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The Impact of ITRW: How Can WBG Power Semiconductors Break Through?

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ABSTRACT Increasing electrification means the world will need a projected total of 1000 TW-units per year in the next 10 years+. A new generation of wide bandgap power electronics devices are potentially 100-1000 times faster and 100-1000 lower loss than today's technology. Current market projections of massive growth (30%+) for WBG technology and market size into the 10 s of mean that this is a vitally important technology that will shape the next several decades of the world. A key role of 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. This paper takes a holistic view of the future of wide bandgap power electronics, the challenges that needs to be addressed and how roadmaps can make a contribution to meeting these challenges.

INDEX TERMS Technology Roadmap, Wide Bandgap Semiconductors, GaN transistors, SiC transistors.

I. INTRODUCTION

The International Technology Roadmap for Wide bandgap power semiconductors (ITRW) was published in 2019 by the IEEE power electronics society [1] with a view to identifying trends, directions and performance metrics for the future of power electronics technology based on the exciting new developments in wide bandgap semiconductors. The philosophy behind the roadmap was to provide a pre-competitive, embracing platform and neutral forum for entities to:

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

A key role of ITRW was to provide indicators that engineers, researchers, manufacturers and policy makers could understand not only the current state of the art and future directions as shown in Fig. 1.

To achieve this, the ITRW team was organized into core technology areas to focus on the immediate challenges facing the power electronics community with the emergence of these exciting new devices: Devices and Materials, SiC Applications, GaN Applications, Packaging and Integration. Each of these areas formed a working group to develop:

- A global perspective of Market Perspectives
- Technology Analysis
- Technology Perspectives

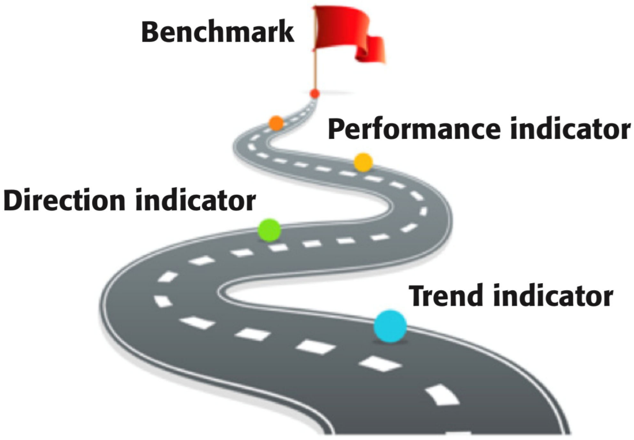

FIGURE 1. ITRW 2019 Roadmap Indicators.

- Research Show Cases
- Product Case Studies
- State of the Art Highlights

The intention of these various activities was to understand the evidence of specific technology opportunities and bottlenecks, with a task of investigating the most effective paths for technology development. Also to undertake a critical evaluation of the benefit of wide bandgap technology in demonstrators and provide well-motivated and supported wide bandgap range of figure of merit projections.

Work on wide bandgap power semiconductors has gathered pace in the last decade, with a huge increase in research, development and delivery of power products using this technology. Since 2015 when the ITRW effort was launched, more than 5 years have elapsed, with some of the trends identified in that period [2] being achieved or surpassed.

The diversity of both technological development and the regional focus for specific applications has led to commercial and policy drivers resulting in major advances. Examples of this impact include the transformation of the Japanese high speed railway network towards using SiC devices [3], the use of SiC devices in Aerospace and Automotive [4]–[7], the explosion of GaN devices in low voltage consumer and lighting applications and the potential for very high efficiency and thermally optimal power electronics in distributed generation systems [8].

Following the publication of the first ITRW roadmap in 2019, the obvious question to be answered was “what’s next?” and this has led to a wide ranging discussion within the power electronics community about where the technology will go and how this should be focused for the next iteration of the roadmap. This paper summarizes some of these discussions and provides an insight as to how this will be managed within the context of the power electronics community. in particular, the paper will focus on what the Impact of ITRW can be and investigate the question of how can wide bandgap power semiconductors break through globally?

II. A HOLISTIC VIEW OF THE FUTURE OF WIDE BANDGAP POWER ELECTRONICS SYSTEMS

A. WHAT IS THE KEY ISSUE?

The world is facing some major decisions over the next decade in order to solve the critical issues of our time. Climate change has evolved from a fringe issue to one of the key political and economic challenges the planet will face. Decisions we take now will impact the remainder of the 21st century in a fundamental way. It is no longer adequate or acceptable to push off decisions to some arbitrary future date, or even to assume that others will take action on our behalf. It has become imperative for us all to take responsibility of our own actions.

Personal decisions about environmentally friendly actions are now becoming political and legislative. For example, the commitments made by the Paris Accord [9] have led to some increasingly bold actions by major world economies to address these fundamental challenges. The United Kingdom decision in 2020 to make it illegal to sell new fossil fuel powered automobiles from 2030 being a specific case in point [10]. While this is a useful step in the reduction of greenhouse emissions at the point of use, similar decisions must be taken to ensure that the emissions are not simply traded upstream to the grid and electricity producers.

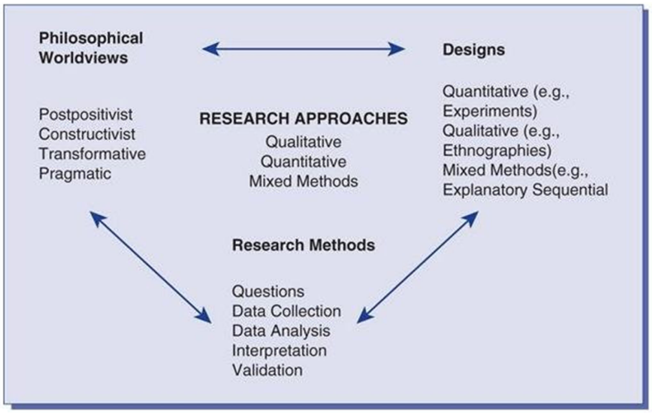

FIGURE 2. ITRW 2019 Research Structure.

An important contribution to this effort is based around increased electrification of transport, and the wider adoption of energy efficient power electronics and technology such as efficient chargers, grid infrastructure, LED lighting, and the wide integration of renewable energy systems into the electricity grid. The impact of wide bandgap power semiconductors is one of the keys to making this a reality.

B. A HOLISTIC VIEW OF THE LANDSCAPE

While it is not necessarily the role of researchers to find all the solutions, it is incumbent on the research community to address the challenges and offer both insight and potential ways forward where we can. It is often the case that applied or engineering research can seem incremental in nature, however with new technology (such as wide bandgap devices) dramatic improvements can be made, and indeed this has been the case with wide bandgap power semiconductors over the last decade.

The role of research approaches (whether quantitative, qualitative or a hybrid) is to link the range worldview to both research methods and also designs as shown in Fig. 2. There are a number of different worldviews, and it is accurate to state that perspectives can be regional or national in nature. This can drive the political and philosophical drivers for technology adoption. For example, national strategies may be to sacrifice environmental good practice in favour of economic growth, and unless the two are symbiotic, this will lead to a conflict between the two goals (in many respects this was the view for most of the 20th century). This is a lesson from history that roadmaps can be useful in identifying and providing insight to the strategic impact of technology change and the drivers for that.

There are a range of philosophical worldviews shown in Fig. 2 that underpin the relationship between research and the ultimate goal of technological change, which include:

- Postpositivism is where the argument is made that research hypothesis, prior knowledge and the collected "wisdom" of researchers can directly impact the observed system.
- Constructivism is more about learning from previous knowledge. This is subtly different from postpositivism in the belief that learning will lead to the "construction" of new ideas that integrate both the old and new knowledge.
- Transformative is the belief that radical and new ideas can transform the world we live in, for the better. This is a positive philosophy.
- Pragmatism is based on the principle that if we see evidence of positive change when applied, then the idea is a good one.

While the philosophical aspects of change may seem esoteric for technology, when it impacts the world so fundamentally, it is important to consider how these changes will make a difference, how this can be measured and what the societal impact might be. At the heart of all these philosophical world views, however, is a common thread of knowledge and understanding. The more we understand the outcome of the research undertaken from both qualitative and quantitative bases, the more positive an impact can be made.

C. THE ROLE OF THE IEEE POWER ELECTRONICS SOCIETY AND ITRW ROADMAP

From a power electronics perspective, which has become a critical part of the technological toolkit to address climate change and global warming, the IEEE Power Electronics Society (PELS) has a crucial role to play in the coordination and dissemination of fundamental technological change and research ideas.

One of the unique aspects of PELS is the truly global nature of the society, and the ITRW roadmap was formed with the fundamental tenets of:

- Being a neutral forum for the exchange of ideas and knowledge relating to Wide bandgap power semiconductors
- Being truly global, with representation from a worldwide range of participants
- Encompass Research, education, policy and industry to ensure the widest societal impact and engagement

The global and neutral forum has been a founding principle of the ITRW and this has led to a wider perspective than would be possible from just a regional or national view. This has also led to shared discussions and a shared vision about strategic elements that takes a wider independent view, that complements regional or national perspectives (which may be valid in themselves, but can co-exist within the framework of a global view).

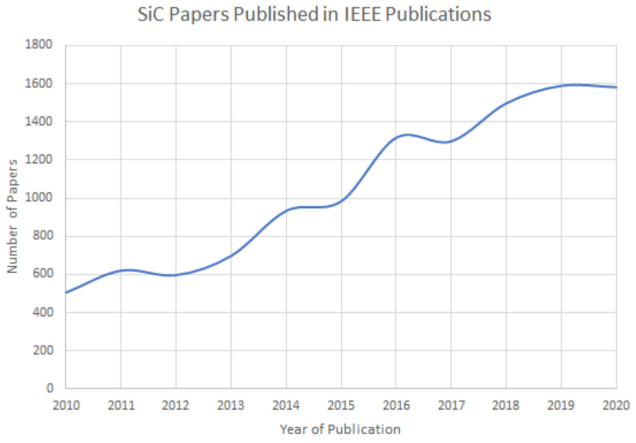

FIGURE 3. Papers Published by the IEEE relating to Silicon Carbide (SiC).

Another important philosophical aspect of the roadmap foundation is the wide technological framework, that not only identifies specific device technology, but also the wider aspects of applications, materials, integration and packaging. This is important as it differentiates the ITRW roadmap from others which may be so focussed on specific technology change that the wider impact can be lost. This also links the impact of technology philosophical world views to identify the potential benefits to the wider community.

An interesting aspect of the adoption of wide bandgap power semiconductors has been the dramatic output of knowledge relating to these devices and their application. Fig. 3 shows the raw numbers of papers published across the IEEE portfolio between 2010 and 2020 (2020 is probably slightly lower than would be expected due to the Covid-19 Pandemic) that mention Silicon Carbide in some way. Clearly some of these papers are not directly applied to power electronics as such, however many are. Looking at the publications over the last decade it is interesting to notice that in the early years much work was focussed on fundamental material and device development, and the research shifts more onto applications and topology investigation, showing a maturation of the technology. Whichever philosophical worldview is used, there has been a 300% increase in ideas and knowledge based on raw paper count from the IEEE alone, which can only be a positive outcome.

The final pillar of the ITRW roadmap effort has been the coordination of the variety of technology areas via the individual working groups. A key function of those working groups is to share knowledge to identify possible pillars and critical issues to be addressed that would be necessary to achieve the ITRW main goal "to facilitate an acceleration in the R&D process for this new technology to fulfil its potential."

III. LIMITATIONS OF ROADMAPS

It is important to understand the limitations of ITRW and relevant sister roadmaps for creating sustainable technology implementation tracks. Technology roadmaps in themselves do not guarantee progress.

Roadmap	Nature	Visible industrial impact
Power America	Raise the TRL level of SiC power semiconductors	Medium; system integration is not addressed
SiC Alliance	Development of SiC based ecosystem with focus on a Japanese strength = locomotives	High; because it actively covers the full system technology ecosystem/chain
CASA	Comprehensive technology study covering the full power WBG scope	Medium; used to lobby for funding of large R&D program, does not directly help technology development
ECPE	Technology document written by and adhoc committee.	Medium; is used to create synergy within an industry consortium
NEREID	Technology document written by and adhoc committee.	Low; no follow-up
HIR	Comprehensive technology study covering the full scope of power HIR	Medium; lacks a motor to drive technology innovation.
ITRW 2021	Comprehensive Technology Roadmap	High; Covering Research and Industry

FIGURE 4. **A soft assesment of the industral impact of roadmaps related to WBG power devices.**

The eponymous "Moore's Law" could be argued to be more accurately defined as Moore's observation or Moore's prediction. But, what the computer roadmap ITRS did achieve was to unify the the complicated technology chain and ecosystem to focus on a single benchmark and specific application, the processor chip. The outcome was a revolution in the development of computers. We learned during the years that ITRW does not lend itself to the same type of singular impact. The reason is that the applications and power levels are extremely diverse in power electronics.

A number of regional WBG power semiconductor roadmaps were written, each with a different focus and underlying goals. The Heterogeneous Integration Roadmap also contains some content that is relevant to ITRW. In ITRW 2019 a section was devoted to discuss these roadmaps. It is explained that the role of ITRW is was serve as an umbrella activity to supplement and coordinate instead of duplication. The real test of a roadmap is the ability to engage industry. As is explained, in our opinion as described in Fig. 4 the direct industry relevance is moderately addressed in most of the roadmaps, including ITRW 2019, with one exception. Behind the SiC Alliance of Japan exists a program to develop locomotives based on SiC devices. In this way the system application becomes an integral part of the roadmap activity.

IV. BRIDGES BETWEEN ACTIVITIES

One of the challenges that surfaced during the working group meetings held by ITRW was that the interfaces between the activities of the working groups were difficult to define. A different technical community deals with devices that the community that concerns itself with packaging of devices in modules. When the module working group asked the converter working group what the future specification for modules will be they did not have an answer ready. Similarly the system integrators had difficulty to express their future technical requirements for converters. The attitude has been: "Tell me what you can offer me". It seems that complexity of a modern converter system is too high for a single technical community to oversee the the whole system, something that is very much needed for a roadmap exercise.

So, for the next phase of ITRW it is important to find better ways to bridge the working group technical activities. To illustrate the challenge two criteria per bridge is shown in Fig. 5. The links between devices, modules and systems can be dealt with expertise residing in ITRW and the IEEE community. More challenging is the link between converter systems and the resulting holistic impact. It is not direct and has to cross two bridges and pass the test of industrial relevance. However, if efforts can be coordinated then the technology transformation does not be limited to new semiconductor devices. Due to the fact that higher levels of circuit integration benefits the operation, the basic building blocks from which converter systems are assembled can be changed. This of course requires investment in new fabrication technologies, but the large volume of power electronics needed to enable the energy transition would make it affordable. An incentive to change the building blocks used in assemblies is to reduce the engineering effort to realise the large number customised designs as a result of the varied system requirements that characterises power electronics.

V. ITRW ORGANIZATION AND STRUCTURE

A. ITRW GOVERNANCE MODEL

Any roadmapping exercise that is intended to be genuinely global and representative of the whole community it represents must ensure that it has clear and transparent governance structures, represents all the stakeholders in the field and is global in nature. To this end, the ITRW has been formed with all three of these fundamental tenets at its heart. The ITRW has a steering committee that consists of leadership from societies, industry, government and academia bodies. The participation and leadership of industry is at the heart of the ITRW process and therefore in addition to key industry people involved on the steering committee there is a wider industry advisory board (IAB) that has a specific role of ensuring that the ITRW is relevant and technology driven.

The steering committee also has strong technical representation from the specific technical working groups, ensuring that a broad participation of individuals across all aspects of wide band gap power semiconductor technologies are represented. As with the steering committee, there is extensive

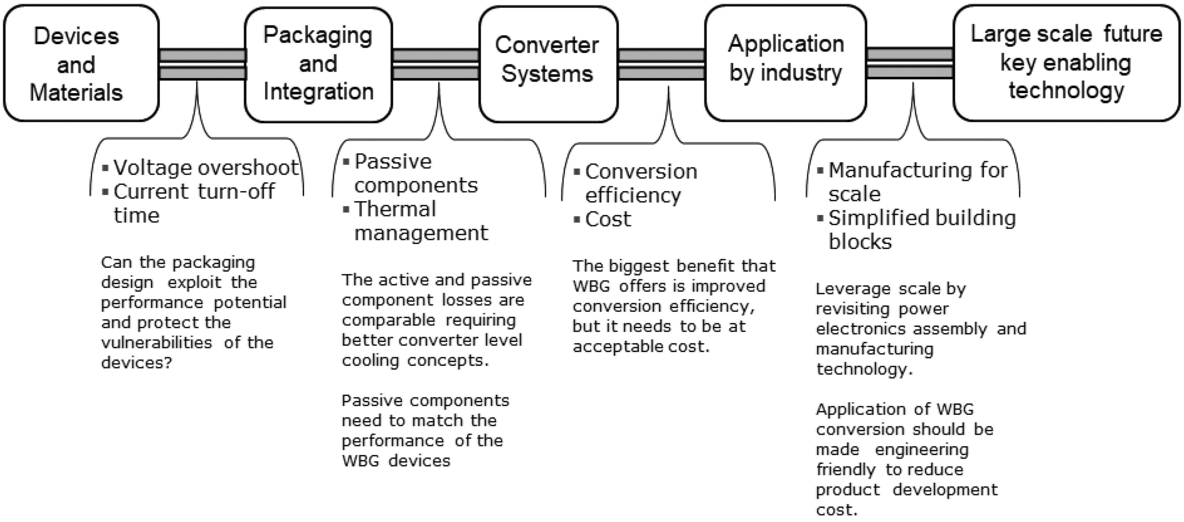

FIGURE 5. **The integral success of ITRW will depend on the ability to connect the various levels.**

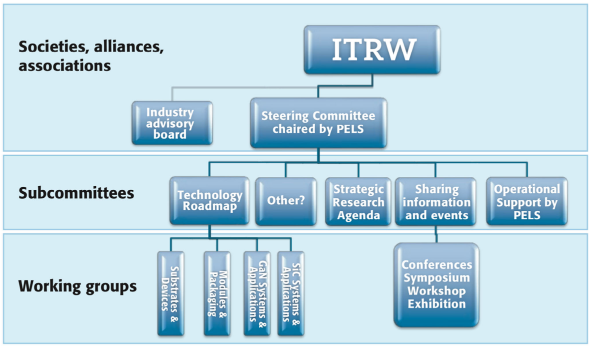

FIGURE 6. **ITRW Structure.**

industry participation in the individual working groups. The structure of the ITRW as shown in Fig. 6 has been designed to be inclusive and participation is open, to ensure that decisions taken are fair and neutral, the voting membership of the steering committee broadly follows the conventional IEEE approach taken for standards activities in that no one company, geographical grouping or constituency can dominate. In the early stages of the ITRW existence, the steering committee was formed based on interest and knowledge of the field, however over time it is envisaged that the future executive officers will be elected as the organization becomes self-sustaining.

As well as the broad technical groupings shown, there will be underpinning technology interests shared across the technical working groups such as reliability, data sheets, testing, design techniques and these will be developed across the working groups where appropriate.

B. THE ROLE OF THE ITRW WORKING GROUPS

The ITRW working groups consist of 4 areas in the ITRW2019 and ITRW2021 revisions with the following technical remits:

- Materials and Devices
- Packaging and Integration
- SiC Applications
- GaN Applications

1) MATERIALS AND DEVICES WORKING GROUP

The Materials and Devices working group is fundamental to many of the processes and device technology required for a successful take-up of wide bandgap power semiconductors. Details of the recent work of the working group was published in [11].

2) PACKAGING AND INTEGRATION WORKING GROUP

The Packaging and Integration working group is fundamental to many of the processes and device technology required for a successful take-up of wide bandgap power semiconductors. Details of the recent work of the working group was published in [12].

3) SiC APPLICATIONS WORKING GROUP

The SiC Applications working group is fundamental to many of the processes and device technology required for a successful take-up of wide bandgap power semiconductors. Details of the recent work of the working group was published in [13].

4) GaN APPLICATIONS WORKING GROUP

The GaN Applications working group is fundamental to many of the processes and device technology required for a successful take-up of wide bandgap power semiconductors. Details of the recent work of the working group was published in [14].

VI. SUMMARY

The ITRW structure has been in place since 2016 and has resulted in the organization of working groups, an effective governance structure and the linkage with an industry advisory board. The leadership of the working groups has cycled through to a second iteration which has been a healthy and welcome update with each working group maintaining continuity and fresh ideas. The overall structure led to the successful publication of the inaugural ITRW roadmap in 2019, less than four years since the ITRW formation in December 2015 and a healthy global community that is recognised not just in the IEEE Power Electronics Society, but across the IEEE and beyond. This is a strong foundation which can be built on for future roadmap efforts.

VII. STRATEGY FOR ITRW 2021

A. NEXT STEPS FOR ITRW

The next steps for the ITRW roadmap are to establish the foundations for its second iteration. This requires a staged approach to the gathering of data for a revision to the roadmap and to this end the ITRW working groups and steering committee have taken a publication based approach to the production of the data for the ITRW to be published in 2021. A key aspect of this approach is to use an Open Access model wherever possible to enable the widest dissemination of the material in the roadmap. This special issue of the IEEE Power Electronics Society Open Journal for Power Electronics [15].

The unique circumstances of 2020 and 2021 (working around the Covid-19 pandemic) has meant many activities have been required to use a different approach for collaborative working and this was not the only reason for taking a publication based approach, but it was considered to be a useful way to accelerate the production of the roadmap taking into account the most recent activities in research and development. This approach is discussed in the following sections of this paper.

B. RESEARCH APPROACH FOR ITRW2021

A key question for ITRW 2021 is how will the roadmap evolve from the 2019 edition. The 4 main working groups are well established and produced a great selection of material for the 2019 roadmap, however it is clear that the perspective of the impact of wide bandgap power devices is broader in 2021. The “Climate Emergency” movement and the general acceptance of the impact of emissions on the climate has propelled the issue of electrification firmly to the top of the global agenda.

With this in mind, it has become imperative that technological efforts to accelerate the move towards transport electrification and the adoption of Smart Grid technology are linked to political and economic drivers and that the providers and innovators of the fundamental technology are aware of not only the performance aspects of research, but are driven by the wider needs of the public. ITRW is already addressing many of these topics (with some shown in Fig. 7, however it is likely that wider input will be required from beyond the IEEE Power Electronics Society to provide the broader perspectives needed to link the technology innovations with the economic and political imperatives.

C. MARKET PERSPECTIVES - MARKET POSITIONING

In the 2019 edition of the ITRW roadmap [1] sections of the roadmap were devoted to detailed market analysis [2], where the rapid expansion of the market for wide bandgap products was clear. With the benefit of perspective, it is possible to make an initial evaluation of the continued market position with regard to demand for wide bandgap power semiconductors and products and it is clear that there is a strong and growing demand, with projections showing strong demand over the next 5 years at least [16].

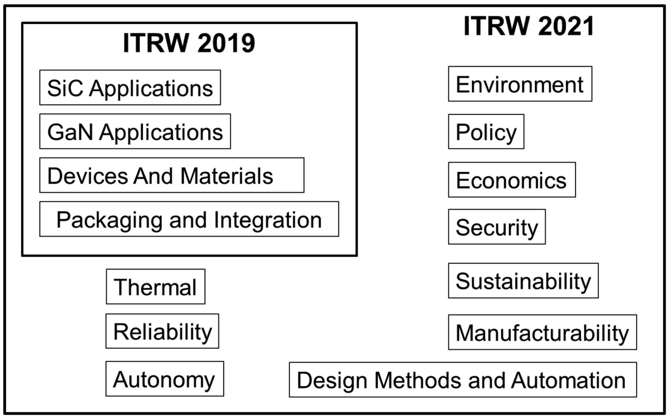

FIGURE 7. Potential Expansion Topics for ITRW 2021.

Key drivers for the continued growth are the likely massive expansion of electrification of transport (particularly electric vehicles (EVs)) and in infrastructure including Grid and LED Lighting, where demand continues to surge for both SiC and GaN products.

D. SHARED TECHNOLOGY ANALYSIS - SHARED TECHNOLOGY FRAMEWORK

Up to now, the ITRW working groups have operated relatively independently, however we see that there will likely be increasing levels of collaboration required, particularly between the technology and application areas. As discussed previously in this paper, there is a natural inter-disciplinary need across bridges between applications, modules and devices, and this will require a shared technology framework to realise the goal of shared technology analysis. How this approach of Shared Technology perspectives will operate will lead to technology integration teams, looking across different discplines and linking experts and users to understand with more depth how best to leverage and apply new innovations in wide bandgap power semiconductors for future research and development of products.

E. HOW WILL ITRW 2021 OPERATE?

ITRW will develop this idea of a shared vision across technology levels and disciplines, to create a shared vision about strategic elements. One of the key aspects will be the shared dissemination of papers in coordinated forms (such as this special issue), with a goal of creating a shared virtual framework to link materials, devices, systems to the philosophical world views discussed in this paper.

This vision, while ambitious, will allow the ITRW roadmap to further develop and have a potentially much greater impact than simply a technology signpost of new research and innovation, but also contain a clear rationale and demonstration of the impact of the great work being carried out by researchers and engineers in this exciting and dynamic field.

VIII. INDUSTRIAL IMPACT

A. THE IMPACT OF WIDE BANDGAP POWER SEMICONDUCTORS

The impact and relevance of wide bandgap power semiconductors for global industry in the power electronics field has been profound. It is safe to say that in certain market sectors (such as Aerospace, Electrification of Transportation (trains, cars and the marine sector) [4]–[7], Grid connected power electronics [8], renewable energy [17], consumer electronics (especially chargers) and in many other fields, the penetration of wide bandgap power semiconductors (primaily SiC and GaN based products) has become so prevalent as to make them the dominant force in those fields for the future (and in some cases the present). Silicon power electronics still have a massively important role to play where breakdown voltage and efficiency are a lower priority than cost, however the cost of SiC and GaN devices has been steadily reducing to close this gap.

B. THE ROLE OF ITRW FOR POWER ELECTRONICS

The impact and relevance to industry is a perennial challenge for roadmaps and this is no exception for wide bandgap power semiconductors. There is always a tension between forecasting and providing a clear direction for the industry and this is where roadmaps, such as ITRW, have a role to play in connecting researchers working at the cutting edge and industry practitioners who need to be able to design products using the best devices available at a reasonable cost. Roadmaps specifically can act as a driver to innovation in this way, but also in focussing standards efforts and also providing a vision for future investment.

C. STANDARDS AND POLICY

Standards are an essential aspect of delivering globally recognised compliant products, and those standards can be defined regionally, nationally and globally (such as IEEE standards). The role of standards in power electronics [18] is a specific niche area where there is a need for further work. Standards that already exist for the design and implementation of power electronics systems, such as IEEE Std 1573 [19], provide a broad framework that can be used as a set of guidelines for power electronics practitioners, with Silicon or Wide bandgap devices, however there are differences in interpretation and also the necessity for new wide bandgap specific standards to be developed.

The Joint Electron Device Engineering Council (JEDEC https://www.jedec.org) has a strong role to play in the definition and application of global standards for semiconductor technology globally, and one of the roles of the efforts such as ITRW is to facilitate good communication and sharing of information between working groups in this field. Bringing researchers and practitioners together within a global forum and identify where common ground exists, looking for opportunities to develop new standards. A great example of the JEDEC industry focus has been its development of wide bandgap specific standards (such as test method guidelines for Gan HEMT dynamic on-resistance JEP173) specifically for industry practitioners.

D. ROADMAPS

There are a number of roadmaps in this area and while a comprehensive list is beyond the scope of this paper, however there are a number of parallel efforts within the IEEE community, such as the The Electronic Packaging Society (EPS) Heterogeneous Integration Roadmap (HIR) covers a wide range of electronic applications, including integrated power electronics (IPE), as part of the system-in-package (SiP) solutions [20].

To maximize the efficiency and effectiveness of both roadmaps, the ITRW will work in cooperation with the HIR team by sharing knowledge and the experience of power electronic packaging and integration. This will be facilitated by cross-representation within relevant groups of the ITRW and HIR.

As described in Fig. 4, there are a number of regional and national roadmaps, each with a scope and purpose that is focussed on the requirements for that region or nation. For example, the Power America roadmap published in 2017 [21], is publicly available online and provides a North American perspective on wide bandgap power electronic devices. whereas the CASA roadmap [22] is a China-centric equivalent.

IX. BARRIERS AND DRIVERS FOR ADOPTION OF WIDE BANDGAP POWER ELECTRONICS

The explosion in growth of wide bandgap power electronics is driving research and development into some critical areas to improve the overall performance and reliability of these new devices. Applications are forcing new innovations in areas such as device reliability and lifetime, higher voltage, improved gate drive circuits, module design and packaging, thermal design and greater efficiencies. These barriers to adoption are rapidly being addressed or investigated. There are also drivers to the increased adoption of these devices, which in many cases are industry or applications specific, such as GaN for LED lighting and SiC for traction and EVs.

With any new device technology, it takes time for both an understanding of the long term capabilities of the devices, but also for processes to improve. Both these factors have led to initial uncertainty of the reliability of wide bandgap devices, however this is now being understood much better than in the early versions of these devices. Recent work into a comparative analysis of the long term reliability and performance of SiC devices [23] has provided detailed insight into these aspects and a similar review for GaN power electronics devices in [24]. In both cases it is clear that while challenges remain, the improvement of both wide bandgap technologies that are of fundamental importance to power electronics has been dramatic.

The barriers to adoption of wide bandgap power semiconductors are relatively well understood and have been documented in [25]. Fundamentally it can be summarised in 4 main areas:

- Cost: The substrate and processing costs for power wide bandgap devices are generally higher than for their equivalent Silicon counterparts.
- Design: new design techniques (such as gate drive circuits or packaging) are required for wide bandgap devices and this adds an upfront design cost (in monetary and time terms). This is reducing as the cumulative design experience grows, and tools come online to support design engineers.
- Reliability: SiC and GaN devices are still relatively new and designers are learning more about the real world application and deployment of the devices. Reliability has been a concern for wide bandgap power devices, however as more are deployed, this knowledge increases.
- Integration: both SiC and GaN devices require special consideration for packaging and layout that require additional effort - it is not always a like for like replacement to a previously used Silicon device.

Despite these issues, the use of wide bandgap power devices is still relatively new and knowledge is being gained rapidly. Production costs are decreasing to some extent as competition becomes more widespread and availability of substrates and materials increases.

As described previously in this paper in Fig. 5, one of the key drivers for future adoption of wide bandgap power semiconductors will be how the technology can be bridged between devices, packaging and integration, systems design, applications and large scale deployments. This is itself a product of the key drivers pushing the demand for the wide bandgap power electronics technology:

- Faster power electronics devices: One of the most obvious advantages from a power electronics perspective is the sheer speed of SiC and GaN devices. Harnessing this speed to reduce design size, especially passives and packaging, and to increase efficiency is a hugely attractive driver for this technology.
- Compact packaging: a combination of higher switching speeds and better thermal efficiency means that power electronics modules can be more compact, lighter and require less cooling infrastructure than previous generation of technology. This has an obvious secondary benefit of potential cost reductions at the system level
- Better Efficiency: The faster switching speeds and improved $R_{ds(on)}$ characteristics lead to converters of very high efficiency, with a trade off against device cost, however this can be significantly offset by much cheaper passive components and smaller packaging.
- New packaging and product design technology: One of the major drivers for upscaling of wide bandgap power electronics is the reduced packaging, simplified cooling systems and reduced size. New design techniques are also pushing towards simplified design and manufacturing techniques opening up the potential for wide uptake of the devices across a range of industry applications.

In summary, while barriers do still remain, they are being rapidly overcome, and the concomitant benefits of reduced packaging and material costs are offsetting the initial increase in device costs.

X. LESSONS FROM THE FIRST DECADE OF POWER WIDE BANDGAP SEMICONDUCTORS

While it is true to say that wide bandgap devices have been around for longer than a decade, it has really only been in the last decade that there has been widespread adoption of SiC and GaN based devices in power electronics on a wide range of applications. One of the major lessons that can be drawn from these years has been the need to focus on the complete "ecosystem" from devices through to applications and to ensure an integrated design methodology and infrastructure is in place to enable this to happen effectively.

A good example of this in practice has been the transition of the Japanese High Speed Train "Shinkansen" to using 3 kV SiC MOSFET technology [3]. This highlights the need for a coordinated and integrated approach to ensure that research, development and innovation are supported strategically with a clear goal in mind. The result has been not just the development of a new generation of high voltage SiC devices, but that they are able to be deployed successfully in a traction system.

Another hugely successful area has been the increasing use of GaN technology for consumer and lighting products. LED lighting is rapidly replacing incandescent technology and as mentioned previously in this paper, where reliability was once an area of concern, now the increased lifetime of LED lighting is seen as a positive aspect of products using this technology.

The explosion of electric vehicles and the increasing drive to zero carbon in road transportation has been a case where the use of SiC devices has been instrumental in accelerating this change [26].

What is striking is how successful the adoption of the new wide bandgap power device technology has been in almost every application area, despite a variety of technical challenges en route. There have been some lessons along the road of wide bandgap power semiconductor device adoption including:

- Packaging and Layout: How devices are packaged is critical to their success. This applies to both electrical and thermal behaviour. The higher dv/dt rates inherent in SiC and GaN devices lead to high frequency transients and these need to be managed carefully to avoid excessive oscillations and EMI effects. Careful management of these effects also leads to more efficient power conversion and more reliable systems.
- Thermal management: while SiC devices are inherently tolerant of a wider thermal range than their Silicon counterparts, this is not always the case for components or packaging around them. A key lesson has been to ensure

that heat is effectively managed and controlled away form the devices to ensure efficent and safe operation.

- Gate Drive circuits: As devices speed has increased, this has led to the need for not only faster gate drive circuits, but also adaptive to be able to achieve the optimum performance possible from the devices.
- Simulation models: while there has been significant progress in development of improved simulation models of devices, there has not necessarily been the same level of progress in model characterization tools, especially for users without access to the device fabrication parameters. This is a perennial issue for power designers, but is more critical in wide bandgap devices where transition speeds and power densities are higher.
- Parasitics matter: Conventional design techniques that take into account parasitic components (especially lead inductances) are even more critical with wide bandgap devices.

While there are certain to be more lessons to be learnt from the use of wide bandgap power devices as the technology matures, some application specific, however one of the key roles in the ITRW effort has been the sharing of good practices among the global power electronics community and highlighting where research needs to be undertaken to solve the ongoing and emerging challenges of using these devices effectively.

XI. CONCLUSION

The rapid adoption of wide bandgap power electronics into the mainstream has been a dramatic shift in the wider sphere of power electronics as a discipline. The role of ITRW as a forum for the exchange of ideas and networking of individuals and teams globally has led to multiple publications, a new global roadmap in the power electronics field, and a future strategic vision for the adoption of wide bandgap power electronics.

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