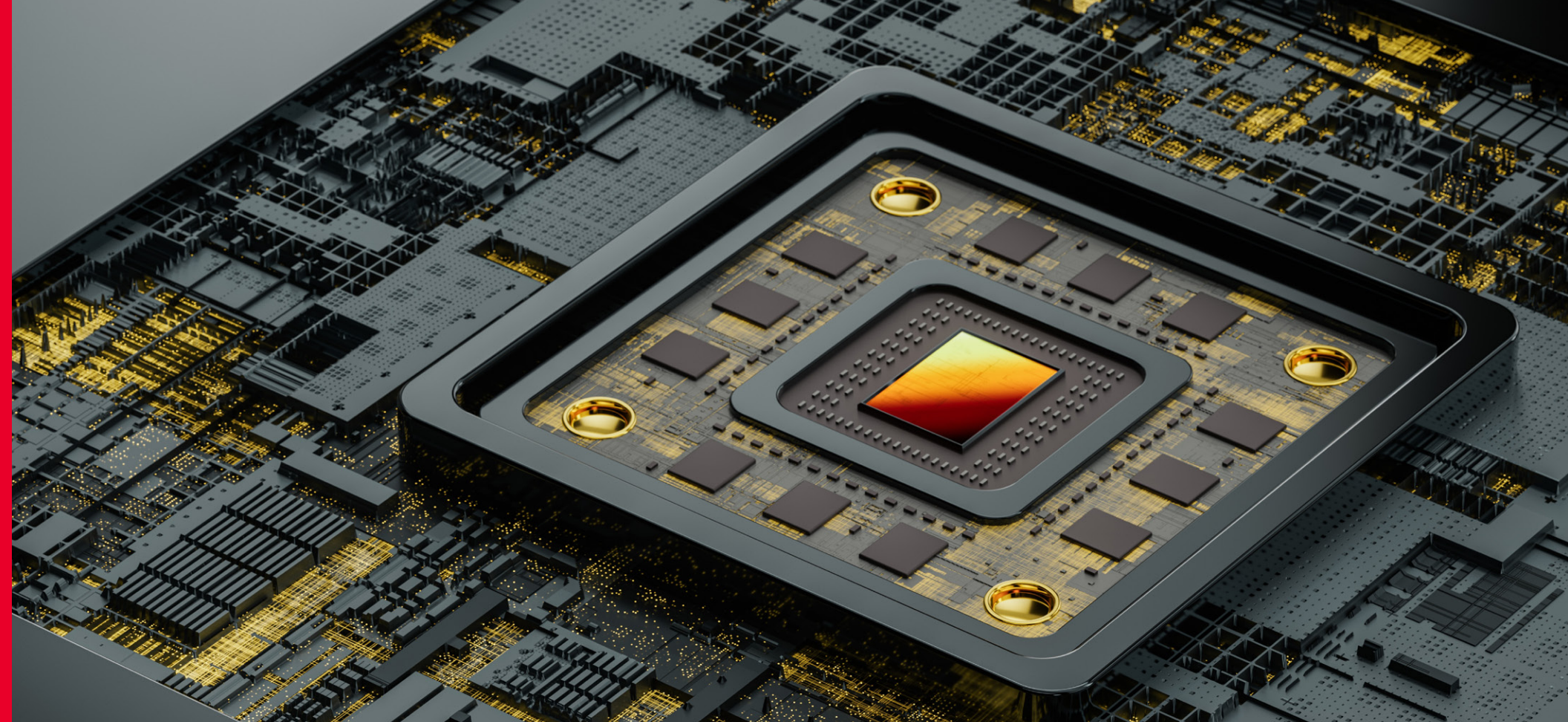




The Essential Guide to GaN Semiconductor Device Modeling

eBook

 KEYSIGHT

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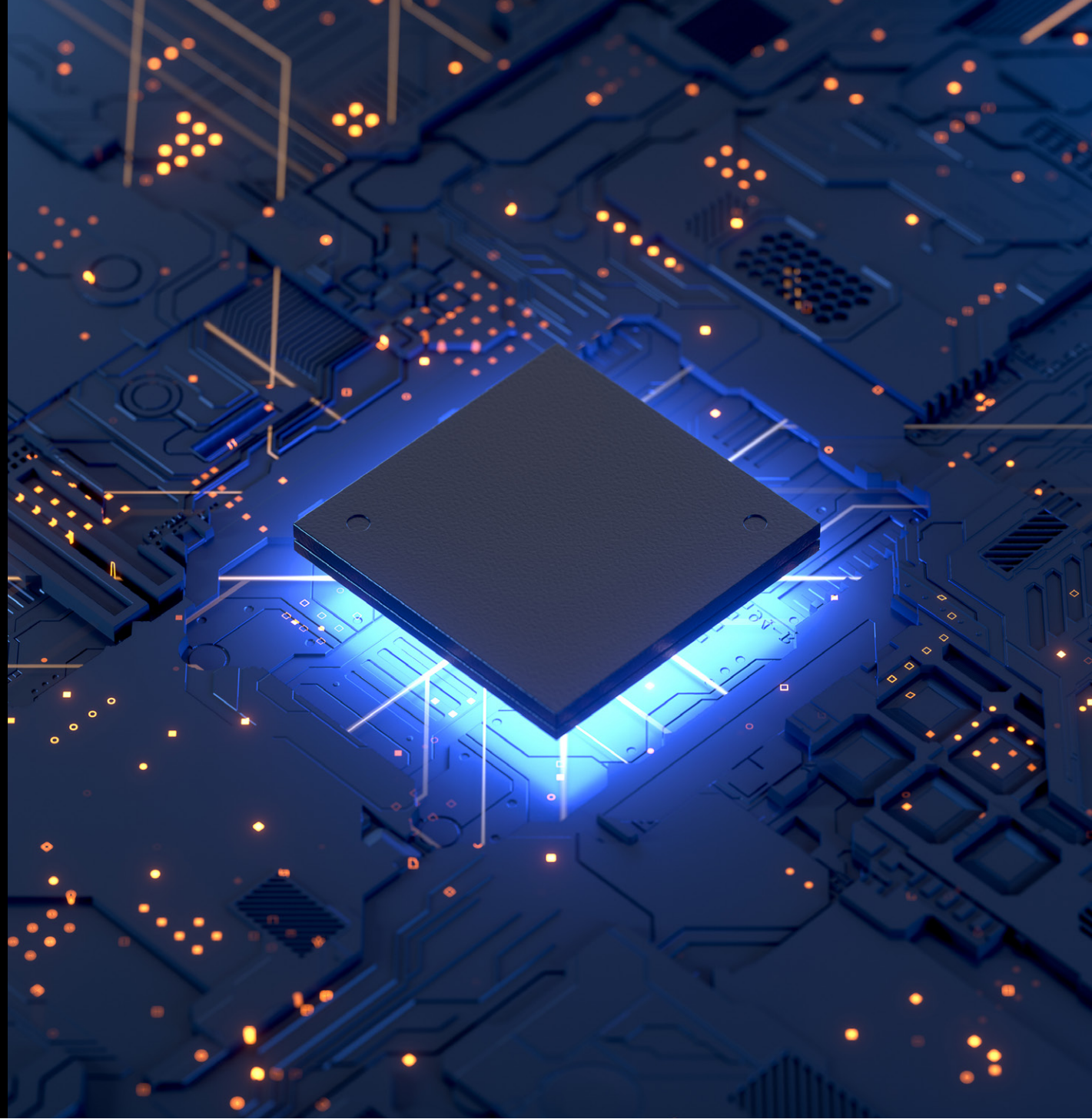
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Conclusion

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CHAPTER 1

Powering the Future of Semiconductors



Powering the Future of Semiconductors

Silicon has long been synonymous with the semiconductor world. As silicon approaches its theoretical limits, research into alternative materials has catalyzed the quest for more compact and energy-efficient devices. With a **\$21 billion market** in 2023, gallium nitride (GaN) is heralding a new age for semiconductor innovations.

GaN has made significant headway across diverse applications in the past few years, phasing out silicon metal-oxide-semiconductor field-effect transistors (MOSFETs).

The three areas experiencing the fastest growth are:

Consumer electronics: GaN makes it possible to charge a smartphone in minutes or reduce power losses in power converters by up to 90% due to its excellent performance at high temperatures and voltages. According to the Yole Développement group, the consumer sector of the GaN device market will surge to over **\$916 million at a 52% compound annual growth rate (CAGR) by 2027**.

Telecommunications: GaN is the driving force behind more reliable and powerful networks. While traditional silicon-based solutions like a laterally diffused metal-oxide-semiconductor (LDMOS) remain effective at lower frequencies, the industry's shift to millimeter-wave frequencies demands GaN amplifiers that can cover up to 100 GHz. As a result, the telecom segment growth could reach over **\$6 million by 2027**.

Automotive: As electrification gains momentum in the automotive industry, GaN is taking the lead. Its ability to reduce conduction and switching losses leads to more efficient energy usage and battery charging. With original equipment manufacturers (OEMs) following suit, the GaN-based automotive electronics device market could reach **\$300 million within four years** at a 97% compound annual growth rate (CAGR), as illustrated in Figure 2.

The rise of GaN is not just about swapping materials — it represents a paradigm shift in modeling, design, simulation, and validation starting from the device level.

To truly harness GaN’s potential, robust modeling strategies are a crucial first step. Explore the challenges in GaN modeling, delve into the latest GaN models, and discover how Keysight EDA device modeling (IC-CAP) software simplifies GaN modeling through a real-world case study in this eBook.



Figure 1. Keysight EDA device modeling (IC-CAP) software

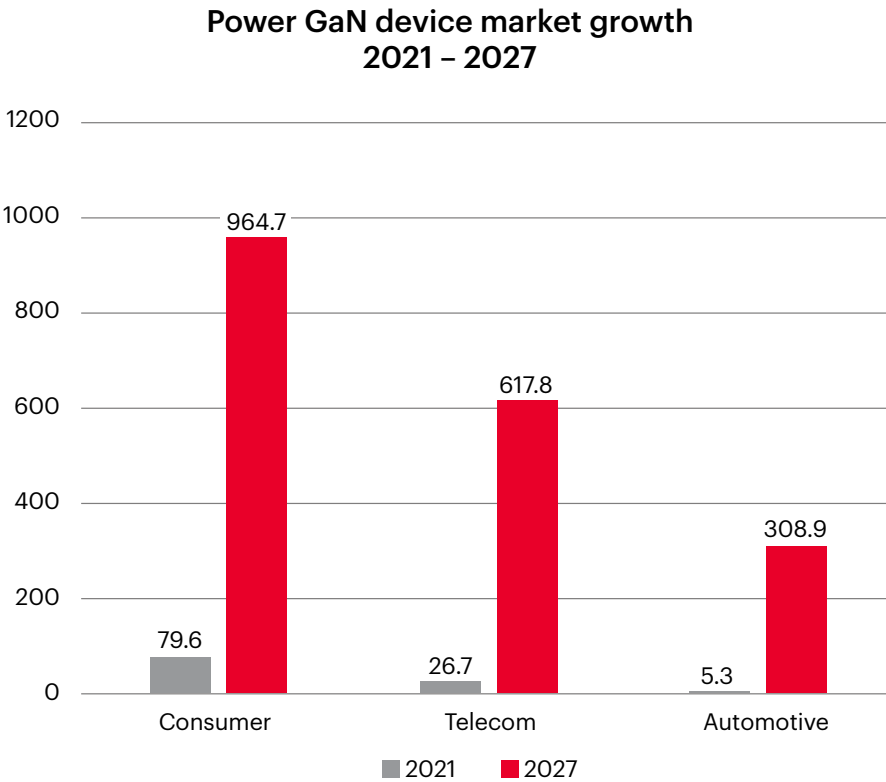
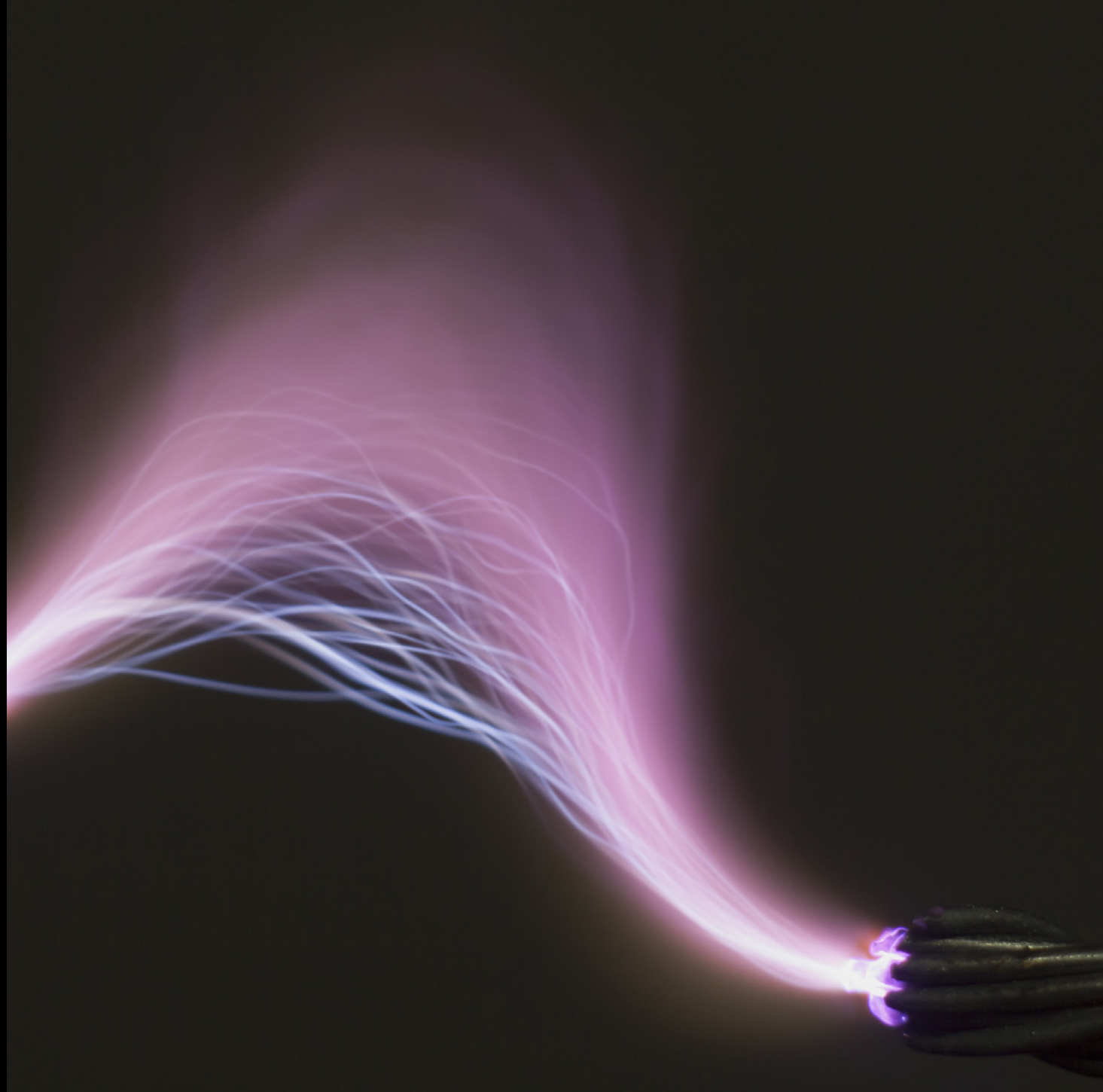


Figure 2. The power GaN device predicted market growth from 2021 to 2027

CHAPTER 2

GaN Benefits in RF and Power Applications



GaN Benefits in RF and Power Applications

Before exploring modeling solutions, it is essential to understand what distinguishes GaN from traditional materials.

Table 1 shows how GaN’s inherent properties profoundly influence the device’s performance in high-frequency and high-power applications. It provides a powerful combination of on-resistance, maximum operating voltage, broadband capacity, and thermal performance.

Table 1. GaN material properties

Properties (at 300 K)	Units	Si	4H-SiC	GaN
Bandgap E_g	eV	1.12	3.26	3.425
Breakdown electric field E_c	MV / cm	0.3	3	3.3
Intrinsic carrier concentration n_i	cm^{-3}	9.6×10^9	8.2×10^{-9}	1.9×10^{-10}
Electron mobility μ_n	$\text{cm}^2 / \text{V} \cdot \text{s}$	1500 (bulk)	1000	1250 (bulk) 2000 (2DEG)
Saturation velocity v_{sat}	$\times 10^7 \text{ cm/s}$	1	2	2.2
Relative permittivity ϵ_r	–	11.8	10	9
Thermal conductivity λ	$\text{W} \cdot \text{K} / \text{cm}$	1.5	4.9	1.3
Maximum working temperature T_{max}	$^{\circ}\text{C}$	150	760	800

Wide bandgap

The bandgap represents the energy barrier that electrons must overcome to move freely. The wider the bandgap, the more energy it takes to move electrons from the valence band to the conduction band. The material’s bandgap shrinks as temperatures rise.

GaN’s performance, with a bandgap three times wider than silicon (Si), is much less vulnerable to temperature increase, enabling it to function in much higher temperatures, often up to 800°C.

High breakdown electric field

A high breakdown electric field is a direct derivative of a wide bandgap, which pulls valence electrons from the atoms when reaching the threshold. This phenomenon can trigger a chain reaction known as voltage breakdown, ultimately destroying the device.

GaN has a breakdown electric field of 3.3, over ten times higher than Si’s 0.3. As a result, GaN is better at managing higher voltages prevalent in power amplification and switching power supply applications.

High electron mobility

Electron mobility indicates how quickly electrons can move in response to a low electric field. A high electron mobility means low on-resistance and knee voltage, which minimizes power losses during switching.

GaN has an electron mobility of 2,000 cm² / V · s, enabling switching frequencies up to ten times higher than silicon and enhancing the performance of switching power applications.

Thermal conductivity

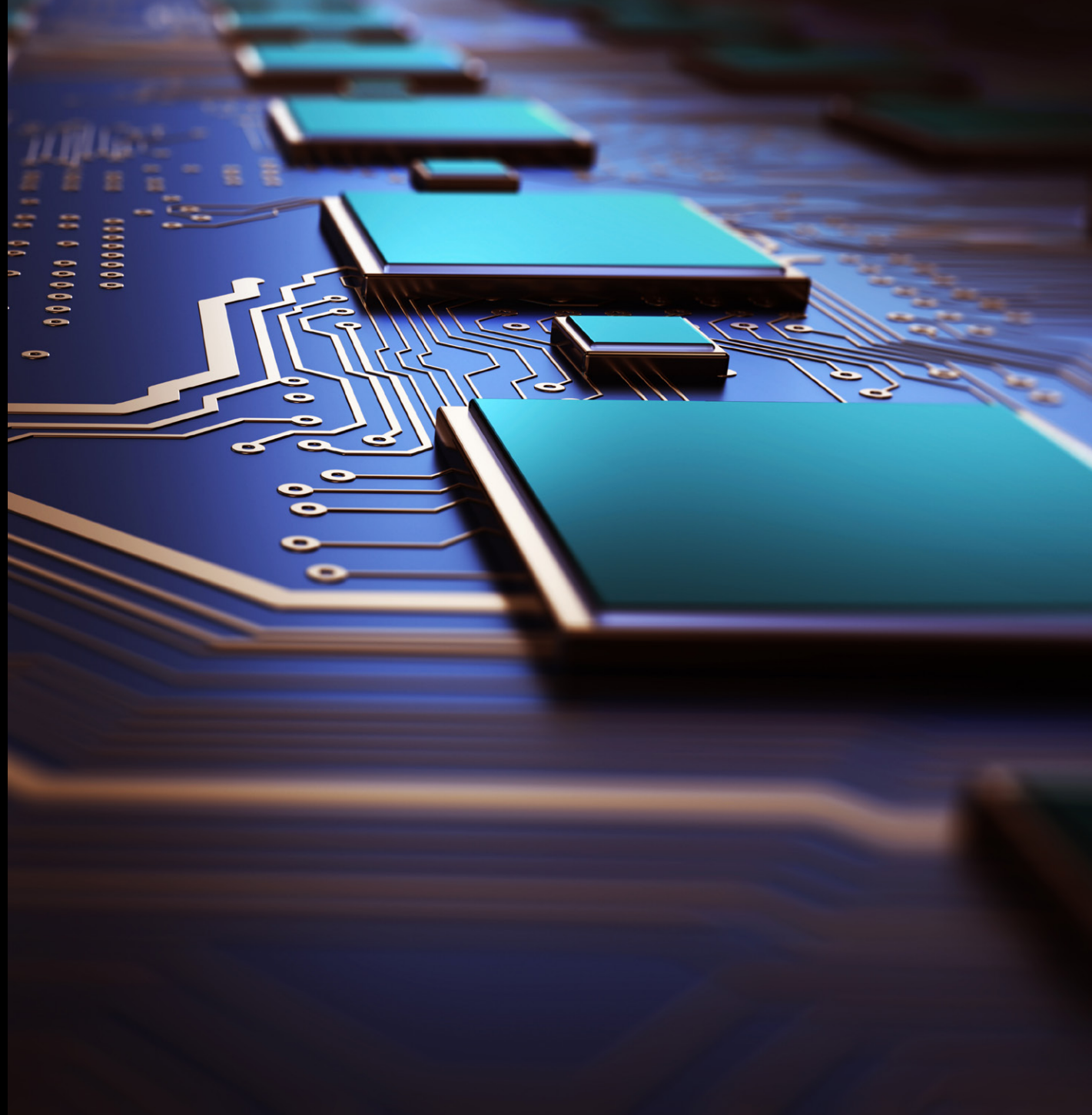
Thermal conductivity measures the material’s ability to conduct heat. The higher the thermal conductivity is, the faster the material dissipates heat.

When combined with SiC substrates, GaN-on-SiC devices can perform at much higher temperatures, resulting in system designs that require fewer cooling materials despite GaN not excelling in thermal conductivity.

Because of the flexible nature of gallium, GaN devices can be much smaller without compromising thermal conductivity. GaN is suitable for a diverse range of applications, spanning from 5G millimeter-wave applications to power electronics in automotive, aerospace, and IoT devices.

CHAPTER 3

Development of GaN devices



Development of GaN devices

Researchers have conducted numerous studies on maturing the epitaxial growth and processing technologies since the debut of the AlGaN / GaN high-electron-mobility transistor (HEMT) in 1993.

The RF industry saw its **first GaN device in 2005**, and the high manufacturing costs restricted its use primarily to the military. The landscape changed four years later when the Efficient Power Conversion Corporation released the first commercial enhancement-mode GaN transistor on silicon wafers as power silicon metal-oxide-semiconductor field-effect transistor (MOSFET) alternatives. These transistors set the stage for more cost-effective production in high volumes.

Today, GaN HEMT has become one of the most power-efficient solid-state RF sources, spanning the 1 GHz to 100 GHz range of the electromagnetic spectrum. Companies such as STMicroelectronics, Infineon, and Navitas have integrated GaN HEMT power components into various markets, such as radar, direct broadcast receivers, automotive, and telecommunications.

How GaN devices work

Like a conventional transistor, GaN HEMT includes three key components: source, drain, and gate. By using metal-organic chemical vapor deposition (MOCVD), manufacturers grow material layers on the silicon or silicon carbide (SiC) substrates. Figure 3 illustrates a typical structure of an RF / microwave GaN HEMT. In this design, the active region, wherein the current flows, is located between the source and drain at the AlGaN layer.

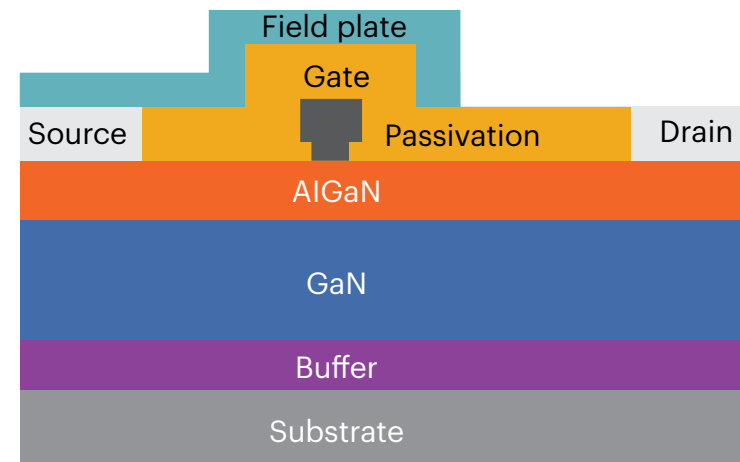


Figure 3. Typical structure of RF / microwave AlGaN / GaN HEMT

Due to bonding asymmetries in the wurtzite crystal structure, the AlGaN and GaN layers possess built-in voltages and electric fields. Consequently, electric field difference ($e\Phi_B$) spontaneously occurs at the AlGaN / GaN interface. Moreover, the strain between AlGaN and GaN arises from the slight difference in their lattice constants. This process triggers the piezoelectric effect, making the electric field difference ($e\Phi_B$) even more significant. When the energy band (E_C) dips below the Fermi level (E_F), electrons become confined to a triangular quantum well, as shown in Figure 4.

In this quantum well, electrons congregate into a dense sheet known as the two-dimensional electron gas (2DEG). The 2DEG is the critical enabler of current flow by offering a channel with high electron mobility ($>1500 \text{ cm}^2 / \text{V} \cdot \text{s}$). A noteworthy distinction is that GaN HEMTs can naturally form the 2DEG. Yet for non-GaN HEMTs, extra doping processes are necessary to cause adequate electric field difference at the interface.

As a result, the combination of GaN's wide bandgap, high electric breakdown field, and high electron velocity, with the introduction of 2DEG at the AlGaN / GaN interface, enables GaN HEMTs with exceptional power performance.

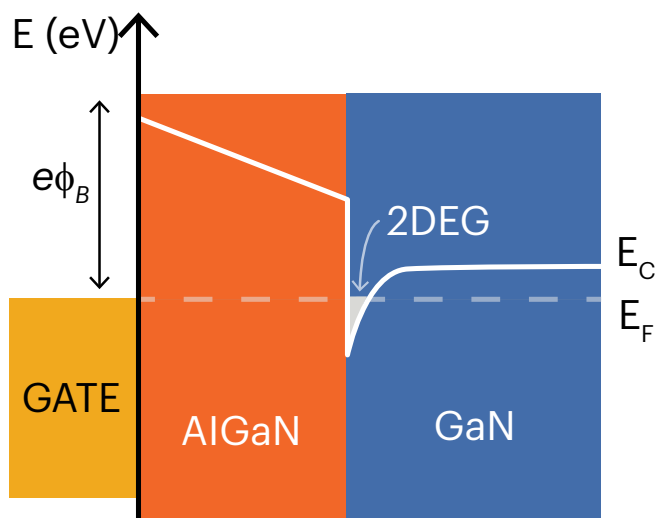
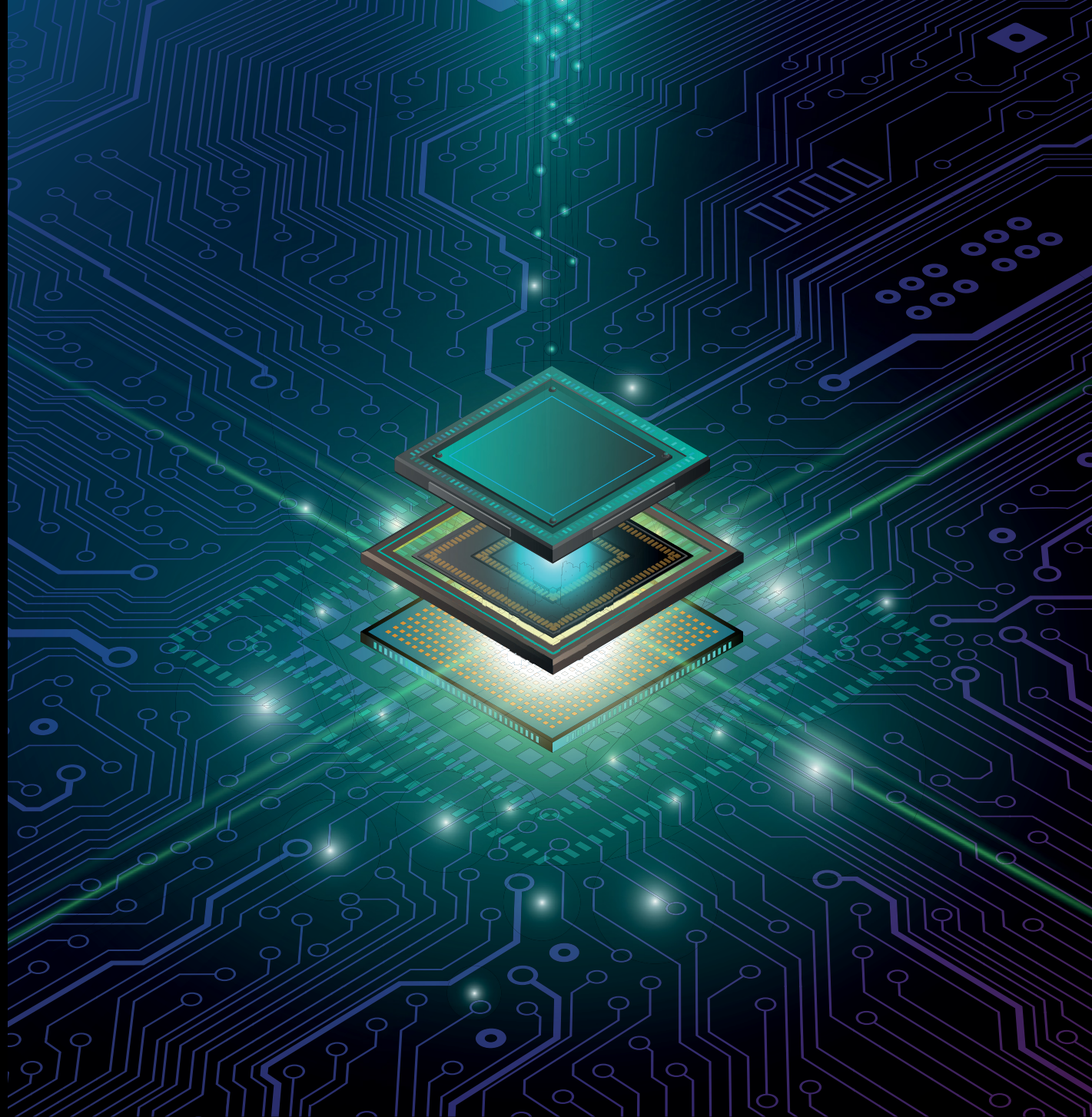


Figure 4. Formation of 2DEG (two-dimensional electron gas)

CHAPTER 4

GaN Device Modeling Challenges



GaN Device Modeling Challenges

With rising demand for GaN devices comes greater pressure to improve circuit model robustness. Despite its promising properties, GaN presents a myriad of complexities in device modeling and characterization.

GaN devices inherently experience low-frequency dispersive phenomena due to self-heating and charge trapping. These effects involve a complex nonlinear relationship with voltages applied to the device ports and greatly affect the performance of RF power amplifiers and switch applications.

Trapping effects

For GaN HEMTs, charges moving in and out of the traps on the surface and in the device heterostructure affect the density of the 2DEG. This leads to various trapping effects that can limit device performance even at relatively low frequencies. The following are two examples when this situation can occur:

Current collapse

Instead of an anticipated uptick in the average output current, as illustrated in the dashed red line in Figure 5, the DC IV curves slump (the green line), leading to current collapse. This current collapse occurs due to the trapping and de-trapping of charge carriers at the device heterostructure.

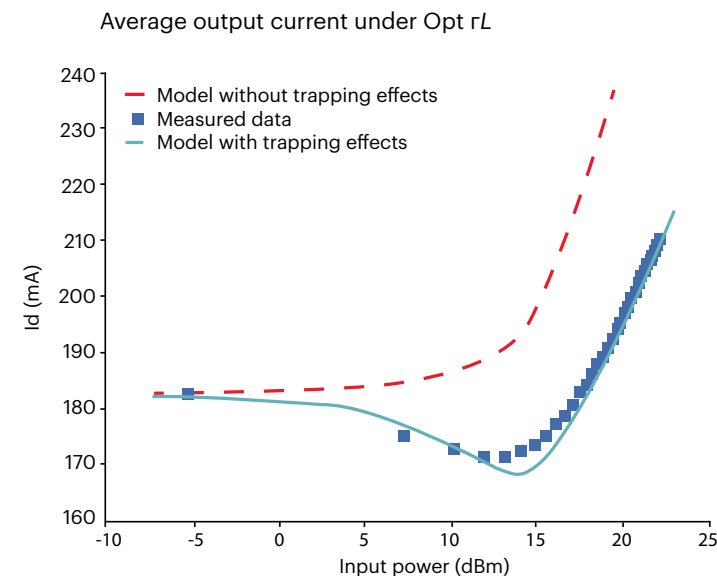


Figure 5. Example of current collapse

Knee walkout

As shown in Figure 6, an input pulse is applied with $V_{\text{gate}} = -0.2 \text{ V}$ and $V_{\text{drain}} = 4 \text{ V}$, which results in an I-V curve of the device's response from that specific quiescent point. Then, the device's response shifts significantly when the input changes to $V_{\text{gate}} = -0.8 \text{ V}$ and $V_{\text{drain}} = 6 \text{ V}$. This shift is known as the “knee walkout” phenomenon, caused by the trapping of charge carriers in the buffer layer. Capturing all these curve behaviors presents a complex challenge.

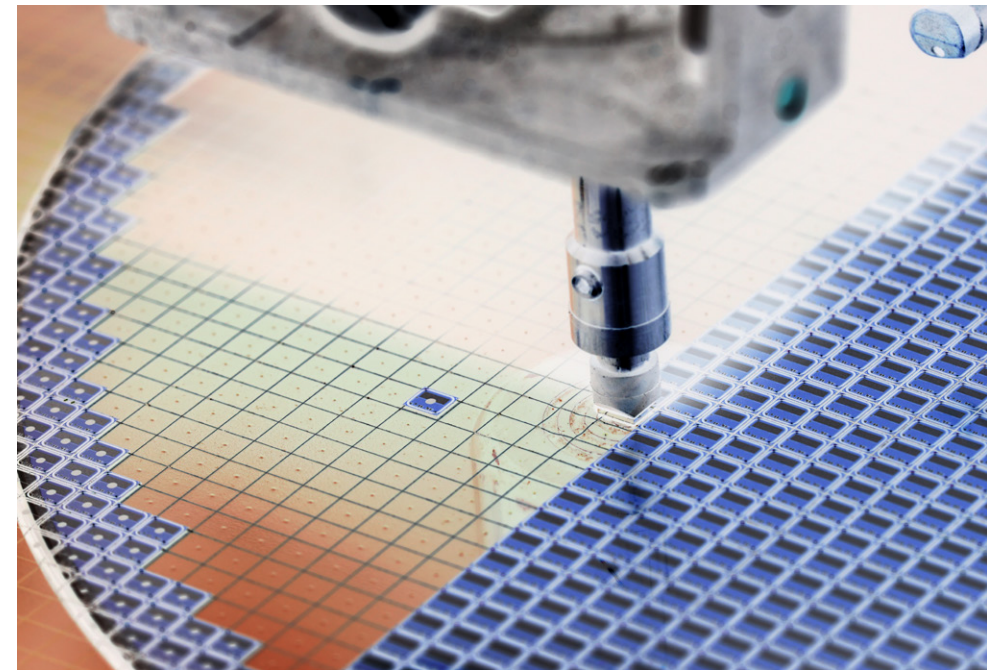
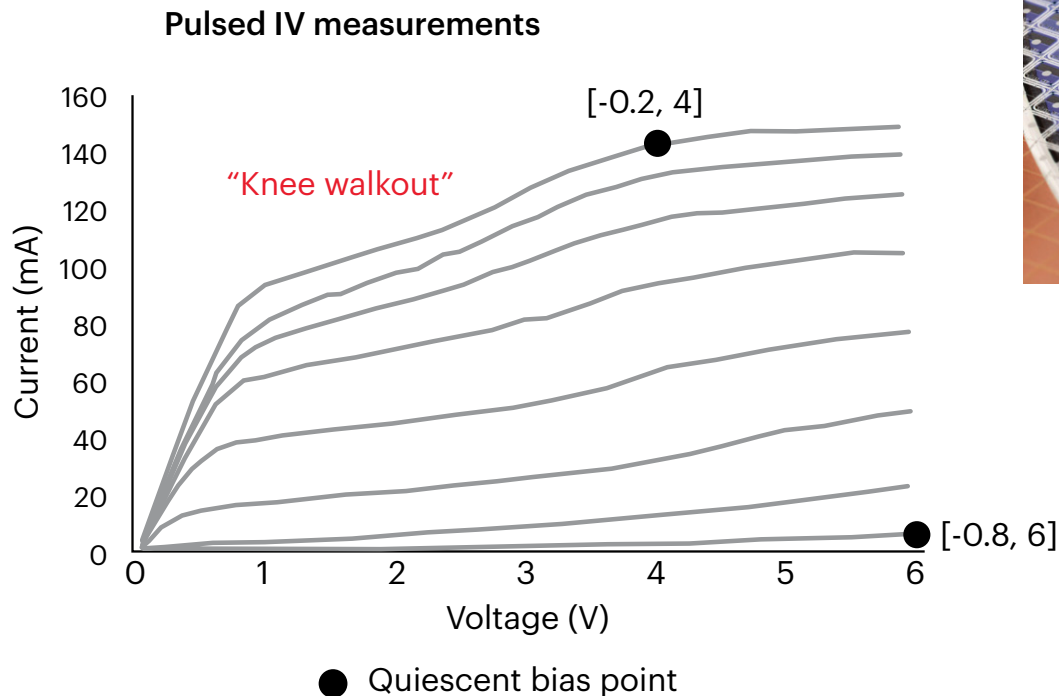


Figure 6. Example of knee walkout

These complex issues make the development of a high-quality compact model for GaN HEMTs a challenging task. Understanding the origin of the traps in GaN-based transistors, their location, and their physical mechanisms is essential for modeling them.

Self-heating effects

High power density is a hallmark of GaN HEMTs, but it also means that these devices are particularly susceptible to self-heating effects that can compromise performance as temperatures increase.

Characterizing the thermal behaviors of GaN HEMTs is a pressing issue for device modeling engineers with three key challenges.

Structural complexity

Thermal boundary resistance (TBR) is crucial in thermal management, especially for high-power and high-temperature applications. GaN HEMTs frequently involve several material interfaces, such as GaN-to-substrate, GaN-to-metal, and other interfaces. The TBR at these boundaries can significantly impact the device’s thermal performance. Thus, accurately modeling the TBR and determining its value is important and challenging.

Thermal dynamics

GaN HEMTs operate under pulsed or modulated conditions, especially in RF applications. The time-dependent dynamics of self-heating, where the device temperature varies with time, is challenging to model.

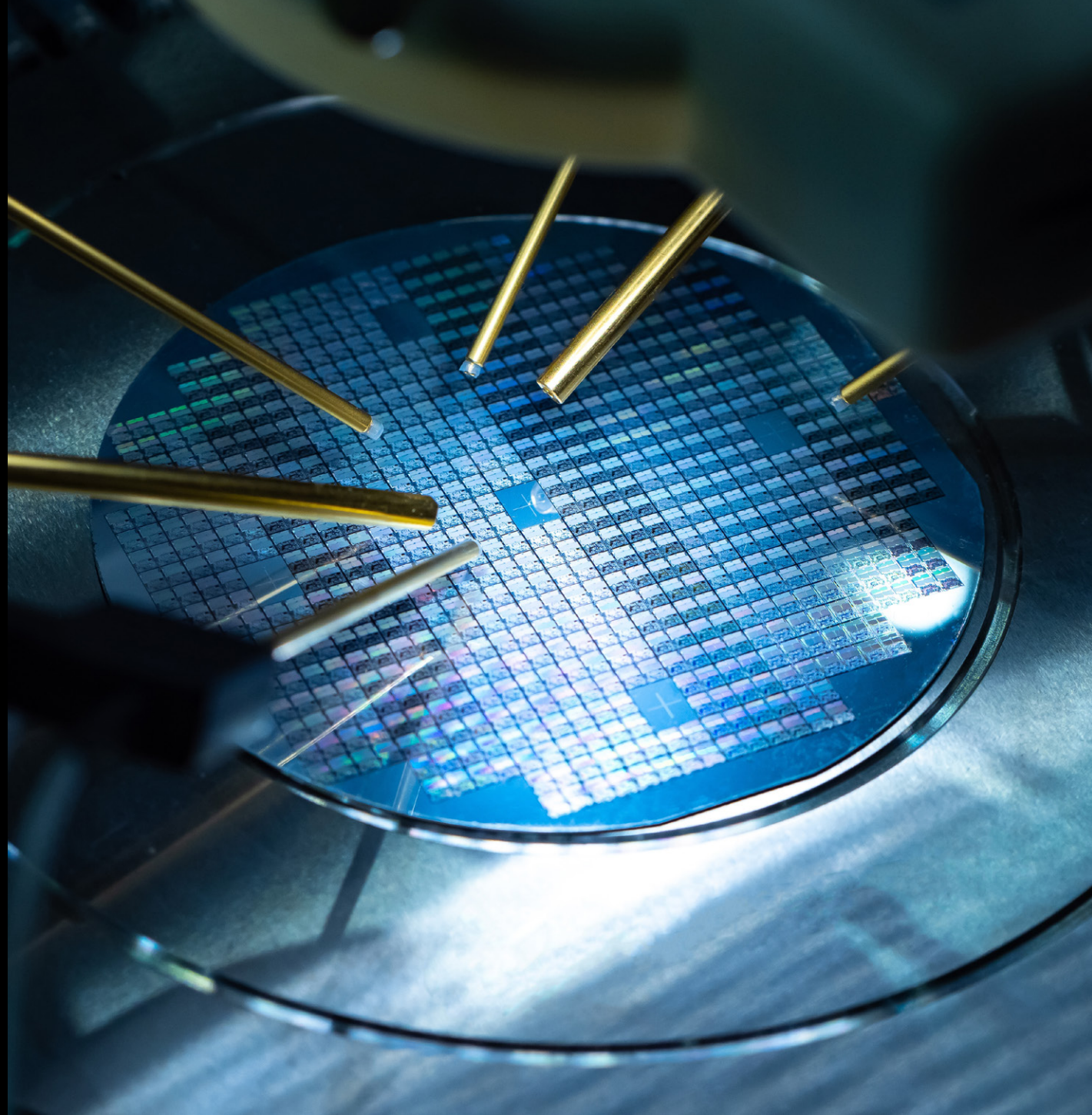
Multi-physics

Currents generate heat, and heat induces material stresses, which can, in turn, affect the electrical properties of the device. Consequently, capturing the self-heating effects requires also an understanding of thermal dynamics and a comprehensive approach to cover coupled electrical, thermal, and mechanical equations.

In the past decade, researchers have made a concentrated effort to unravel the trapping and self-heating effects of GaN. Scientists are leveraging advanced modeling tools like Keysight EDA’s IC-CAP to deepen our understanding of GaN and unlock its transformative potential in next-generation RF and power electronics design.

CHAPTER 5

A Survey of GaN Models



A Survey of GaN Models

The journey of GaN models traces its lineage from compact models developed initially for GaAs metal-semiconductor field-effect-transistors (MESFETs) and HEMTs or customizations of such models. The ongoing pursuit for accurate models for GaN is twofold: first, GaN has unique nonlinearities in behavior that GaAs models are not accurate enough to simulate; second, there is a desire for improved accuracy to take full advantage of the performance wins in high-power, high-frequency areas. Subsequently, over the last two decades, GaN models have evolved from empirical models to ANN (artificial neural network) and physical-based models.

Table 2. Available GaN models

Model	Institute / Company	Year
EEHEMT	Agilent / Keysight	1998
Angelov	Chalmers University of Technology	1992
Angelov-GaN	Chalmers University of Technology	2008
DynaFET	Agilent / Keysight	2014
ASM-HEMT	Indian Institute of Technology Kanpur and University of South Florida	2015
MVSG	Massachusetts Institute of Technology	2013

Empirical models

Empirical models such as Angelov-GaN or EEHEMT have gained significant traction among design houses as they only require measured data for the extraction flow. These models use empirical functions to model the drain current, gate current, and terminal capacitances. However, because a set of measurements creates them, they have limitations in scalability or predictability. The early adopters of empirical models had to develop their variants of empirical models to suit their specific technologies better.

Artificial neural network models

The **artificial neural network (ANN)** model has proven highly accurate over small and large signal conditions, primarily due to the special attention given to trapping and self-heating effects. Artificial neural networks are computational paradigms based on how the neural network works. They can approximate nonlinear functions using a network of neurons. Machine learning algorithms train these neurons, consisting of interconnected nonlinear processing functions, using diverse datasets such as DC, S-parameter, and large-signal waveforms, as shown in Figure 6.

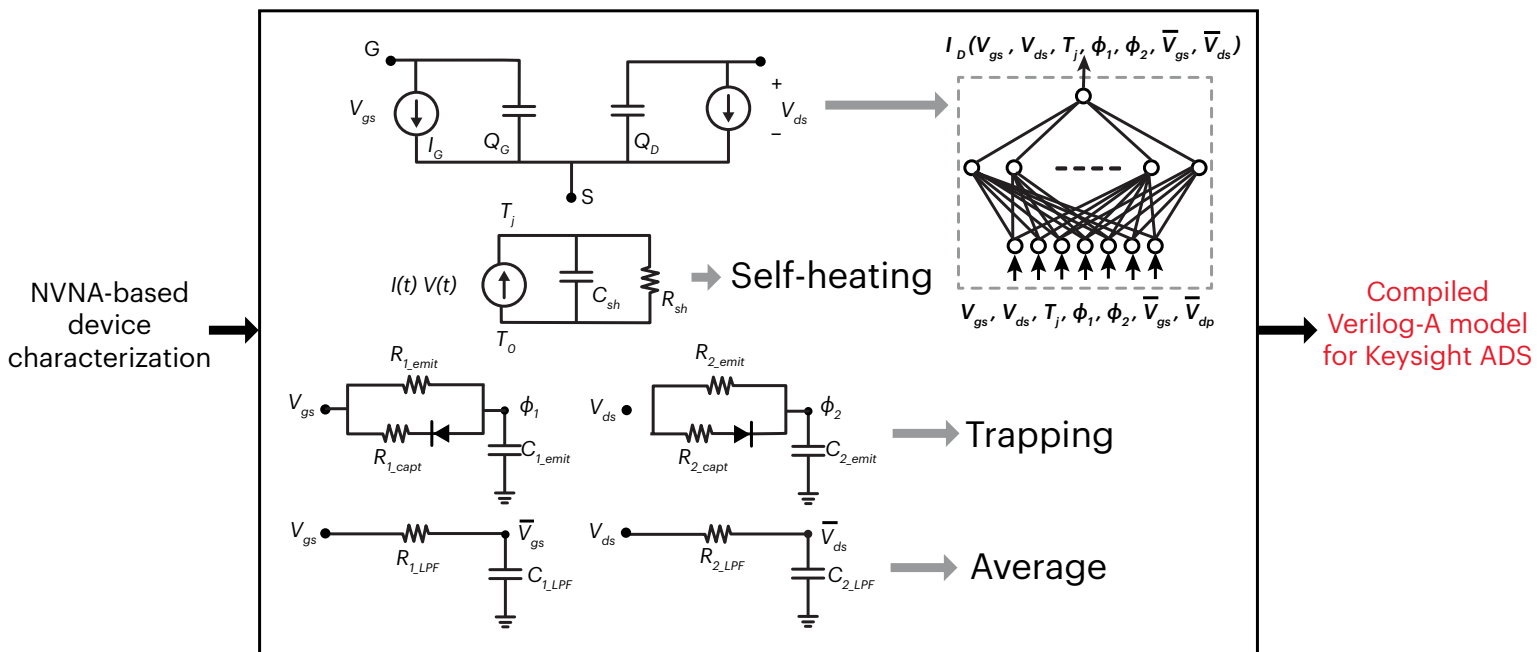


Figure 6. Process flow of Keysight's DynaFET compact model

Keysight's **DynaFET model** sets a new benchmark within the realm of ANN models. This solution provides modeling dynamic self-heating and trapping effects with precision. Moreover, it improves broadband performance across the entire device operating frequency range. In addition, it scales well and improves the prediction of large-signal nonlinearities (distortion, load-pull, PAE) and long-term memory effects.

Physics-based models

In 2018, the Compact Model Coalition (CMC) accepted two new physics-based GaN models: the University of Berkeley advanced SPICE model for high electron mobility transistors (ASM-HEMT) GaN model and the Massachusetts Institute of Technology (MIT) virtual source GaN (MVSG) model. Thanks to a physics-based formulation, both models outperform empirical GaN models in global accuracy, especially under large signal conditions.

Another advantage is the scalability these models offer. Modeling engineers can modify the process parameters to predict their influence on device performance or tune process parameters on existing models to fit the new data instead of re-extracting the entire models when the process changes. The IC-CAP CMC GaN extraction flow (Figure 7 examples), developed in collaboration with ASMHEMT and MVSG developers, provides a user-friendly gateway for those new to physics-based GaN modeling, making extraction faster and easier.

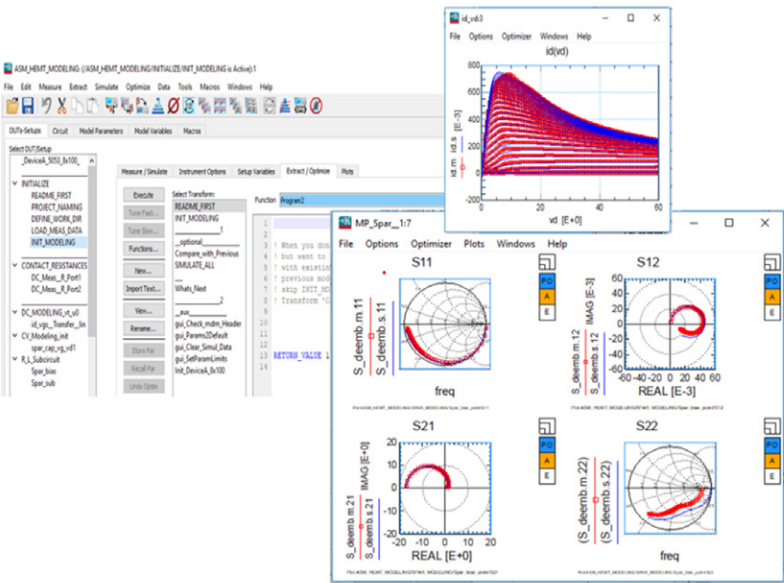
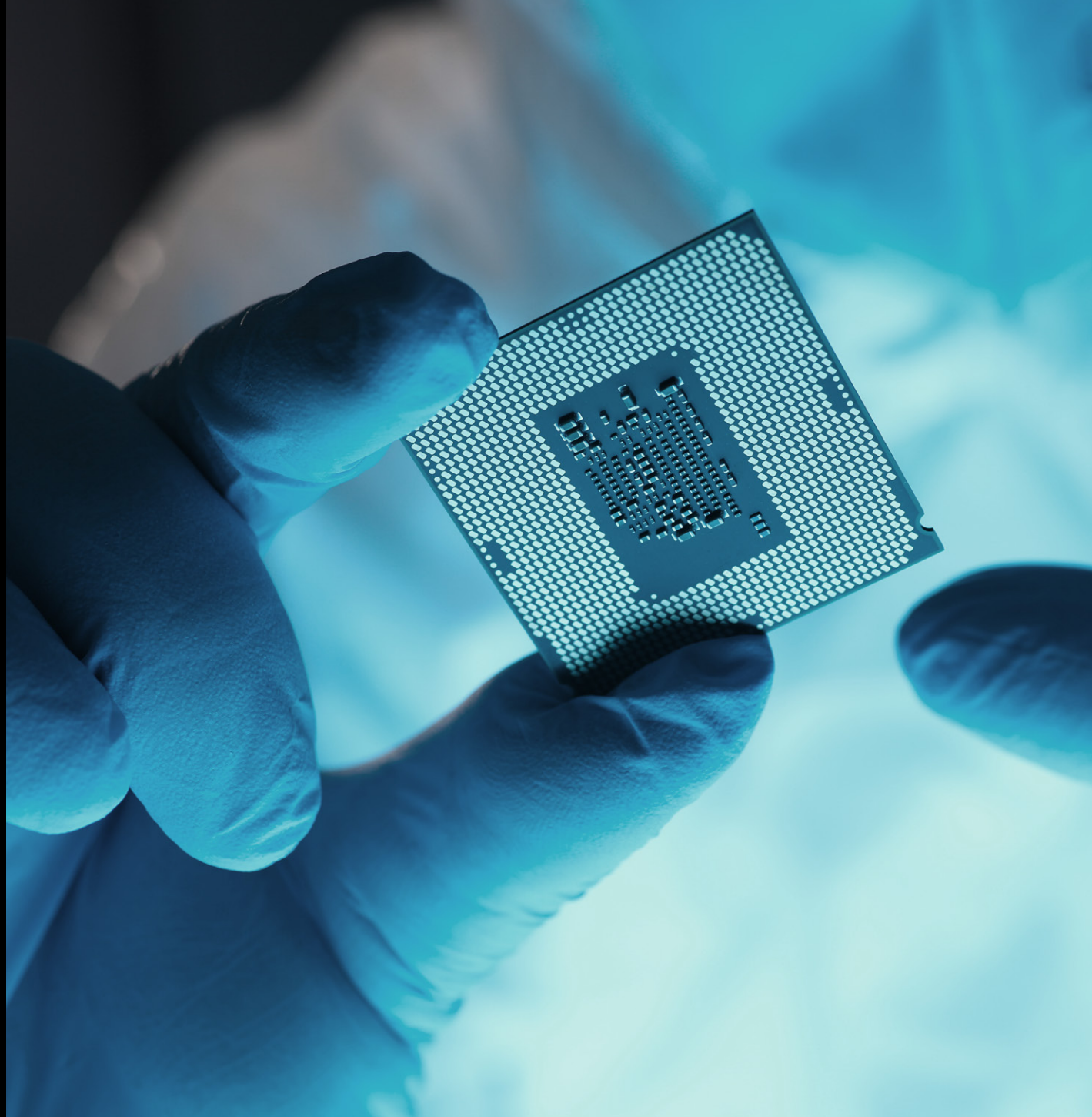


Figure 7. Examples of Keysight's IC-CAP GaN CMC modeling package results

CHAPTER 6

Select the Right Model for Your Requirements



Select the Right Model for Your Requirements

With various types of GaN models available, the key question becomes, **which model would best fit your requirements?** Here are four factors to help guide your decision.

Scalability

During the design process, tuning and simulating the model for various scenarios is key to achieving optimal performance. Compact models must adapt to these changes in parameters such as width, length, and the number of fingers. The model’s scalability hinges on its ability to predict electrical behavior changes with varied input parameters.

Conversely, modeling engineers can predict the outcome at the circuit level with the new mobility and contact resistance values using a physics-based model. Imagine a fabrication house updating its process to increase mobility and reduce contact resistance. An empirical model governed by non-physical parameters requires extracting the entire model again for a different device. Instead, with a physics-based model, modeling engineers can predict the outcome at the circuit level with the new mobility and contact resistance values.

Global accuracy

Global accuracy measures how closely a compact model can consistently represent the actual data on the device. When process information is readily available, opting for physics-based or ANN-driven models enhances accuracy, especially under large signal conditions. The reason is primarily because a large signal operation would put the device in a region that is not measurable. Physics-based and ANN models excel at extrapolating or predicting device behaviors in such areas, surpassing empirical models.

Simulation robustness

Compact models must support various circuit simulations, such as DC, small-signal AC, transient, or large signal nonlinear harmonic balance simulations. For reliable results, it is crucial that these models consistently converge in all simulation types. Empirical models, however, might lead to non-convergence when simulators apply inputs beyond the ranges used to create these models.

Extraction flow

While ANN models offer advantages in accuracy, they require a vast and detailed set of training data involving nonlinear vector analyzer measurements. In contrast, physics-based and empirical models offer simpler extraction flows.

CHAPTER 7

Case Study: Setting the New Standard for GaN Modeling



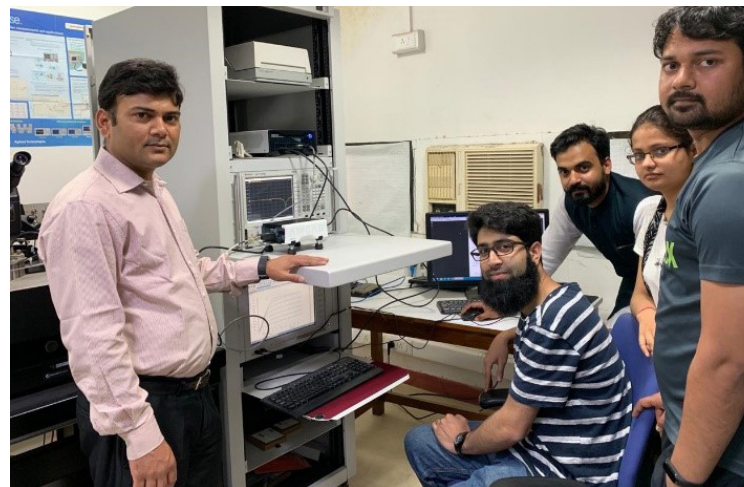
Case Study: Setting the New Standard for GaN Modeling

Modeling GaN HEMTs is a substantial challenge, as it requires massive data processing and takes weeks, if not months, to extract and verify model libraries. With over 30 years of research in device modeling, the Keysight EDA device modeling solution supports the latest GaN models and continuously collaborates with the model developers to enhance extraction flows.

Professor Yogesh Chauhan of **the Indian Institute of Technology Kanpur** envisioned a SPICE model for GaN devices to strike the perfect balance between accuracy and efficiency. The desired model had to be accurate to create precise simulations, ensuring fast simulation time and simple parameter extraction.

Professor Chauhan's objectives centered around accuracy and efficiency. The IC-CAP solution and a suite of high-precision tools tailored for parametric and device characterization became the cornerstone of his efforts.

In collaboration with Dr. S. Khandelwal, Professor Chauhan's team created the industry's first advanced SPICE model for high electron



mobility transistors (ASM HEMT). In 2018, the Compact Model Coalition (CMC) recognized the ASM HEMT as an industry-standard model after successfully completing its rigorous standardization process.

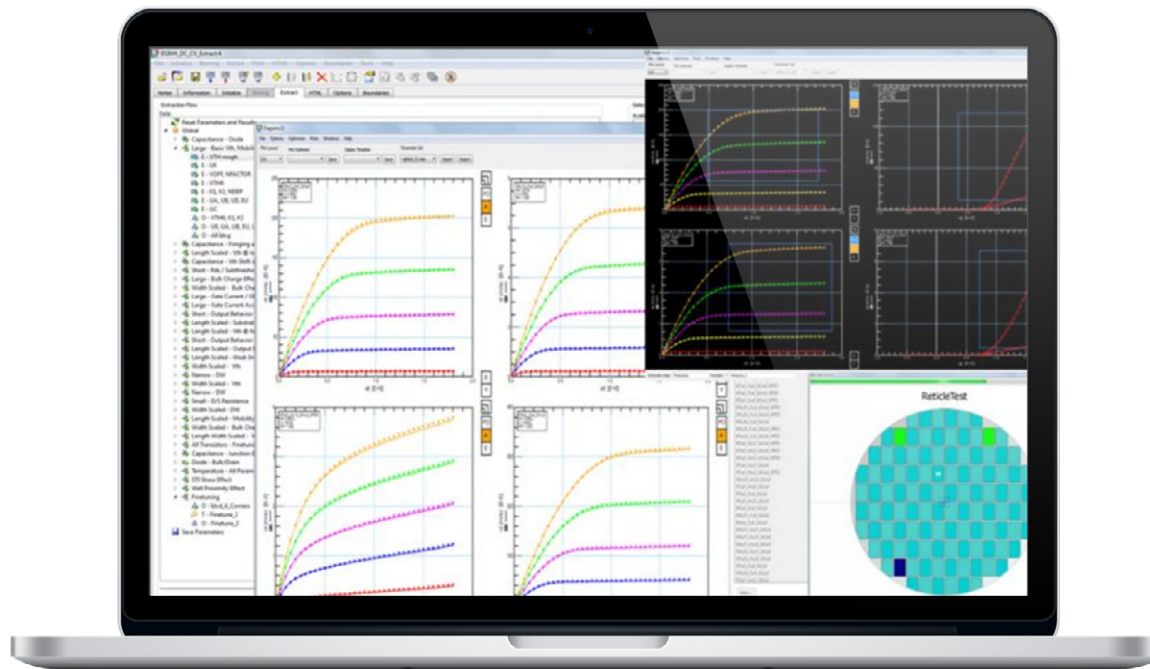
With its unmatched convergence rates, microsecond-scale simulation time, and accuracy requirements of approximately 1% root mean square (RMS) error after fitting, the ASM HEMT model now sets the new standard for GaN models in RF and power electronics applications.

Trusted by leading foundries, Keysight's IC-CAP provides a holistic solution for GaN modeling, from device characterization and model extraction to verification and documentation. For advanced users, IC-CAP offers unparalleled flexibility, enabling user-defined extraction flows and model customization — all powered by Python.

CONCLUSION

In the post-Moore's Law era, GaN is leading a new wave of semiconductor innovations that enable a more efficient and sustainable future. As industries like automotive and telecommunications increase their focus on GaN semiconductors, the importance of robust GaN device models becomes paramount. Leading semiconductor foundries and integrated device manufacturers (IDMs) entrust Keysight's IC-CAP with navigating the complexities of GaN modeling.

To learn how IC-CAP can empower you to take your GaN modeling to the next level, please visit our [device modeling solution](#) or [request a free trial](#).





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