

Device Modeling IC-CAP

A complete and accurate measurement and parameter extraction solution for semiconductor device modeling

About Device Modeling IC-CAP

Device Modeling IC-CAP is the industry standard software for characterizing and modeling DC, analog, and RF semiconductor devices. IC-CAP extracts accurate models and sub-circuits for high-speed/digital, analog, Power Electronics (PE), and RF applications. It offers device engineers and designers a state-of-the-art modeling tool that fills numerous modeling needs, including automated instrument control, data acquisition, parameter extraction, graphical analysis, simulation, optimization, and statistical analysis. IC-CAP combines these capabilities in a flexible, automated, and intuitive software environment to extract efficiently and accurately active, passive, and user-defined devices and circuits.

Today's leading semiconductor foundries and Integrated Device Manufacturers (IDMs) depend on IC-CAP for modeling silicon CMOS, bipolar, Compound Gallium Arsenide (GaAs), Gallium Nitride (GaN), and various other device technologies.

New UI, Python 3, and AI-based modeling

Recently, we introduced a modern User Interface (UI) look and feel. The UI design reflects the newly adopted Keysight UI style standards, featuring light and dark themes, redesigned dialogs, icons, and fonts. In addition to the new UI, numerous usability enhancements signal a fresh beginning for Keysight's flagship modeling platform. IC-CAP offers an immersive Python 3 experience with expanded package support, integrated plotting, and custom linkage to remote installations. The new Model Generator facilitates efficient organization and management of your modeling projects, including one-click data imports of scalable device data, generating scaling plots, creating a flow to extract the model, and verifying the extracted model.

Keysight has pioneered deploying Artificial Neural Networks (ANN) to model new technologies, such as GaN and GaAs HEMT devices. Keysight ANN technology is now accessible through a convenient Python API. It can be utilized to create measurement-based models for any device that can be simulated in any industry-standard simulator. Additionally, ANN Hybrid enhances existing equation-based models by incorporating ANN components to improve accuracy.

Our most recent release integrates AI technology to enhance the automation and accuracy of device modeling extraction. The new Keysight Machine Learning (ML) Optimizer successfully extracts numerous parameters from extensive data, reducing flow complexity and improving consistency.

Features at a glance

- Open software architecture provides the ultimate flexibility to create and automate measurement, extraction, and verification procedures.
- Python 3 and PEL Programming enable advanced data processing, automation, instrument links, and display capabilities. IC-CAP GUI Studio and PySide2 allow you to create custom UI to integrate any proprietary extraction or characterization strategy.
- A new Machine Learning (ML) Optimizer designed to streamline and automate the parameter extraction process for complex compact device models.
- Turnkey extraction solutions for industry standard CMOS models, such as BSIM3/BSIM4, PSP, HiSIM, and HiSIM_HV, minimize the learning curve and maximize model accuracy.
- Direct links to most commercial simulators (e.g., ADS, HSPICE, Spectre, and Eldo) ensure consistency between extracted models and the simulators used by circuit designers.
- The IC-CAP Wafer Professional (WaferPro) add-on enables wafer-level automated measurement and characterization.
- Robust data handling capabilities. Leverage powerful Python packages such as Pandas, NumPy, Matplotlib, h5py, ReportLab, etc., to process, visualize, and import/export.
- The IC-CAP Model Generator (MG) enables advanced device extraction. It integrates Python 3 to access key components (Data import, Flows, Scaling plots, De-embedding, Re-centering, Simulator technology, Model QA, etc.).
- The Power Electronics Model Generator (PEMG) enables the extraction of SiC MOSFET, GaN HEMT, and IGBT power device models and works with Keysight's PD1000A Measurement System.
- IC-CAP provides access to unique nonlinear high-frequency modeling for GaN and other semiconductor devices. Supported models include the recent Compact Modeling Council (CMC) GaN models, ASM-HEMT and MVSG, Keysight's DynaFET, NeuroFET, and Root. Models for high-frequency BJT, MOSFET, MESFET, and PHEMT devices are also available.

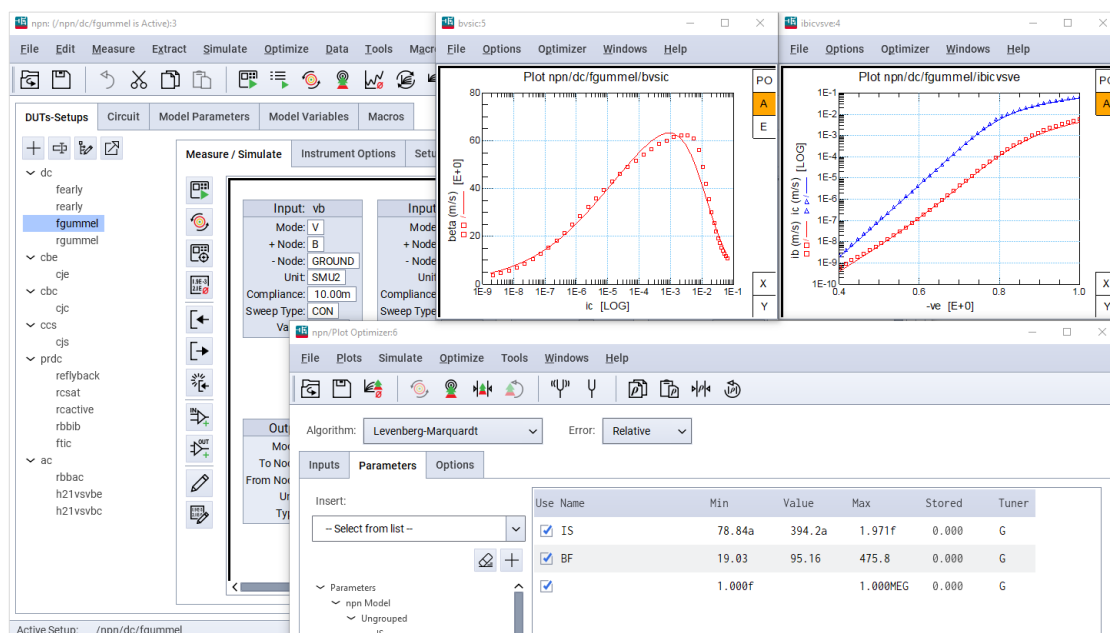


Figure 1. IC-CAP project, plot optimizer, and display windows.

The Device Modeling IC-CAP platform

Industry challenges

The semiconductor industry faces continuing challenges to maximize product performance and yield, decrease time-to-market, and reduce production costs. As technology nodes get smaller and smaller, the need to use accurate models and control statistical variations in device processing performance becomes ever more critical. With 5G/6G applications, typical circuit operating frequencies advance well into the RF and microwave frequency range. Circuit designers need models that accurately predict device behaviors at DC, RF, and millimeter-wave regions.

The amount of data measured for device modeling purposes has been increasing exponentially. With measurements taking several hours or even days, it is essential to be as efficient as possible without compromising measurement accuracy. Measurement control software must work with the probe's native control software and each instrument to allow automated temperature measurements.

Keysight solution

Device Modeling IC-CAP addresses these challenges and provides significant competitive advantages to companies within the semiconductor industry.

IC-CAP modeling software offers modular products so that you can choose precisely the modules required for your particular modeling scenario. Central to the IC-CAP platform is the IC-CAP software environment, which supports graphical analysis, programming via Parameter Extraction Language (PEL) and Python, and custom model and user interface development. The analysis module enables simulation, optimization, statistical analysis, and interfacing with external simulators. The new ML optimizer is part of the existing IC-CAP Analysis product, and it can be applied to the extraction of any compact model. IC-CAP supports an extensive list of measurement instruments, including industry-standard DC analyzers, LCRZ impedance analyzers, and network analyzers.

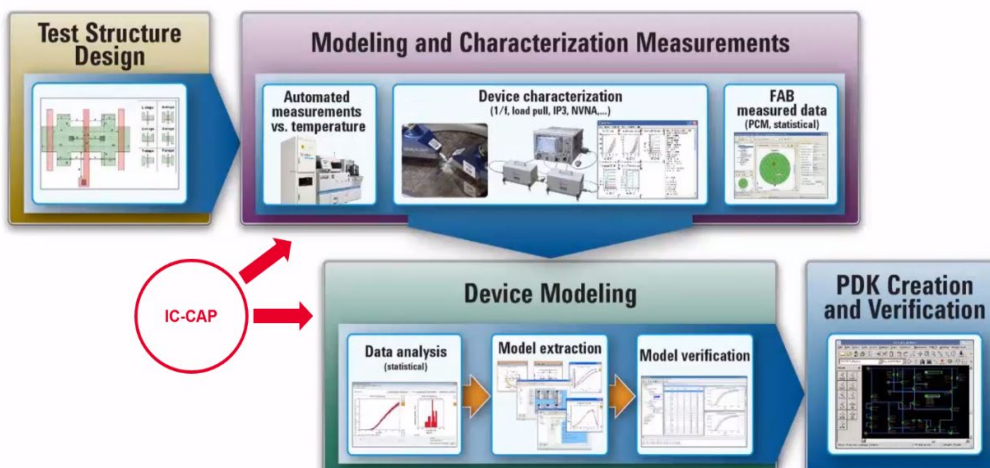


Figure 2. The device modeling flow and IC-CAP.

Accurate proprietary and industry-standard models

Within a single environment, you can use IC-CAP to automate measurements, simulate device performance, extract data, optimize model parameters, perform statistical analysis, and generate best-case and worst-case models. IC-CAP provides extraction routines for industry-standard and Keysight proprietary models such as diodes, BJT, MOSFET, MESFET, HEMT, noise, thermal, etc. Extraction modules offer complete DC to RF parameter extraction capabilities. IC-CAP also supports models and extraction routines developed by third parties and numerous other simulation software packages to accommodate customer requirements. IC-CAP also supports the use of Verilog-A models.

RF and microwave modeling capabilities

Accurate modeling of RF effects requires reliable measurement data. IC-CAP connects and controls various RF instruments, such as the Keysight PNA, PNA-X, and ENA series. IC-CAP RF extraction modules for proprietary and industry-standard models include RF-dependent parameter extraction, ensuring your models are suitable for high-frequency circuit simulation.

GaN modeling

IC-CAP offers complete coverage for GaN devices, from the traditional, empirical-based Angelov-GaN model to the most recent physics-based models promoted to industry standards by the Compact Modeling Council, the ASM-HEMT, and MVSG models. The Artificial Neural Network (ANN)-based DynaFET model achieves the highest accuracy for highly nonlinear PA applications. For more details on GaN modeling, please see the GaN Modeling section in the Product Configuration chapter.

The newer Hybrid physical-ANN modeling offers a powerful new approach to device modeling, combining the advantages of physics-based models and data-driven ANNs. The original compact model is maintained and augmented with ANN-based elements carefully targeting second-order effects. An example of Hybrid ANN modeling applied to the CMC standard model ASM-HEMT is now included.

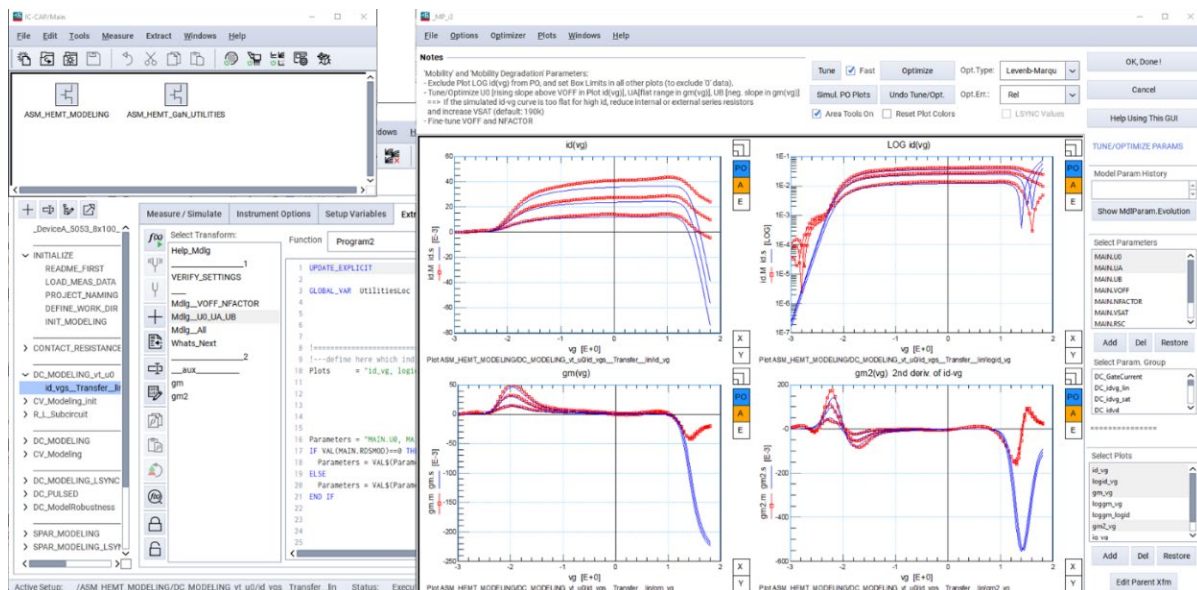


Figure 3. The GaN CMC ASM-HEMT model extraction example

Power Electronics (PE) modeling

Keysight's Power Electronics Model Generator (PEMG) supports three power electronics device models. These models have been implemented in Verilog-A and are available in Keysight ADS. The Si/SiC MOSFET and IGBT models are for customers who do not have access to the device's detailed process parameters, a typical case in power electronics design labs.

Flexible software environment

IC-CAP features an open and flexible software architecture. While we provide turnkey modeling solutions for various industry-standard and proprietary models, measurement and extraction algorithms can be tailored. Utilizing the IC-CAP Parameter Extraction Language (PEL) or the Python programming environment, users can directly define and incorporate their models or extraction methodologies into IC-CAP. The open measurement interface of IC-CAP enables users to write measurement drivers to control instruments as needed. Additionally, it is possible to design custom modeling packages by creating personalized user interface dialogs with IC-CAP GUI Studio.

Advanced automated wafer-level measurements

With IC-CAP WaferPro, IC-CAP provides the most advanced solution for device modeling automated measurement. A dedicated test plan environment within the IC-CAP Platform allows the test engineer to measure and post-process data using various Keysight and third-party instrumentations.

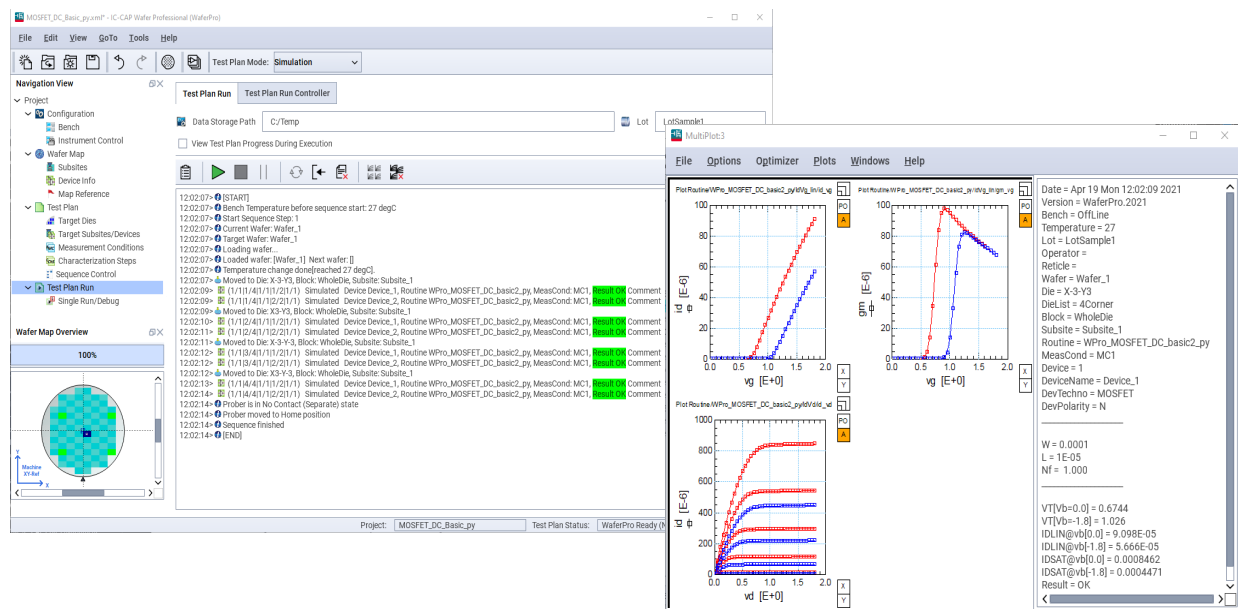


Figure 4. IC-CAP WaferPro Test Plan log information and display capabilities. The DUT information and the calculated data (or spot data) included in this routine are also shown.

Device Modeling IC-CAP Key Components

Graphical User Interface (GUI) and programming

The IC-CAP GUI enables you to create and manage measurement and modeling projects and read, organize, and display data using single or multiple plot window displays. Multiplot windows allow for unlimited plots, easy navigation, and zooming capabilities.

IC-CAP organizes measured and simulated data in units called "Setups." Data are processed and displayed in real-time using Python 3 or PEL scripts. IC-CAP PEL is a simple-to-learn legacy language derived from HP Basic. Python is an open-source, modern, object-oriented, and efficient language that maximizes speed and productivity.

Writing PEL and Python scripts allows you to process data and create extraction and measurement algorithms within the IC-CAP environment. PEL and Python will also enable you to interactively develop new models and extraction routines and modify existing extraction modules, making IC-CAP an extraordinarily open and flexible working environment.

IC-CAP supports Python 3. The standard configuration for IC-CAP Python 3 now includes additional packages such as Pandas, SymPy, H5Py, and OpenPyXL, as well as the latest versions of SciPy, NumPy, and Matplotlib (refer to the documentation for a complete list of packages and the current Python version). IC-CAP Python 3 features:

- Convenient Python 2 to 3 script to convert legacy model files to Python 3
- Python demos and examples now use Python 3

- Python 3 modeling application examples to showcase the power of Matplotlib, NumPy, Pandas, HDF5, and more.
- A powerful API allows Python scripts to interact with IC-CAP objects and data structures, enabling automation and maximum customization.

IC-CAP Macros can automate tasks within an extraction or even entire extraction routines. A macro is a programming routine that executes a sequence of IC-CAP commands, functions, PEL, or Python programs or calls to the user environment. Using Macros, extraction routines developed by R&D can be automated and leveraged in your production areas to minimize user interaction and maximize productivity.

Efficient data management

The IC-CAP Data Manager enables you to import and export data in an ASCII format called MDM. This format is recognized as a standard within the device modeling community, and numerous Keysight and third-party measurement tools export data into this specific IC-CAP format. Data in other file formats, such as .csv, .s2p, and .xls, can be imported and exported. Thanks to IC-CAP's powerful Python API, there are no practical restrictions on the input format.

Wide choice of industry-standard simulators

Each IC-CAP project can simulate a user-defined netlist that typically includes the model card and, optionally, a subcircuit representing the model. The IC-CAP simulator engine creates and maintains a Parameter Table based on the model and subcircuit parameters. IC-CAP includes SPICE simulators and provides direct links to several external simulators (see the complete list of supported simulators in Table 6). The IC-CAP analysis license enables linear and transient analysis with the powerful Keysight ADS simulator at no extra charge.

Powerful optimizers, including ML optimizer

IC-CAP offers a variety of optimization algorithms. Combining different optimization algorithms can be a real advantage when enhancing the model's fit. Besides automated optimizers and manual tuners, which PEL or Python can invoke, a powerful tool called plot optimizer makes dynamic interactive optimization easy. The plot optimizer is a user interface that enables you to set up all parameter optimization tasks on the fly quickly. You can open the plot optimizer from every IC-CAP plot and automatically load the target and simulated data for quick tuning and optimization.

Machine Learning (ML) optimizer

The new ML Optimizer overcomes the limitations of traditional gradient-based optimizers. These optimizers are often inefficient and may fail to converge as the number of parameters increases. Furthermore, calculating gradients can be time-consuming, and in high-dimensional optimization, gradient algorithms can easily become trapped in local minima. As a result, engineers develop complex extraction flows, where each step extracts only a few parameters, leading to a manual process that can take weeks and may not produce optimal and consistent results. The new Keysight Optimizer enables the simultaneous optimization of over 40 parameters, allowing engineers to simplify their workflow and achieve results in minutes or hours for most problems. The core ML algorithm learns the problem and directs the next evaluation point based on past evaluations. Using the new ML Optimizer is straightforward. Select the new ML optimizer algorithm, the parameter ranges, and the number of iterations, and run.

Several example projects using the new ML optimizer are included. Please refer to the documentation for details on where to find them in the examples' directory under the IC-CAP installation.

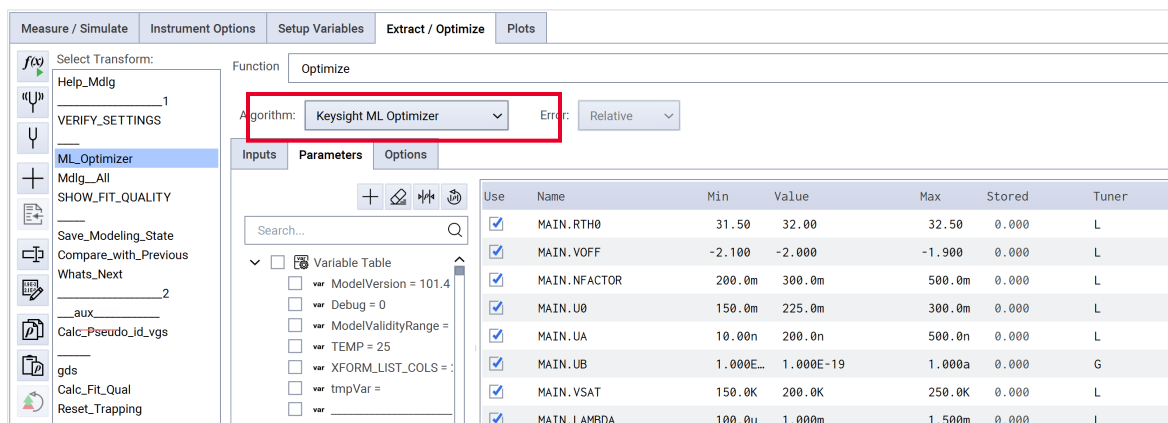


Figure 5. Choosing the new ML optimizer in the optimizer settings

IC-CAP GUI studio

The GUI Studio adds powerful capabilities for developing custom graphical user interfaces to the highly flexible IC-CAP software environment. Engineers use IC-CAP Studio to create user interfaces that automate and simplify entire measurement or extraction process flows. The optimized UI modeling environment can then be shared and exchanged with colleagues or external customers who can easily understand the flow and quickly perform the necessary measurement and extraction steps. Python PySide can also be utilized to design custom UIs. However, IC-CAP GUI Studio is easier to learn and more integrated with IC-CAP data structures such as Parameter Tables.

Model Generator

The Model Generator (MG) is a workflow manager that helps device modeling engineers perform model extraction on any scalable device faster and more efficiently. It offers several helpful features:

- Automatic import of measured data (DC, CV, and S-parameters when available)
- New UI, fast data visualization, preconfigured and flexible extraction flow
- Automatic load circuit and subcircuit in each DUTs. Allow users to import or export a Circuit Netlist (.cir) to or from a Model Generator project
- Scalability plots can be efficiently generated against various parameters, including geometry, temperature, bias, and frequency
- Performing RF de-embedding, recentering, and modeling of corners with the use of plots in the extraction flow
- Easily validate the extracted model and create customized reports
- Easily compare results from two simulators or model cards with the Model Generator QA
- Including many examples to help users get started

MG embraces a workflow approach and is part of the core environment license. Recentering and corners modeling need an extra license.

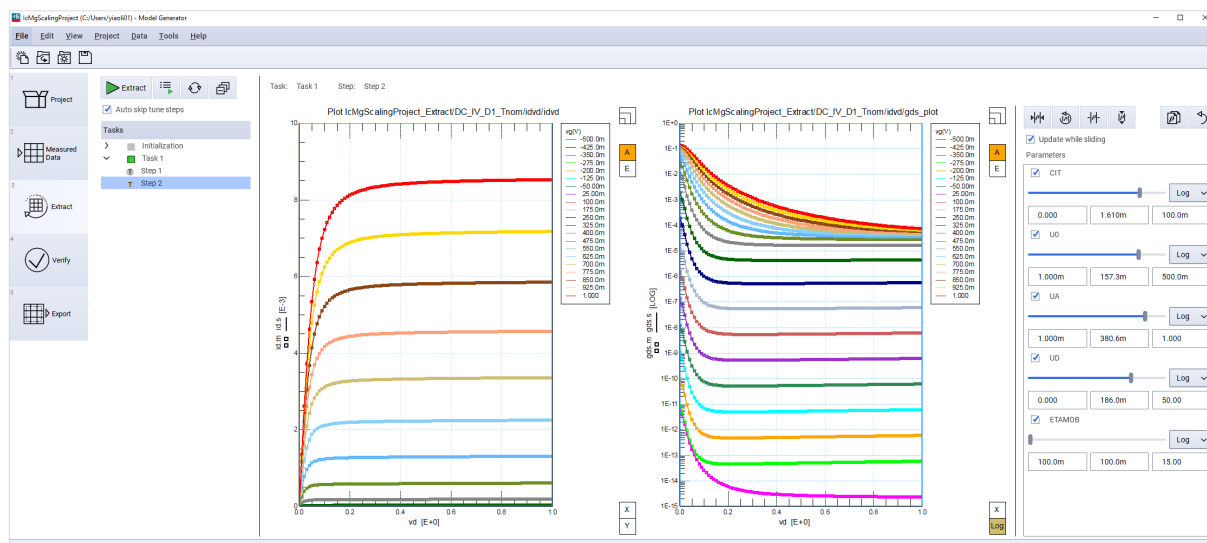


Figure 6. IC-CAP Model Generator (MG)

Power electronics model generator

The Power Electronics Model Generator (PEMG) is an advanced device modeling software tailored towards the model extraction requirements of semiconductor power electronic devices. It supports the following capabilities:

- Industry standard ASM-HEMT model support for GaN discrete and IC devices used in power electronics

- Keysight SiC and IGBT models that do not require process parameter information
- Automatic import of measured data (DC, CV, and S-parameters when available)

New UI, fast data visualization, preconfigured and automated model extraction

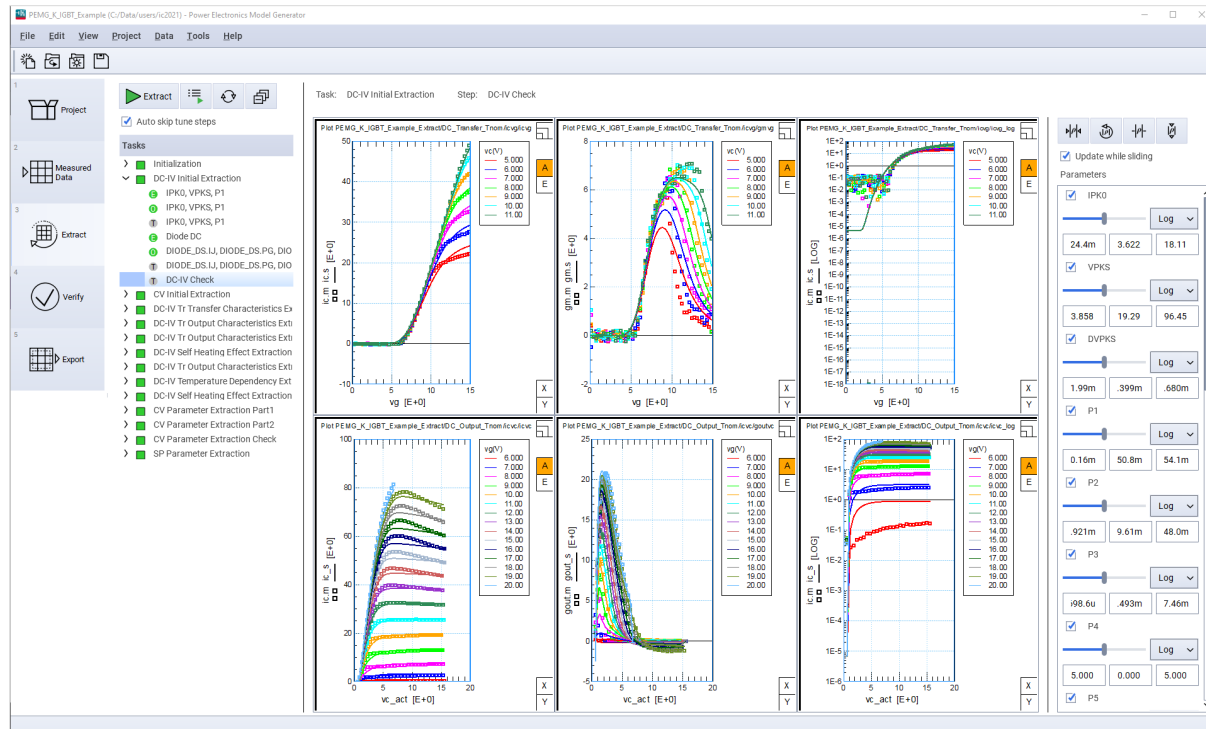


Figure 7. IC-CAP Power Electronics Model Generator (PEMG)

Making Measurements with IC-CAP

Successful device modeling requires accurate measured data and a thorough understanding of the complex integration between the measurement hardware and the modeling software. The IC-CAP software is a powerful modeling tool that can automate industry-standard instruments and systems. Its measurement interface provides turnkey measurement drivers for various single instruments and modeling systems configurations for DC, CV, and RF measurements. See Table 4 for a list of supported instrument drivers.

IC-CAP WaferPro

IC-CAP WaferPro drives industry-standard measurement equipment, ranging from benchtop instruments to parametric testers, and includes third-party probers, switch matrices, and thermal chucks for efficient, automated on-wafer measurements across temperatures. Additionally, IC-CAP WaferPro utilizes a custom library of measurement routines, such as adaptive measurement algorithms, designed to significantly reduce overall measurement time.

Since the measurement routines operate within the IC-CAP environment, both complex and straightforward post-processing- such as calculating spot measurements or figures of merit, RF de-embedding, and direct extraction- can be applied to the measured data before saving. Swept data are generally saved in the IC-CAP MDM format, while spot measurements are stored in Excel CSV files. Refer to Table 5 for a list of probers, switching matrices, and thermal chucks supported by WaferPro. The W7311B IC-CAP Wafer Professional Measurement Bundle includes the IC-CAP Environment, WaferPro, and all measurement drivers.

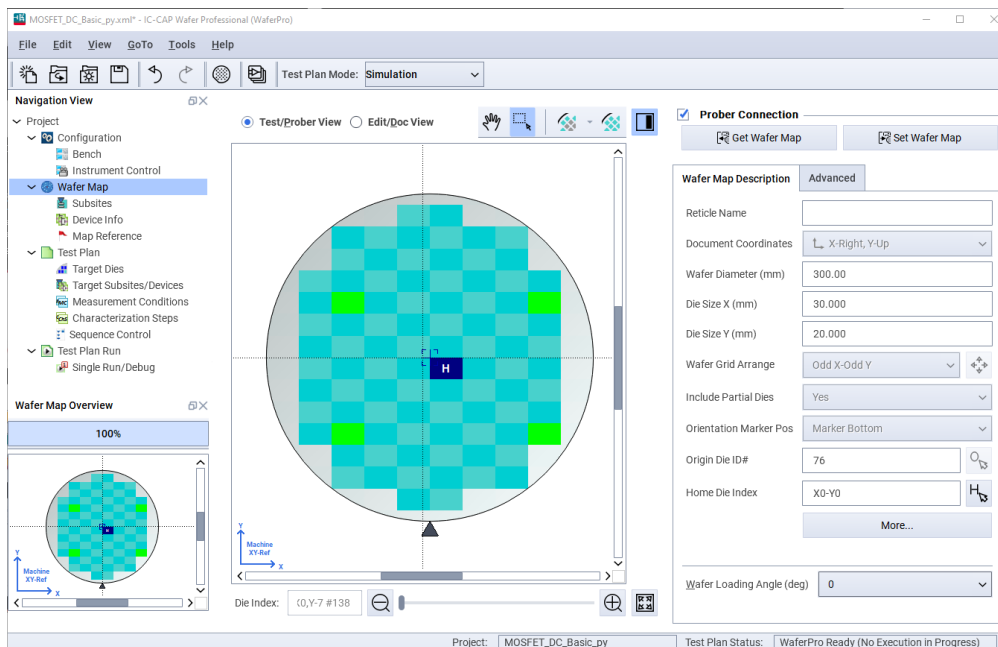


Figure 8. IC-CAP WaferPro's user interface enables prober control with comprehensive wafer map visualization.

IC-CAP DataPro

IC-CAP's Data Selection and Processing tool (DataPro) enables users to identify the "golden" or most representative die for modeling. DataPro utilizes statistical analysis on measured data and custom critical figures of merit (such as the max gm or the ring oscillator frequency). Based on statistical distribution and variances, DataPro detects outlier devices and excludes them from further analysis. It also identifies the typical (mean) and corner devices, exporting their data to other tools for target, typical, or corner modeling. The W7300B IC-CAP Device Modeling Platform Bundle includes IC-CAP DataPro at no additional cost.

Data viewer for WaferPro and WaferPro Express data

An automated test plan in IC-CAP WaferPro or WaferPro Express software produces measurement data organized into a complex hierarchy of subdirectories based on lot name, wafer, temperature, device type, polarity, reticle location, and specific measurement parameter groups. This hierarchy can be challenging to navigate when plotting device data from different reticles side by side. The IC-CAP Data Viewer automatically traverses the directory structure, locates relevant data, and generates plots, simplifying the study of data across devices. The most common plots are now easily created, including measurements over bias and statistical data from across the wafer, presented as a histogram or a wafer map distribution.

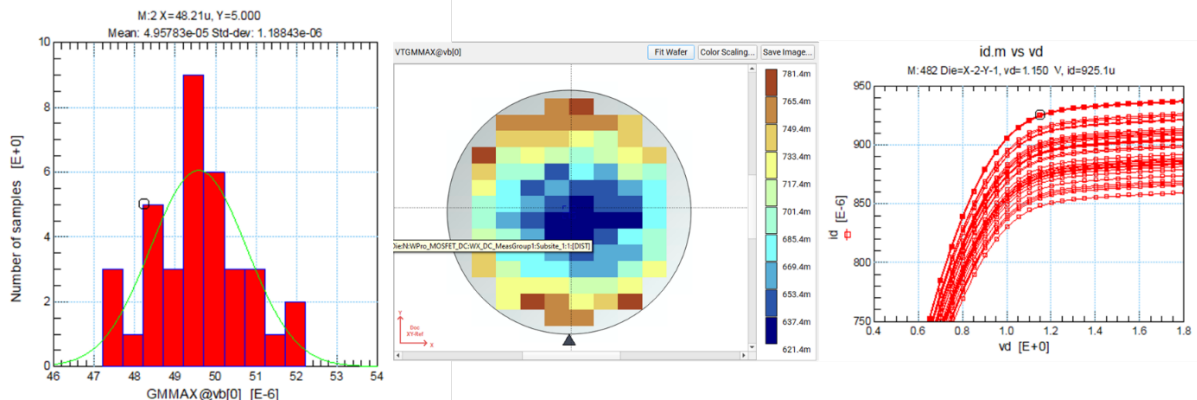


Figure 9. IC-CAP Data Viewer lets you sort and display measured data generated by WaferPro. The picture shows the various diagrams used to study the data distribution across the wafer: histograms, color/bin mapping, and multi-curves.

Extracting Models with IC-CAP

A typical modeling flow begins with selecting a model based on the process technology and its intended circuit application (e.g., DC, high frequency, or both). Next, the necessary measurements are performed to characterize a device or a set of devices, and finally, a methodology is applied to extract the model parameters. This last step is accomplished by calculating the parameters using built-in or custom model equations derived from the measured data or utilizing tuning or optimization techniques.

With IC-CAP, you can either investigate and implement your extraction methodology or use one of the turnkey modeling extraction packages and be up and running by day one. Keysight and third-party modeling experts provide extraction packages and examples.

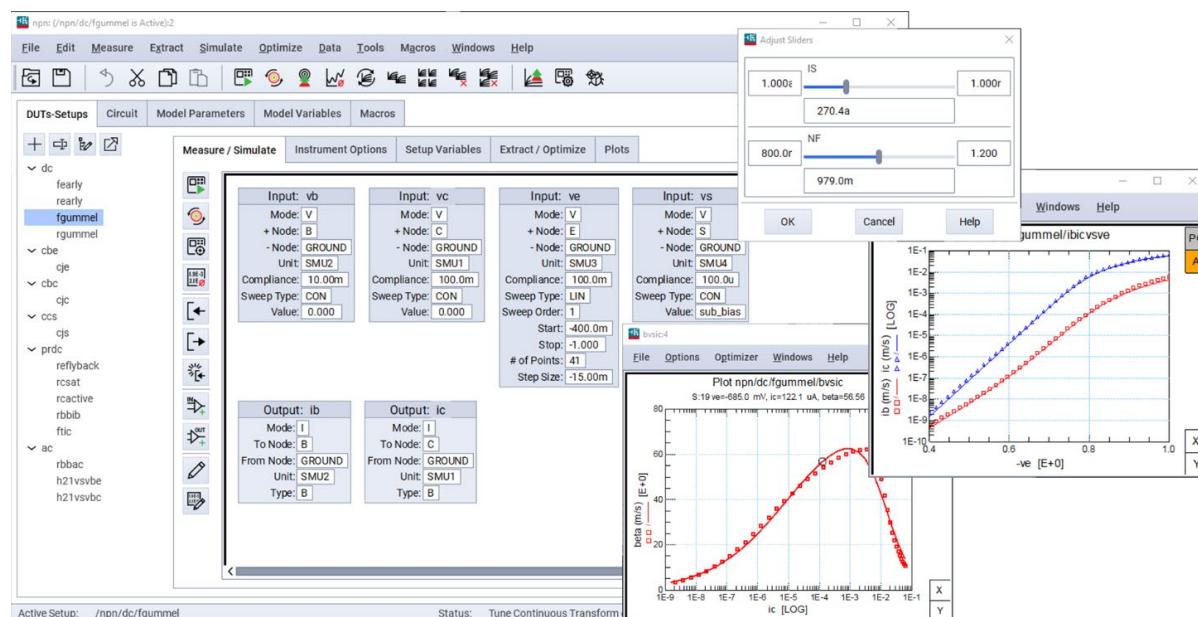


Figure 10. Tuning model parameters to match measured and simulated data of a basic BJT model

Model Generator (MG)

The IC-CAP-based modeling flow described above becomes less convenient when dealing with large amounts of data based on different device sizes. Modeling engineers need to do much programming to achieve their goals. The Model Generator can help them manage data better and maintain flexibility while reducing programming effort.

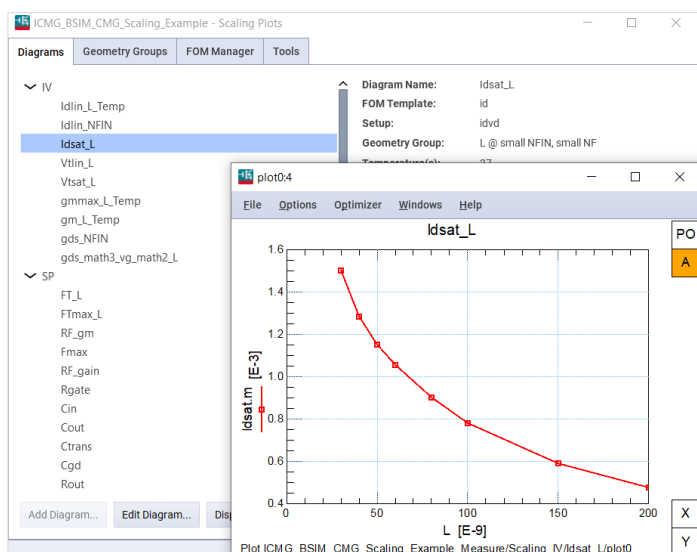
The MG framework allows you to:

- Define project parameters, set model flags and device constants related to your device and project
- Load the measured data from a highly structured directory with one-click
- Run the manual or automatic model extraction to get to the final model parameters
- Easily create scaling plots for target modeling and device extraction analysis
- Implement RF de-embedding and assign the de-embedding plots in the extraction flow

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Scaling plots tool

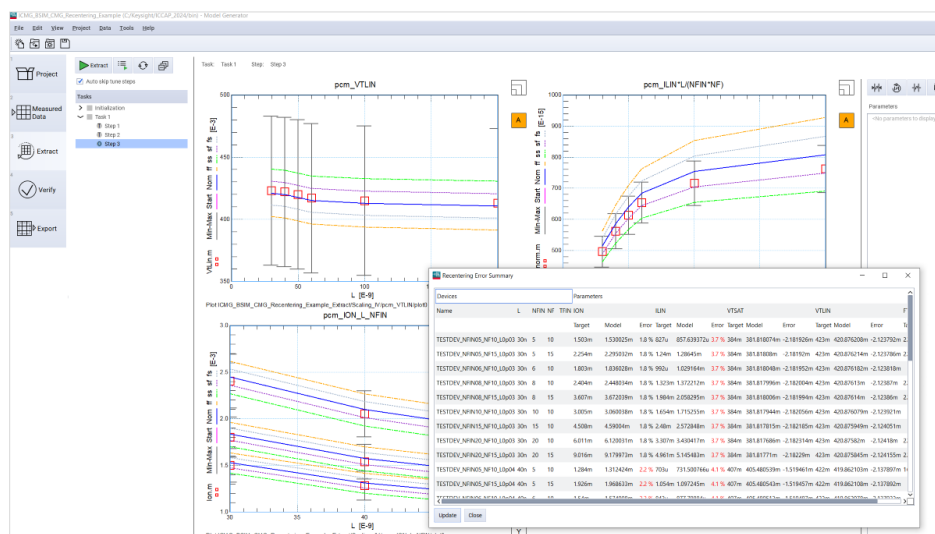




Recentering and target modeling

The Model Generator Recentering and Target Modeling add-on is a powerful tool for adapting existing model cards to new process specifications or targets. The recentering tool makes it easy to adjust selected model parameters and optimize the model to align it with new targets. It also provides statistical corners, error monitoring through a convenient table, and report generation capabilities.

This add-on offers exceptional versatility, enabling you to execute multiple simultaneous simulation processes (up to 30 ADS). Whether tackling a complex project or refining your models, the Recentering and Target Modeling add-on facilitates the swift and efficient achievement of your objectives.



RF De-embedding tool

The De-embedding tool performs RF de-embedding based on the imported measured S-parameters data and the selected de-embedding method. The tool also displays the S-parameters before and after de-embedding. Three default de-embedding methods are provided, and you can also use the customized methods.

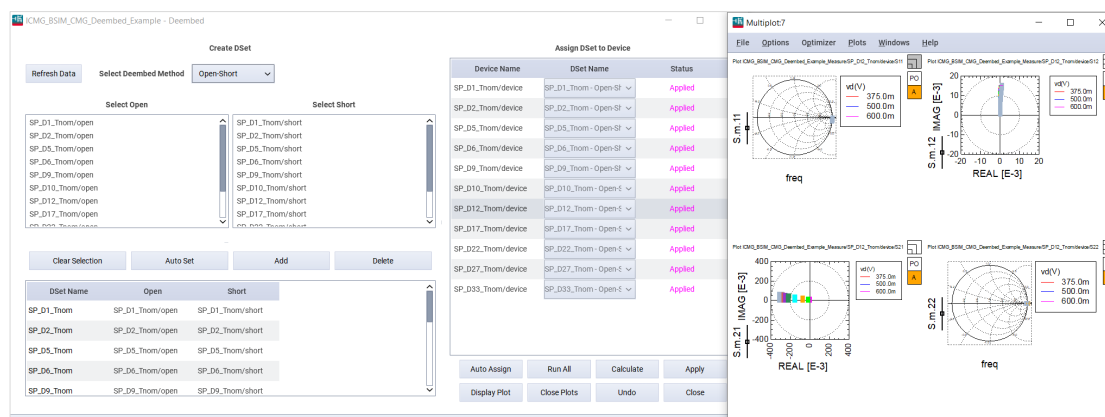


Figure 14. Using the De-embedding tool in the model generator to perform RF de-embedding

CMOS modeling

IC-CAP offers turnkey extraction packages for CMOS models, including BSIM3, BSIM4, BSIMSOI, PSP, HiSIM, BSIM-BULK, and HiSIM_HV. These packages share a common architecture, allowing the same measured data to extract various CMOS models.

The packages provide the following key features:

- DC, CV, and temperature-dependent modeling with geometry scaling and binning
- An easy-to-use user interface makes CMOS modeling easy and convenient
- Open and flexible extraction methodologies. All packages come with a robust extraction methodology that can be highly customized to adapt to specific process technologies
- Where fine-tuning and optimization are necessary, the extraction process guides you through predefined optimizer and tuner steps
- Powerful multiplot data display allows users to create and customize plots, including geometry and temperature scaling plots
- Automatic generation of complete model documentation in HTML format
- Automatic failure tracking and reporting during measurement and extraction
- Highly accurate RF extraction methodologies with enhanced, scalable RF gate and substrate resistance models
- Target modeling capabilities. Target modeling allows users to extract a preliminary model based on targets (spot data) or re-center an existing model to match new process specs.
- Based on process parameters variations and their typical values, the Corner modeling extraction package allows the user to extract corner libraries for a CMOS process. The final library is verified for various devices, temperatures, and bias conditions on all supported simulators.

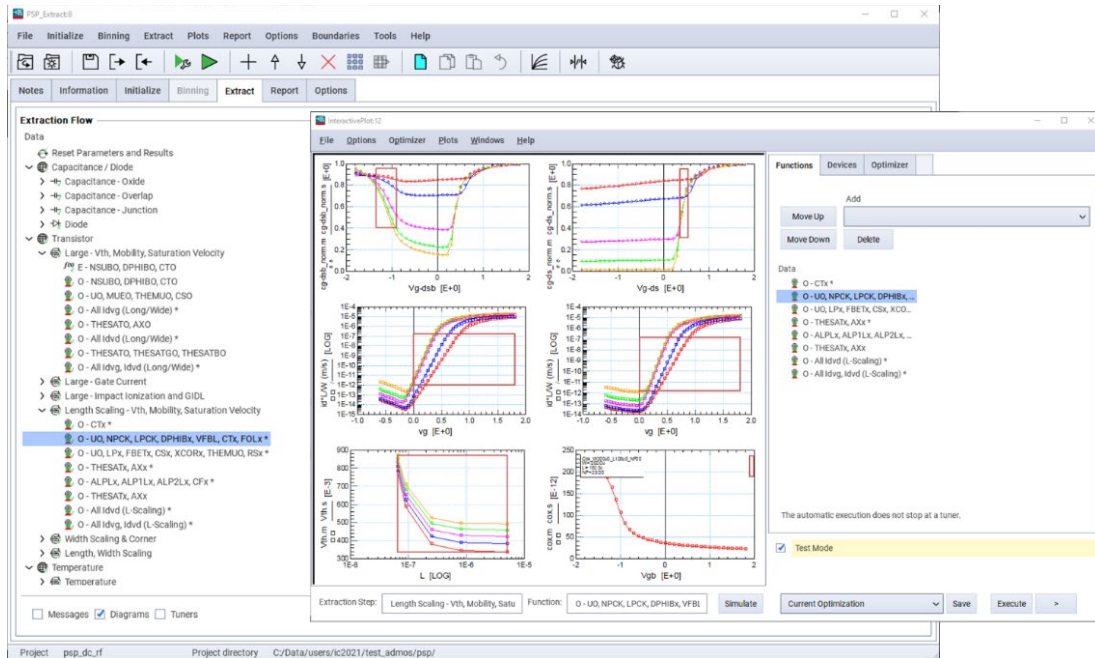


Figure 15. The CMOS PSP modeling package. On the left, the PSP extract main window shows the extraction flow. The display window shows the extraction step, an optimization, under execution.

The CMOS extraction packages are regularly updated to support the latest model versions. Please check the product documentation for updated information on supported versions and simulators. IC-CAP offers legacy extraction packages for NXP's MOS Model 9, UCB level 2 and 3 models, and the data-based Root MOS Model. For a list of CMOS modeling packages and product numbers, refer to Table 3.

BJT and HBT modeling

The W7011E IC-CAP BJT Plus Extraction Package Plus Add-on includes VBIC, Gummel-Poon, and Keysight ADS HBT. Philips/NXP Research Labs, TU Delft, and Keysight EDA jointly developed the Mextram extraction. The model has been extensively used within Philips/NXP and has proven highly robust and accurate. Mextram extraction examples are provided at no charge.

BCTM VBIC BJT model

VBIC is an abbreviation for Vertical Bipolar Inter-Company, a public domain model developed by the Bipolar Circuits and Technology Meeting (BCTM) consortium. It models quasi-saturation, avalanche, and substrate effects. The latest release includes self-heating effects.

Gummel-Poon and EEBJT2 models

The Gummel-Poon (GP) model has been the industry-standard model for BJT devices for decades. IC-CAP includes an RF-based version of the GP model extraction well-suited for RF applications. CV measurements are replaced with S-parameter measurements, making the junction capacitance extraction more accurate. The GP example includes improved methods for extracting ideality, base resistance, and reverse early voltage. In addition to the standard GP model, the BJT package includes the Keysight EEBJT2 model, a modified GP model to improve AC and DC accuracy.

ADS HBT modeling package

The Keysight ADS HBT (AHBT) extraction package provides comprehensive measurement and extraction procedures for III-V HBT device modeling. AHBT is a complete HBT model explicitly designed for GaAs, SiGe, and InP processes, supporting both single and double heterojunctions. The turnkey package includes comprehensive measurement and extraction procedures.

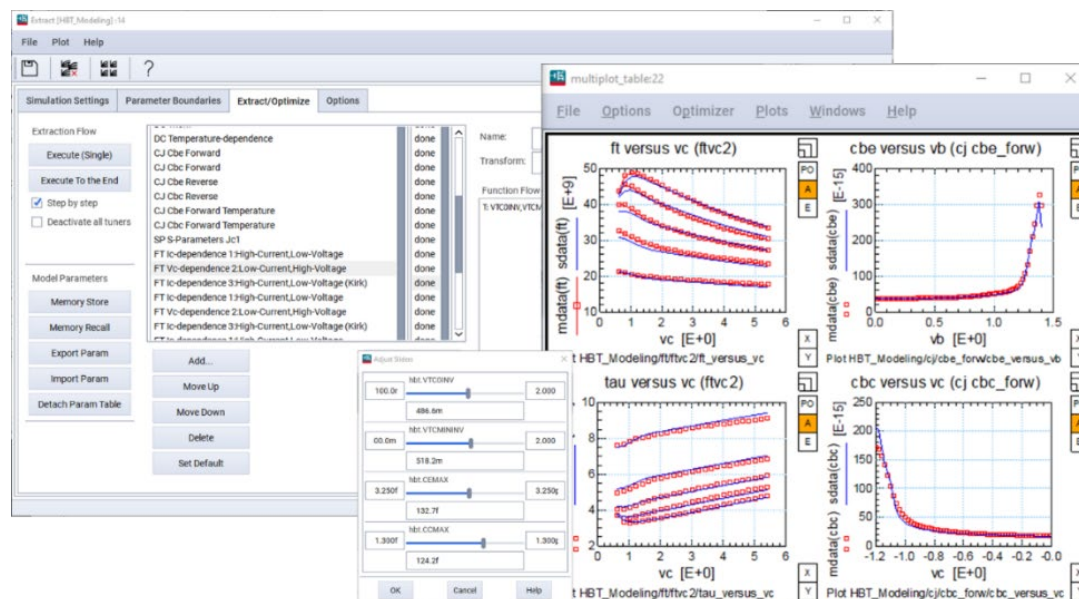


Figure 16. The extraction flow of the Keysight ADS HBT modeling package

GaN modeling

CMC ASM-HEMT and MVSG GaN modeling examples

Accurately modeling Gallium Nitride (GaN) devices is challenging due to trapping and thermal effects on the device's electrical characteristics. Empirical GaAs models may not be accurate enough for certain nonlinear applications. After an extensive qualification process, the Compact Modeling Council (CMC) has promoted two new physics-based models to CMC standards: the ASM-HEMT developed by UC Berkeley in collaboration with IIT Kanpur and the MVSG_CMC model, initially developed by MIT and now maintained by the University of Waterloo. If you are new to GaN modeling or the new CMC models, the IC-CAP CMC GaN basic extraction flow examples for ASM-HEMT and MVSG_CMC can save you valuable time. Keysight developed the extraction flow in collaboration with the model developers. The step-by-step extraction guide lets you quickly learn the model fundamentals and how to extract the core parameters. ASM-HEMT 101.4 and MVSG_CMC 4.0.0 are used in the examples individually.

The framework is open and flexible and allows you to:

- Organize and import measured data automatically
- Execute the flow, step by step, using a novel Modeling UI
- Review overall fit, save intermediate and final steps
- Quickly customize the flow to your specific GaN process
- Extract self-heating and trapping effects

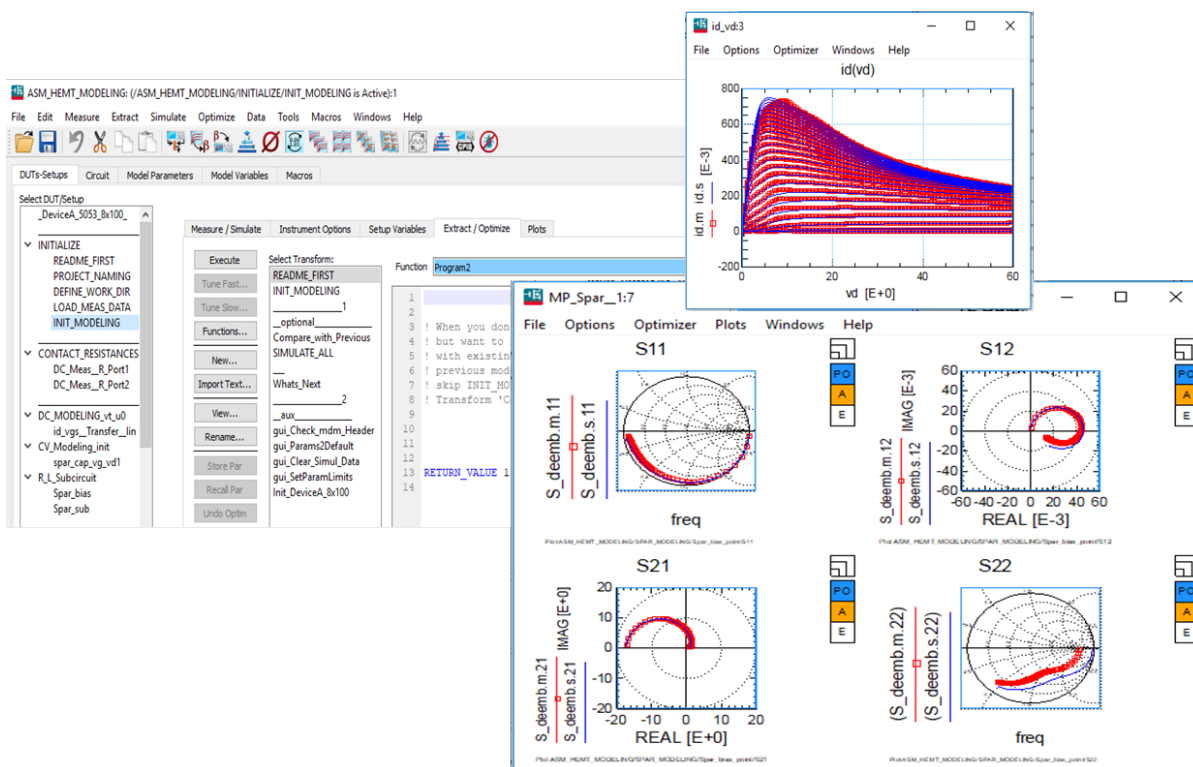


Figure 17. The CMC GaN modeling package (ASM-HEMT model shown)

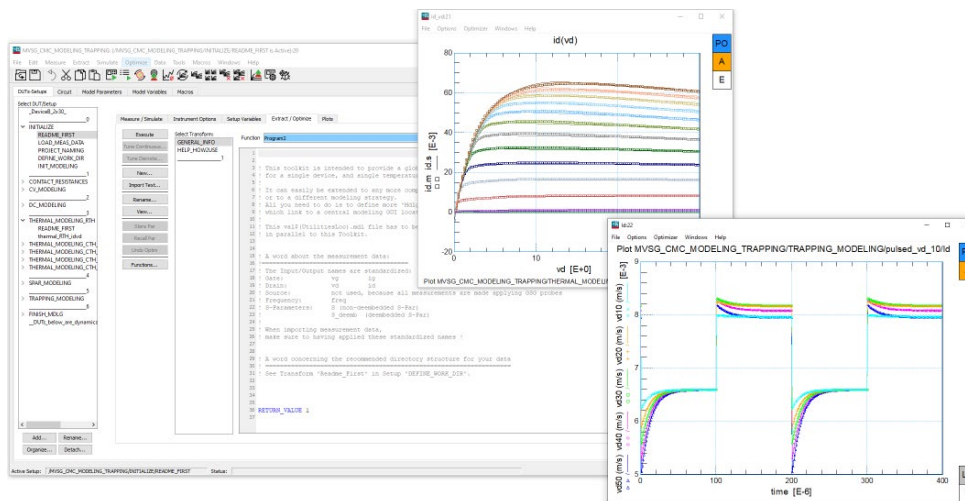


Figure 18. The CMC GaN modeling package (MVSG_CMC model shown).

The MVSG_CMC example's extraction flow includes steps for the thermal resistance, capacitances, and trapping and verification using large signal-measured data.

Angelov-GaN modeling package

The Angelov-GaN model, developed by Prof. I. Angelov at the Chalmers University of Technology, has become widely popular across the industry. The IC-CAP Angelov-GaN extraction package provides a dedicated software environment that allows users to perform the necessary measurements and extract the Angelov-GaN model. A convenient user interface lets users execute a step-by-step extraction flow to extract the model parameters. A turnkey flow provided in the Package enables complete customization. Simulations use Keysight ADS.

The Angelov-GaN modeling is part of the W7012E IC-CAP FET Plus Extraction Package.

Keysight DynaFET model

The patented Keysight DynaFET model represents another significant innovation in device modeling. It models dynamic self-heating and trapping effects attributed to critical III-V FET dynamic phenomena such as drain lag, current collapse, and gate lag.

DynaFET uses a novel model identification procedure to identify (extract) trap states and junction temperature from large-signal waveform data and derive the detailed coupling of these dynamical variables to the device's electrical behavior. Like NeuroFET, DynaFET also uses ANNs to describe device charges and currents, but its formulation includes device temperature and charge trapping states as additional inputs to the neural networks. A sophisticated machine learning algorithm trains the networks using DC, S-parameter, and large-signal waveform measurement data at different ambient temperatures. Nonlinear waveform data are measured with the Keysight Nonlinear Vector Analyzer (NVNA) at a low fundamental frequency (100 MHz) for various temperatures, DC operating points, power levels, and load impedances.

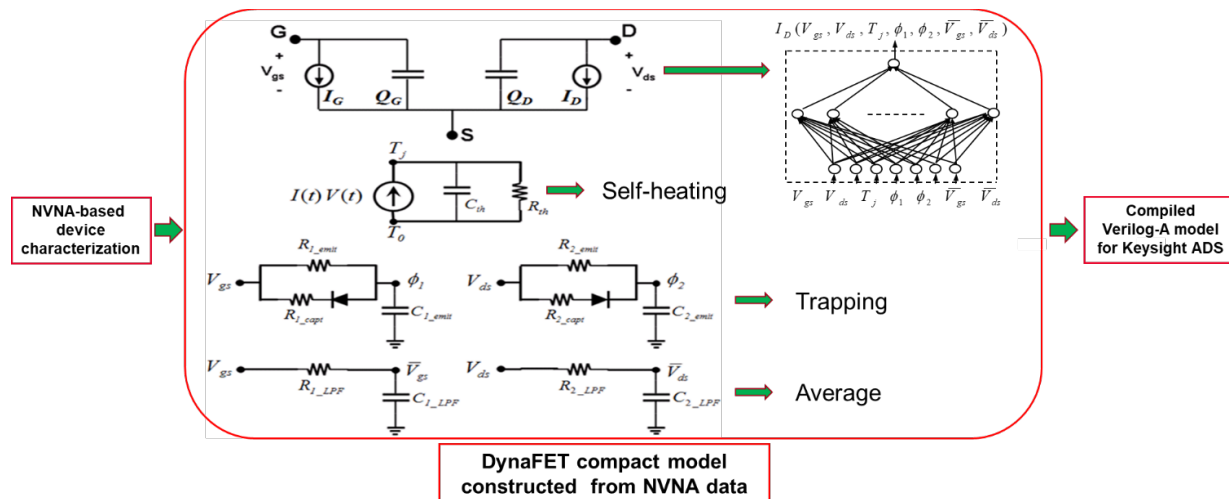


Figure 19. The DynaFET equivalent circuit and the Artificial Neural Network describe the current and charges constitutive equations.

The DynaFET model applies to high-efficiency power amplifiers, radar applications, and low noise amplifiers of GaN and GaAs FETs / HEMTs. It does not cover switching or passive mixer applications. DynaFET inherits all the advantages of NeuroFET but adds some key benefits:

- Accurate results vs. temperature with dynamic self-heating and temperature dependence
- Improved broadband performance versus frequency across the entire device operating range
- Improved prediction of large-signal nonlinearities (distortion, load-pull, PAE) and long-term memory effects
- Improved transient performance by independently modeling each dynamic device mechanism and correctly coupling them together self-consistently

Demonstrated large-signal validation for harmonic tuning at both input and output ports

The W7020A IC-CAP DynaFET Model Generation software add-on controls DC and S-parameters measurements, imports nonlinear measured data from the Keysight NVNA, and extracts the DynaFET ANN for simulator use. DynaFET model extraction and training are also available as a service.

MESFET and HEMT modeling

The W7012E IC-CAP FET Plus Extraction Package includes extractions for the following models and packages except for the NeuroFET, which is a standalone product.

Curtice, Statz MESFET models

The package includes extraction routines for three popular industry-standard MESFET models: the Curtice quadratic, Curtice cubic, and Statz (Raytheon). The three models differ in the empirical relationships that describe the device's DC and AC characteristics. IC-CAP extracts the model parameters from a combination of DC and S-parameter measurements.

EEFET3/EEHEMT1 models

These are empirical, nonlinear models for general GaAs FET or HEMT applications, including large-signal, three-terminal IC, and packaged devices. They accurately model DC and bias-dependent S-parameters, time delay, sub-threshold current, and dispersion of R_{ds} . Also included is the drain current model based on Keysight EDA original equations and advanced models for C_{gs} and C_{gd} , including transcapacitance effects.

The EE models also consider static self-heating effects in the drain current. The modules provide highly automated parameter extraction techniques with package parasitics extracted automatically. HEMTs are similar to MESFETs but with one distinguishing difference in the behavior of G_m versus V_{gs} . EEHEMT1 is a superset of EEFET3 and has a set of analytic functions for modeling the G_m compression of a HEMT.

The W7012E IC-CAP FET Plus Extraction Package includes the Angelov-GaN Modeling Package. For details, see the GaN Modeling section.

Root MESFET/HEMT models

Root Models are process and technology-independent, data-based models for large-signal, three-terminal applications. They model the nonlinearities of GaAs FETs and HEMTs, including frequency dispersion, and are scalable. The models feature automated data acquisition and high-speed model generation.

Keysight NeuroFET model

While the Root model was a significant invention for its day, it had some limitations due to the table-based representation of device currents and charges. With the table-based model, non-optimal trade-offs had to be made when modeling all the multi-variate capacitances and conductance over the full bias range of device operation. The NeuroFET model is an evolution of the Root model, with the same topology but with tables replaced by Artificial Neural Networks (ANN). ANNs are a computational paradigm based on how the brain works - they can smoothly approximate any nonlinear function using a network of highly interconnected nonlinear processing functions called neurons. A sophisticated Machine Learning (ML)

training algorithm identifies the weights between nodes to optimally and smoothly approximate the model's nonlinear current and charge functions. Smooth derivatives are critical for accurately representing distortion behavior, particularly at low signal levels, where high-order derivatives must be continuous to achieve the best accuracy.

The NeuroFET model also adds a sophisticated extrapolation methodology beyond the boundaries of the measured data, resulting in robust DC and large-signal simulator convergence behavior. The resultant model is technology-independent and works well for both HEMT and FET devices in silicon and III-V materials. NeuroFET does not cover passive mixer or switching applications.

Advantages of the NeuroFET over table-based Root models:

- Improved DC and RF convergence
- Improved distortion simulation at low amplitude
- More accurate S-parameters vs. bias

The IC-CAP NeuroFET Extraction package controls the DC and S-parameter measurements necessary to extract the model. The software then performs ANN training through a specific error optimization procedure. The output model file can then be simulated via ADS within the IC-CAP environment or exported to ADS for use with the built-in NeuroFET circuit simulation component.

Artificial Neural Network (ANN) modeling

The Artificial Neural Network (ANN) solution within Device Modeling (IC-CAP) provides the capability to create nonlinear model building blocks (e.g., controlled current sources and controlled charge sources). These can be easily configured to produce accurate device models from data without a robust physically based or conventional empirical model. The ANN library provides rapid model generation to support the fastest possible device or circuit evaluations in any design phase and explore the circuit consequences of novel technologies where models are currently unavailable or simply not accurate enough.

The Keysight ANN library has unique capabilities compared to other ANN commercial solutions. The Keysight solution provides advanced fitting capabilities to train the ANN from either (x,y) and $(x, dy/dx)$ types of datasets, where x is the input, y is the output, and dy/dx is the (partial) derivative of the output. dy/dx can extract the charge models from capacitive information, which is essential for device modeling.

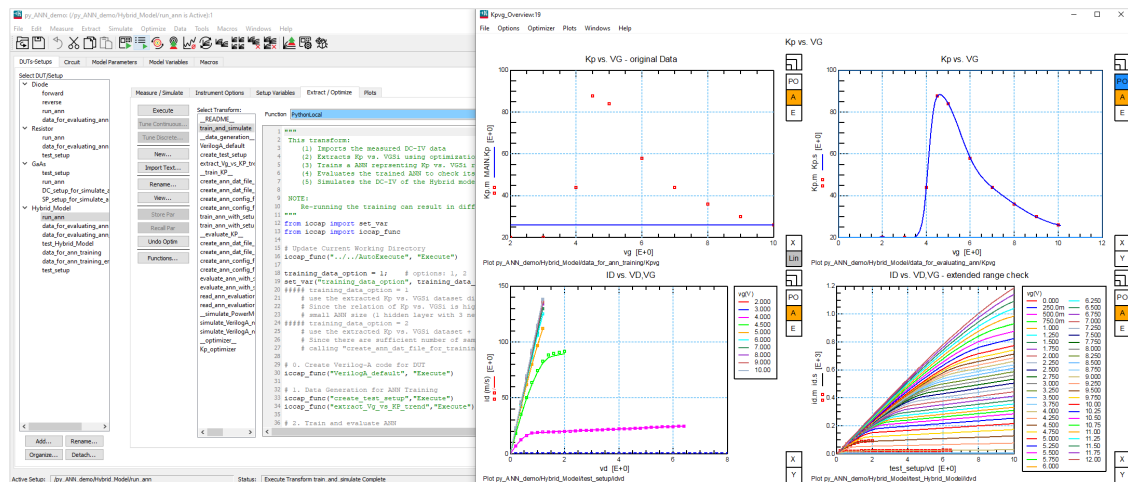


Figure 20. Artificial Neural Network (ANN) modeling toolkit

Third-party models

The unique, open, and flexible IC-CAP framework enables third parties to design and develop models and related extraction packages that work as add-ons in the IC-CAP environment. The IC-CAP GUI Studio enables third parties to design and implement custom extraction packages with specific user interfaces and related extraction routines.

BSIMSOI3v2 and EKV 2.6 Extraction Packages are available from AdMOS www.admos.de

Product Configuration

Bundles and elements

Device modeling IC-CAP includes six major components:

- Core Environment – Model generator, GUI, IC-CAP GUI Studio, examples, Python/PEL programming environment, and graphics
- Simulation and analysis – Simulation, optimization, tuning, and DataPro
- Instrument connectivity – Instrument drivers
- Wafer Professional (WaferPro) – Automated Wafer-level measurements
- ANN library
- Add-on licensed extraction packages for various technologies (e.g., MOSFET, BJT, HEMT)

Table 1 lists the available bundles, and below is a description of the most popular bundles and core elements. Table 2 shows the core elements that can be used as an alternative to bundles. In addition, extraction packages and examples are also available as add-ons, as listed in Table 3.

Table 1. IC-CAP bundles

Model	Name	Description
W7300B	IC-CAP Device Modeling Platform	It contains all the tools to characterize and model semiconductor devices, including the software environment, all measurement drivers, optimization, Python/PEL programming, the Model Generator, and all simulation links with a 20-pack ADS simulator license. The legacy W8503EP DataPro is also included in this bundle.
W7301B	IC-CAP Model Generator Plus	It includes the W7300B and the W7008E Model Generator Advanced Tools, which enables tuning and optimization techniques to efficiently adjust important parameters to adapt the model to the new targets. It also includes the Model Generator QA and an additional 10-pack of ADS simulation licenses.
W7311B	IC-CAP Wafer Professional Measurement	It enables automated wafer-level measurement with turnkey measurement drivers and Python/PEL programming to customize measurement algorithms and data processing. This bundle does not include simulation.
W7325B	IC-CAP CMC GaN RF Modeling	The CMC GaN bundle includes the W7300B and the GaN RF modeling extraction examples for the ASM-HEMT and the MVSG models.
W6325B	MBP/IC-CAP Device Model Extraction	This cross-platform bundle includes the W7001E and W7010E IC-CAP Core Environment and Analysis elements and the W6300B MBP core bundle.
W6347B	MQA/IC-CAP Modeling Bundle	This cross-platform bundle Includes the W7001E and W7010E IC-CAP Core Environment and Analysis elements and the W6800B MQA core bundle.

W7300B IC-CAP device modeling platform bundle

The Device Modeling Platform Bundle lets users set up custom extraction routines, measure data using instrument drivers, analyze results, perform simulations, and optimize extracted parameters to create and run any custom model extraction or unlicensed extraction examples. It provides the essential tools to start measuring and modeling devices and circuits. It consists of the following components:

- W7001E IC-CAP Core environment
- W7010E IC-CAP Simulation, Analysis, and DataPro
- W7015E IC-CAP Instrument Connectivity

Numerous modeling examples and tutorials are available at no extra cost as starting points for building and designing your extraction toolkits.

W7301B IC-CAP Model Generator Plus Bundle

W7301B includes the Device Modeling Platform bundle and the W7008E Model Generator Advanced Tools. It includes the MG Recentering tools, which enable tuning and optimization techniques to efficiently adjust important parameters to adapt the model to the new targets. This bundle also includes the Model Generator QA and provides an additional 10 packs of ADS licenses, bringing the total number of available licenses to 30.

W7311B IC-CAP WaferPro bundle

The W7311B allows you to run automated wafer-level DC, CV, and RF measurements using the WaferPro test executive. It includes the following components:

- W7001E IC-CAP Core environment
- W7015E IC-CAP Instrument Connectivity – See Table 4 for supported instrument drivers
- W7014E IC-CAP Wafer Professional (WaferPro)

IC-CAP WaferPro works within and in conjunction with the IC-CAP platform and lets users create and execute automated test plans. Note that this bundle does not include the W7010E Simulation and Analysis needed to run the simulation mode's test plan.

W7325B IC-CAP CMC GaN modeling bundle

The W7325B provides all the necessary capabilities to characterize and extract GaN devices using the CMC ASM-HEMT and MVSG GaN models. Like the W7300B, it includes the IC-CAP environment, instrument connectivity, and analysis. It also includes the W7027E element, which enables the ASM-HEMT and MVSG examples.

The MVSG and ASM-HEMT examples give you a head start in learning the basic capabilities of the models, i.e., learning the core parameters and how to extract them. As we gain more experience and

insights into these new models, our examples are updated to cover more advanced effects like thermal and trapping.

W7001E IC-CAP core environment

The W7001E is the necessary foundation element in all bundles. In addition to the UI framework, it provides the Python and PEL programming environments. These environments allow you to process data with mathematical transforms, display and customize plots, write Python and PEL macros, create and automate extraction routines, and write user-defined functions using the C programming language. Python and PEL include extensive math, utilities, and modeling function libraries. Also included is IC-CAP GUI Studio, which allows you to develop custom graphical user interfaces.

W7010E IC-CAP simulation, analysis, and DataPro

The analysis module, the IC-CAP simulator engine, allows users to simulate device or circuit performance using the default ADS simulator, the custom SPICE3 simulator, and by linking to a wide range of other external simulators (third-party licenses may be required). The W7010E includes linear (DC, CV, and AC), nonlinear (Harmonic Balance), and transient simulation with ADS.

IC-CAP DataPro applies statistical analysis to selected measured data and identifies golden and corner die based on statistical distribution and variances. DataPro can import data directly from WaferPro or a simple IC-CAP project format. The statistical analysis applies to either sweep or spot types of measurements.

Table 2. Device modeling IC-CAP core elements and extraction packages

Model	Name	Description
W7001E	IC-CAP Core Environment	Core, GUI, data display, PEL/Python programming, and Model Generator
W7008E	IC-CAP Model Generator Advanced Tools	Adds the Model Generator Recentering and Targets tool with tuning and optimization techniques to efficiently adjust important parameters to adapt the model to the new targets. It also includes the new Model Generator QA.
W7009E	IC-CAP ANN Modeling Toolkit	Adds ANN solution to substitute the standard compact model with ANN technology to improve the model's accuracy
W7010E	IC-CAP Simulation and Analysis	Adds Optimization/tuning, simulation with ADS (20-pack simulations), and all other supported simulators. Note that most commercial simulators require a license.
W7014E	IC-CAP Wafer Professional (WaferPro) Add-on	Adds IC-CAP WaferPro for automated wafer-level measurement. Requires W7015 Instrument Connectivity
W7015E	IC-CAP Instrument Connectivity	Enables all supported instrument drivers

Table 3. Device modeling IC-CAP extraction packages

Device technology	Product number	Product name	Description
GaN, HEMT, MESFET	W7012E	IC-CAP FET Plus Extraction Package	EEHEMT, EEFET, Curtice, Root FET/Diode/MOS, and Angelov-GaN
	W7013E	IC-CAP GaN Model Extraction Package Plus	ASM-HEMT, MVSG, and Angelov-GaN models.
	W7019E	IC-CAP NeuroFET Extraction Package	Keysight ANN-based model, NeuroFET for GaAs devices
	W7020E	IC-CAP DynaFET Model Generation	Keysight ANN-based model, DynaFET for GaN RF devices
	W7027E	IC-CAP CMC GaN RF Modeling Add-on	GaN RF modeling extraction examples for the ASM-HEMT and the MVSG models.
BJT	W7011E	IC-CAP BJT Plus Extraction Package Plus	Keysight HBT, VBIC, Gummel-Poon, and Mextram models
MOSFET	W7021E	IC-CAP PSP Model Extraction Package	PSP Model Extraction Package, Target, and Corner modeling
	W7022E	IC-CAP HiSIM Model Extraction Package	HiSIM Model Extraction Package, Target, and Corner modeling
	W7023E	IC-CAP BSIMSOI Model Extraction Package	BSIMSOI Model Extraction Package, Target, and Corner modeling
	W7024E	IC-CAP BSIM3 Model Extraction Package	BSIM3 Model Extraction Package, Target, and Corner modeling
	W7025E	IC-CAP BSIM4 Model Extraction Package	BSIM4 Model Extraction Package, Target, and Corner modeling
	W7026E	IC-CAP HiSIM_HV Model Extraction Package	HiSIM_HV Model Extraction Package, Target, and Corner modeling
Power Electronics Models	W7016E	IC-CAP Power Electronics PowerMOS SiC Extraction Package	Keysight PowerMOS SiC model for SiC and Si power devices for power electronics applications
	W7017E	IC-CAP Power Electronics IGBT Extraction Package	Keysight IGBT model for power electronics applications
	W7018E	IC-CAP Power Electronics GaN Extraction Package	ASM-HEMT model for power electronics applications

Supported instruments, probers, and switch matrices

Table 4. Supported instrument drivers in W7015E IC-CAP Instrument Connectivity

Instrument connectivity	Supported instruments
DC measurement drivers	<p>Keysight B1500A Semiconductor Device Analyzer</p> <p>Keysight B1505A Power Device Analyzer/Curve Tracer</p> <p>Keysight E5270 Series parameter analyzer: E5270B, E5272A, and E5273A</p> <p>Keysight E5260 Modular Source/Measure Units</p> <p>Keysight B2900 Series Precision Source/Measure Unit</p> <p>Keysight M9601A PXIe Precision Source/Measure Unit</p> <p>Keysight PZ2100A High-Density Precision SMU Mainframe</p> <p>Keysight N6705 DC Power Analyzer</p> <p>Keysight 4156x Semiconductor Parameter Analyzer¹</p> <p>Keysight 4140 pA Meter/DC voltage source¹</p> <p>Keysight 4141 DC source/monitor¹</p> <p>Keysight 4142x Modular DC source/monitor¹</p> <p>Keysight 4145x Semiconductor Parameter Analyzer¹</p> <p>Keysight 4155x Semiconductor Parameter Analyzer¹</p> <p>Keysight 4071A Parametric Semiconductor Tester</p> <p>Keithley instrument drivers for the 2410, 26xx Class Sourcemeters, and 4200-SCS are provided as open-source and are not covered by standard maintenance.</p> <p>¹ Discontinued or obsolete product - Keysight provides limited or no maintenance effort.</p>
AC measurement drivers	<p>Keysight PNA-X Series (S-parameters, multi-port, gain compression, and intermodulation)</p> <p>Keysight PNA Series (S-parameters, multi-port)</p> <p>Keysight ENA, E5080B, E5081A ENA-X, Streamline Series (S-parameters, multi-port)</p> <p>Keysight 3577 Network Analyzer¹</p> <p>Keysight 8510 A/B/C/XF Network Analyzer¹</p> <p>Keysight 8702 Network Analyzer¹</p> <p>Keysight 87xx Network Analyzer¹</p> <p>Keysight 89410 Vector Signal Analyzer</p> <p>Anritsu 37000 Network Analyzer¹</p> <p>Anritsu VectorStar Network Analyzer²</p> <p>Rohde & Schwarz ZNA Series Vector Network Analyzers</p> <p>Please see the product documentation for an updated list of supported and discontinued Keysight PNA-X, PNA, and ENA network analyzers.</p> <p>¹ Discontinued or obsolete product - Keysight provides limited or no maintenance effort.</p> <p>² Provided by Anritsu. Contact Anritsu for questions/support about this driver.</p>
LCRZ measurement drivers	<p>Keysight E4991A1, E4991B RF Impedance/Material Analyzer</p> <p>Keysight E4990A Impedance Analyzer</p> <p>Keysight E4980A Precision LCR meter</p> <p>Keysight 4194 Impedance Analyzer¹</p> <p>Keysight 4271 1 MHz digital capacitance meter¹</p> <p>Keysight 4275 Multi-frequency LCR Meter¹</p> <p>Keysight 4280 2 MHz Capacitance Meter¹</p> <p>Keysight 4284 Precision LCR Meter¹</p> <p>Keysight 4285 Precision LCR Meter¹</p> <p>Keysight 4294A Precision Impedance Analyzer¹</p> <p>¹Discontinued or obsolete product - Keysight provides limited or no maintenance effort.</p>
Time-domain measurement drivers	<p>Keysight 54120T-54124T Digitizing Oscilloscopes¹</p> <p>Keysight 54510 Digitizing Oscilloscopes¹Keysight 54750 TDR Oscilloscope¹</p> <p>Keysight 8130 Pulse Generator¹</p> <p>Keysight 8131 Pulse Generator¹</p> <p>Keysight 54720 Module Real_Time Oscilloscope¹</p> <p>Keysight Infinium Oscilloscope 54800 Series¹</p> <p>Keysight 85124 Pulse System¹</p> <p>¹Discontinued or obsolete product - Keysight provides limited or no maintenance effort.</p>
Noise measurement drivers	<p>Keysight 35670A Dynamic Signal Analyzer¹</p> <p>¹Discontinued or obsolete product - Keysight provides limited or no maintenance effort.</p>

Table 5. Supported Wafer Probers, Switch Matrixes, and Thermal Controllers

Wafer probers	Switch matrixes	Thermal controllers
FormFactor Velox & VeloxPro FormFactor Nucleus ¹ 3 & 4 FormFactor PS21 ¹ FormFactor Summit ¹ 12K MPI ² Sentio Suss PA300 ¹ Accretech UF3000 ¹ Tokyo Electron (TEL) P8, P12 EG6000 Micromanipulator ² P300L	Keysight B2200A Keithley 707/708 Keysight HP4070 ¹ Keysight HP4080 ¹	FormFactor Velox & VeloxPro Tokyo Electron (TEL) Accretech Cascade ¹ Summit Cascade ¹ PS21 Temptronic ¹ TP032A
¹ Discontinued or obsoleted product - Keysight provides limited or no maintenance effort. ² Contact manufacturer for support.		

Supported simulators

Table 6. Supported simulators

Simulator	Company	Licenses required
ADS (hpeesofsim, spmodeads, hspicemodeads)	Keysight	The W7010E Analysis and Simulation Element includes linear, transient, and Verilog-A simulations with ADS.
HSPICE	Synopsys	License required
SABER	Synopsys	License required
MMSIM (SPECTRE)	Cadence	License required
AFS	Mentor Graphics	License required
ELDO	Mentor Graphics	License required
SmartSpice	Silvaco	License required
Spice3, PSPICE, HSPICE	Various	Included in the W7010E, however, these simulators are no longer actively supported (legacy simulators)

Please refer to the documentation for a detailed description of the analysis supported by each simulator.

License and Subscription Types

Each IC-CAP module is available in two license versions:

1. A node-locked version allowing the software to execute only on a single PC
2. A network-licensed version for execution on multiple workstations or PCs on a network, allowing various workgroups to share the software. Four types of floating licenses are available: N - Single site: 1-mile radius from the server; Q – Telecommuter: A time-zone in Americas, a country in Europe/Asia; R - Single region¹: Americas, Europe, Asia, and W - Worldwide (export restriction identified in End User License Agreement (EULA))

Table 7. KeysightCare software support subscription

Subscription	Description
KeysightCare support subscription	Perpetual ² licenses are sold with a 12 (default), 24, 36, or 60-month software support subscription. Support subscriptions can be renewed for a fee after that.
	Subscription licenses already include a software support subscription throughout the license term.

1. Americas (North, Central, and South America, Canada); Europe (European Continent, Middle Eastern Europe, Africa, India); Asia (North and South Asia Pacific Countries, China, Taiwan, Japan).

2. The purchase of EDA perpetual licenses is no longer available. For more information, refer to <https://www.keysight.com/find/eda-perpetual-license-letter>

World Wide Web

For the latest news in Device Modeling, visit [What's New in Device Modeling Webpage](#)

Our Keysight EDA World Wide Web includes a dedicated Support Web area for downloadable patches, defects and solutions, and online technical support. In addition, Keysight EDA gives you access to other services, including:

- News and events
- Product information and online demos
- Product applications and examples
- Online product documentation
- Customer training classes
- Online and telephone technical support

World-Class Service, Support, and Training

Keysight EDA is committed to helping you achieve success with IC-CAP through customer education courses, technical support, and custom solution services.

To help you ramp up with IC-CAP quickly and productively, Keysight offers a comprehensive three-day training course at various locations, including the Keysight EDA facility in Santa Rosa, California, USA.

A support contract includes automatic software updates, literature, and documentation for the latest product enhancements and features.

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