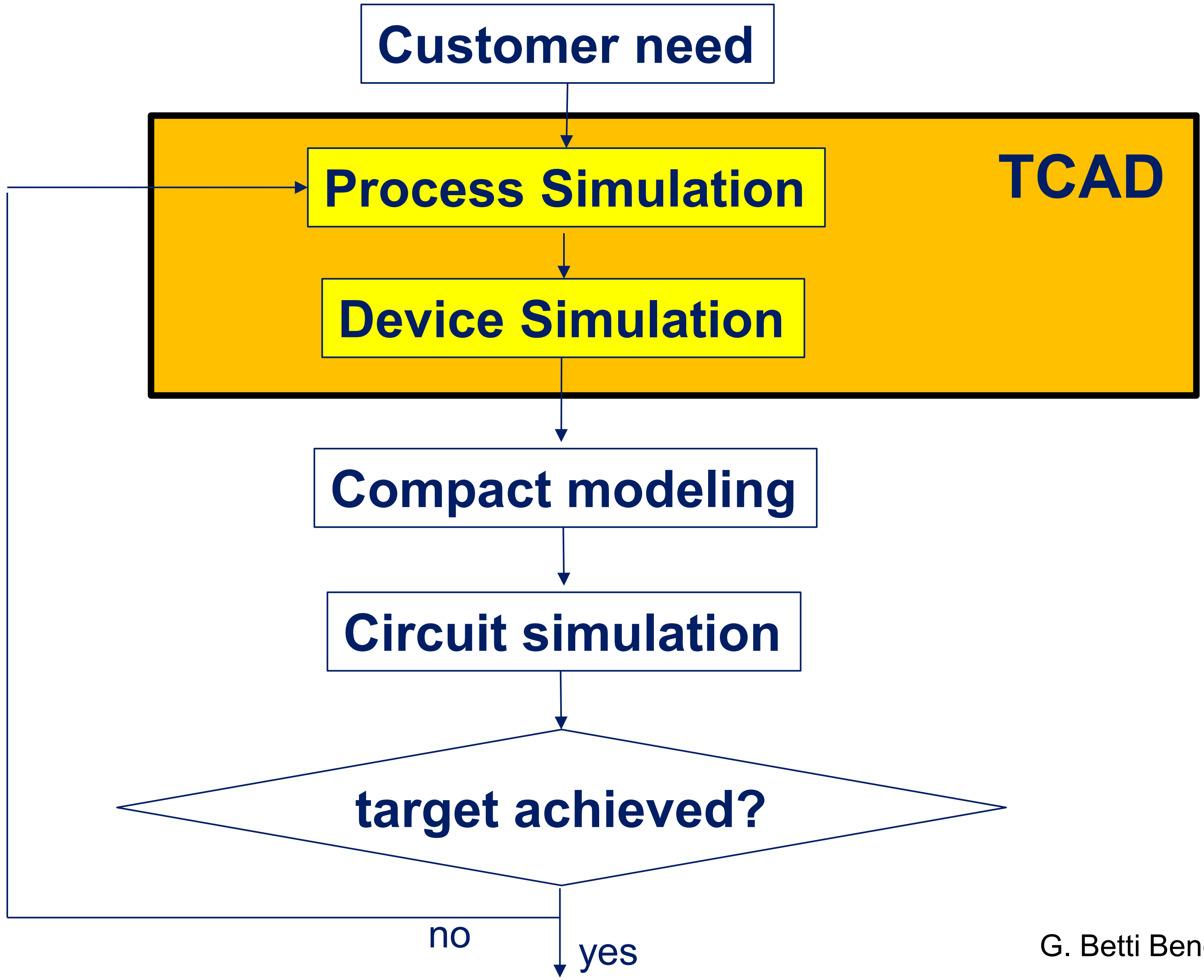
- There are two main components in physical device simulation:
  1. Electric field given by a net charge distribution (electrostatics).
  2. Charge motion due to electric field and diffusion (transport).
- Typically, analytical solutions are possible only in 1-D and using the Maxwell-Boltzmann statistics instead of the more general more Fermi statistics (problem with highly-doped samples).
- The most popular and efficient model for device simulation is the Drift-Diffusion model (see Prof. Rudan's part on model theory)
- Numerical solutions require the discretization of the equations for electrostatics and transport over a grid (mesh), followed by the simultaneous (self-consistent) solution of the resulting algebraic equations.



What is TCAD? – TCAD in microelectronics



What is TCAD? – Technology Development



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Why TCAD? (1)

1. To optimize the device features when hands-on calculations are too complicated or impose unacceptable assumptions.
2. To make predictions (scaling, new device concepts) when hands-on calculations are not viable (e.g., complex devices, modeling of distributed statistical effects or process yield).
3. To get insights. No real experiment will probably be ever able to measure some of the physical quantities calculated by TCAD tools (e.g., local distribution of carriers, local electric field, etc.).
4. To quickly screen technological options and drive the industrial strategy.

"R&D cost continues to rise due to the increasing complexity of processes. In the early exploratory stage of a new technological node, companies face tough decisions to choose from a multitude of technological choices. It is rarely the case to have enough experimental data at this stage to help narrow down the technological choices. Therefore TCAD, with proper physical models, if applied to pre-screen and help down select, brings tremendous value to R&D."

J. Wu et al., (TSMC),
"Expanding Role of Predictive TCAD in Advanced Technology Development", SISPAD 2013.

Why TCAD? (2)

- Thus, TCAD can be applied for both **analysis** and **design** of semiconductor processes and devices.

Analysis → Model development

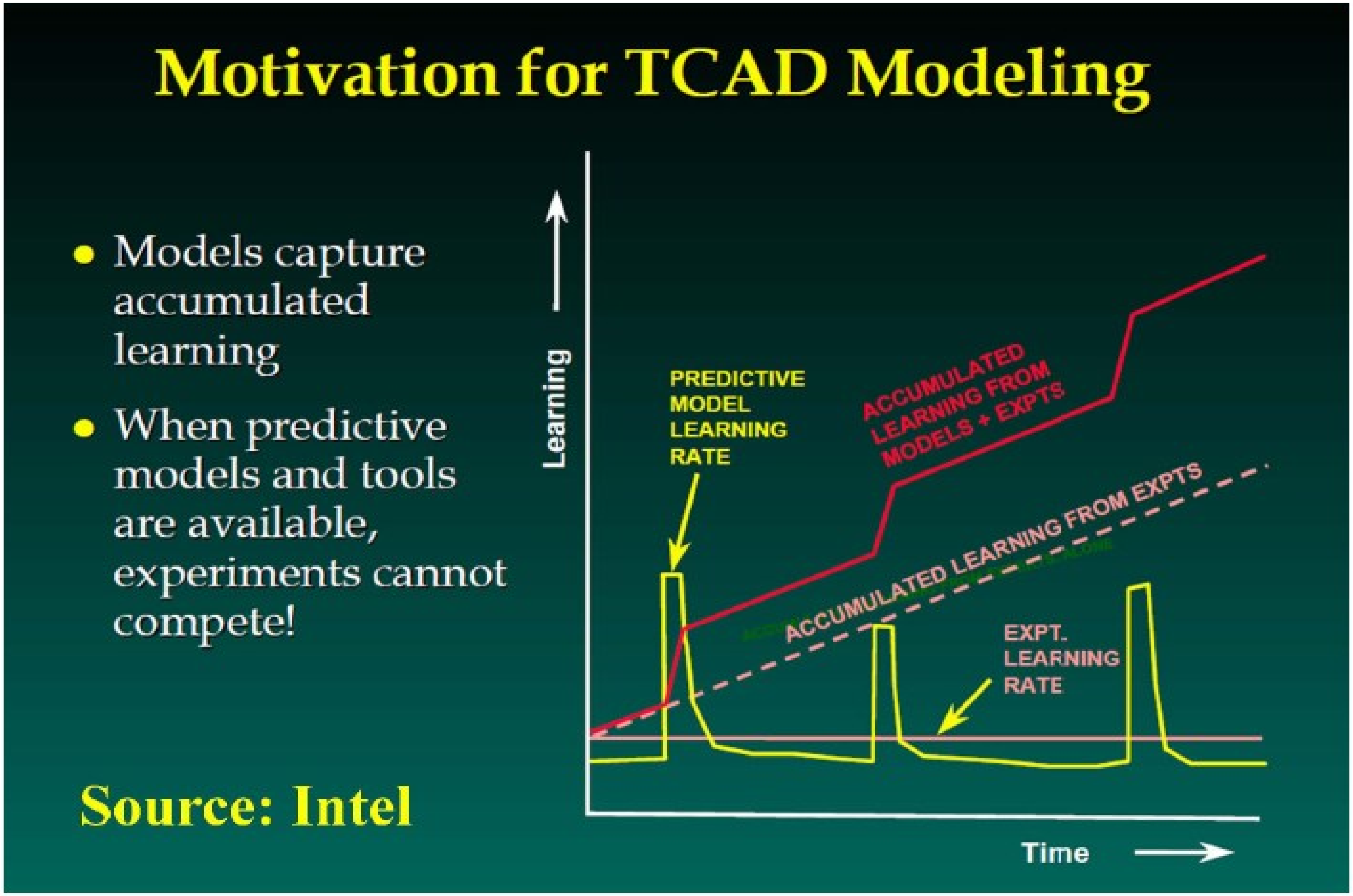
Analysis is important in the first stage of a model development. Careful comparison with experimental data is needed to develop a suitable model. Once the model has been developed, analysis techniques can be used to simulate the behavior of a system to understand the dependence of system performance on physical parameters and the physical mechanisms limiting the system performance.

Design → Model application

Once a robust physical model of the system has been developed, it can be used to devise more suitable device architectures (geometry, materials..) to achieve a desired functionality.

Often analysis is used to rapidly explore the ***sensitivity*** of the system performance on the system's degrees of freedom. Then, design approaches are used to provide more detailed indication in order to ***optimize*** the system degrees of freedom thus achieving the desired performance.

Why TCAD? (3)



T. Ma (Synopsys),
"TCAD Present State and Future Challenges", IEDM 2010

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A link to the context (1) – EDA/ECAD tools

- While the general term CAD (Computer Aided Design) is usually referred to software for mechanical/fluid-dynamics calculations, the electronics engineering community refers to: EDA/ECAD=Electronic Design Automation or Electronic CAD.
- EDA is a category of software tools for designing electronic systems such as printed-circuit boards and integrated circuits. The tools work together in a design flow used to design and analyze the entire semiconductor chip.
- Under the “EDA” label one can find basically all possible engineering activities concerning electronics systems, such as system architecture design, circuit design, layout verification, electromagnetics, and TCAD as well.
- Principal suppliers (software house) providing commercial EDA software are:
  - *Synopsys* (leader of sw tools for digital systems)
  - *Cadence Design Systems* (leader for sw tools for analog systems)
  - *Mentor Graphics*
- As for today, considering TCAD, the two major players are
  - Synopsys Sentaurus (the most used) → this course ! SYNOPSYS
  - Silvaco ATLAS SILVACO

A link to the context (2) – TCAD & microelectronics industry

Q: Which companies use TCAD tools to develop and optimize their products?

A: The big players in the microelectronics industry with large fabrication facilities

- USA:
  - *Intel, IBM/Globalfoundries, Texas Instruments, Micron*, …
- Asia:
  - *TSMC, Samsung, Renesas, Hynix,Toshiba, …*
- Europe:
  - *STMicroelectronics, Infineon, NXP , ON Semiconductor, ABB …*
- TCAD in small corporations is much less diffused since the price of a minimum set of TCAD licenses typically exceeds company’s quarterly profits, and also because small companies typically do not survive in the microelectronics market.
- Also many research centers and universities have scientific groups devoted to TCAD or advanced TCAD. They use both TCAD commercial tools for research purposes (software houses provide cheaper research licenses but without technical support) and also develop their own new models, and new simulators, in order to account for advanced physical effects occurring in novel device concepts and scaled devices.

A link to the context (3) – a bit of history (1)

Microelectronics Industry. Past trend (1960-2000), 1D/2D devices:

Hands-on calculations to design semiconductor devices and/or trial-and-error approach. Partially due to limited availability of both quick and accurate simulation tools, and partially due to the fact that hands-on calculations were sufficient to get the targets.

1949: Beginning - Shockley's Theory.

"*The p-n-p transistor has the interesting property of being calculable to a high degree*"*– W. Shockley, Nobel Prize, 1956*

1950–1960: Golden Era of BJTs – Analytical calculations and design plots.

1960–1975: Foundation of IC Engineering – Isolated (IBM, etc.) computer calculations of devices and processes – device/process design still based on hand calculations and design plots.

1975–2000: CMOS Scaling – Commercial simulators ramp up to ubiquitous use. Use of Drift-Diffusion numerical model becomes popular since the 2D nature of the carrier density in the MOSFET becomes the dominant aspect of the device physics.

at UniBo: *G. Baccarani, R. Guerrieri, P. Ciampolini, and M. Rudan, HFIELDS: A highly flexible 2D semiconductor device analysis program, Proc. NASCODE-IV, pp.3-12, June 1985*.

A link to the context (4) – a bit of history (2)

Microelectronics Industry. Today and future trend (2000- …), 3D devices:

Ever increasing availability of powerful calculators. Extensive use of TCAD and advanced TCAD tools. Hands-on calculation as “first guess”. The tendency is to avoid as much as possible trial-and-error approaches to save time & money. In fact, the increase in device complexity will require the optimization of an ever increasing number of parameters, while, at the same time, the cost of process runs of advanced technology will exponentially increase as well.

- Constantin Bulucea, TI, (2007), "TCAD Revisited, 2007: An Engineer’s Point of View”, https://nanohub.org/resources/3638.

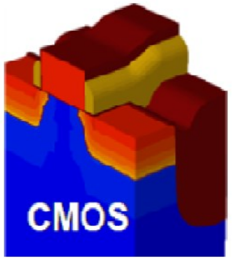
2013: “*In the ITRS the saving of development times and costs of new technologies and devices by the use of TCAD is estimated at about* <u>*one third*</u> *for best practice case*”

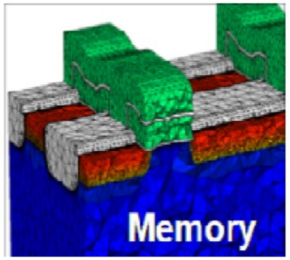
- J. Lorentz et al., Fraunhofer IISB, Challenges and opportunities for process modeling in the nanotechnology era, J. Comput. Electron.

A link to the context (5) – TCAD today: applications

<u>More Moore</u>
CMOS logic
Memory
Interconnect,

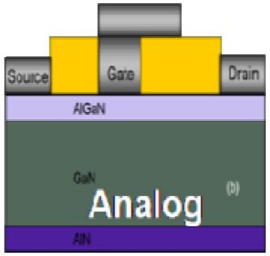
USA, Asia

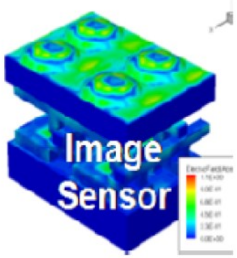


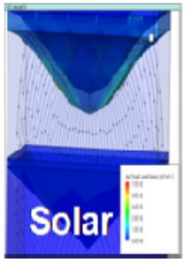


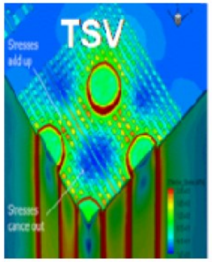
<u>More Than Moore</u>
Analog
Power
Image Sensor
Solar
TSV

USA, Asia, Europe

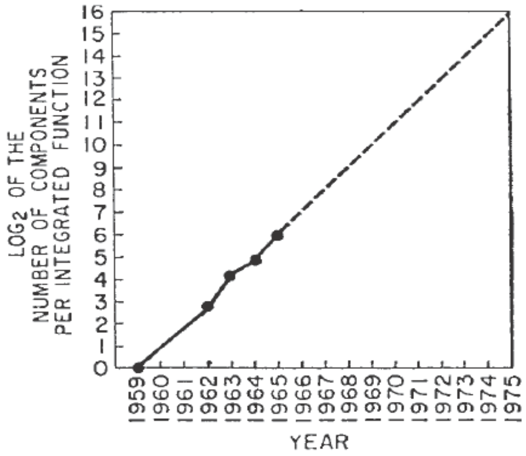








T. Ma, "TCAD Present State and Future Challenges", IEDM 2010



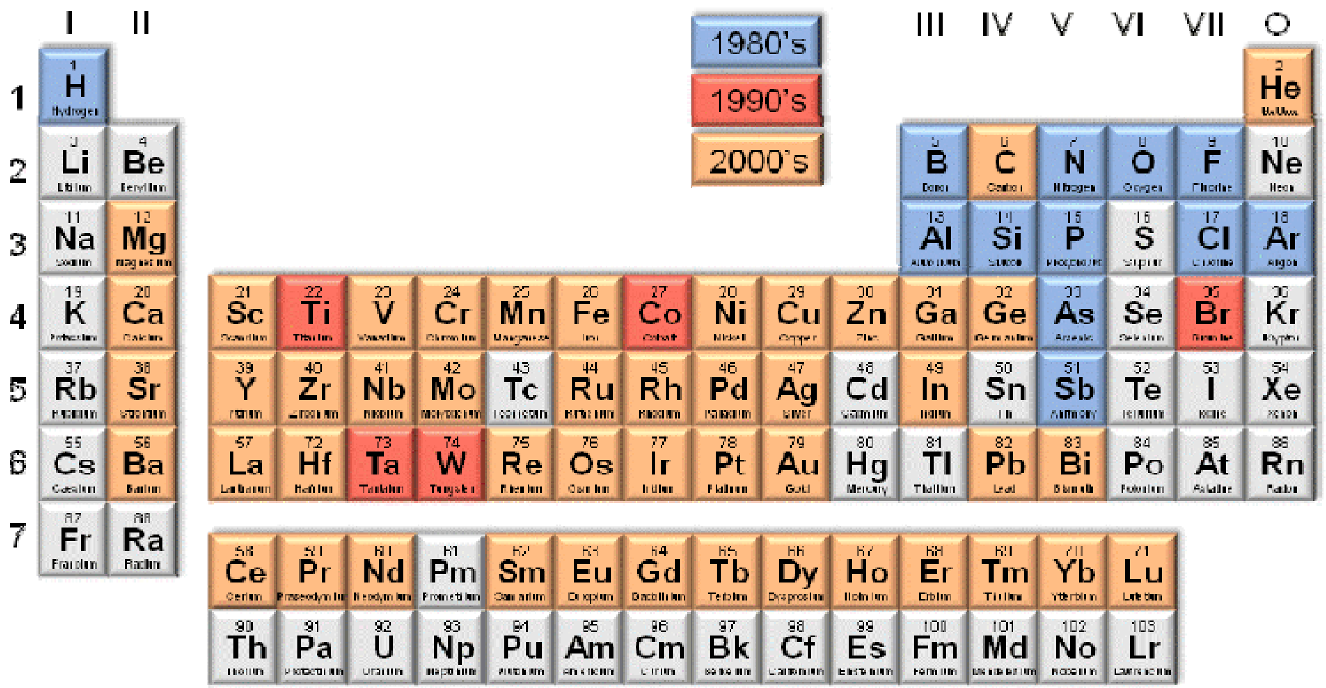
<u>Moore's law</u>: the number of transistors in a chip increase by a factor 2 within 18 or 24 months

G.E. Moore, "Cramming more components onto integrated circuits', Electronics, 114-117, pp. 1965

A link to the context (6) – TCAD today: challenges (1)

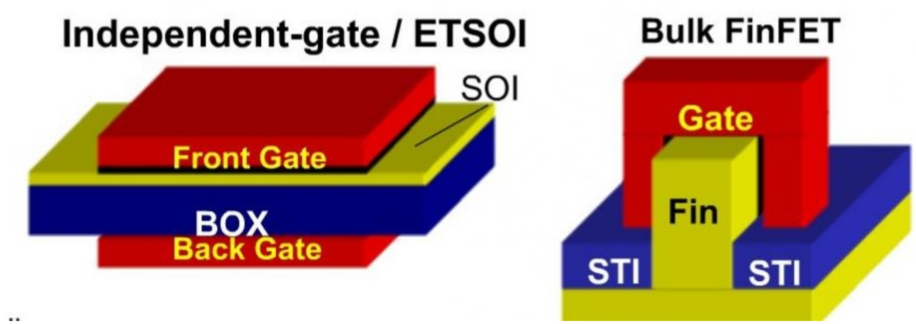
New materials used in microelectronics technology have increased tremendously since the 1980s. This brings about two fundamental needs:

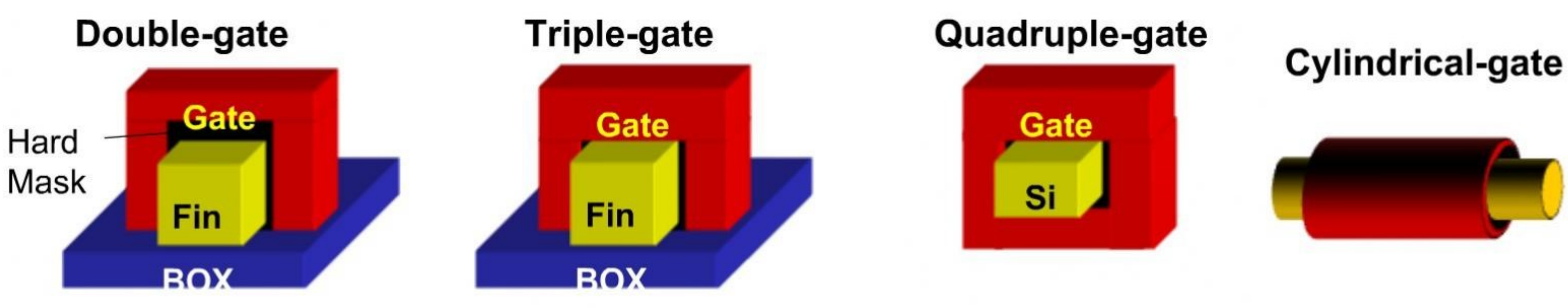
1. Validate existing models for new materials, or develop new models, if needed.
2. Calibrate the models to extract parameters of new materials. Material simulation tools (ab-initio, molecular dynamics) are used to investigate material behavior and fed the TCAD tools with appropriate material parameters.



A link to the context (7) – TCAD today: challenges (2)

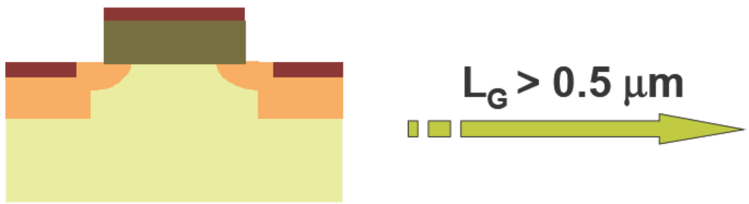
The introduction of advanced technological features like stressors, high-*k* metal gates, and multi-gate architectures (e.g., FinFET) to improve mobility and device electrostatics, makes the process manufacturing & reliability assessment extremely more challenging, the same hold for TCAD.





TCAD in the semiconductor modeling hierarchy

"TCAD"



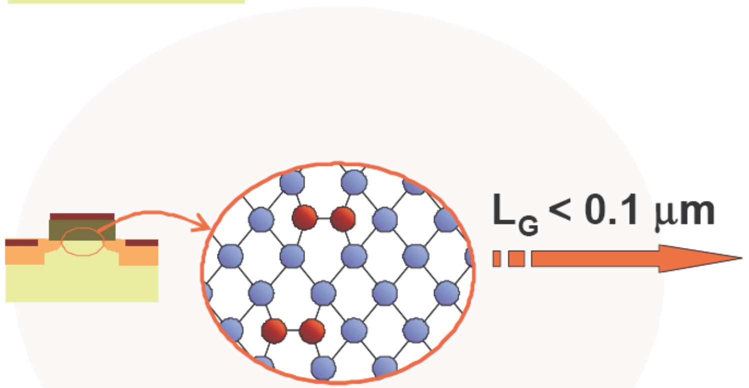
<u>Drift-Diffusion model</u>

Good for devices with gate length > 0.5μm, but with appropriate advanced add-on features (quantum models, advanced mobility models) can be extended to channel lengths of few tens of nm.

<u>Hydrodynamic model</u>

Hot-carrier effects, such as velocity overshoot, included into the model.

Overestimates the velocity at high fields.



<u>Particle-based simulators (Monte-Carlo method)</u>

Allows for a proper treatment of the discrete impurity effects and for electron-electron, electron-ion interactions.

Time consuming.

<u>Quantum models</u>

More rigorous but extremely time-consuming. More and more used in these days owing to the need of exploring the features of extremely scaled devices and thanks to the availability of ever more powerful computers.

D. Vasileska, (2006), "Introduction to Computational Electronics," https://nanohub.org/resources/1501

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✓ ***In this class***

- To probe further

In this class

- Practical TCAD activity using the nowadays most used tool for TCAD in both industry and research, i.e., *Synopsys Sentaurus* commercial software (academic license).
- Due their importance in the Electronics Engineering curriculum, we will simulate the following devices:
  - Diode.(simple pn-junction and integrated diode)
  - MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor).
- The concepts used and developed in this class are strictly related to the courses of semiconductor-device physics provided by the University of Bologna Master curriculum in Electronics Engineering (Microelectronics & Solid-State-Electronics, Prof. M. Rudan, and Nanoelectronics, Prof. G. Baccarani).
- In this course, the mathematical and physical foundation needed to understand the physics behind the simulations will be provided by the lessons given by Prof. M. Rudan. The laboratory classes only addresses device physics from a *phenomenological point of view to provide an intuitive feeling of device physics when needed*, as a support for the simulations.
- The goal of the course is to provide a general framework that should allow students to understand the working methodology of TCAD and, more generally, of CAD. Another goal of the course is provide an intuitive feeling of the physics of the above semiconductor devices, which are at the heart of each electronic system.

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To probe further (1): websites

- EDA/ECAD

  http://en.wikipedia.org/wiki/Electronic_design_automation

  – Comprehensive list of tools for electronic design automation (analog, digital, circuit level, system level, and TCAD as well).

- Synopsis TCAD homepage

  http://www.synopsys.com/Tools/TCAD/Pages/default.aspx

- *www.nanohub.org* (Purdue University)

  – Courses, on-line presentations, simulation tools and other useful free resources about modeling & simulation of semiconductor devices and materials.

To probe further (2): scientific literature

IEEE (Institute of Electrical and Electronics Engineers).

Journals

IEEE Transactions on Electron Devices (T-ED)

IEEE Electron Devices Letters (EDL)

Solid-State Electronics

Journal of Computational Electronics

Journal of Applied Physics (JAP)

Applied Physics Letters (APL)

IEEE Transactions on Nanotechnology (T-NANO)

Conferences

The International Conference on Simulation of Semiconductor Processes and Devices (SISPAD)

The International Electron Device Meeting (IEDM)

International Workshop on Computational Electronics (IWCE)

European Solid-State Device Research Conference (ESSDERC)

Device Research Conference (DRC)