IEEE

IEEE POWER ELECTRONICS SOCIETY
Powering a Sustainable Future

International Technology Roadmap for Wide Bandgap Power Semiconductors

2019 Edition

THE ITRW IS DEVISED AND INTENDED FOR TECHNOLOGY ASSESSMENT ONLY AND IS WITHOUT REGARD TO ANY COMMERCIAL CONSIDERATIONS PERTAINING TO INDIVIDUAL PRODUCTS OR EQUIPMENT.

September 2019

Table of Contents

Chapter 1: Foreword

1.1 Foreword from the IEEE Power Electronics Society President

The International Technology Roadmap for Wide Bandgap Power Semiconductors (ITRW) has been developed as an IEEE Power Electronics Society Initiative to inspire leadership in the emerging and fast moving field of wide bandgap power electronics. The impact of wide bandgap power electronics has been nothing short of revolutionary across all aspects of power electronics giving dramatic changes in efficiency, performance and physical size.

In 2015, the IEEE Power Electronics Society initiated the ITRW project to develop a strategic roadmap to provide vision and leadership to academia, industry and consumers as to where the wide bandgap technology was moving. Several working groups were formed as well as an industry advisory board and a global steering committee to ensure that the resulting work would be genuinely global in nature, and build on the IEEE's role as a neutral forum for advancing humanity. Meetings have been held across the world since the inaugural meeting in December 2015 at TU Delft, including North America, Europe, and Asia to allow as many stakeholders as possible to influence the work of the roadmap and provide their valuable input.

The publication of this inaugural ITRW roadmap is a direct result of the sponsorship and leadership provided by the IEEE Power Electronics Society, with a long-term commitment of several presidents supporting this initiative including Prof. Bram Ferreira, Prof. Alan Mantooth and Prof. Frede Blaabjerg. As can be seen from the extensive list of volunteers who have contributed to the roadmap, much time and effort has been provided by the PELS community at large and this is reflected in the diversity of technology (both fundamental and applications oriented) presented in the ITRW roadmap. The team has also highlighted key technological successes to illustrate how wide bandgap power electronics have made a major impact across the world from grid-connected systems, to mobile communications and computing and transport electrification.

I hope you enjoy reading the ITRW roadmap and find the material contained within it interesting, inspiring, valuable and thought provoking.

Frede Blaabjerg
President, IEEE Power Electronics Society

1.2 Foreword from the ITRW Advisory Board Chairman

Over the last decade, Wide Bandgap Power Semiconductors (ITRW) left the initial niche of being used in isolated applications only. With the availability of more products and especially transistors by various suppliers world wide the penetration increased significantly. Connected to this development there is an increasing interest of all participants worldwide to get guidance and confidence about future developments and the ultimate potential of the new technologies. The industry is excited to be a part of IEEE's initiative to offer such a program in form of the ITRW roadmap. This is reflected by the constitution of the IAB itself where leading representatives from the major players in the field agreed to serve voluntarily as reviewers for the roadmap drafts.

Thanks to the enormous efforts of Bram Ferreira as the face and heart of the initiative, supported by a powerful international team of experts, we can now present the first edition of the WBG roadmap. We are convinced that the document is able to support all aspects of the new technology today and in the near future, beginning from materials over devices until the ultimate end application. Similar to previous IEEE roadmap efforts we believe that the ITRW document will become one of the key information sources for stakeholders in the wide band gap area.

A special thanks again is given to the working groups which spent an tremendous amount of time in collecting information, conducting interviews and evaluating questionnaires. The result can be judged as the best available essence of the global view and future or wide band gap technologies.

Of course roadmaps are always living documents, so the ITRW team will be excited to get feedback and further inspiration. Provided you are inspired by the content, feel free to join us in the working groups or the advisory bodies in order to work on next editions of the ITRW roadmap.

Peter Friedrichs
Chair of the ITRW IAB

1.3 Acknowledgements

The International Technology Roadmap for Wide Bandgap Power Semiconductors Committee

Chair	Prof. Braham Ferreira
Vice Chair	Prof. Peter Wilson
Secretary-General	Prof. Guoqi Zhang
Executive Secretary	Dr. Jing Zhang
Executive Secretary	Ms. Christina Dimarino

Industry Advisory Board

Chair	Dr. Peter Friedrichs
Co-Chair	Mr. Dan Kinzer

Working Groups

Materials and Devices

Chair	Dr. Robert Kaplar
Co-Chair	Dr. Victor Veliadis

Mietek Bakowski	Olufisayo Olanrewaju	Richard Woodin
Andrew Binder	Ali Salih	Al Burk
Hrishikesh Das	Hiroshi Sato	Thomas Neyer
Mark Hollis	Yoichi Shimba	Chih-Fang Huang
Daniel Johannesson	Daisuke Takeuchi	Kung-Yen Lee
Tomohisa Kato	Yasunori Tanaka	Peter Friedrichs
Sameh Khalil	Simon Wang	Ruito Aiba
Sudip Mazumder	Winsman WU	Jason Neely
Stefan Moench	Qingchun (Jon) Zhang	Jack Flicker
Peter Moens	Subhashish Bhattacharya	Yun Zhang

Packaging and Integration

Chair	Prof. Mark Johnson
Co-Chair	Dr. Daniel Shi

Tamara Baksht	Mikhail Guz	Ty McNutt
Lauren Boteler	Geoff Haynes	Yunhui (Joe) Mei
Bill Bottoms	Doug Hopkins	David Sanderlin
Stephane Butler	Jared Hornberger	Daniel SHI
Louis Burgyan	Mark Johnson	Peter Wilson
Cyril Buttay	Thomas Lei	Hiroshi Yamaguchi
Bill Chen	Lin Liang	Yiying Yao
Liliana De Lillo	Guoquan Lu	Jing Zhang
Lee Empringham	Fang Luo	Liqi Zhang
Darshan Gandhi	Andy Mackie	GQ Zhang
Ziyang GAO	Alan Mantooth	Jing Zhang
Suxuan Guo	Tim McDonald	Xie Bin

System Integration and Application: GaN

Chair	Dr. Fred Wang
Co-Chair	Prof. Dr. Ing. Sibylle Dieckerhoff
Co-Chair	Prof. Laili Wang

Michael de Rooij	Brian Miller	Jim Walker
Michael Harrison	David Sanderlin	Alexander Young
Phuong Le	Mike Seeman	Shunfeng Li
Tim McDonald	Howard Sin	Huaiyu Ye

System Integration and Application: SiC

Chair	Prof. Jin Wang
Co-Chair	Dr. Victor Veliadis
Co-Chair	Dr. Chaobo Dai

Hirofumi Akagi	Shiqi Ji	Jack Wang
Yazan Alsmadi	Liming Liu	Peter Wilson
Mietek Bakowski	Ali Marzoughi	Yaosuo Xue
Lihua Chen	John Muth	Jing Zhang
Richard Colin	Tatsuo Oomori	Jon Zhang
Christina DiMarino	Mikeal Ostling	Zheyu Zhang
Rick Eddins	Mark J. Scott	Yufeng Qiu,
Peter Friedrichs	Peter Sandvik	Chengzhan Li
Qiang Fu	Paul Talyor	Yonggang Ru
Ulrike Grossner		

IEEE Power Electronics Society Executive Director
Michael Kelly

IEEE Power Electronics Society Project Manager
Alicia Tomaszewski

Chapter 2: Executive Summary

2.1 Motivation

The world is changing rapidly with ever-increasing demands of reliable energy supply and increased electrification of devices and transportation. This is giving a compelling market pull for power electronics products to support expanding markets related to e-mobility and renewable energy. This market is expected to exceed **1000 TW-units per year in 10 years.** (For comparison, the current market for computer and laptop power supplies is **2 TW-units**). On the one hand, there is this market pull of substantial growth related to the energy transitions and on the other hand, there is in the technology push of the potential transition from silicon device to new wide bandgap (WBG) semiconductors. The new generation of WBG semiconductor power electronic devices are potentially **100 – 1000 times faster** and potentially have **100 – 1000 times lower losses** than their silicon counterparts. The latest report from market research firm Yole Développement SA suggests that total market for **SiC power devices by 2023 will be over $1.5 billion** with a compound annual growth rate **(CAGR)** of **31% for next five years, and** with rising GaN adoption in a variety of applications, Yole is projecting the **GaN device business** to reach around **$423 million by 2023 with a CAGR of 55%**. Projections by PowerAmerica are that the total market for WBG devices in power electronics will be **over $11 billion by 2027**.

There is, however, a cost related to this new technology. Existing silicon technology is well established, with proven reliability and lower costs generally per unit than the newer wide bandgap technologies. There is therefore a trade-off between the **superior characteristics** in many regards of the wide bandgap devices compared to their silicon equivalents, **a positive market outlook** (which will eventually drive down the cost of wide bandgap technology) against the status quo of silicon based devices and systems. Several regional roadmaps exist that are already exploring how this new technology will impact on their regional markets: USA (Power America), Europe (ECPE and NEREID), China (CASA) and Japan (SiC Alliance); anticipating opportunities for their industry when suitable technology readiness levels will be achieved.

A key role of this roadmap, the International Technology Roadmap for Wide bandgap Power Semiconductors (ITRW) is to facilitate an acceleration in the R&D process for this new technology to fulfil its potential. ITRW provides a pre-competitive, embracing platform for entities to:

1. **Share** R&D progress and identify opportunities and bottlenecks,
2. **Identify** most effective paths for technology development,
3. **Develop** technology specific content within working groups,
4. **Create** a reference framework for regional roadmaps.

As the ITRW falls within the IEEE, it has a unique position to present a global perspective and to provide a neutral forum that is not dictated by national or regional market or regulatory demands.

2.2 A Market View

It is clear that wide bandgap power semiconductors are already gaining in initial markets where there is a **clear technological advantage** without an excessive cost to entry. One of the earliest WBG devices to enter the marketplace is the Silicon Carbide (SiC) power diode, with broad penetration into specific sectors including PV converters and electrical machine drives. These devices offer **immediate improvements in efficiency, higher voltages and thermal behavior.** Gallium Nitride (GaN) devices are also becoming commonly used in applications such as low voltage lighting, where regulatory constraints on the sale of incandescent lighting has provided an opportunity for higher cost products to gain a foothold where they would normally be uncompetitive, and consumer electronics applications.

An important question is why would the market accept these new devices over an established silicon based system, with an established eco-system of supply and production? There are **several compelling arguments** in favor of WBG device technology for power electronics applications that provide an opportunity for these devices to become prevalent in at least **50% of the existing market in power electronics**.

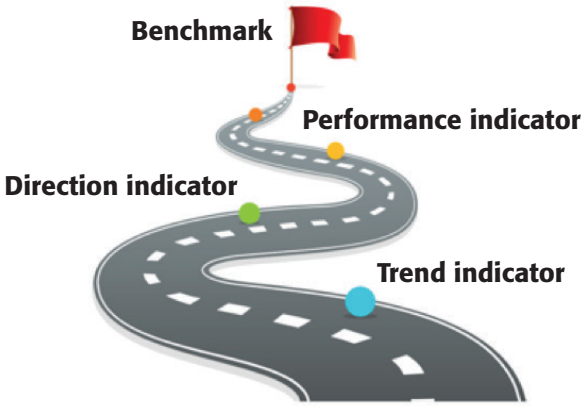
1. **Reduced power losses** and increased efficiency: typical 50% improvement is possible,
2. **Reduced complexity** due to reduced power conversion stages made possible by high voltage performance,
3. **Improved power density** by increasing the switching frequency,
4. **Reduced acoustic noise or EMI signature**, by increasing the switching frequency beyond audible range and conducted EMI band.

The most important market categories for market penetration are the growing established markets that would benefit from the adoption of WBG technology for power electronics including **PV converters, automotive hybrid and pure electric drivetrains, aerospace and data centers,** and new applications such as **wireless power and electric grid components.** There are also some niche applications exist where WBG has a very clear benefit, for example radiation hardened electronic systems for **space and medical MRI equipment**.

2.3 Looking in the Crystal Ball

The mechanism by which the **ITRW can facilitate an acceleration of the R&D process** is to signpost paths of technology development, using a series of cause and effect events that lead to a specific destination. Providing a list of metrics and benchmarks is not enough in itself, as this is essentially static, and does not describe adequately the path to the desired outcomes. **The participants in the ITRW process come from the world leading R&D groups** that are intimately involved in the dynamic path that the technology development has and will be following.

As active experts, we can try to map some future paths, taking history and experience into account, and noting carefully current developments. These dynamic paths have a series of indicators based on the horizon distance, with **short-term performance indicators and benchmarks** being appropriate for existing products and devices, particularly useful for independent and objective comparison of technology.



Direction indicators of **medium term innovations of proven research** show how these technologies could transition into the marketplace and become products of the future.

Finally, indicators that are more "blue sky" in nature show **longer term trends** and the extent of the research landscape and **highlight the potential for research that could lead to exciting new technology in the future**.

ITRW participation comes from the world leading R&D groups that intimately involved in the dynamic path of technology development. The following are potential high impact paths that could unfold during the next 10 years:

- Wide bandgap power device robustness defined in converter context. SiC and GaN do not necessarily need to on par with Si, but the overall converter robustness should be able to meet stringent requirements. For this new test, procedures and equipment could be developed to be used in new standards.
- Heterogeneous integrated power circuits with small footprint on organic substrate using GaN devices. The eminent very large production numbers in existing and new market products makes the required investment in fabs viable.
- Smaller footprint ceramic substrate based power modules with higher level of integration sophistication, made possible by the large market and the need for better EMC management.
- Solid State Transformers in power systems that can outperform conventional transformers with the similar power capacity and voltage class.

- Effective solutions for simplifying the engineering effort development in custom designs. Wide Bandgap power electronic circuits are more complex, but this complexity cannot be passed on the design engineer; standardized building blocks and design automation are two possible approaches.

The International Technology Roadmap for Wide bandgap Power Semiconductors (ITRW) is the only global roadmap that will facilitate an acceleration in the R&D process for this new technology to fulfil its potential.

IEEE POWER
ELECTRONICS SOCIETY
Powering a Sustainable Future

International Technology Roadmap for Wide Bandgap Power Semiconductors