Report Summarizing the Outcomes of a Two-Day Technology Roundtable

# GaN Standards Roundtable

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The Institute for Energy Efficiency
UC Santa Barbara

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# Acknowledgements

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### *Participants*

| **Name** | **Organization** | **Title** |
|---|---|---|
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| Sandeep Bahl | Texas Instruments | Director of Reliability, Devices & Modeling, III-V Products group |
| Herbert Bennett | NIST | NIST Fellow and Executive Advisor |
| Paul Chow | Rensselaer Polytechnic Institute | Professor, Electrical, Computer and Systems Engineering Department |
| Paul Delaney | Southern California Edison | Senior Engineer |
| Pawel Gradski | Booz Allen Hamilton | |
| Monty Hayes | Delphi | Manager, NA Advanced Hardware Electronic Controls, Electronics and Safety |
| Al Hefner | NIST | Power Semiconductor Devices Project Leader, and Smart Grid Team Member |
| Karl Hobart | U.S. Naval Research Laboratory | Head, High Power Devices Section, Power Electronics Branch |
| Charles Kim | Southern California Edison | Sr. Engineer, Energy Codes & Standards, DSM Engineering |
| A.J. Nadler | RFMD | General Manager, Power Conversion Devices Product Line |
| Aivars Lelis | U.S. Army Research Laboratory | Electronics Engineer, Team Lead |
| Qiang Li | Virginia Tech | Assistant Professor, Center for Power Electronics Systems |
| Alan Mantooth | IEEE & University of Arkansas | Distinguished Professor of Electrical Engineering |
| Pallavi Madakasira | Lux Research | Analyst (Report Writer) |
| Tim McDonald | International Rectifier | Vice President, GaN Technology, Device Engineering and Product Development |
| Umesh Mishra | UCSB | Professor, Electrical and Computer Engineering |
| Dennis Monticelli | Texas Instruments | Texas Instruments Fellow, Kilby Labs |
| John Parsee | ON Semiconductor | Senior Scientist and Director, Advanced Materials Technology Development |
| Klaus Pietrczak | Power Integrations | Marketing Director |
| Peter Savagian | General Motors | General Director, Electric Drive and Systems Engineering, Electrification, Global Vehicle Engineering |
| Hemal Shah | Fairchild Semiconductor | Product Line Director |
| Jin Wang | Ohio State University | Associate Professor<br>Department of Electrical and Computer Engineering |
| Yifeng Wu | Transphorm | V.P. of Product Development and Applications |
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## 1. Introduction and Roundtable Goal

Power electronics are devices that transform and control electrical energy, managing the attributes – such as voltage (V), current (I), frequency, and waveform – that are necessary for the proper functioning of almost anything that runs on electricity, from consumer electronics to electric motors to renewables to the electricity grid itself. As a result, power electronics will be a key enabling technology for providing efficient, intelligent, and optimal use of energy resources. They're growing in importance now both because of an increasing drive for energy efficiency and a resurgence of innovation in power electronic components, including materials innovations like the use of silicon carbide (SiC) and gallium nitride (GaN).

There's clearly a growing opportunity in power electronics, but the challenge for both current market players and would-be entrants is finding the places where these emerging technologies meet customer needs at the right price points. While consumer electronics is a "here and now" opportunity, fast-growing industries like renewable energy and industrial power applications are likely to challenge the power electronics manufacturers to innovate on form factor and improve efficiency at the lowest cost.

Historically, almost all power electronic devices have been based on silicon (Si) semiconductor material. However, Si-based power electronic devices are reaching their theoretical limits, and other semiconductors, most notably SiC and GaN, are steadily making inroads into the power electronics industry. Along with new device architectures and structures, these materials offer the promise of better performance devices, as well as superior thermal management – critical for temperature-sensitive applications like automotive and industrial motor control and enabling for longer-term high-voltage grid application (see Figure 1). These emerging materials still have higher costs than Si, but their performance advantages and the energy savings they can bring make them the lynchpin for innovation in emerging power electronics.

Figure 1 – Comparison of Material Properties

| **Material Properties** | **Silicon (Si)** | **Silicon Carbide (SiC)** | **Gallium Nitride (GaN)** |
|---|---|---|---|
| Bandgap (eV) | 1.1 | 3.2 | 3.4 |
| Critical field ($10^6$ V/cm) | 0.3 | 3 | 3.5 |
| Electron mobility ($cm^2$/V-sec) | 1450 | 900 | 2000 |
| Thermal conductivity (Watts/ $cm^2$ K) | 1.5 | 5 | 1.3 |
| Electron saturation velocity ($10^6$ cm/sec) | 10 | 22 | 25 |

On March 11 and March 12, 2014, UC Santa Barbara's Institute for Energy Efficiency convened a two-day technology roundtable that brought together 24 industry leaders representing device and system integrators, research institutes, government laboratories, standards organizations, and academics. This technology roundtable was one in an ongoing series hosted by UC Santa Barbara's Institute for Energy Efficiency, each aimed at accelerating the development of a different technology driving energy efficiency.

The roundtable aimed to address critical needs in GaN-based power electronics device manufacturing. Specifically:

- The need for a GaN-device product roadmap that developers can agree upon to drive faster commercialization of the products as well as to set broad market expectations of product roll-outs

- The need for a consensus on the applications best positioned to adopt GaN-based power devices to enable better market preparedness and eliminate any misconceptions about the technology
- Very importantly, the need to establish performance and efficiency standards for GaN-based power device manufacturing, which was central theme of the roundtable

At the end of the two-day discussion, all participants came to a consensus on the methodology to implement standards, the applications where GaN will be better suited as well as relevant terminal specifications for GaN power devices.

## 2. Roundtable Methodology

### 2.1 Meeting Agenda

The roundtable was anchored by five presentations providing background on the following key focus areas: GaN devices and applications; GaN reliability and terminal specifications, and standards and the role of technical standards and regulations; and current energy efficiency regulation activities and legislation. At the end of these presentations, participants were allowed to ask questions and generally discuss the findings presented in each of the presentations.

Participants were then divided into two smaller groups to engage in further discussion in two back-to-back break-out discussions. Both break-out discussions had different topics. Discussion in these groups was unstructured, so each participant could independently put forward topics he or she thought relevant to the discussion. At the conclusion of the breakouts, a representative from each group summarized the discussion for the larger group, sparking further discussion. Topics for the break-out sessions are described in Figure 2.

Figure 2 – Break-out Session Topics

| **Break-out Session** | **Topic** |
|---|---|
| Session 1 | What applications are ready to adopt GaN technologies? What application performance and efficiency standards might be achieved? Where are there adequate standards? Where are there not? |
| Session 2 | What device terminal characteristics and reliability specifications, and what application performance specifications, are needed for devices and systems for GaN? |

## 3. Challenges in GaN Commercialization

There are a number of hurdles in the commercialization of GaN-based power devices. For a start, GaN substrates are not available in commercial quantities and at competitive prices; hence, GaN devices are being made using cheap Si or much more expensive SiC substrates. The lattice mismatch between the GaN epitaxy layer and the underlying substrate requires the formulation of complex buffer layer solutions, with each manufacturer using varying methods and recipes. In addition to this underlying challenge in the development of GaN-based power devices, industry skeptics have largely questioned the relevance of GaN in many applications. Specifically:

### 3.1 GaN technology is new and mostly pursued by start-ups

GaN-based power device manufacturing is mostly being pursued by start-ups, such as Transphorm, Efficient Power Conversion, VisIC, and GaN Systems, with few incumbents, such as IR, RFMD, and Panasonic, with plans to release GaN-based power device products near-term. With venture capitalists continuing to be the primary backers in most of these start-ups, competing SiC and Si power device players are skeptical of the ability of start-ups to roll out products in the near future. Even though this is slowly changing – Transphorm, for example, is working with Yaskawa and acquired the GaN assets from Fujitsu – competitors continue to be skeptical of the technology and its viability.

### 3.2 Misconceptions around technology fit

As with any industry that is mostly dominated by start-ups, there are misconceptions around how GaN technology fits in different applications. One of the big reasons for this misconception is due to the differing near-term application focus for each of the developers. While some start-ups are entirely focused on power factor correction (PFC) and power supply applications, others appear to be much more focused on potentially longer term electric-vehicle applications. With limited off-the-shelf GaN products, developers need to address the misconceptions around technology fit.

### 3.3 Lack of standard device characteristics and metrology specifications

With several product developers rolling out their GaN transistors and diodes, there is a lack of consensus around on what key device characteristics should be reported in data sheets. For example, some device characteristics such as on-state static and threshold voltage for GaN are very different compared to silicon devices and yet GaN product developers resort to using existing data sheets prescribed for silicon devices. Since the technology is still new to the market, to win customer confidence, the discussion group raised concerns around the lack of universal test standards for GaN (like the ones that exist for silicon devices). In addition, there are no metrology specifications to determine wear-out mechanisms for GaN devices.

### 3.4 Lack of standards for terminal specifications and reliability or best practices

Unlike in the traditional Si semiconductor industry, the GaN manufacturing industry lacks a recommended best practice or prescribed standards for terminal specifications and reliability. This deficiency in turn has created confusion in the industry as to the claims made by GaN power device developers around specific device metrics and test methods and conditions. GaN product developers will need to work with standards bodies, such as Joint Electron Device Engineering Council (JEDEC), the Institute of Electrical and Electronics Engineers (IEEE), or National Institute of Standards and Technology (NIST), to ensure there is interoperability between different electrical components.

The roundtable participants reviewed all of the above perceived and existing challenges to successful GaN power device commercialization.

## 4. Roundtable Summary and Recommendations

The roundtable participants discussed reasons for the misconceptions around GaN, technology fit, and applications best suited for GaN. The group came to a consensus on all these topics and recommended next steps to ensure the efforts of the roundtable are carried forth.

These recommendations can be clustered into four sub-topics: GaN manufacturing roadmap and application fit; performance and efficiency standards for GaN device manufacturing; device characteristics and metrology specifications for GaN; and next steps in engaging with JEDEC, NIST, and IEEE standards organizations.

### 4.1 GaN Product Roadmap

Among the different GaN developers, each has a different product roadmap – with some targeting power supply and PFC applications, and others targeting the solar inverter and electric vehicle markets. Unlike the power supply and PFC markets, the solar inverter and electric vehicle markets are especially sensitive to product reliabilities that are directly tied to product warranties. Product certification times in the electric vehicle market are especially long – taking anywhere from 18 months to three years. In fact, a growing trend across most applications in power electronics is the increasing power density. Given this trend, there is a tendency to develop complex GaN circuits that are too sophisticated for volume manufacturing. The group agreed that in fact, a simplification of GaN circuits is necessary for mass appeal and manufacture.

Participants in the roundtable agreed that to remove any misconceptions around technology fit, the GaN industry needs to agree to a product roadmap so as to set market expectations for a successful adoption of GaN-based systems. The group hence came to a consensus that PFC, resonant converters (LLC), and solar inverters would be applications that will incorporate GaN-based devices by 2015, while power adapters using GaN components will be rolled out in 2016.

The roundtable group further concluded that lower voltage applications like PFC, LLC, solar inverters, and power adapters would be better suited for GaN adoption instead of electric vehicles and motor drive applications that will require substantially more time to qualify GaN. They also concluded that it was better to focus on markets where incumbent Si is struggling to cope instead of higher current applications, given the lack of progress in this regard with GaN-based power devices.

### 4.2 Performance and Efficiency Standards Needed for GaN Manufacturing and Adoption

To ensure GaN products made from any developer are consistent in quality and performance, the roundtable group agreed that performance and efficiency standards for GaN manufacturing needed to be better understood and established. However, given the lack of any standards in the GaN industry, the group discussed existing performance and manufacturing standards that are used for Si devices. Due to the difference in device performance between Si and GaN, there was consensus that some new criteria needed to be established to accurately reflect the performance and efficiency of GaN devices in applications. These standards should make it easy for the system integrators to understand the benefits GaN provides in light load efficiency, size, and weight, along with the lower cooling requirements at a system level.

For a start, there was consensus in that titanium standards would enable GaN to enter PFC and LLC applications. While discussing existing performance and efficiency standards that are particularly effective, European and Chinese efficiency standards were identified as being especially stringent on efficiency requirements in pumps and refrigeration applications. California Energy Commission (CEC) criteria for photovoltaic (PV) inverter efficiency standards were also pointed out as being a model for the roll-out of consistent quality of products in the PV industry. The group agreed that such stringent requirements similarly for GaN would instill confidence in GaN products globally and enable broader adoption of GaN-based products.

As for gaps in existing performance and manufacturing standards, there was overwhelming consensus that Energy Star should require the specification of more than just full-load and standby power efficiency. Having better standards for electromechanical efficiency in variable speed drive (VSD) efficiency standards was also pointed out as being a gap in the existing requirements. The group also suggested instituting manufacturing standards to account for lower consumption of rare materials and recycling, which would create a drive towards adoption of GaN.

## 4.3 Device Characteristics and Metrology Specifications for GaN

With developers looking to roll out off-the-shelf products using GaN, there is a need to harmonize definition and measurement of key performance characteristics of GaN devices (including depletion mode, single-chip enhancement mode, cascode, and devices with built-in gate drivers). This is particularly true for characteristics that are different from incumbent Si devices.

Specifically, the group pointed out that the metrology and JEDEC standards that exist for silicon devices today need to be modified for GaN devices for terminal characteristics – such as on-state static, dynamic on-resistance ($R_{on}$), threshold voltage, and leakage at rated voltage ($V_{bd}$) – along with an update to the JEDEC guideline for measuring gate charge ($Q_g$). To also ensure customer confidence, participants at the roundtable suggested that universal test standards be developed/specified and used to specify device robustness. This includes, for example, forward-bias safe operating area (FBSOA) and reverse-bias safe operating area (RBSOA) for the different flavors of GaN devices.

The group also voiced consensus around the need to determine reliability wear-out mechanisms for GaN-based power conversion devices. For example, this may entail accelerated life testing in high-temperature reverse bias (HTRB) and high-temperature operating life (HTOL) to confirm failure mechanisms and to extract their acceleration factors and activation energies ($E_a$). This will require extended study of reliability behavior and mechanisms by the research and industrial communities using test devices and structures to evaluate, for example, dielectric breakdown, surface passivation integrity, and contacts. The aforementioned work is a necessary prerequisite to calculate GaN power conversion component useful life under customer-specified use conditions to determine suitability for use in different markets/applications.

## 4.4 JEDEC, NIST, and IEEE Standards for GaN Manufacturing

In addition to discussing GaN product roll-out roadmaps and the need for a modified set of standards for performance and manufacturing, the roundtable participants also heard from Herb Bennett from NIST, Jason Hochstetler from JEDEC, and Alan Mantooth from the University of Arkansas (IEEE) on the existing manufacturing standards and recommendations for best practices in place today in the Si industry.

It was pointed out that different standards, such as IEEE and JEDEC, are better suited for different technologies, depending on what the market needs are. The standards experts urged the participants and the broader GaN industry to come to a consensus on the market needs for GaN; this way, establishing standards for the GaN industry broadly will be an easier process. They specifically stated that motivated industry groups could move the process of standards development faster.

Typically, a standards-setting organization (SSO) like JEDEC moves faster than an organization like IEEE, and can complete the process in about one year. The most time-consuming process is typically related to convening the working group. Participants also voiced their concerns around the perceived risk in moving too quickly with standards for GaN manufacturing; some participants pointed out setting standards too quickly could inhibit innovation in the GaN industry. Regardless of concerns, the standards experts said that having standard recommended practices early on could be very effective in ensuring longer-term success of GaN products' commercialization.

## 5. Conclusions and Next Steps

The roundtable proposed a number of next steps to further the discussion at the roundtable event:

- Plan to attend the next IEEE and JEDEC meetings in 2014 to more intimately understand the inner workings of these standards organizations
- Form smaller task teams from among the participants to engage both IEEE and JEDEC in early discussions regarding setting standards and best practices for the GaN power device industry
- Prioritize and synchronize efforts to develop test structures to better understand specific GaN device characteristics
- Develop a plan to engage with other start-ups and larger organizations globally also focused on GaN power device manufacturing
- Develop strategy to disseminate the summary of discussions at the two-day roundtable discussion at the Institute for Energy Efficiency at UCSB