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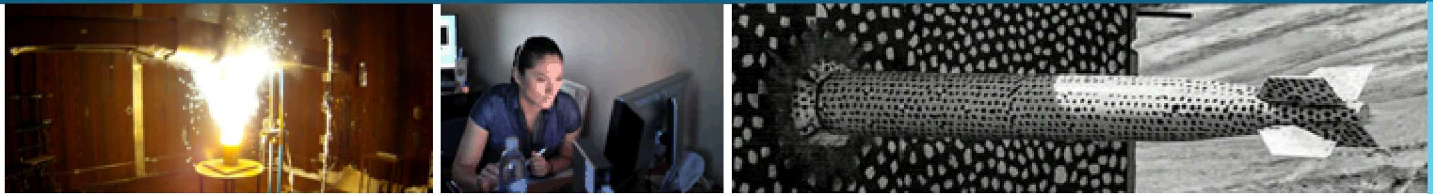
ITRW: Formulating a Roadmap for WBG and UWBG Materials and Devices



International Technology Roadmap for Wide Bandgap Power Semiconductors

Materials and Devices Working Group

Victor Veliadis, Robert Kaplar, Jon Zhang, Sameh Khalil, Jack Flicker, Jason Neely, **Andrew Binder**, Stanley Atcitty, Peter Moens, Mietek Bakowski, and Mark Hollis

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Purpose and Organization

Our goal is to formulate a roadmap for wide-bandgap and ultra-wide-bandgap materials and devices

- This effort has been split into four sub-working-groups
  1. SiC materials and devices
  2. Lateral GaN materials and devices
  3. Vertical GaN materials and devices
  4. Emerging UWBG materials and devices

This working group is lead by Victor Veliadis (primarily representing SiC) and Robert Kaplar (primarily representing GaN and emerging UWBG materials)

- This effort is volunteer based, if you would like to contribute please get in touch with us

The primary focus of this chapter is on developments in subgroups 1 & 2

- These subgroups represent technology that is far more mature and are available commercially
- Vertical GaN and UWBG materials are covered briefly, with future material as they mature technologically

SiC Materials and Devices – Market Forecast

Prices for SiC devices are rapidly declining

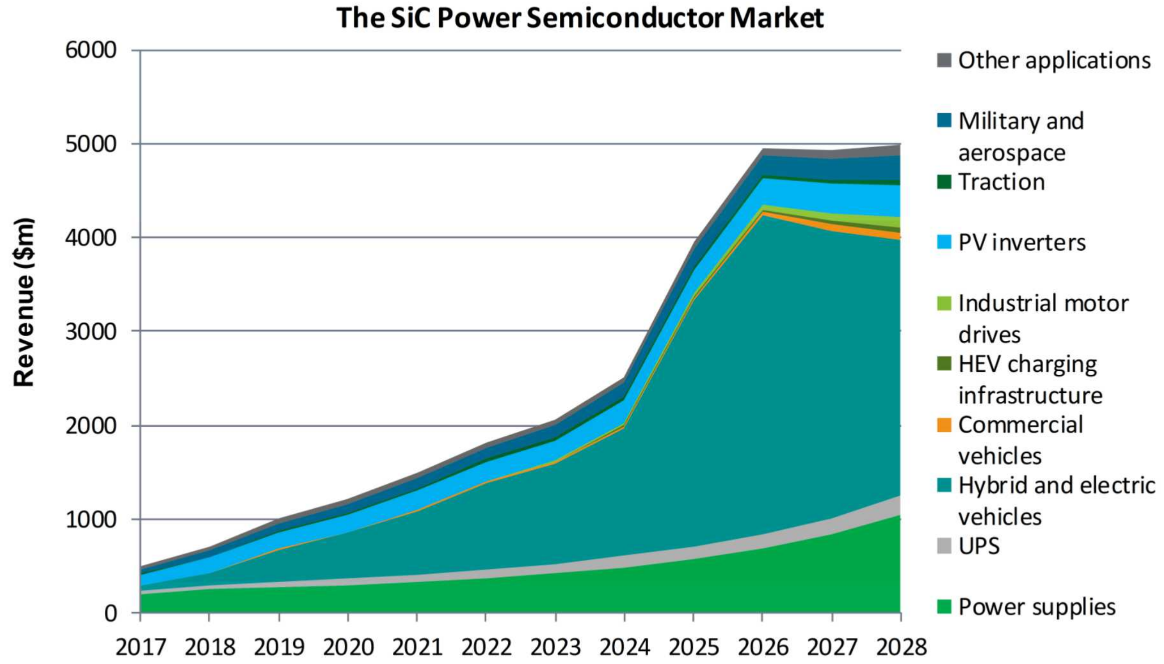
- SiC MOSFET prices dropped 50% from 2012 to 2015
  - Development of 200 mm wafers is expected to lead to further cost reductions and improved competitiveness

Additional growth in automotive electrification makes hybrid and electric vehicles a large target for SiC: with over 20 million electric vehicles predicted to be on the road by 2020

- The key near-term application for SiC is EV/HEV inverters
  - Estimated to reach $4 billion in revenue by 2026
- Cost competitiveness is the primary obstacle for EV/HEV inverter adoption

Present principle market for SiC:

- UPS, power supply, PV, and traction



Source: IHS Markit

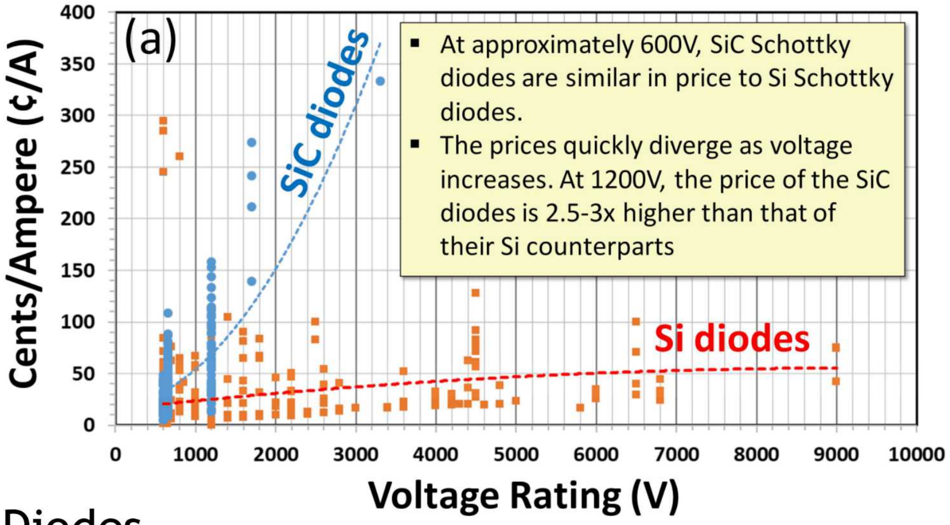
SiC Power Devices Pricing Comparison

How does SiC compare to Si in both diodes and switches?
- Considering cost/Amp for a given voltage rating
  - Data taken from Digikey distribution price list

SiC power devices become increasingly more expensive than Si as voltage rating increases
- Diodes are similar in price near 600 V, but diverge quickly as voltage increases
- For switches, Si IGBTs are less expensive than SiC MOSFETs across the board

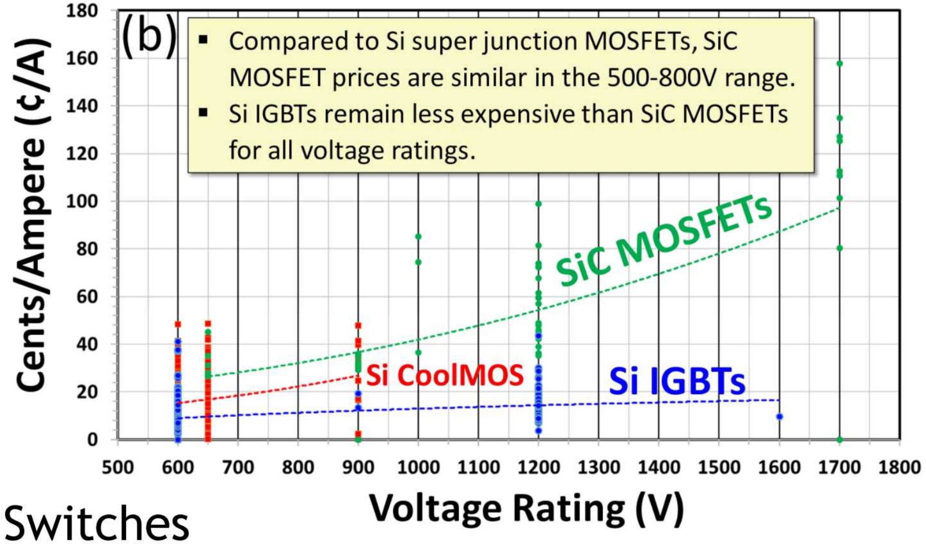
Price differential is mainly attributed to the higher material cost of SiC substrate/epitaxy, and higher cost of SiC devices with larger chip area

More info on SiC materials and devices will be presented at WiPDA 2019 in Raleigh, NC by Victor Veliadis



- At approximately 600V, SiC Schottky diodes are similar in price to Si Schottky diodes.
- The prices quickly diverge as voltage increases. At 1200V, the price of the SiC diodes is 2.5-3x higher than that of their Si counterparts

Diodes



- Compared to Si super junction MOSFETs, SiC MOSFET prices are similar in the 500-800V range.
- Si IGBTs remain less expensive than SiC MOSFETs for all voltage ratings.

Switches

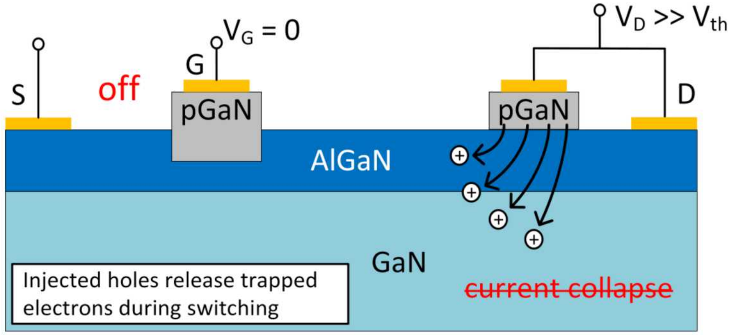
Lateral GaN – Current State-of-the-Art

Commercial normally-off GaN power devices are thus far limited to p-GaN gate devices and d-mode GaN HEMTs in a cascode configuration

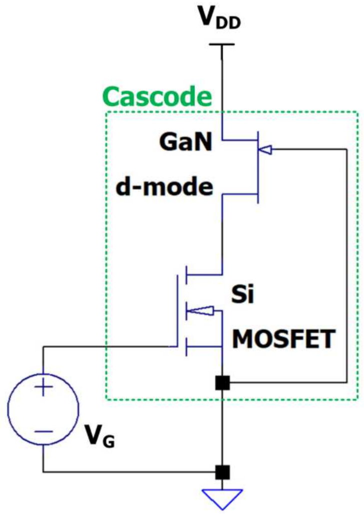
- Recent advances have been made to reduce current collapse such as by implementing a HD-GIT structure
- Enhancement-mode performance is typically lower than performance from depletion-mode devices
  - Need more innovation in this area

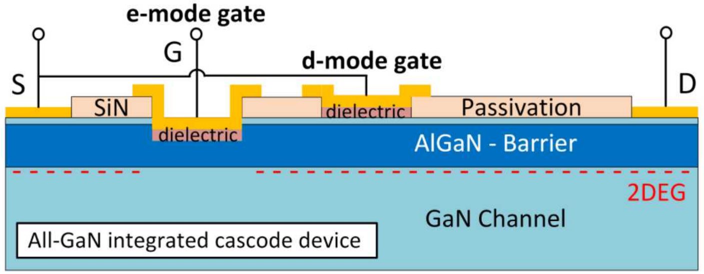
The monolithically integrated cascode structure is a promising alternative to the commercially available GaN+Si cascode

- Reduced parasitics, improved circuit stability



HD-GIT





Monolithically integrated GaN cascode

GaN+Si cascode circuit diagram

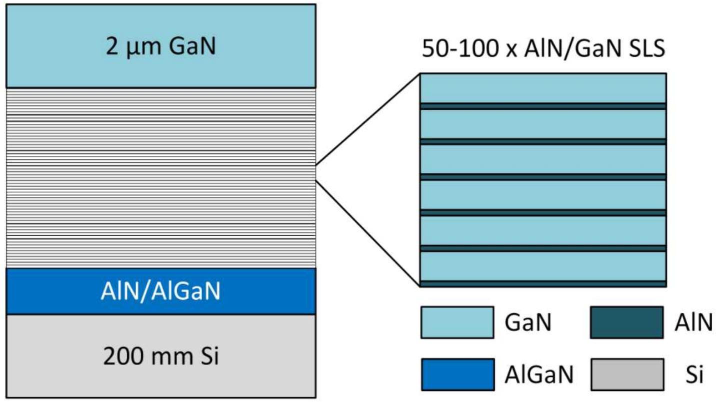
Lateral GaN Roadblocks

Many challenges in GaN stem from heteroepitaxy on non-native substrates

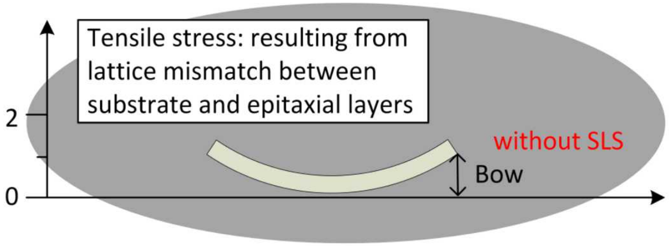
- Epi growth on non-native substrates results in a significant bulk defect density, and stress accumulation in the heterostructure
- Bulk defects result in trap centers, which adversely affect performance
- Surface stress accumulation impacts passivation, resulting in surface interface states that can cause current collapse or the virtual gate effect

Stress management can be achieved through superlattice stress relief layers

- This comes at the cost of poorer thermal performance



(a)



Tensile stress: resulting from lattice mismatch between substrate and epitaxial layers

(b)

Lateral GaN – Foundational Keystones / Market Forecast

Foundational Keystones:

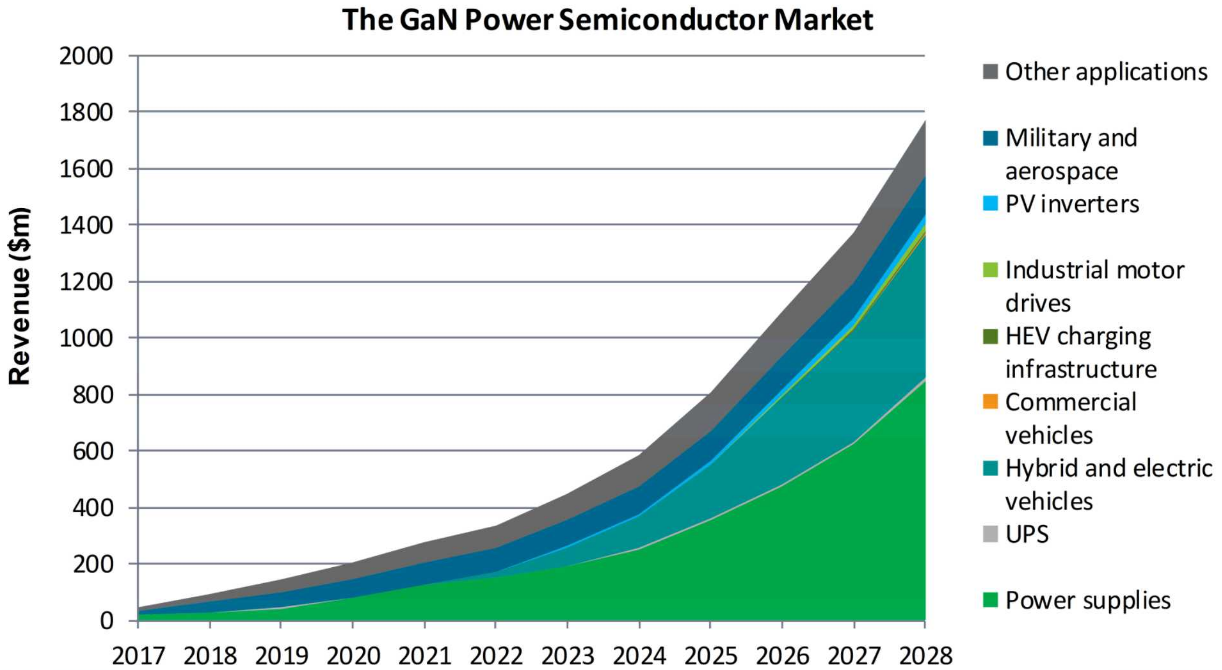
- Improved heterostructure growth
  - Necessary to minimize wafer bow and associated growth stress
    - More critical as GaN-on-Si transitions from 6” to 8” wafers
- Robust normally off device designs
  - New structures such as the HD-GIT have produced a more robust outcome, but add complexity and face challenges such as process uniformity
- Refined reliability characteristics
  - Expand device ruggedness and safe operating area to rival that of Si

Market Forecast:

- GaN-based RF devices commercially valued above $100M

Key near-term applications:

- Power supplies
- Hybrid and electric vehicles



Source: IHS Markit

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Lateral GaN – Seminal Publications

List of seminal publications and key recent technical advances

- Epitaxial growth of GaN layers on Si substrates up to 8" diameter [1]
- Device processing in CMOS-compatible fabrication lines [2]
- Achievement of normally-off operation using approaches such as p-gates or cascade configuration [3]
- Extension of breakdown voltage using edge termination techniques such as field plates [4]
- Mitigation of reliability concerns such as dynamic on-resistance, threshold voltage shift, and time-dependent dielectric breakdown [5]

This list was organized to facilitate the review of lateral GaN and provide a base of reading for those who would like to learn more

[1] M. Ishida, T. Ueda, T. Tanaka, and D. Ueda, "GaN on Si Technologies for Power Switching Devices," IEEE Trans. Elec. Dev., vol. 60, no. 10, p. 3053, 2013.

[2] D. Marcon et al., "Manufacturing Challenges of GaN-on-Si HEMTs in a 200 mm CMOS Fab," IEEE Trans.Semicond. Manuf., vol. 26, no. 3, p. 361, 2013.

[3] K. J. Chen et al., "GaN-on-Si power technology: Devices and applications," IEEE Trans. Elect. Dev., vol. 64, no. 3, pp. 779–795, 2017.

[4] S. Karmalkar and U. K. Mishra, "Enhancement of Breakdown Voltage in AlGaN/GaN High Electron Mobility Transistors Using a Field Plate," IEEE Trans. Elec. Dev., vol. 48, no. 8, p. 1515, 2001.

[5] G. Meneghesso et al., "Reliability of GaN High Electron Mobility Transistors: State of the Art and Perspectives," IEEE Trans. Dev. Mat. Rel., vol. 8, no. 2, p. 332, 2008.

Vertical GaN Development

Availability of native 2- and 4-inch GaN substrates is enabling development of vertical GaN devices
- Vertical GaN can deliver higher breakdown voltage and higher power density
  - Also promises higher reliability compared to lateral GaN by shifting the peak e-field from the surface to the bulk

Vertical GaN devices can survive and operate in the avalanche region
- Avalanche energy capability has been demonstrated at 1000 mJ

Design of an effective junction termination is a significant challenge for vertical GaN devices
- Without a proper junction termination, the breakdown voltage is often less than 50% of the theoretical ideal breakdown voltage
  - This can be improved to ≥ 90% of ideal breakdown with an effective junction termination
- Limitations with selective-area p-type doping in GaN make this a more complex issue than it is with SiC or Si

Ultra-Wide-Bandgap Semiconductors

Ultra-wide-bandgap materials can withstand higher electric fields, and thus enable a higher breakdown voltage

Work on these materials is still in an early research phase

- Present challenges include:
  - Growth of large-area substrates
  - Ability to effectively dope the materials
  - Ability to form low-resistance ohmic contacts
  - Integrating the semiconductors with other materials such as dielectrics

Conclusions

Our chapter addresses primarily SiC and GaN HEMT device roadmaps

- This is done in close collaboration with the module/packaging working group, as well as the applications working groups

SiC devices are expected to target high-value applications with voltage ratings above 900 V

Lateral GaN devices are expected to address high-value applications at 650 V and below

- Some overlap will likely occur in the 650-900 V range

In the long term, vertical GaN devices or even ultra-WBG devices may compete with SiC

- These devices are still in the research phase and have a ways to go

Questions?