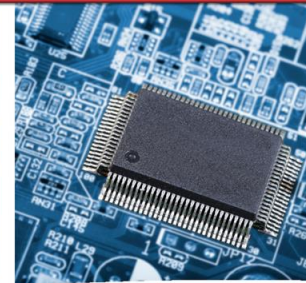
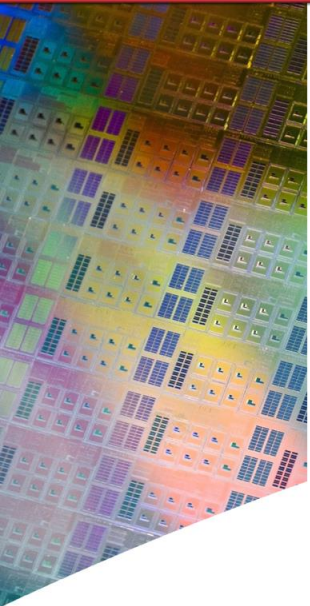


# Silvaco TCAD for Radiation Simulation



**Ahmed Nejim**  
**R&D Projects Manager**  
**[eusupport@silvaco.com](mailto:eusupport@silvaco.com)**  
**Silvaco Europe Ltd., St Ives, Cambridgeshire, UK**

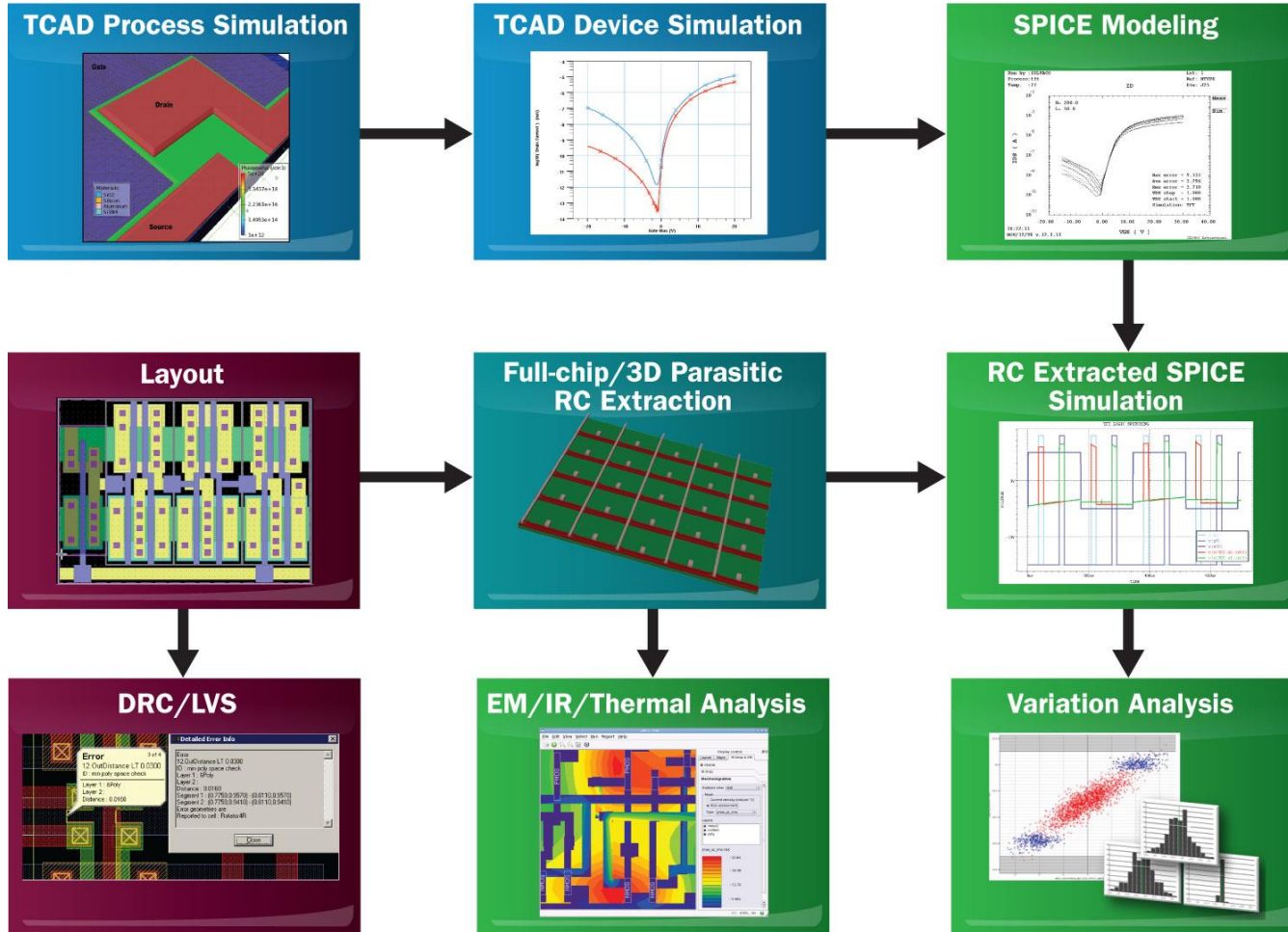
**SILVACO**

# Silvaco - Introduction

- Founded in 1984.
- Market leader in TCAD, Spice simulation & IC CAD.
- Large customer base of Foundry, IDM, ASIC and Fabless semiconductor Companies.
- Debt free, privately held. No VC funding.
- Fifteen locations worldwide.
- Silvaco Europe is a major R&D centre for TCAD and EDA modelling.



# Silvaco – Software flow



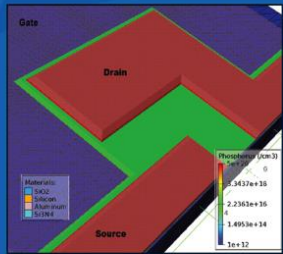
# Topics

- Why use physical TCAD simulations
- Available resources for Silvaco software users
- Silvaco TCAD overview
- ATHENA
- ATLAS
- VICTORY
- Interactive tools
- C-Functions
- Conclusions

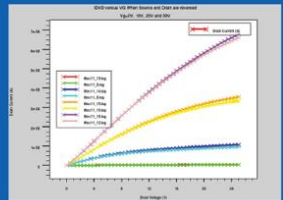
# Design for various technology sectors

## Display

TFT, LCD, LED, OLED



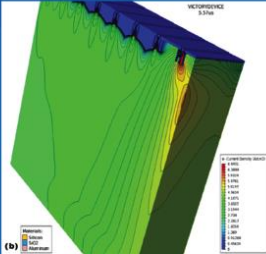
3D A-Si:H TFT



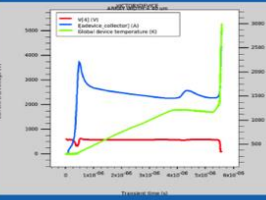
IdVd simulation with reverse source and drain

## Power

BCD, SJ-IGBT, SiC, GaN, ESD



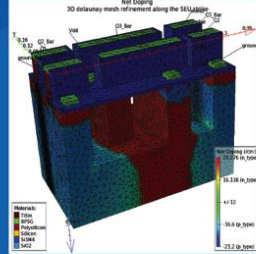
3D IGBT with rounded edge trench



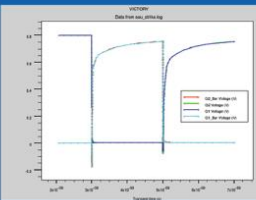
Electron current density distribution at device failure point  $t = 5.57 \mu s$ .

## Reliability

SEB, SEGR, SEU, HCI, NBTI



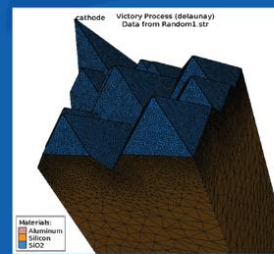
SRAM 22 nm



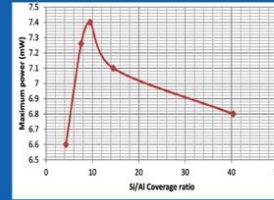
6T SRAM cell hit with an SEU causing switching of the memory

## Optical

CCD, CIS, Laser, Solar Cell, Photodiode



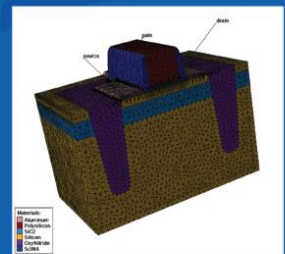
3D CMOS image sensor



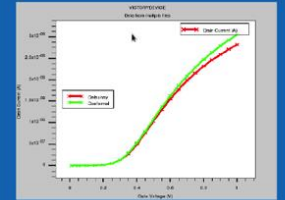
Showing the relationship between the maximum output power and the metal coverage ratio R.

## Advanced Process Development

FinFET, FDSOI, 3D Flash, STTRAM, TFET



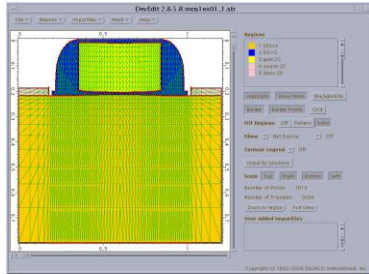
3D FinFet



Vth simulation comparing a conformal and a Delaunay mesh

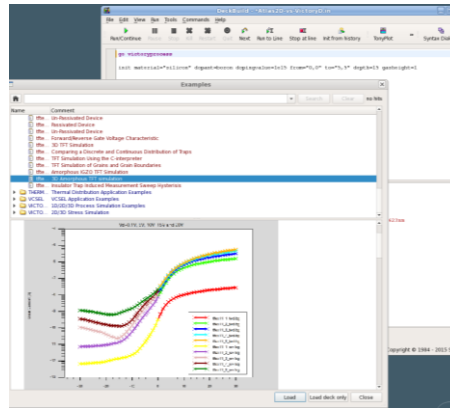
Physical design plays a crucial role in a variety of technology sectors.

# Why use physics based modelling?

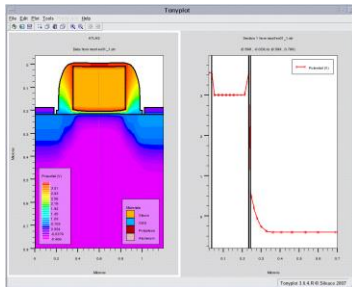


Define structure

Define models



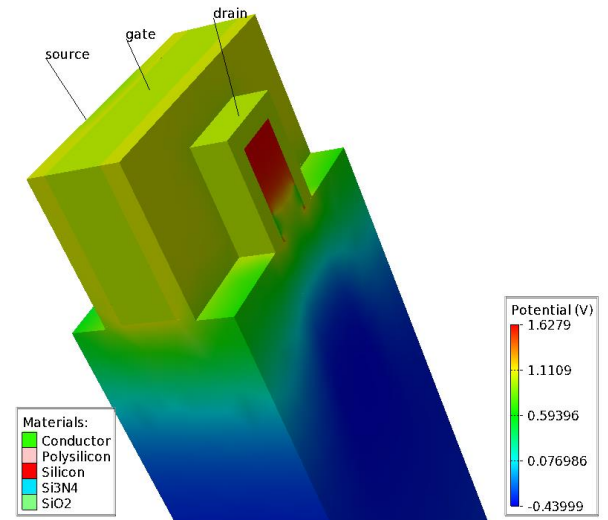
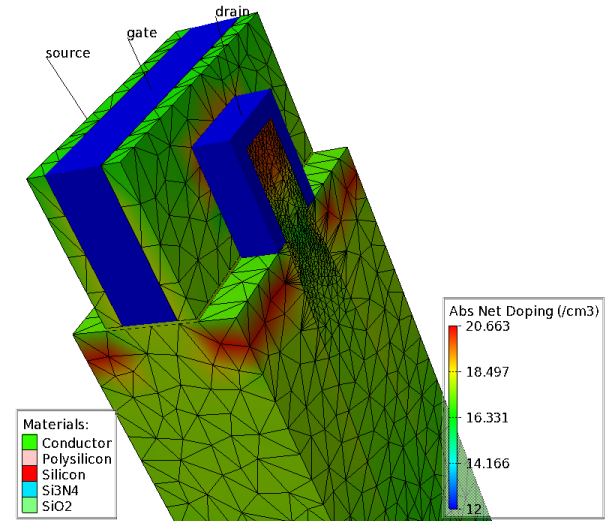
Obtain data



- Three main reasons to opt for physical simulations:
  - Predictive.
  - Provides insight.
  - Captures and visualizes theoretical knowledge.
- Unlike empirical models, physically-based simulation provide insight, and encapsulates fundamental phenomena.
- Complements experimental investigation.
- Provides information that is difficult or impossible to measure.
- **Challenge:** requires in-depth knowledge of device physics..

# Available utilities

- Advanced interactive GUI tools.
- Design space exploration (DOE & Optimisers) tools.
- Worked standard examples with results. Available on the Silvaco web site and through deckbuild.
- Simulation Standard articles with archive extending back to 1992.
- Webinars. Recorded archives available.
- Presentation materials.
- Extensive manuals and release notes.
- Active support, training & seminars.
- Partner in many EU collaborative projects.



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# Silvaco TCAD Overview

Athena 2D Process

Atlas 2D / 3D Device

DevEdit 2D / 3D Editor

Victory Process Mode  
Full 3D (inc stress dependent oxidation)

Victory Cell Mode  
Full 3D (optimised for large area)

Victory Device

## Interactive Utility Tools

DeckBuild  
Deck Editor

\*new release

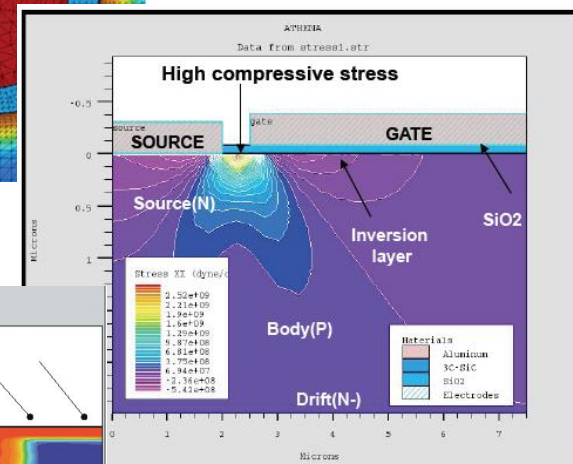
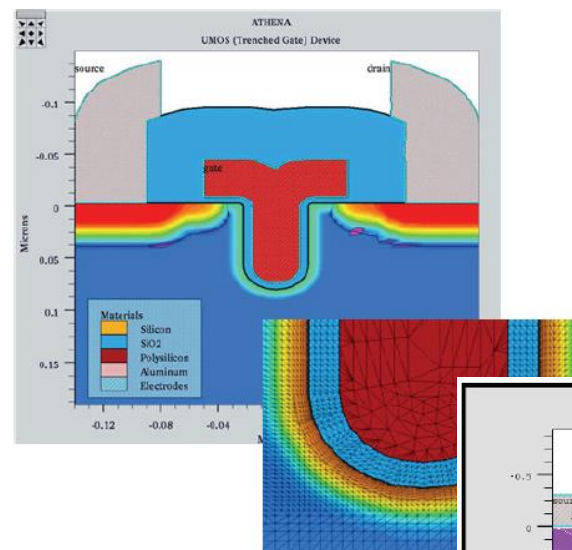
TonyPlot 2D/3D  
View structure and  
analyse results

VWF  
Design Of  
Experiments

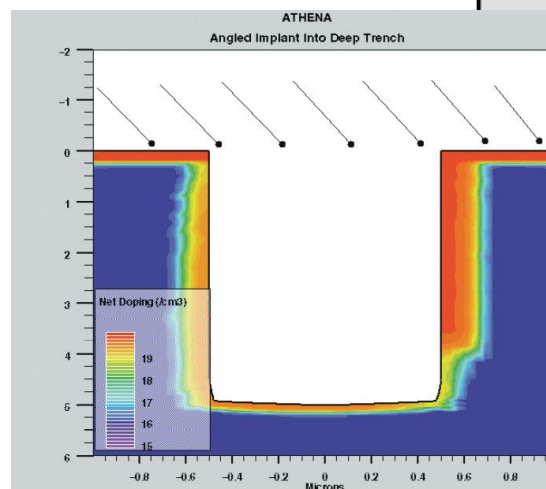


# Athena: 2D Process Simulator

- Simulation of all critical fabrication steps
- Prediction of multi-layer topology, dopant distributions, and stresses
- Import mask files
- Automatic and user-defined mesh generation and control
- Run-time extraction of process and device parameters
- Optimization of process flow and calibration of model parameters

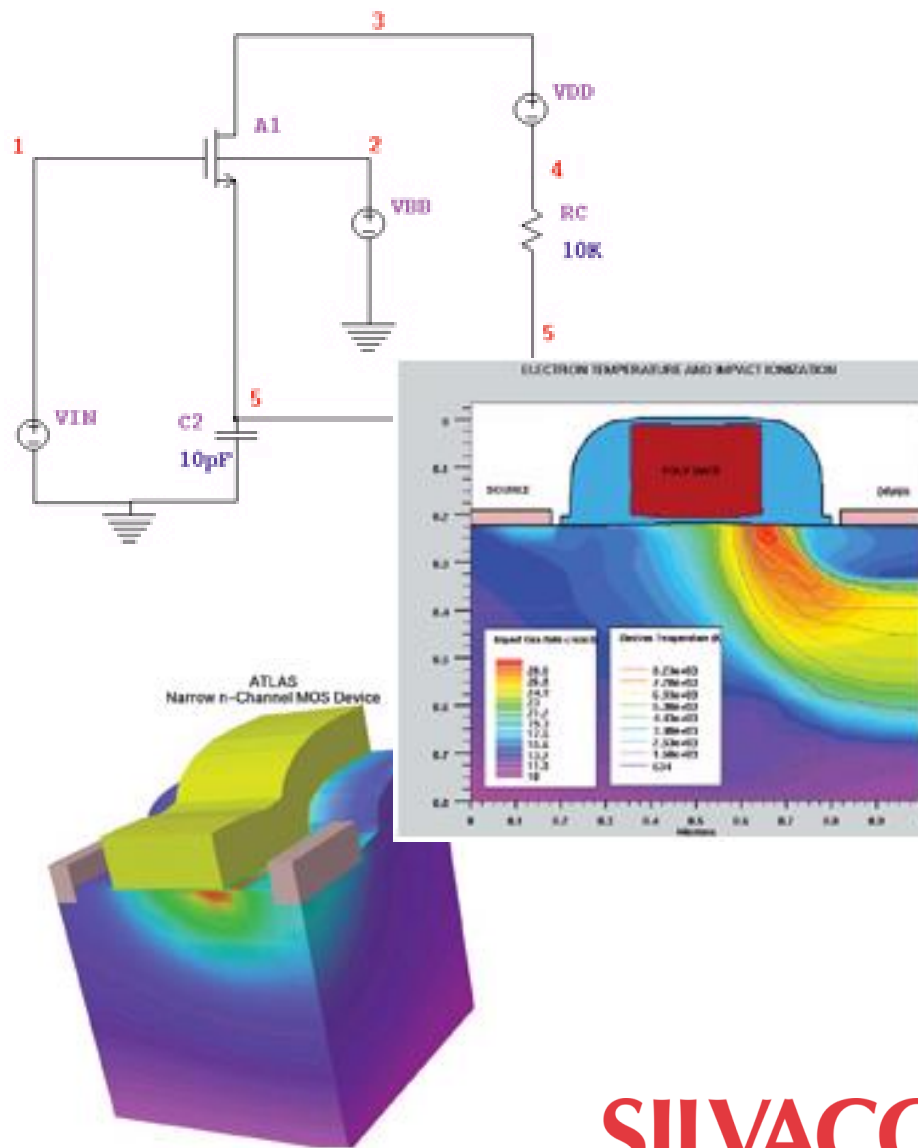


Stress distribution in X-direction  
(principal current element)



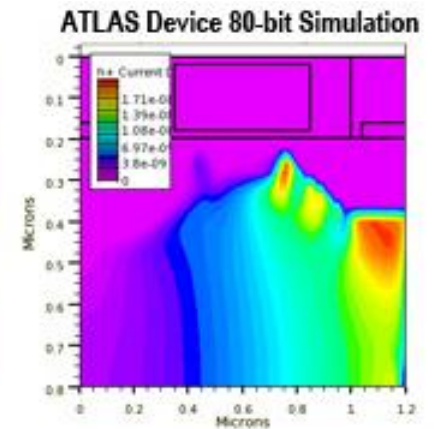
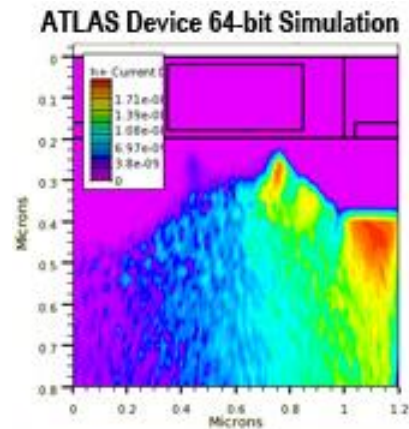
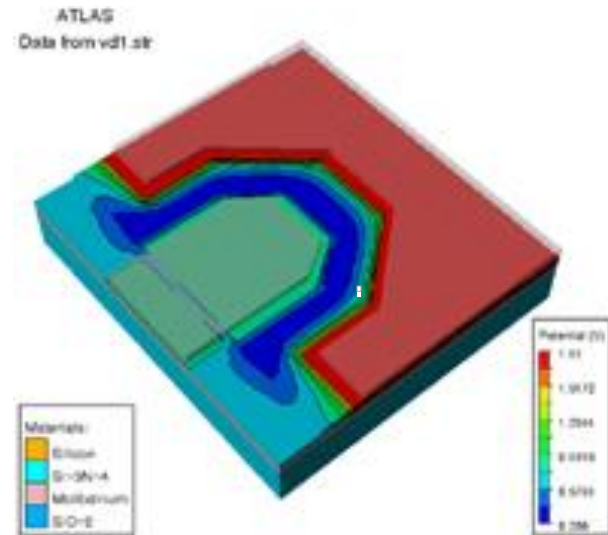
# Atlas: 2D/3D Device Simulator

- Modular, and extendible platform
- Analyze DC, AC, and time domain responses for all semiconductor based technologies in 2D/3D
- Parallel processing supported on multi-core machines
- Fully integrated with Athena & DevEdit
- MixedMode: circuit and device simulation using SPICE netlists and SmartSpice models



# Atlas: Advanced Solutions

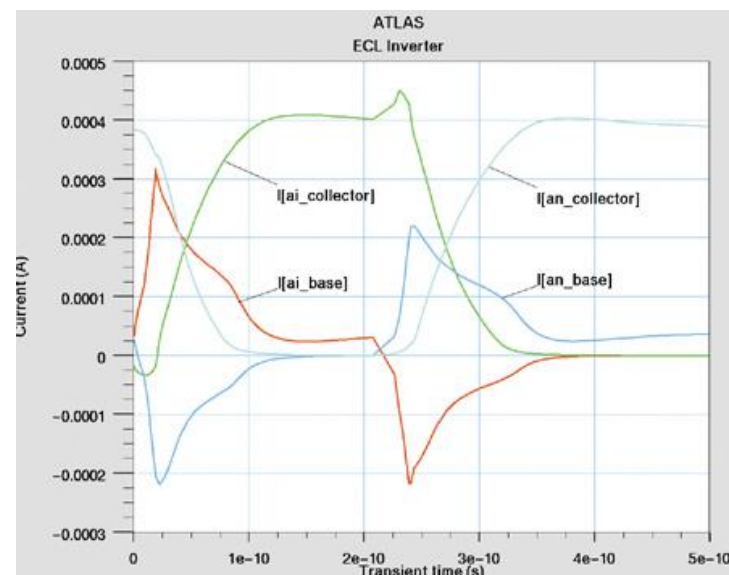
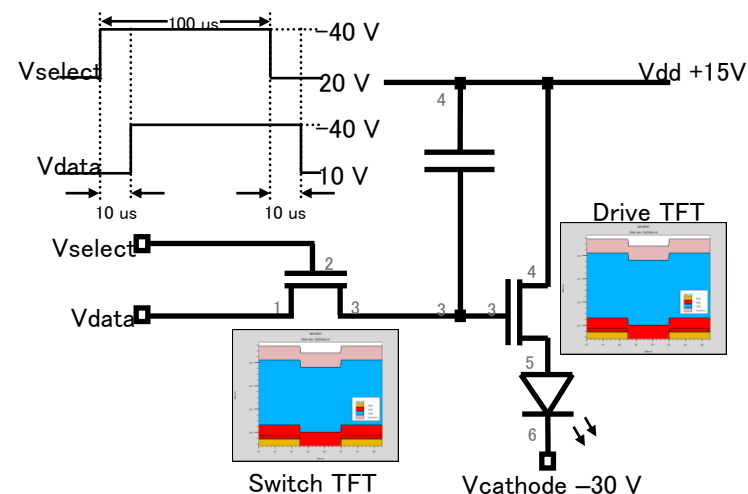
- Incorporate effects of self-heating in 2D/3D device simulation, DC, AC, transient analysis
- Extended precision (80, 128, 160 & 256 bit)
- Curvetrace algorithm
- Traps, interface traps, and defects
- Comprehensive library of binary, ternary, quaternary and organic semiconductors
- User defined models with C-Interpreter



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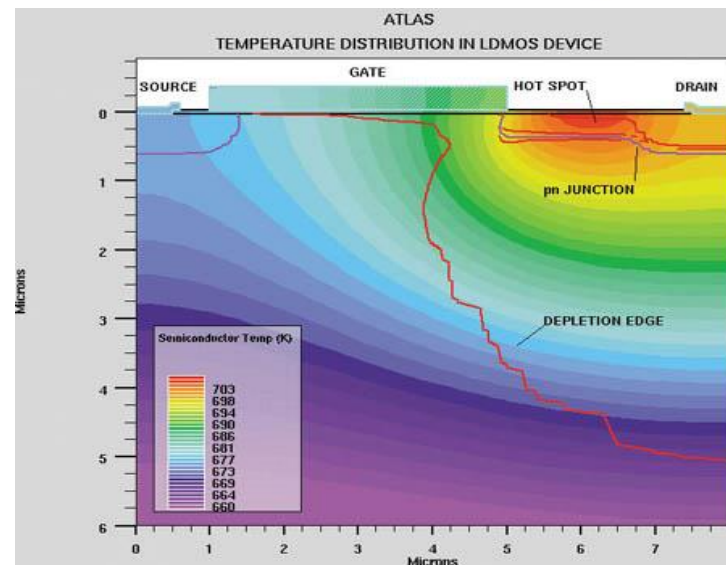
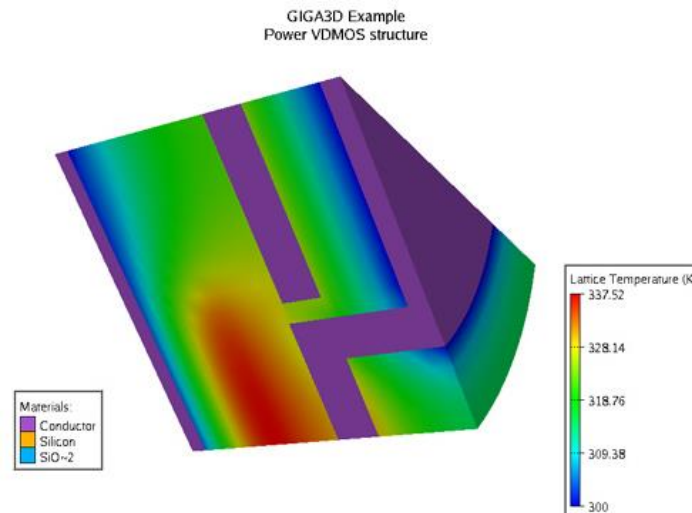
# Atlas: MixedMode / Circuit Simulation

- Simulate physics-based devices in combination with compact analytical models in a circuit environment
- Any combination of Atlas 2D/3D modules
- Devices simulated with a SPICE netlist circuit description
- Wide range of SPICE models available
- Unlimited number of physical devices or compact model elements with MixedModeXL



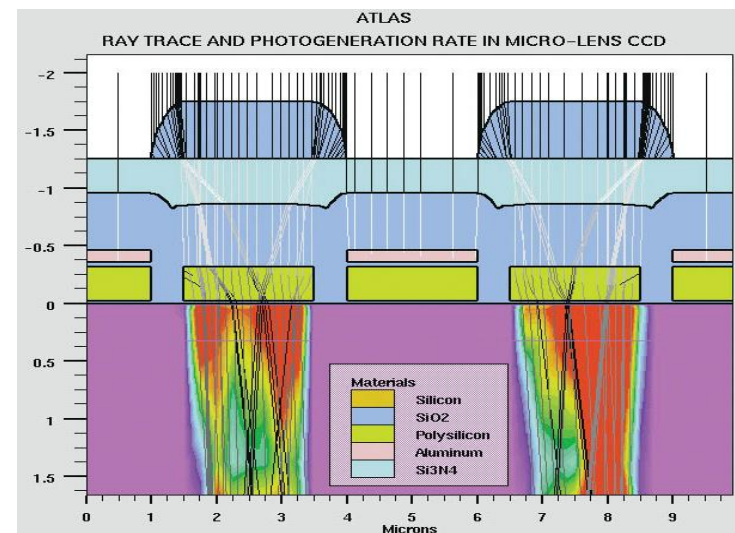
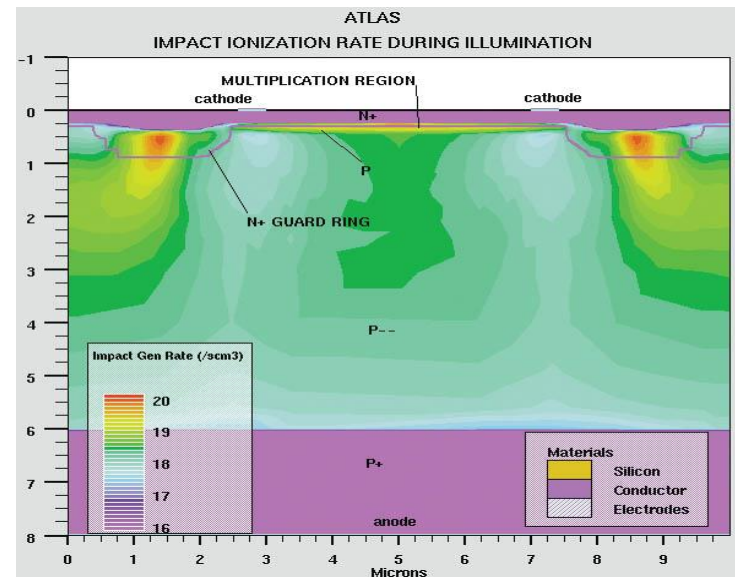
# Atlas: GIGA – Electro-Thermal

- Wachutka's thermodynamically rigorous model for Joule heating, Generation and Recombination and Peltier-Thomson effects
- Dependence of material and transport parameters on lattice temperature
- Specify heat-sinks, thermal impedances, and ambient temperatures.
- Compatible with both the drift-diffusion and energy balance transport models



# Atlas: Luminous – Optoelectronic Module

- Model light absorption and photogeneration in devices
- Arbitrary topologies, internal and external reflections and refractions, polarization dependencies and dispersion
- Mono-chromatic or multi-spectral optical sources
- DC, AC, and transient response in the presence of arbitrary optical sources



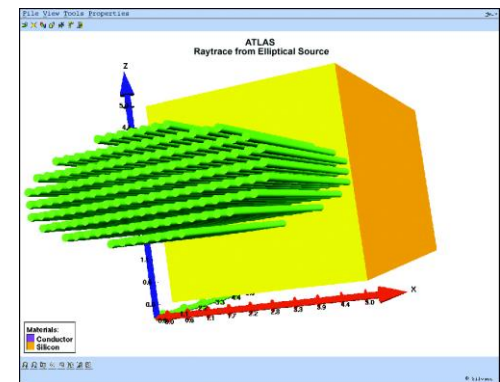
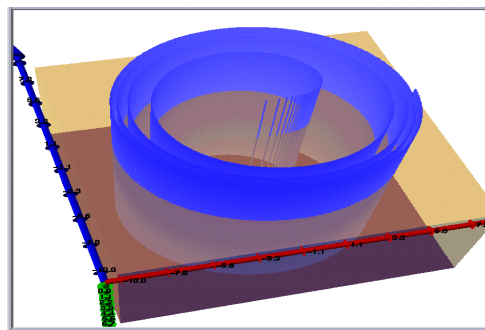
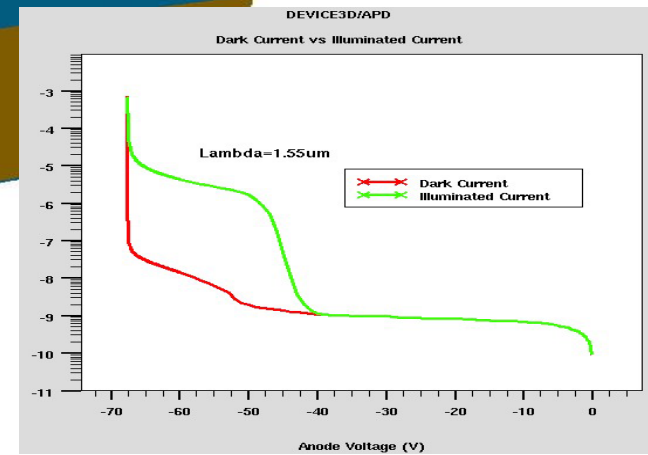
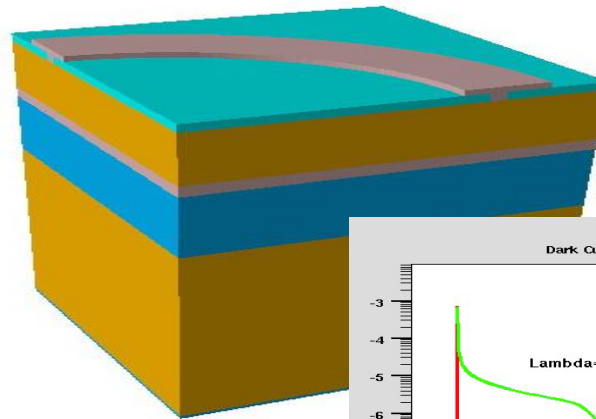
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# Atlas: Luminous – Optoelectronic Module

Light propagation algorithm options:

- Ray Tracing Method (RTM)
- Transfer Matrix Method (TMM)
- Beam Propagation Method (BPM)
- Finite Difference Time Domain (FDTD)

- Uniform and Gaussian illumination
- Circular and elliptical optical source
- User defined optical source



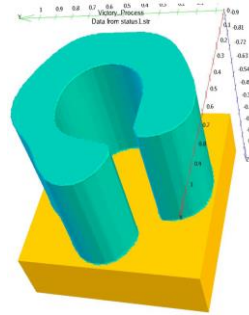
# The Victory Suite

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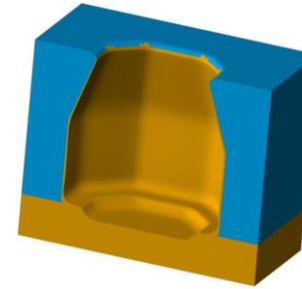


# Victory: Process Mode

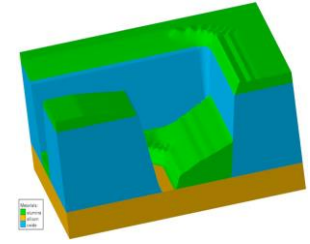
- Multi-particle and flux models for physical deposition and etching with substrate material re-deposition
- Open Modelling Interface – import your own models
- Monte Carlo implant simulation
- 3D oxidation (including stress)



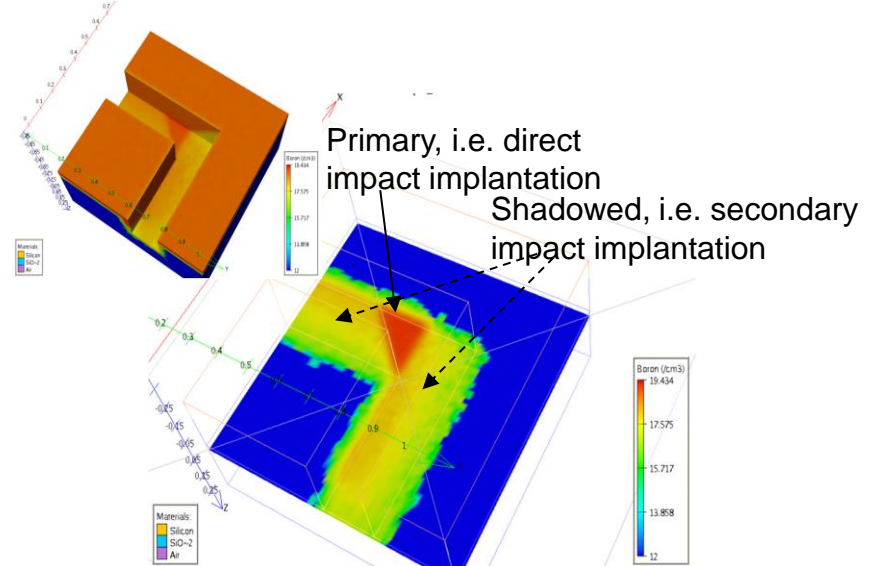
3D Geometrical Etching



Physical Ion Milling Etching



Ion beam deposition with tilted beam

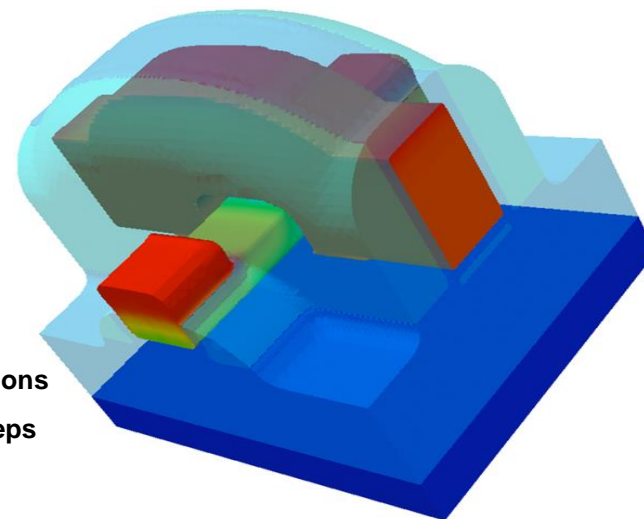
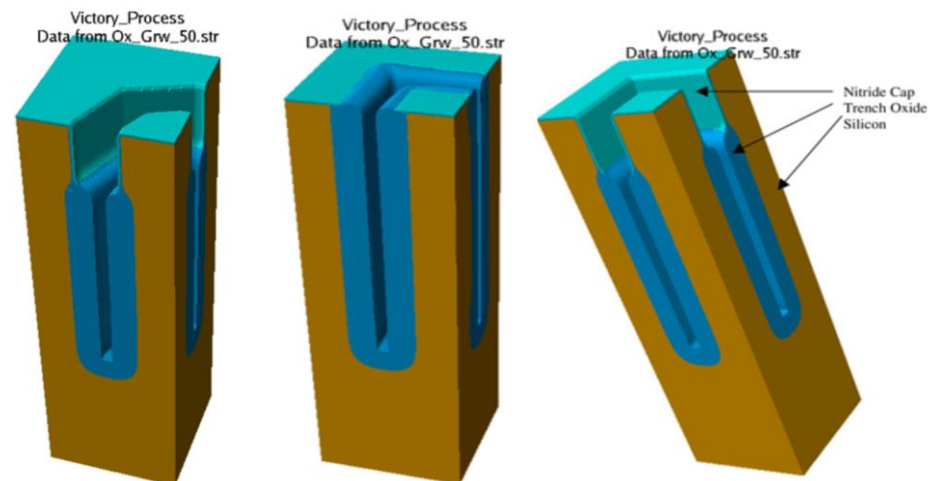


Monte Carlo trench implantation angled at  $50^\circ$  with twist along structure's diagonal

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# Victory: Process Mode

- Automatic meshing and Adaptive Mesh Refinement
- Multi-threading
- Mirroring
- Adaptive doping refinement
- Comprehensive set of 3D diffusion models: Fermi, three-stream, five-stream



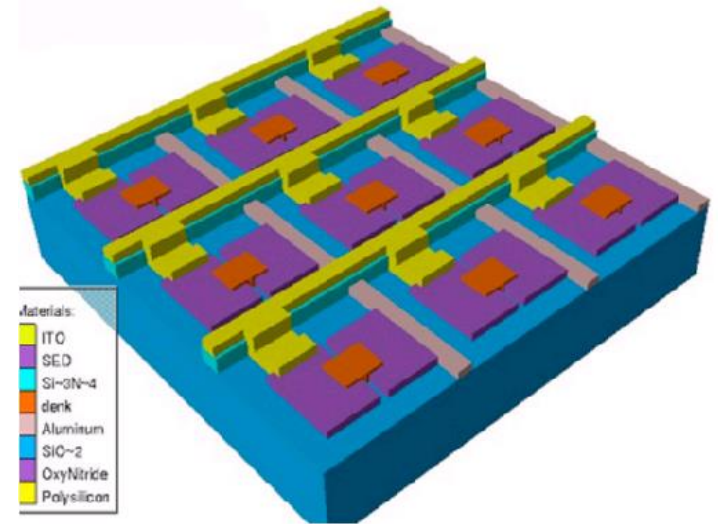
## 28nm FINFET

- 20 etch/depo steps
- 3 Monte Carlo ion implantations
- 4 oxidation and diffusion steps
- ~800,000 mesh points
- < 2 hours on 8 CPU's

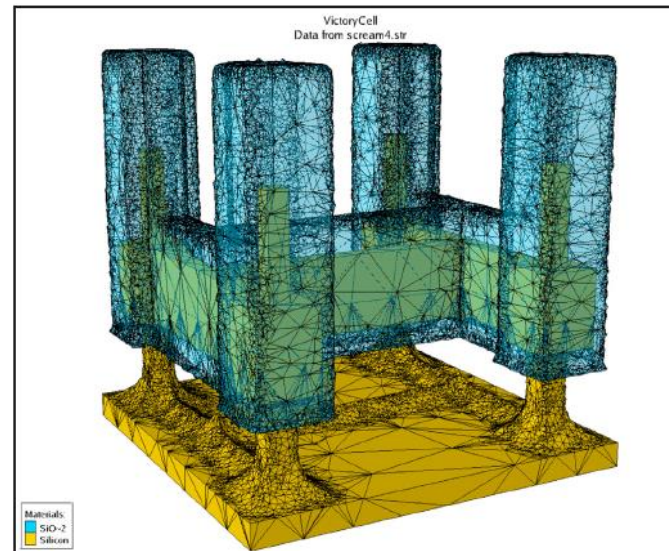
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# Victory: Cell Mode

- Fast, layout-driven 3D process simulator specifically designed for large structures
- Layout-driven mesh generation
- User-controlled mesh placement
- Easy to learn and user-friendly SUPREM-like syntax



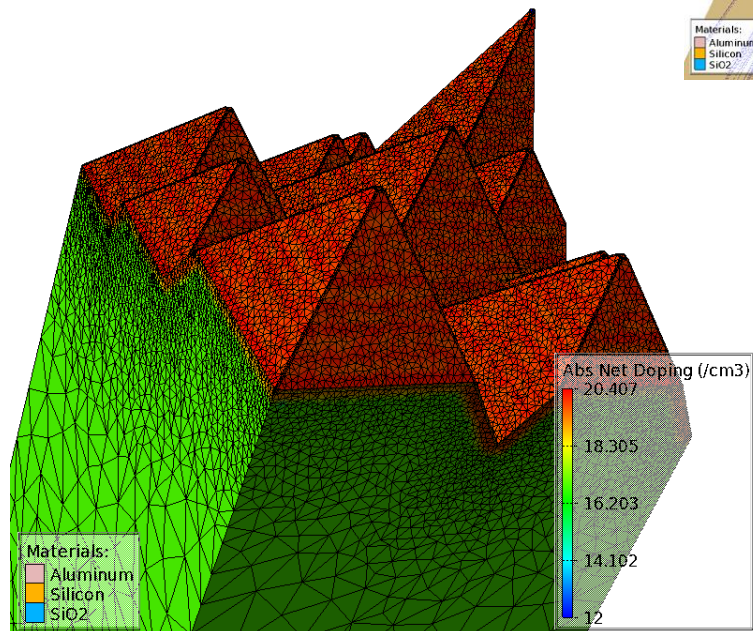
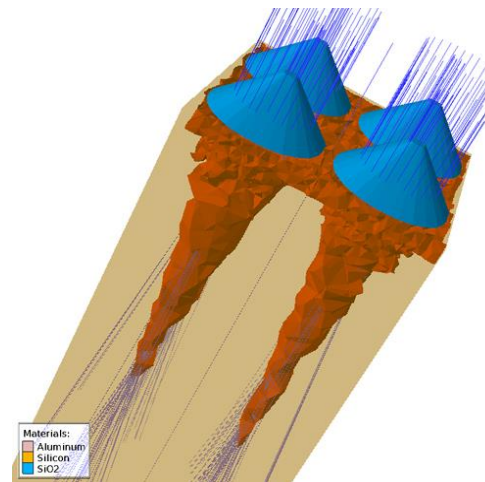
Flat panel LCD and TFT circuits.



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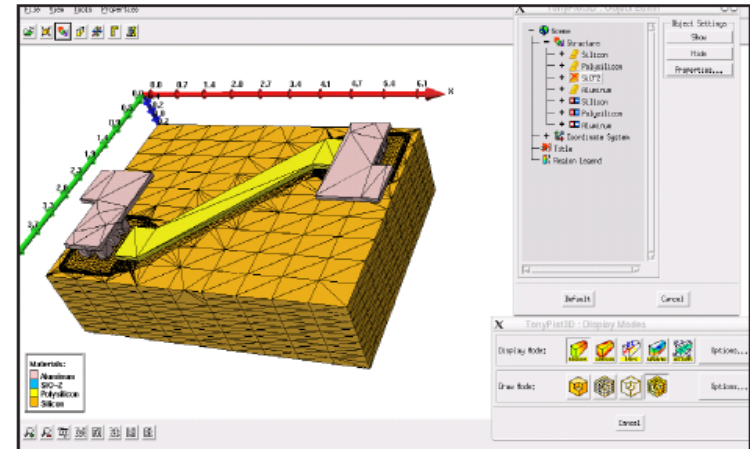
# Victory: Cell Mode

- Mask Layout-based Processing
- In-deck mask definition and manipulation
- Multi-threaded
- Unstructured mesh

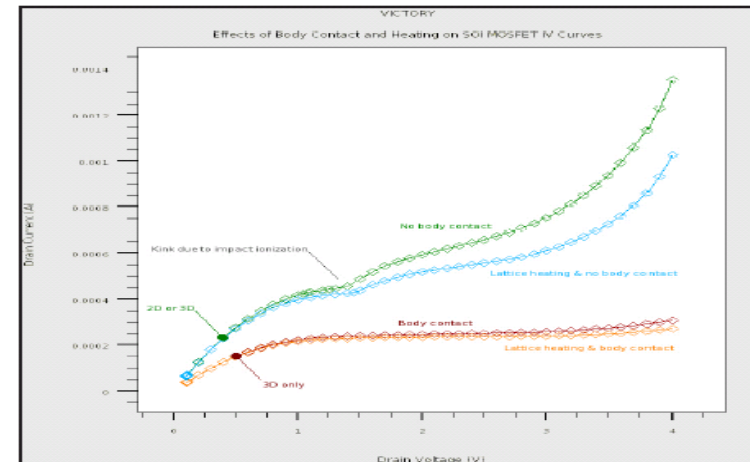


# Victory: Device Simulator

- Tetrahedral meshing for fast and accurate simulation of complex 3D geometries
- DC, AC and transient analysis for silicon, binary, ternary, quaternary and organic material devices
- Customizable material database
- Stress-dependent mobility and bandgap models



Diagonal MOSFET structure with the oxide layer removed to show the polysilicon and metalization layers.

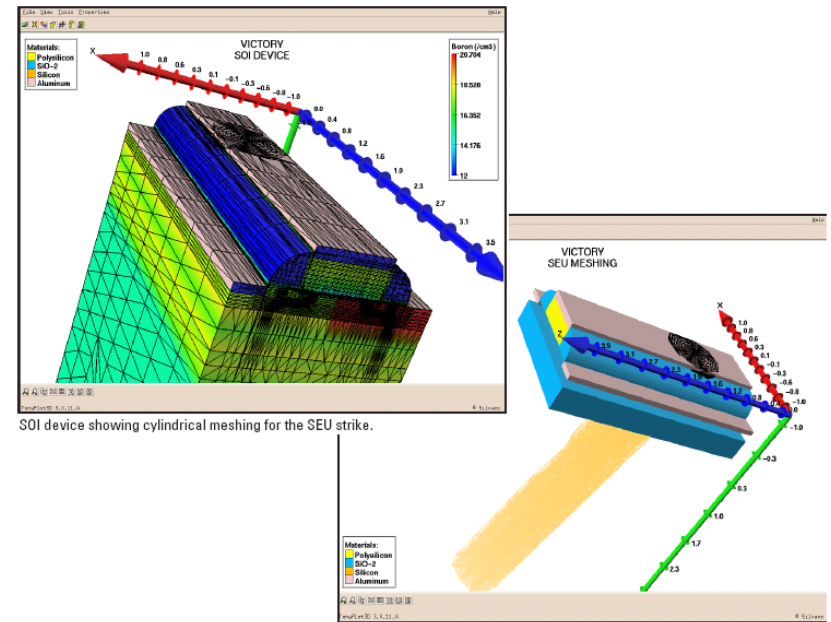


IdVd 3D SOI NMOSFET simulation with body contact showing the kink suppression effect.

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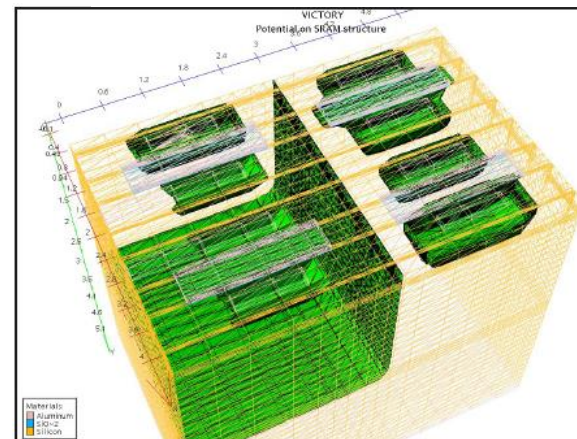
# Victory: Device Simulator

- Customisable physical models
- Drift-diffusion and energy balance transport equations
- Self-consistent simulation of self-heating effects including heat generation, heat flow, lattice heating, heat sinks and temperature dependent material parameters
- Multi-threaded
- Atlas-compatible



SOI device showing cylindrical meshing for the SEU strike.

The SEU strike volume was refined with a circular mesh in order to accurately capture charge generation along the length of the track. This has all been achieved without dramatically increasing the number of mesh points.



Electrostatic potential isocontour for the SRAM cell.

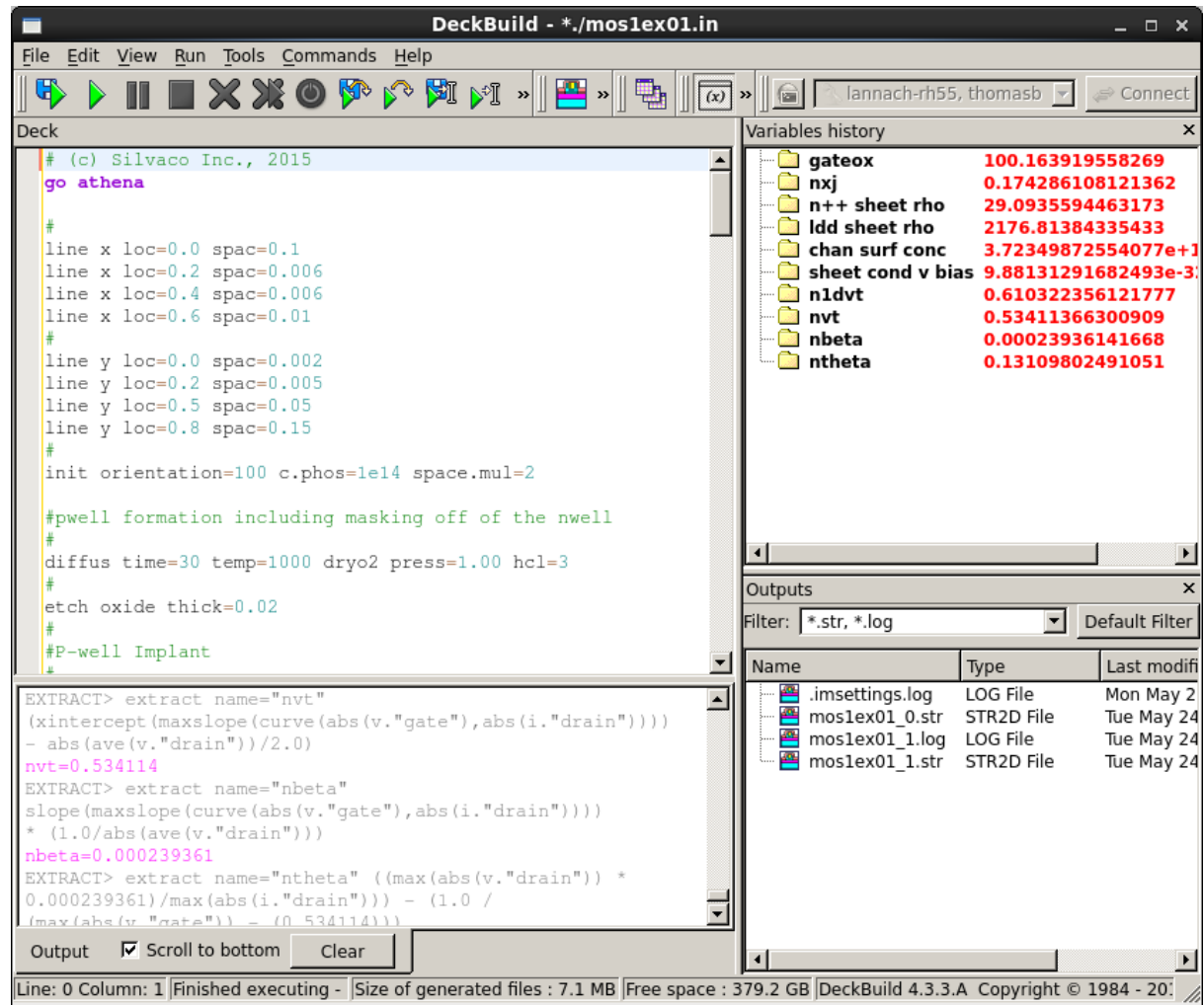
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# Interactive Utility Tools

**SILVACO**

# GUI for programme debugging & execution

- Fully documented and searchable examples database
- Quick launch of interactive tools: through toolbars or right clicking on file names
- Remote execution of simulations; utilize local graphics hardware for visualization
- Contextual highlighting of deck and run-time output syntax
- Separate Outputs and Variables panels to track variables and files
- Common look & feel in both Windows and Linux operating systems



The screenshot shows the DeckBuild GUI with the following components:

- Deck:** A text editor showing a simulation deck with parameters like `line x loc=0.0 spac=0.1`, `init orientation=100 c.phos=1e14 space.mul=2`, and `#P-well Implant`.
- Variables history:** A table listing variables and their values:

Variable	Value
gateox	100.163919558269
nxj	0.174286108121362
n++ sheet rho	29.0935594463173
ldd sheet rho	2176.81384335433
chan surf conc	3.72349872554077e+1
sheet cond v bias	9.88131291682493e-3
n1dvt	0.610322356121777
nvt	0.53411366300909
nbeta	0.00023936141668
ntheta	0.13109802491051
- Outputs:** A table listing output files:

Name	Type	Last modified
.imsettings.log	LOG File	Mon May 2
mos1ex01_0.str	STR2D File	Tue May 24
mos1ex01_1.log	LOG File	Tue May 24
mos1ex01_1.str	STR2D File	Tue May 24
- Output Panel:** Shows the results of EXTRACT commands, such as `nvt=0.534114` and `nbeta=0.000239361`.
- Status Bar:** Displays "Line: 0 Column: 1 | Finished executing - | Size of generated files : 7.1 MB | Free space : 379.2 GB | DeckBuild 4.3.3.A Copyright © 1984 - 2016".



# GUI for programme debugging & execution

- Quick launch of interactive tools through toolbars



- Right click on a deck line to open file in plotting tool
- Offer options to append a plot to a previously started tool or start a new instance of the tool
- Extension sensitive:
  - .str(2D)/.log in Tonyplot2D
  - .str(3D) in Tonyplot3D
  - .lay in MaskViews
  - .de in DevEdit or Sedit
  - .dat/.txt launch in Sedit or plot in TP2D

The screenshot shows the DeckBuild window for a file named `*/./moslex01.in`. The main area displays a code deck with the following content:

```
113 electrode name=source x=0.1
114 electrode name=drain x=1.1
115 electrode name=substrate backside
116
117 structure outfile=moslex01_0.str
118
119 # plot the structure
120 tonyplot moslex01_0.str -set moslex01_0.set
121
122 ##### Vs Test #####
123 go atlas
124
125 # set material models
126 models cvt srh print
127
128 contact name=gate n.poly
129 interface qf=3e10
130
131 method newton
132 solve init
133
```

A context menu is open over line 122, showing the following options:

- Plot append moslex01\_0.str
- Plot moslex01\_0.str
- Devedit moslex01\_0.str
- Run append ... tonyplot moslex01\_0.str -set moslex01\_0.set
- Run ... tonyplot moslex01\_0.str -set moslex01\_0.set
- Open moslex01\_0.set
- Set stop
- Undo (Ctrl+Z)
- Redo (Ctrl+Shift+Z)
- Cut (Ctrl+X)
- Copy (Ctrl+C)
- Paste (Ctrl+V)
- Select All (Ctrl+A)
- Scroll lock
- Toggle comment (Ctrl+)
- Run to Line (Ctrl+F10)

At the bottom of the window, the output area shows the following text:

```
nbeta=0.000239361
EXTRACT> extract name="ntheta"
0.000239361)/max(abs(i."drain
ntheta=0.131098
EXTRACT> quit

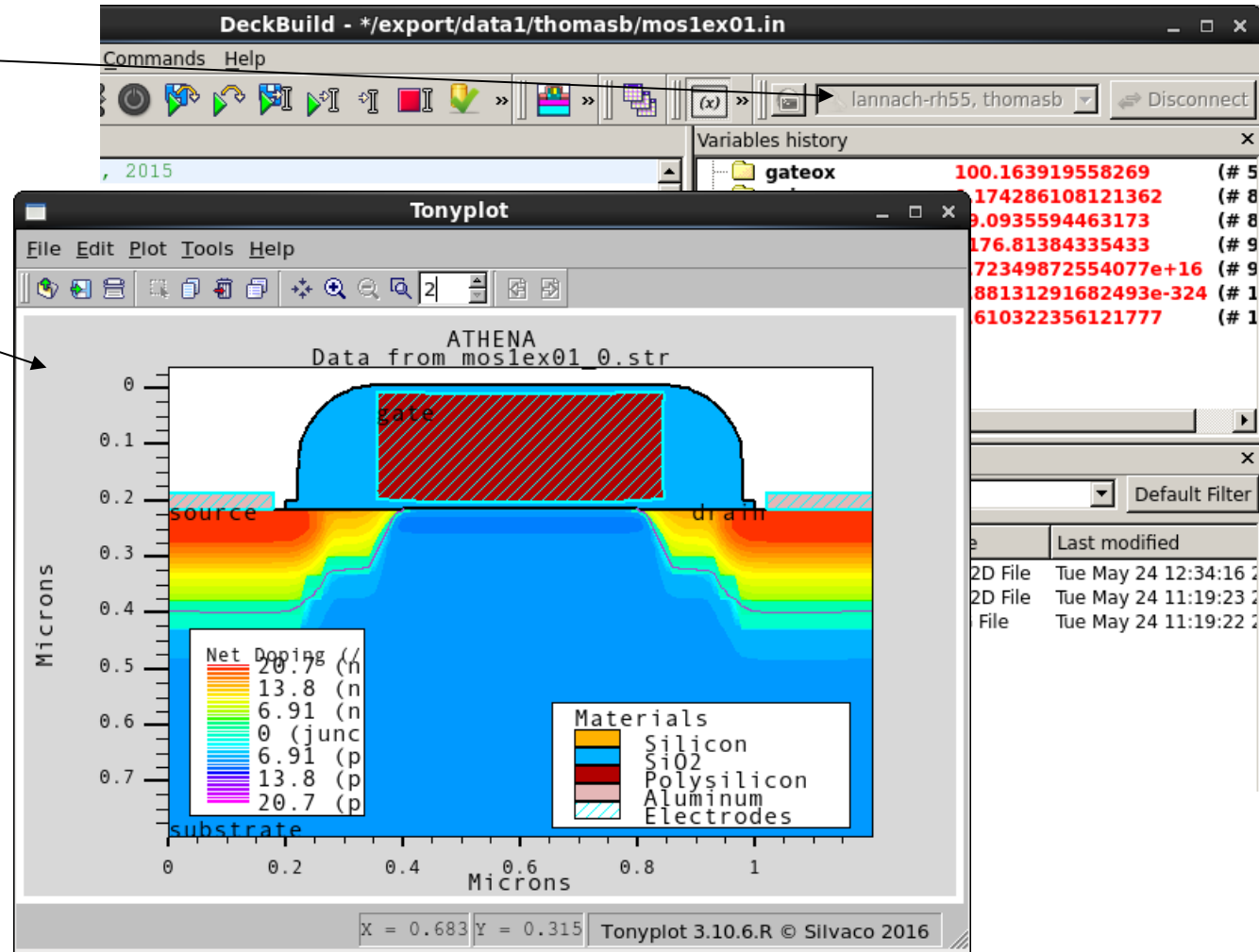
ATLAS> quit

ATLAS version 5.23.3.A finish
10.500 2.460 0.15 00 00 78
```

The status bar at the bottom indicates "Line: 121 Column: 12 Finished executi".

# GUI for seamless software execution & visualisation

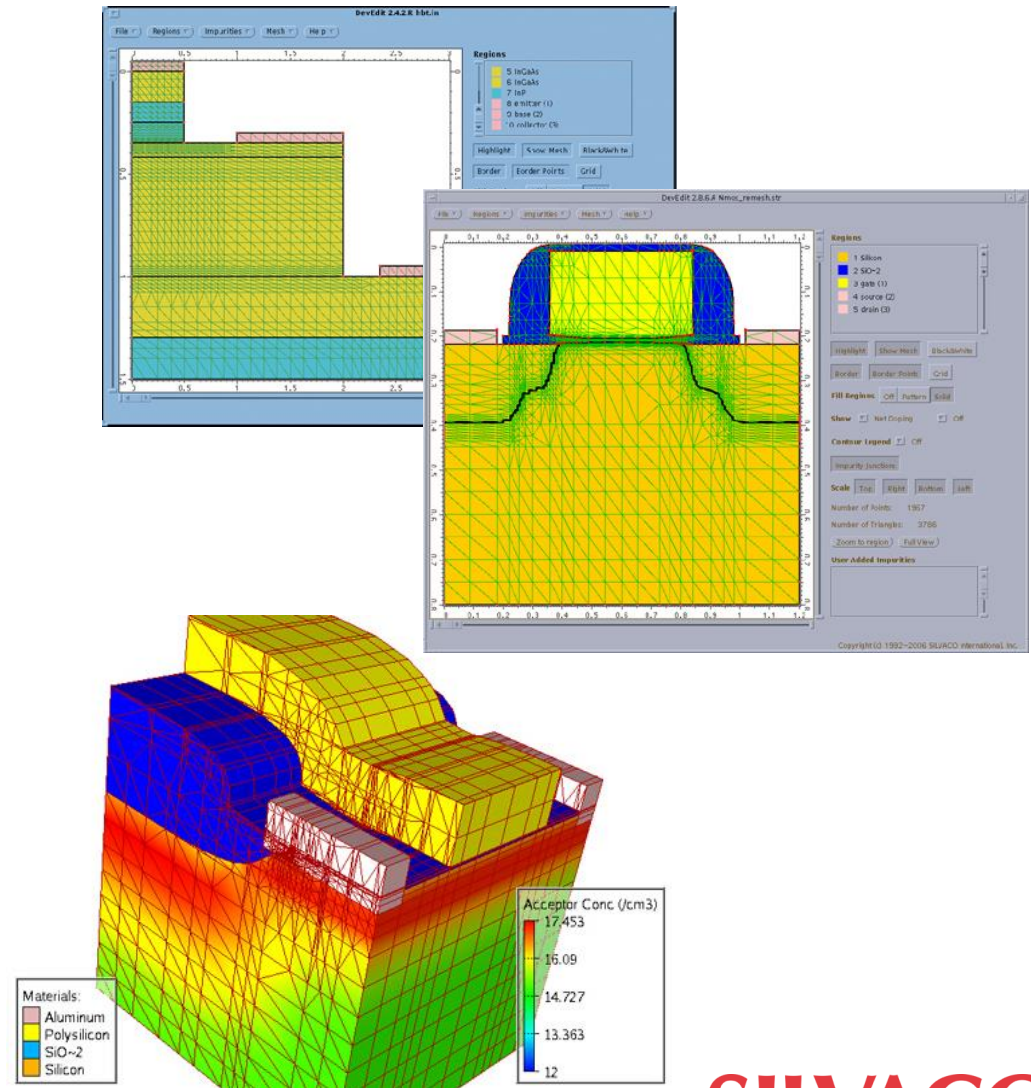
- simulator runs on remote machine
- Any visualization is run locally to utilize graphics hardware



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# DevEdit: 2D / 3D Device & Mesh Editor

- Create a device from scratch, re-mesh or edit an existing device
- Parameterize and vary automatically with DeckBuild or VWF
- Mirroring, stretching, cloning and joining
- GUI to draw or edit devices directly
- Re-mesh on volume data
- Import 1D doping profiles



# Design Space investigation - DOE

Automated utilities such as Virtual Wafer Fab (VWF) allow users to define a split lot experiment to probe available design space. Queuing system can be used to efficiently execute the calculations in parallel.

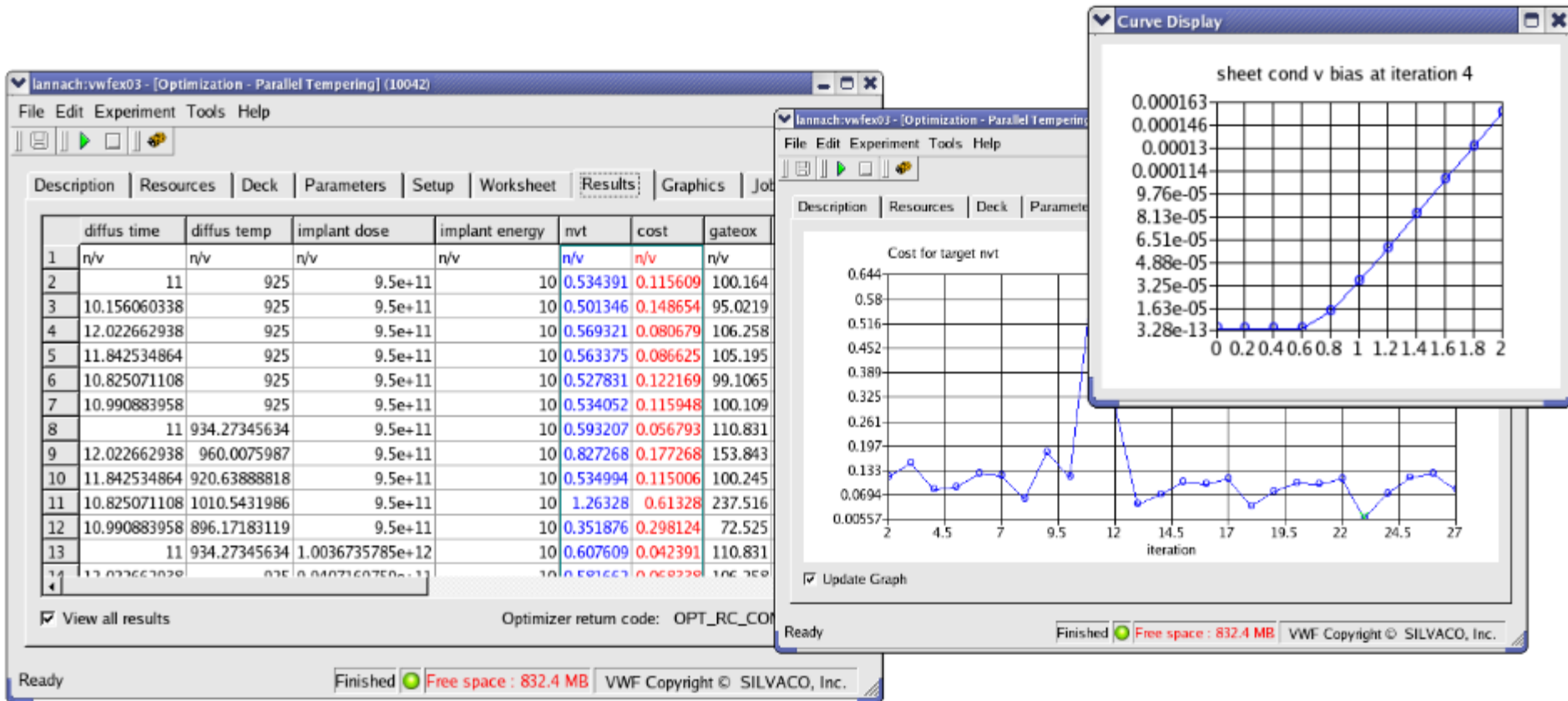
The screenshot displays the Virtual Wafer Fab (VWF) software interface. The main window shows a table with columns for 'diffus time', 'diffus temp', 'implant dose', 'implant energy', 'gateox', 'nit', and 'rbe'. A context menu is open over the table, with 'Add Multiple Branch' selected. An 'Add branches' dialog box is overlaid, showing options for 'Additive', 'Multiplicative', 'Percent', and 'List', along with fields for 'Initial Value' (11), 'Number Of Steps' (0), and 'Step size value' (0). Another dialog box, 'Experiment design', is open, showing a table of variables and their ranges:

Variable	Initial	Low	High
1 <input checked="" type="checkbox"/> diffus time	11	5.5	16.5
2 <input checked="" type="checkbox"/> diffus temp	925	850	1000
3 <input checked="" type="checkbox"/> implant dose	9.5e+11	4.75e+11	1.425e+12
4 <input checked="" type="checkbox"/> implant energy	10	5	10

Below the 'Experiment design' dialog, a tree diagram illustrates the experimental design space. The bottom status bar indicates 'Preparing VWF 2.8.10.R Copyright © 1984 - 2011 SILVACO, Inc.'

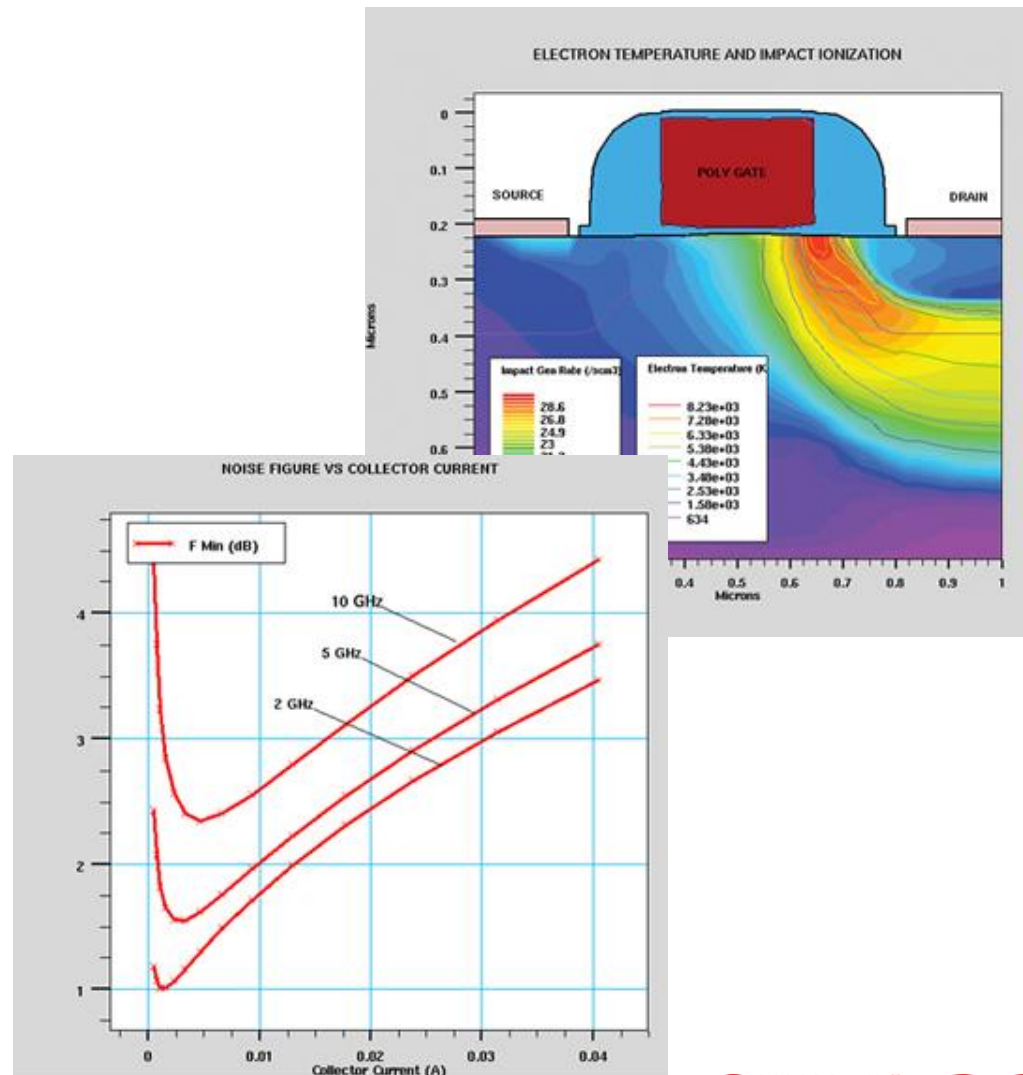
# Design Space investigation - DOE

Further automation for optimizers allow users to “discover” optimal characteristics within the design space.



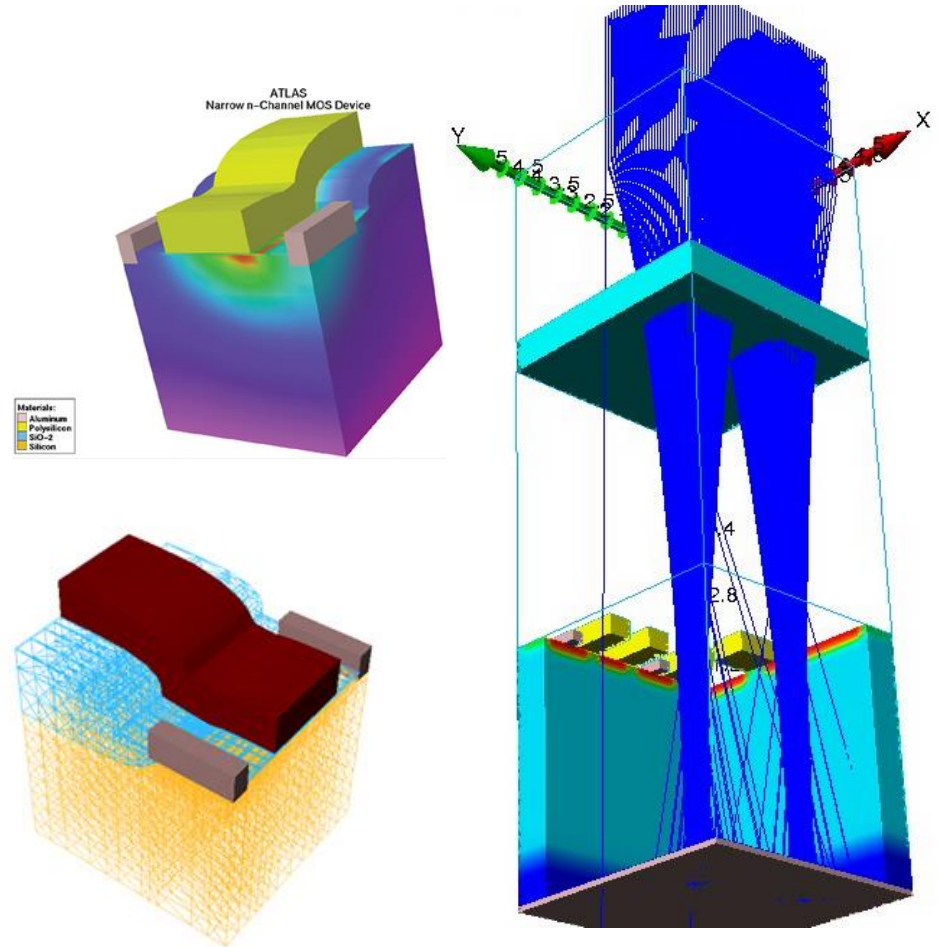
# TonyPlot 2D: Interactive Visualisation Tool

- Supports 1D, 2D, meshed data, Smith and polar charts
- Export data for use in third party tools
- Measurement tools (probes, rulers, etc)
- Overlay plots
- Movie Mode
- Cut lines
- Function and Macro



# TonyPlot 3D: Interactive Visualisation Tool

- Graphical rotation around any axis (x, y, z), repositioning and zoom in/out
- Surface contours
- Isosurfaces
- Probe within the 3D structure
- Hide materials or regions
- Fully customizable
- Cut-plane: 2D slice exported to file or TonyPlot 2D



# Flexible user defined c-functions

The screenshot displays the Silvaco Atlas software interface. The main window shows a deck file with the following content:

```
region num=6 material=CIGS      bottom thick=0.1 ny=2 \
                                accep=8.5e15 x.comp=0.0

#
#
# Standard electrode names on top and bottom
#
elec num=1 name=cathode top
elec num=2 name=anode  bottom
#
#
# Assign the c-interpreter functions to calculate the composition
#
doping region=3 f.composit=beta_interpolation_2.c
doping region=5 f.composit=beta_interpolation_2.c
doping region=6 f.composit=beta_interpolation_2.c

material region=1 eg300=3.3 affinity=4.45 permittivity=9 mun=100
material region=2 eg300=2.36 affinity=4.2 permittivity=10.6 mun=1
```

The output window shows the execution progress:

```
#####
#####
#####      Running on 2 CPUs      #####
#####
#####
ATLAS> x.m loc=0 s=0.25
ATLAS> x.m loc=1 s=0.25
ATLAS> #
ATLAS> #
ATLAS> # n-ZnO
ATLAS> region num=1 material=ZnO      bottom thick=1.1 ny=40 donor
ATLAS> # n-CdS
ATLAS> region num=2 material=CdS      bottom thick=0.064 ny=15 don
ATLAS> # S-CIGSe
ATLAS> region num=3 material=CIGS     bottom thick=0.18 ny=10 acce
ATLAS> # p-CIGSe
ATLAS> region num=4 material=CIGS     bottom thick=0.6 ny=12
ATLAS>
```

The SEdit window shows the implementation of the `beta` function:

```
31 * This uses 1000 trapezia to approximate the area.
32 */
33 double
34 beta(double w, double a, double b)
35 {
36     double dt, t, f1, sum;
37
38     dt = w / 1000.0;
39     t = 0.0;
40     f1 = f(t, a, b);
41     sum = 0.0;
42
43     for (t=0.0; t<w; t+=dt)
44     {
45         double f0, area;
46
47         f0 = f1;
48         f1 = f(t+dt, a, b);
49         area = 0.5*(f0+f1)*dt;
50         sum += area;
```

The status bar at the bottom indicates: Line: 44 Column: 27, Finished executing line 23 - atlas, No files generated, Free space: 927.9 GB, DeckBuild 4.1.23.A Copyright © 1984 - 2015 Silvaco, Inc.



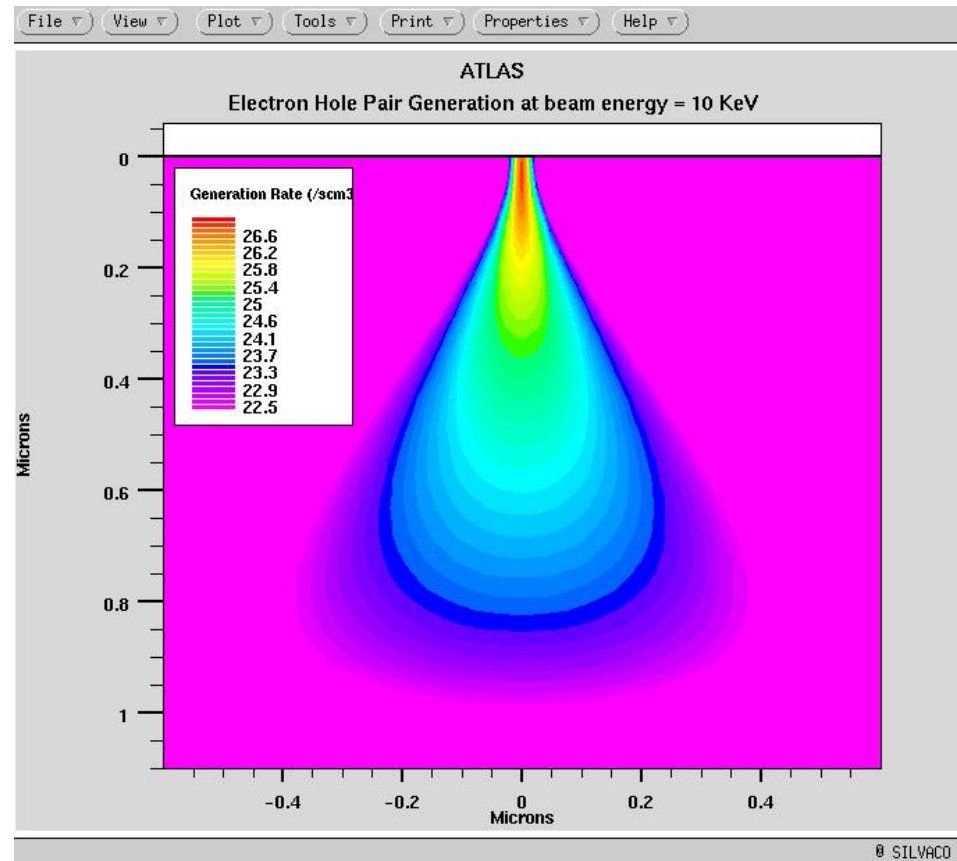
# Flexible user defined c-functions (II)

```
/*
 * Generation rate as a function of position
 * Statement: BEAM
 * Parameter: F.RADIATE
 * Arguments:
 * x      location x (microns)
 * y      location y (microns)
 * t      time (seconds)
 * *rat   generation rate per cc per sec.
 */
int radiate(double x,double y,double t,double *rat)
{
  double E=10; double I=1e-11; double Eg=1.08;
  double q=1.6022e-19; double beam_dia; double ei;
  double R; double A; double sigma_sq;
  double F; double G0; double Rnorm;

  /* Energy requires for formation of e-h pairs */
  ei = 2.596 * Eg + 0.714 ;

  /* Primary Electron Penetration Depth in cm */
  R = (3.98e-6) / 2.33 * pow(E, 1.75) ;

  /* Beam Diameter = 1% of R */
  beam_dia = 0.01 * R ;
```



# Conclusions

- Physical device simulations captures theoretical knowledge to provide essential insight. They can predict behaviour in the entire design space.
- TCAD simulations provides data that is difficult to measure to help speed up innovation and development cycles.
- Silvaco offers simulation tools for 2D and 3D process simulations as well as 2D and 3D device simulation.
- Simulation tools are complemented with user friendly interactive tools.
- Users have access to extensive resources to help them maximise the return out of their simulation effort.