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Role of Simulation Technology for the Progress in Power devices and Their Applications

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Abstract— **The modern power electronics era started with the commercialization of the silicon controlled rectifier (SCR) in 1957, since when power electronics systems have been installed in a wide range of applications from appliances to traction and utility systems as the technology has advanced. Meanwhile, simulation tools have played an important role in the research and development of power semiconductors and power electronics systems. As power devices and power electronics become increasingly important technologies in today's electric society, it is worth examining the overall integration of power electronics design. This paper reviews the history of simulation technology with reference to power device modeling and discusses the future of power electronics system design.**

***Index Terms*—Power semiconductor, Numerical simulation, Thyristor, LTT, GTO, IGBT, Cosmic ray, Design platform**

I. Introduction

Almost sixty years have passed since the Silicon Controlled Rectifier (thyristor) was first commercialized by General Electric (GE) in 1957. This led to studies on power inverter technology, which is a core part of power electronics, and subsequent development of improved power devices. Many studies on device physics and basic device concepts both for unipolar and bipolar devices were then conducted in the 1970s. Most of the major power devices such as Power MOSFETs, Gate Turn-Off thyristors (GTO) and Insulated Gate Bipolar Transistors (IGBT) were developed during the 1980s. Since the 1990s, silicon power devices have made remarkable progress, especially in advanced power MOSFETs and IGBTs; they have been used for a wide range of power electronics applications such as consumer electronics, Information and Communication Technology (ICT), automobiles, industrial drives, and power utilities, with voltages ranging from several tens of volts to more than several kV.

Analytical modeling of power devices started to clarify the behavior of high voltage diodes and thyristors as well as bipolar power transistors in the 1950s and 1960s. Based on these analytical studies, in the 1970s research on the modeling of power devices focused on two important areas: a numerical device simulator and a circuit simulator. The numerical device simulator was developed to solve exactly the basic semiconductor device equations and is now commercially available as an essential tool for power device design.

The performance of power devices such as conduction and switching losses, easy gating and ruggedness has been improved greatly. As power devices have advanced, a compact circuit simulator with a device circuit model is becoming increasingly important for optimizing the design of power converters. Device circuit models are therefore being intensively investigated for IGBT as well as for wide band-gap power devices.

Power electronics is now prevailing in society as a cross-cutting technology for effective use of electricity, and simulation technologies are becoming more system oriented for integrated next-generation power electronics system. This paper first looks at the history of simulators in terms of both devices and circuits. Issues of advanced device simulators are considered, including wide band-gap devices. A future integrated simulation platform is discussed, taking the integrated power electronics system into consideration.

II. History of Simulation Technology for High Voltage Power Semiconductors

A. Prior to the numerical simulation era

Power semiconductor technology was featured in the August issue of the Proceedings of IEEE in 1967, with more than 200 pages. The then-latest technologies of high voltage thyristors and PiN diodes were reported, focusing on device technology, device design and measurement. The new power device technology paved the way for the modern power electronics era, enabling the efficient and precise control and conversion of electric energy and power for many applications including various motors, power transmissions and power supplies. Regarding the device analysis approach, Spenke, for example, reported dynamic stored carrier behavior in PiN diode reverse recovery based on analytical model equations [1]. The report unveiled the switching mechanism of carrier storage devices for the first time and contributed to the understanding of high voltage power diode physics. The proposed analytical model was very successful and read by many engineers and researchers, however, it was for only a one-dimensional formulation, and was solved under many assumptions in physical parameters and engineers required strong mathematical skills to understand the model with 89 equations typed on a particular paper, and thus

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the model could only be used by a small number of device designers or users.

B. In-house 1-D device simulators

The pioneers in power device numerical simulation in the mid 1970s were Kurata of Toshiba and Engl of TH Aachen [2][3]. They established one-dimensional numerical simulation technology for power semiconductor devices. They had independently built their own simulators for thyristor structure devices, as shown in Figure 1, operating under static and dynamic conditions.

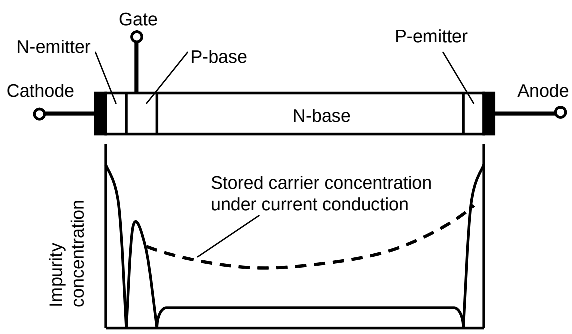

Figure 1. Schematic of thyristor structure and impurity concentration. Broken line shows high-level stored holes and electrons under current conduction injected from both P-emitter and N-emitter.

Thyristors had become the key device in modern power electronics technology by the 1970s since they were the first semiconductor device that actively controlled the high power conversion circuits used for motors, infrastructure power management and utility systems. Unlike MOSFETs, thyristors have a floating N-base layer and high density of conduction hole-electron carriers in the layer injected from P and N emitters, thus creating a high ambipolar state, which often caused convergence problems in Newton iteration. They successfully simulated the operation of a thyristor by employing advanced methods for the discretization of the basic equations and physical models of semiconductors, completely coupling the basic equations of semiconductors in Jacobi matrices, enabling the equations to be solved even with the very limited computing power available in those days. Thyristor technology has dramatically expanded the application of power semiconductors to higher power ranges, and the technology is inherited by the successful new Light Trigger Thyristor (LTT) for very high power conversion systems, such as the Sakuma frequency conversion station (300 MW, 60Hz/50Hz, 275 kV, 1993) and Kii-channel High Voltage DC Transmission System (up to 1.4 GW with 8kV-3.5kA LTT series connection handling +/-250 kV in 2000) in Japan. The one-dimensional simulation contributed to the development of the gate turn-off thyristor (GTO) and clarifying the operation mechanism. GTOs were the first semiconductor devices that enabled switching of some kA/kV level power at a frequency of 500 to 1 kHz and are widely used in traction applications and motor drives in industry.

C. Simulator as design tool

Device simulation technology rapidly evolved from being an analysis tool for clarifying the operation mechanism of devices into a device design tool for power device research and manufacturing. Among a number of research groups, Adler and his group at GE published many important papers on physical models and parameters related to the accuracy of numerical simulators for power semiconductors, including the band-gap narrowing model [4] for power device emitter injection efficiency, impact ionization model and field limiting ring simulation method. At the same time, power devices started to employ planar technology in edge termination (Figure 2) and thus in-house two-dimensional simulators greatly boosted the technological advantage of companies such as Toshiba, GE, Siemens and Philips [5-8].

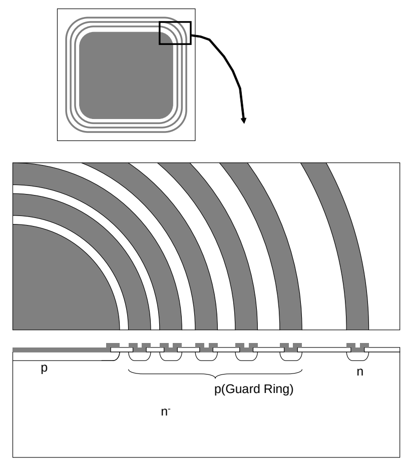

Figure 2 Example of planar edge termination structure (guard ring structure). Floating p-rings relax electric field concentration near the edge of power device chips.

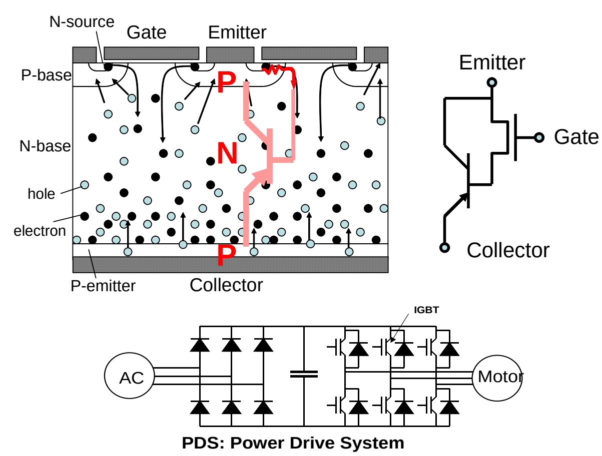

Figure 3 Schematic of IGBT, simplest equivalent circuit and example of motor drive circuit. Similar to thyristors, the IGBT exhibits low conduction loss with a high concentration of injected holes and electrons.

Two-dimensional device simulation technologies greatly contributed to the early development of Insulated Gate Bipolar Transistor (IGBT) in the 1980s. Figure 3 shows a schematic diagram of an IGBT, a simple equivalent circuit and an example of a motor drive (PDS) circuit. IGBTs are very successful devices, replacing Power Bipolar Transistors and GTOs later on. IGBTs feature MOS gate control and high current capability with high blocking voltage thanks to the high injection carriers in the N-base. Power device simulators at that time already had sufficient performance for simulating two-dimensional MOS-bipolar structures. The latch-up-free design reported by Nakagawa, which was a breakthrough technology for the practical use of IGBTs in motor drive applications, was established by a research group of Toshiba employing a two-dimensional in-house simulator [9, 10].

Today, IGBTs can control a couple of hundred amperes per chip and blocking voltages in the range of 3.3-6.6 kV [11-14], and so are used in diverse applications including appliances, HEVs, tractions (such as the Shinkansen 700 series and later), and high voltage DC transmission systems (e.g. an HVDC system with several hundred megawatt capability).

D. *Device failure simulations*

Device destruction phenomena limit the safe operating area (SOA) of power semiconductors and require a substantial safety margin of current, voltage and switching speed, which directly affect the cost, volume and efficiency of power electronics systems. As well as experimental analysis of operating failures and destruction of devices, numerical simulation technology has helped enlarge the SOA of power semiconductors. An example of reproducing the failure phenomena by simulation was GTO turn-off failure analysis, which unveiled the mechanism of gate circuit-related redistribution of current inside GTOs triggered by dynamic avalanche during turn-off [15]. The simulation was accomplished by complete coupling of circuit-device equations and all of the physical model derivatives, such as impact ionization model, were included in the Jacobi matrix so that the Newton iteration convergence problem was solved in spite of the strong non-linearity of the system. Failure phenomena analysis with multiple GTOs [16] and IGBT failure mechanism analysis [17] were also performed with commercial simulators.

Simulation of cosmic ray induced failures is another example. These failures in high voltage GTOs were reported independently in 1994 by different companies [18-20] based on experimental data, forcing to device designers to change the N-base design of high voltage devices. To clarify the mechanism, cylindrical 2-D simulations were performed introducing new carrier generation models into the simulators [21-22]. The simulation results were verified by experiments, showing the usefulness of device simulation for failure analysis on computers.

E. *Compact model for IGBT*

The IGBT models used for circuit simulation are required to be sufficiently simple for performing simulations within a practical computation time and sufficiently accurate for engineers to use the output data in actual power electronics system design. The Hefner model was the first compact model to express the operation of IGBTs considering stored carrier behavior inside the device. The model includes an analytical equation for high level stored carriers in the N-base of the IGBT. Compact models of power semiconductors such as the Hefner model have become very important in power circuit level design for reproducing waveforms in power electronics systems [23-25].

Figure 4 summarizes the history of device modeling with power device development.

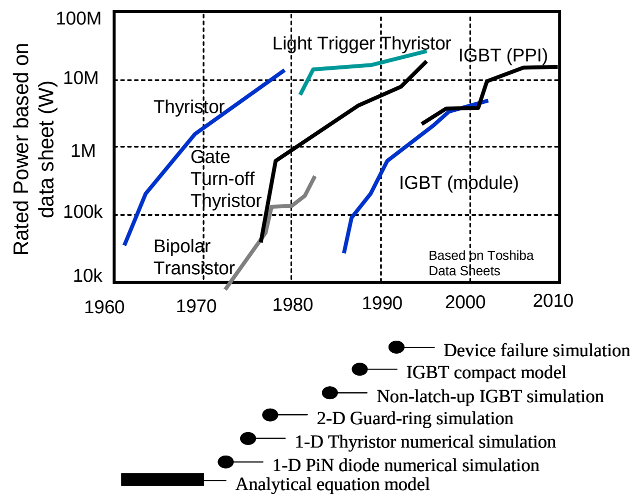

Figure 4. High voltage power semiconductor development and simulation technology.

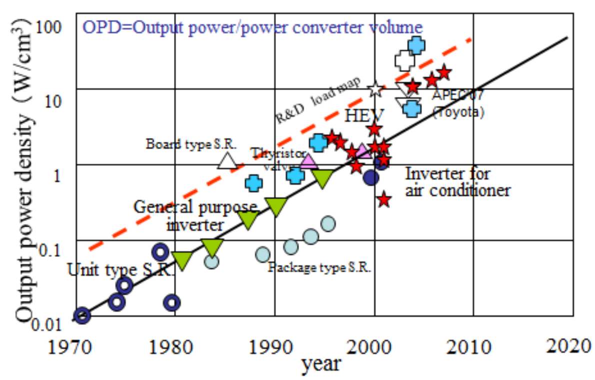

Figure 5 Output power density trends.

III. Requirement for Advanced Power Device Modeling

A. *Trends of advanced power devices*

Lower power consumption is always important for power devices to improve the efficiency of power converters. However, the efficiency is gradually reaching its limit of 100%, so future development work can no longer target efficiency. Instead, the output power density of a converter is being used as a new target for the development of power electronics. As shown in Fig. 5, power density has increased by almost three orders of magnitude in the last 40 years [26], enabling the volume of power converters to be reduced to 1/1000 during the same period. This has been mainly achieved by reducing the volume of the heat sink and passive components by using devices with lower power consumption and faster switching speed. The road map for advanced power devices shown in Fig. 6 has been proposed [27] by considering the following trend of power devices.

a) Si power devices still have much room for development toward ultimate MOSFETs and IGBTs.
b) The combination of Si-switching devices and SiC-free-wheeling diodes will be a significant step not only for strengthening the SiC market but also for Si-device development.
c) Si-IGBT will be replaced by SiC MOSFET in the voltage range of more than 1000 V and SiC-IGBT has the potential to be used for applications of more than 10 kV.
d) GaN power devices will replace Si-power ICs and will be used for faster switching applications.
e) The unique properties of diamond have potential for new power devices especially in high voltage applications [28-29].
f) The ultimate CMOS has the potential to be used for power integrated devices in ICT applications.

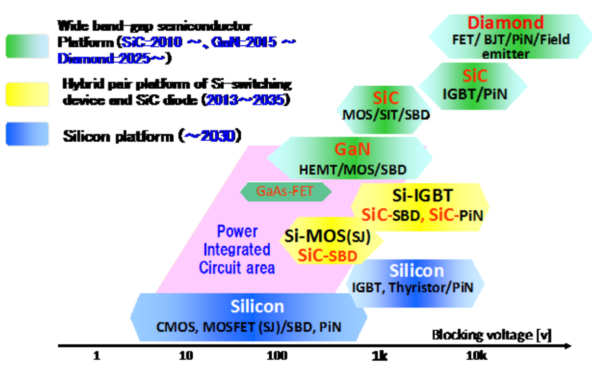

Figure 6 Advanced power semiconductor trends.

It is necessary to continue research on the modeling of advanced power devices as shown in Fig. 6. The design and virtual prototyping/testing of power electronics systems are reviewed in the next section.

B. *Models for Advanced Power Devices and Their Applications*

Power device and related configuration designs, such as power circuits, gate drive circuits, packaging and wireframes have been influencing each other as the power density and complexity of power electronics systems have increased and as device performance has progressed toward higher current density, higher electric field and faster switching speed. Meanwhile, advanced power semiconductors are closely related to new materials and physics, and so may require designers to understand new types of semiconductor phenomena. These two recent circumstances will continue and are closely related to the design of power semiconductors and power electronics systems in the future.

As shown in the product development scheme in Fig. 7, both the physical model expressing basic semiconductor phenomena for exact simulation and the compact models expressing device- and component-level characteristics for higher level system design contribute to the fundamental design and prototyping scheme of power electronics with experimental validation of models [30-32].

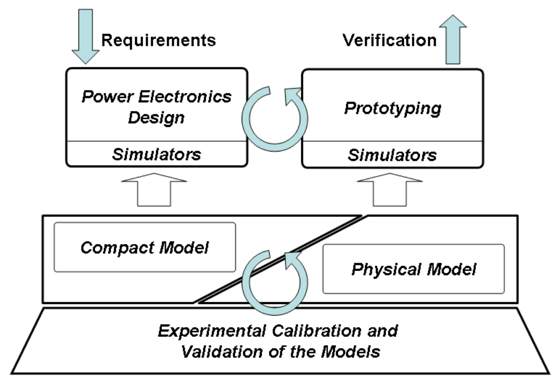

Figure 7 Fundamental scheme of product design and prototyping supported by simulation technology.

C. *Expansion of requirements for compact models of power semiconductors*

Improvements in speed, accuracy and validity are key requirements for compact models of power semiconductors for advanced high power density power electronics and devices. A high speed capacitance stored energy model was proposed for unipolar power semiconductors such as superjunction MOSFETs, SiC-FETs and Schottky barrier diodes (SBDs) [33]. This model is valid for high switching speed power devices and enables switching loss calculations without simulating the switching waveform. The model is also applicable to high voltage AlGaN/GaN HEMTs [34].

Accurate yet fast computation time compact models have been developed based on Hiroshima-University STARC IGFET Model (HiSIM) platform with the surface potential based MOSFET model expanded to the drift region of high voltage MOSFETs [35], [36]. An IGBT compact model has also been developed based on the same simulation platform and successfully reproduced switching waveforms of IGBTs under various temperature conditions [37]. To increase the validity, a structure oriented compact model has been proposed. Although the model is valid only for trench IGBTs, it accurately simulates forward conduction losses for a variety of device structures, blocking voltages and operation temperatures without fitting parameters [38]. SiC PiN diode, merged PiN Schottky (MPS) diodes and SBD practical compact models were reported based on experimental parameter extraction [39].

D. *Requirements for physical models for advanced power semiconductor devices*

Different from silicon device modeling, for wide band-gap semiconductor materials it is difficult to model the basic carrier properties, such as electron mobility and carrier lifetime, as well as the carrier transport mechanism itself. This difficulty originates from the anisotropy of crystal, high band-gap energy and resultant very small intrinsic carrier concentration, and deeper impurity levels for special acceptors.

The anisotropic properties of electron mobility and impact ionization have been modeled based on measurements of angular factor [40, 41], accounting for 20% of the difference in mobility for angle. Carrier lifetime under high level carrier injection have been measured to design and model SiC high voltage bipolar devices over 10 kV. The current recovery time (CRT) measurement and open circuit voltage decay (OCVD) are simple yet practical methods [42], and a sufficiently long hole lifetime of 3.7 µs was reported [43], showing that high injection conduction carriers are stored in a 4H-SiC PiN diode.

Regarding diamond as a high voltage power device material, the transport mechanism itself must be considered in order to construct the basic transport equations. In 1962, Wilson measured the temperature dependence of resistivity and pointed out the existence of hopping transport phenomena in boron doped diamond [44]. Recent measurements have also shown the variable range hopping in heavily boron doped diamond [45].

IV. CHALLENGES FOR THE FUTURE

A. *Ubiquitous power electronics world*

As electricity is a safe, clean and convenient form of final energy in comparison with fossil fuel energy sources, the demand for electricity as final energy has continuously increased not only in advanced countries but also in developing countries. The International Energy Agency (IEA) forecasts that global electricity consumption will double by 2030 [46]. According to a report of the Ministry of Economy, Trade and Industry (METI) in Japan [47], the share of electricity in final energy consumption will rise from 25% of today to more than 50% in 2050, achieving a 50% reduction in CO_2 emissions with 40% energy saving. The report envisions an even more “electric society” by 2050, with major trends including: 1) renewable energy generation, 2) e-mobility, 3) heat utilization by heat pumps, 4) expansion of information traffic and 5) creation of a new grid.

In the society of tomorrow, electricity will be the major energy, and so the ubiquitous, effective use of power electronics will become increasingly important for saving energy. Efficiency improvements and the prevalence of power electronics systems are key factors for efficient energy, and so the role of power electronics as “nega-watt” [48] has been examined. Energy saving by highly efficient power electronics systems is equivalent to an electrical energy dynamo, based on which the concept of nega-watt cost is defined as follows [27].

$$\text{nega-watt cost} = \frac{\text{System Cost} + \text{Running cost}}{\text{Saved energy} \times \text{Operation time}} \quad (1)$$

It is essential to reduce nega-watt cost in order to provide people and industry with an affordable, efficient system. For this purpose, higher power density and lower watt-cost power converters will be key targets as well as high efficiency.
The basic scheme of next-generation power electronics is shown in Fig. 8. The scheme consists of application and seed technology domains. Ubiquitous Power Integrated Converters (U-PIC) are distributed in the application domains of power electronics for green IT, homes and offices, and social infrastructure. Various types of grids such as smart grids, mini-grids, micro-grids and inter-grids will be interconnected by many U-PICs.

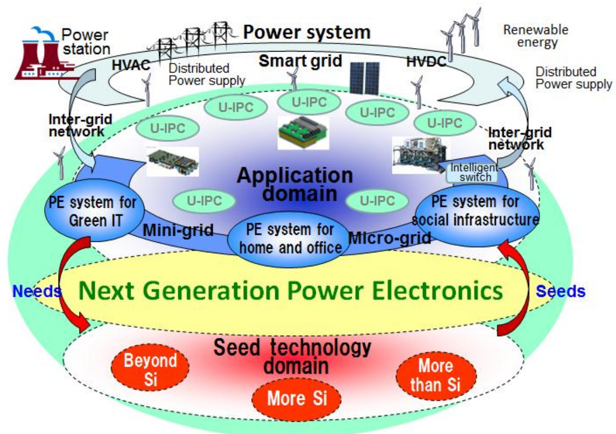

Figure 8 Technology scheme of next-generation power electronics.

B. *Enabling technologies*

Higher power density is very important for reducing nega-watt cost as described previously. The seed technology map to achieve next-generation power electronics is shown in Fig. 9. The map consists of three main parts: “More Silicon”, “Beyond Silicon” and “More than Silicon”.

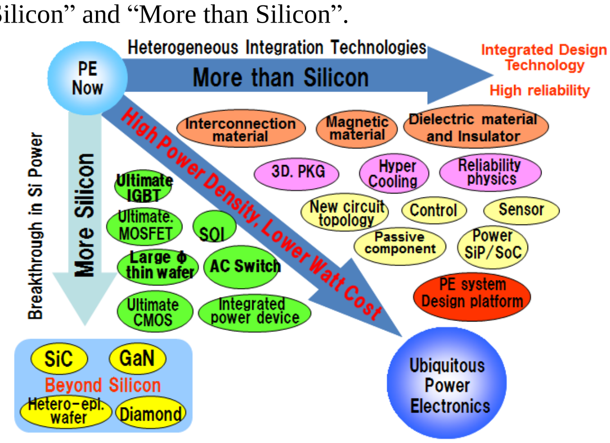

Figure 9 Seed technology map for next-generation power electronics.

A platform for designing power electronics systems will become important as a core technology for optimizing various design requirements for reducing nega-watt cost, such as output power density, watt-cost, and reliability. Therefore, it is necessary for future modeling activities to identify technological barriers and to develop new technologies in advance. There is a tradeoff relationship between the efficiency and power density of power converters, and so “More than Silicon Technology” will become important to improve the tradeoff relationship. All of the various heterogeneous integration technologies, shown in Fig. 9, should be considered for resolving design platform issues.

Thanks to the progress in computer performance, simulation technologies will enable the design and prototyping of heterogeneous integration systems to be conducted virtually on a computer with various domains and scales of models for seed technologies. Figure 10 shows the progress in simulation technology, with simulation scale plotted against the number of users. The expansion of applicability of simulation technology will enable the coupling of different types of simulations for integrated power electronics system design and virtual prototyping and testing for design verification.

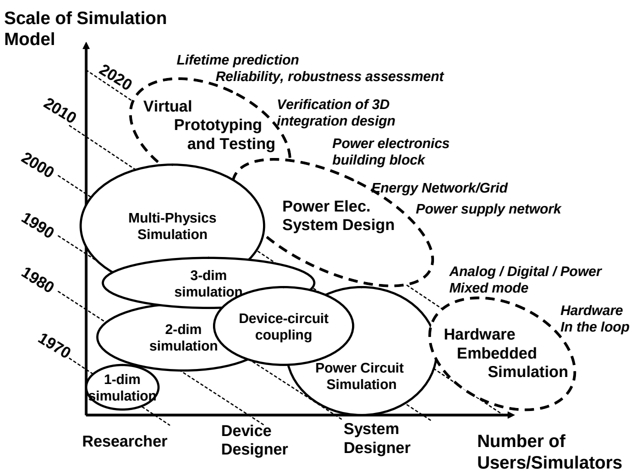

Figure 10 Progress of simulation technologies and their applicability.

Figure 11 shows an example of the design platform, which was developed in the AIST. The platform consists of three design blocks, namely, circuit design, power electronics system design and core technology.

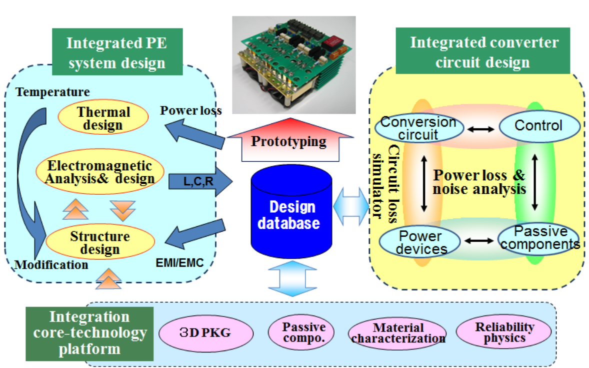

Figure 11 An example of the design platform, developed in the AIST.

V. Summary

This paper reviewed the role of simulation technology in the progress of power devices and their applications. The history of simulation technology was described, focusing on high voltage power semiconductor devices, and taking into consideration the progress in analytical and numerical simulation as well as compact circuit device modeling. The requirements for advanced power device modeling were examined based on the trend of advanced power device studies and considering recent progress in wide band-gap and silicon power devices. The importance of power electronics in the electric society of the future was mentioned. The role of simulation technology for next-generation power electronics was described in terms of an integrated total design platform.

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