When we hear the term *semiconductor device*, we may think first of the transistors in PCs or video game consoles, but transistors are the basic component in all of the electronic devices we use in our daily lives. Electronic systems are built from such components as transistors, capacitors, wires, light-emitting diodes and semiconductor lasers. These components are typically integrated into a single chip made of a semiconductor material.

Almost every college or university department of Electrical Engineering offers instruction in the fundamental concepts of semiconductor devices. These concepts typically include lattices, crystal structure, bandstructure, band models, carrier distributions, drift, diffusion, pn junctions, solar cells, light-emitting diodes, bipolar junction transistors (BJT), metal-oxide semiconductor capacitors (MOS-caps), and multi-acronym-device field-effect transistors (mad-FETs).

Advanced courses go more deeply into semiconductor theory, device physics, fabrication processes, as well as advanced and special purpose devices, such as heterostructure devices, power devices, and optoelectronic devices.

This nanoHUB “topic page” provides an easy access to selected nanoHUB educational resources.
material on semiconductor devices that is openly accessible.

We invite users to participate in this open source, interactive educational initiative:

- **Contribute content** by uploading it to the nanoHUB. (See “Upload your own content”) on the nanoHUB mainpage.
- Provide feedback for the items you use on the nanoHUB through the review system. (Please be explicit and provide constructive feedback.)
- Let us know when things do not work by filing a ticket through the nanoHUB “Help” feature on every page.
- If you have suggestions for improvements, submit a wish.

Thank you for using the nanoHUB, and be sure to share your nanoHUB success stories with us. We like to hear from you, and our sponsors need to know that the nanoHUB is having impact.

### Crystal Structures, Lattices

**Crystal Viewer**

The [Crystal Viewer in ABACUS](#) enables the interactive visualization of different Bravais lattices, crystal planes, and materials (diamond, silicon, indium arsenide, gallium arsenide, graphene, and buckyball).

First time use of the tool is supported by: [Crystal Viewer Tool: First-Time User Guide](#).

It is supported by a homework assignment in [MS Word](#) and [Adobe PDF](#) format.

**Exercise: Crystal Lattices**
Crystal Viewer Tool Learning Materials – Comprehensive set of learning materials for the Crystal Viewer Tool.

Band Models / Band Structure

Piecewise Constant Potential Barriers Lab

This tool computes the transmission and the reflection coefficient of a five, seven, nine, eleven and 2n-segment piecewise constant potential energy profile. It enables the rapid visualization of the formation of band structures in a finite superlattice.

First time use of the tool is supported by: Piece-Wise Constant Potential Barriers Tool: First-Time User Guide

The materials below provide a detailed description of the physics required both to use this tool correctly and to interpret the results obtained:

- Open Systems
- Double-Barrier Case Explained
Exercises that illustrate the importance of quantum-mechanical reflections in state-of-the-art devices and the resonance width dependence upon the geometry in the double-barrier structure that is integral part of resonant tunneling diodes are given below:

- Quantum-Mechanical Reflections
- Quantum-Mechanical Reflections in Nanodevices
- Double-Barrier Structure

The following assignments help to illustrate the formation of bands in periodic potentials and how the width and number of the energy bands changes by varying the geometry of the n-well potential:

- From one well, to two wells, to five wells, to periodic potentials
- Bands as a function of the geometry of the n-well potential

One can also use this tool to calculate the transmission coefficient through barriers that are approximated with Piece-Wise constant segments.


Periodic Potential Lab
The **Periodic Potential Lab in ABACUS** solves the time independent Schrödinger Equation in a one-dimensional spatial potential variation. Rectangular, triangular, parabolic (harmonic), and Coulomb potential confinements can be considered. The user can determine energetic and spatial details of the potential profiles, compute the allowed and forbidden bands, plot the bands in a compact and an expanded zone, and compare the results against a simple effective-mass parabolic band. Transmission is also calculated through the well for the given energy range.

**Exercises:**

- **Periodic Potentials and Bandstructure: an Exercise**

**Periodic Potential Lab Learning Materials** – Comprehensive set of learning materials for the Periodic Potential Lab.

**Band Structure Lab**

The **Band Structure Lab in ABACUS** enables the study of bulk dispersion relationships of silicon, gallium arsenide, and indium arsenide. The users can apply tensile and compressive strain and observe the variation in the band structure, bandgaps, and effective masses. Advanced users can study band structure effects in ultra-scaled (thin body) quantum wells, and nanowires of different cross sections. Band Structure Lab uses the \( sp3s^*d5 \) tight-binding method to compute \( E(k) \) for bulk, planar, and nanowire semiconductors.
Exercises:

- **Bulk Band Structure: a Simulation Exercise**
- **Computational Electronics HW - Simplified Band Structure Model**
- **Exercise: Density of States Function Calculation**
- **Can we define unique effective masses in Si nanowires?**

**Band Structure Lab Learning Materials** – Comprehensive set of learning materials for the Band Structure Lab.

### Bulk Semiconductors

**Carrier Statistics Lab**

The **Carrier Statistics Lab in ABACUS** demonstrates electron and hole-density distributions based on the Fermi-Dirac and Maxwell-Boltzmann equations. This tool shows the dependence of carrier density, density of states and occupation factor on temperature and fermi level. The user can choose between doped and undoped semi-conductors. silicon, germanium, and gallium arsenide can be studied as a function of doping or Fermi level, and temperature. The Carrier Statistics Lab is supported by a homework assignment in which students are asked to explore the differences between Fermi-Dirac and Maxwell-Boltzmann distributions, compute electron and hole concentrations, study temperature dependences, and the phenomenon of freeze-out.

First time use of the tool is supported by: **Carrier Statistics Lab: First-Time User Guide**

Exercises:

- **Exercise: MATLAB Tool Construction for Degenerate/Nondegenerate Semiconductors**
That Includes Partial Ionization of the Dopants
- Exercise: Dopants and Semiconductor Statistics
- Hall Effect - Theoretical Exercise

Carrier Statistics Lab Learning Materials – Comprehensive set of learning materials for the Carrier Statistics Lab.

Drift Diffusion Lab

The Drift Diffusion Lab in ABACUS enables users to understand the basic concepts of the drift and diffusion of carriers inside a semiconductor slab using different kinds of experiments. Experiments like shining light onto the semiconductor, applying bias, as well as both processes simultaneously, can be performed. This tool provides important information about carrier densities, transient and steady state currents, Fermi-levels and electrostatic potentials. It is supported by two related homework assignments #1 and #2 in which students are asked to explore the concepts of drift, diffusion, quasi Fermi-levels, and the response to light.

Exercises:
- Conductivity - Theoretical Exercise

Drift-Diffusion Lab Learning Materials – Comprehensive set of learning materials for the Drift-Diffusion Lab.

PN Junctions

PN Junction Lab
**PN-Junction Lab in ABACUS** is everything users need to explore and teach the basic concepts of P-N junction devices. Edit the doping concentrations, change the materials, tweak minority-carrier lifetimes, and modify the ambient temperature. Then, see the effects in the energy band diagram, carrier densities, net charge distribution, current-voltage (I/V) characteristic, and other phenomena.

There is a significant set of associated resources available for this tool.

- a [demo of this tool](#)
- a [Primer on Semiconductor Device Simulation](#)
- a Learning Module entitled [PN Junction Theory and Modeling](#) that walks students through the PN-junction theory and let’s them verify concepts through on-line simulation.
- Homework assignment on the [depletion approximation](#)
- Homework assignment on the [depletion approximation](#)

**Exercises:**

- [PN Diode Exercise: Series Resistance](#)
- [Exercise: PIN Diode](#)
- [PN Diode Exercise: Graded Junction](#)
- [Basic operation of a PN diode - Theoretical exercise](#)
- [PN diode - Advanced theoretical exercises](#)
- [Schottky diode - Theoretical exercises](#)

**PN Junction Lab Learning Materials** – Comprehensive set of learning materials for the PN Junction Lab.

**Bipolar Junction Transistors (BJT)**

**Bipolar Junction Lab**
The Bipolar Junction Lab in ABACUS allows Bipolar Junction Transistor (BJT) simulation using a 2D mesh. It allows users to simulate either the npn- or pnp-type of device. Users can specify the emitter, base and collector region depths and doping densities. Also the material and minority-carrier lifetimes can be specified by the user. The tool is supported by a homework assignment in which students are asked to find the emitter efficiency, the base transport factor, current gains, and the Early voltage. Also, students are requested to provide a qualitative discussion.

Exercises:

- BJT - Simulation Exercise
- BJT - Theoretical Exercise
- BJT Operation Description

BJT Lab Learning Materials – Comprehensive set of learning materials for the BJT Lab.

MOS Capacitors

MOScap
The **MOScap Tool in ABACUS** enables a semi-classical analysis of metal-oxide-semiconductor (MOS) capacitors. It simulates the capacitance of bulk- and dual-gate capacitors for a variety of different device sizes, geometries, temperature, and doping profiles.

First time use of the tool is supported by: **MOSCap: First-Time User Guide**

Exercises:

- [Exercise: CV curves for MOS capacitors](#)
- [MOSCAP - Theoretical Exercises 1](#)
- [MOSCAP - Theoretical Exercises 2](#)
- [MOSCAP - Theoretical Exercises 3](#)
- [MOS Capacitors: Theory and Modeling](#)

**MOSCap Learning Materials** – Comprehensive set of learning materials for the MOSCap Tool.

**MOSFETs**

**MOSfet Lab**
The **MOSfet Lab in ABACUS** tool enables a semi-classical analysis of current-voltage (I/V) characteristics for bulk and SOI Field-Effect Transistors (FETs) for a variety of different device sizes, geometries, temperature, and doping profiles.

**Exercises:**

- **MOSFET Exercise**
- **Exercise: Basic Operation of n-Channel SOI Device**
- **MOSFET - Theoretical Exercises**
- **MOSFET Operation Description**

**MOSFet Learning Materials** – Comprehensive set of learning materials for the MOSFet Tool.

### About ABACUS Constituent Tools

The Assembly of Basic Applications for Coordinated Understanding of Semiconductors (ABACUS) has been put together from individual tools to provide educators and students with a one-stop-shop in semiconductor education. It therefore benefits tremendously from the hard work that the contributors of the individual tool builders have put into their tools.

As a matter of credit, simulation runs that are performed in the ABACUS tool are also credited to the individual tools, which help the ranking of the individual tools. We do also count the number of usages of the individual tools in the ABACUS tool set, to measure the ABACUS impact and possibly also improve the tool.

In the description above, we do not refer to the individual tools since we want to guide the users to the composite ABACUS tool. We cite the individual tools here explicitly so they are being given the appropriate credit and on their respective tool pages are being linked to this ABACUS topic page.

**Crystal Viewer Lab (New Interactive Front End), Piece-Wise Constant Potential Barriers Tool, (Resource(kronigpenney) failed), Band Structure Lab, Carrier Statistics Lab, Drift-Diffusion Lab, PN Junction Lab, BJT Lab, MOSCap, and MOSFet.**

### Additional Reading and Tools

**Solar Cells**
ADEPT is not supported within ABACUS because it is a research-oriented tool that enables the study of solar cells for various material systems. A Reference Manual and a ADEPT Heterostructure Tutorial are available. The interface is not a simple point-and-click interface, as for example the PN junction lab, but simulation commands are entered via a command line.

MOS Capacitors with Quantum Corrections

Schred

Schred is not formally supported in ABACUS. It contains more advanced quantum mechanical concepts and is a nanoHUB contributed tool. It calculates the envelope wavefunctions and the corresponding bound-state energies in a typical metal-oxide semiconductor (MOS) or semiconductor-oxide-semiconductor (SOS) structure and a typical SOI structure by solving self-consistently the one-dimensional (1D) Poisson equation and the 1D Schrödinger equation.

Exercises:

- Schred: Exercise 1
- SCHRED: Exercise 2
- Schred: Exercise 3
- Quantum Size Effects and the Need for Schred
- Schred Tutorial Version 2.1

madFETs—more Field Effect Transistors
The Field-Effect Transistor has been proposed and implemented in many physical systems, materials, and geometries. A multitude of acronyms have developed around these concepts. The “Many-Acronym-Device-FET” (madFET) was born. The author of this document was able to trace an attribute to the acronym madFET from Bill Frensley to Herbert Kroemer.

nanoHUB.org hosts a variety of tools that enable the simulation of field effect transisors for a variety of different geometries in a variety of different levels of approximations. There is a madFETs topics page that provides an overview of many of the nanoHUB.org madFET tools.

**Technology Computer Aided Design—TCAD**
Once students have mastered the basics of semiconductors they may be quite interested in venturing into TCAD. There is a topics page for aTCADlab and associated single aTCADlab tool that assembles various TCAD tools available on the nanoHUB. Process, device, and circuit simulation is represented in aTCADlab.