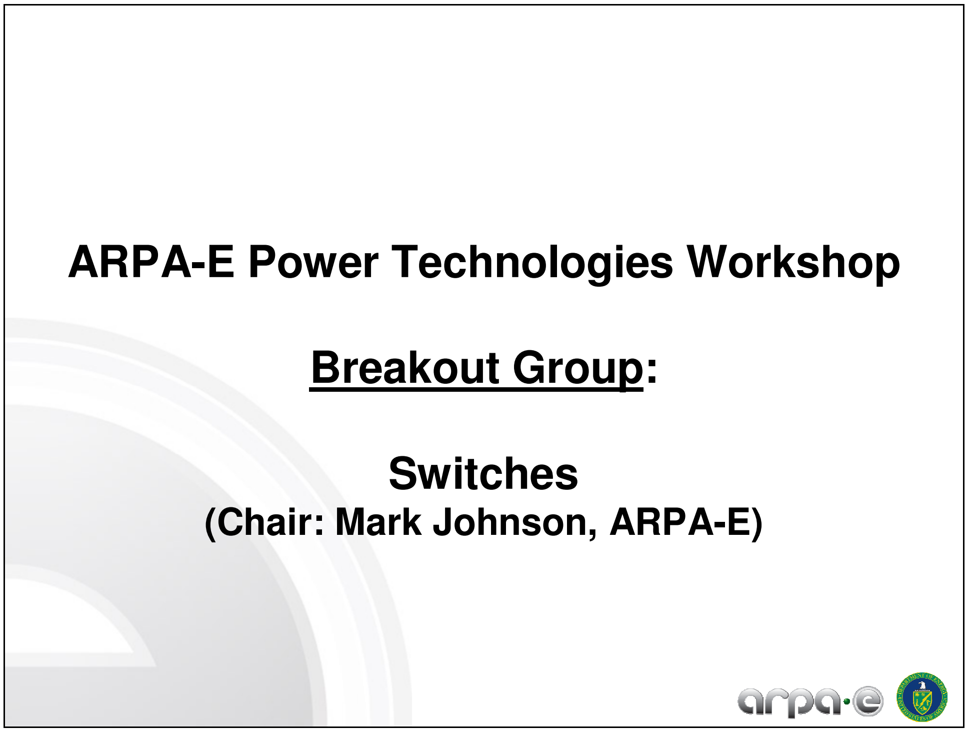
Switches Breakout Session

2/9/2010



Presentation from Cree

- 2.4X reduction in SiC price since ’05; higher quality materials, wafer size from 3” to 100mm; volumes increased; 600V diodes (2A-20A); also have 1200V
- Increased efficiency of SiC diodes saves electricity (reduced need for generation expansion on grid)
- 2.4% eff increase using SiC DMOSFET; SiC is more expensive, but pays for itself over time
- 10kV as upper limit for SiC unipolar (DMOSFET and Shottky diode)
    - Cost is limiting factor, not technology; don’t see applications willing to pay for higher voltages yet
- Above 10kV, need bipolar: SiC n-IGBTs
- Storage: BESS (400V) – DC/DC (750V) – Converter (3-phase 480) – Transformer (3-phase 13.6kV)
    - Streamlined system proposed: SiC 1.2 kV MOSFET and 10 kV MOSFET or 15-20 kV IGBT eliminate transformer

- Where does SiC make biggest impact? 1200V (GaN at lower voltages ~600V and below)
- Goal is not to beat Si price; it is finding apps that derive benefit from SiC, and justify higher price
- Ease of deployment is key factor

- SiC: technically ideal above 1200V, and high temperature
- % cost of substrate + epi not big issue in MOSFETs
- Japan has major effort supporting SiC

Presentation from Kyma

- GaN: $50/2”wafer is reasonable assumption with high yields (cost of materials is not barrier) and volumes (2015 “stake in the ground”); current prices at $2K/2” wafer
- $1B has been invested in bulk GaN development in Japan (vs. several million in US)
- GaN approaching (or has exceeded) theoretical limits of SiC (BFOM chart)
- High efficiency switches operate at high frequency; GaN operates at 4X
- Thermal conductivity of GaN due to increase
- Crystal growth is a key area; HVPE, AMT, AMT on HVPE seed, HVPE on AMT seed (ammonothermal – very slow growth rate)

What are the critical performance metrics for switch components to support high switching frequency (>10 MHz) converters at 10 W (SSL), 50 W (SSL/PV), 250 W (PV), 3kW (PV), 300 kW (PV)?

- Blocking voltage: ~600V / 1200V is cool-MOS point
  Automotive ~ same voltage range
- Switching frequency: ‘HV, high frequency SiC is a potential game changer’
- On resistance: Achieve low resistance for blocking voltage related to defects
- Heat transfer
- Reliability: Validation of Technology is a Critical Issue
- Integration (lateral vs. vertical)

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- Reliability testing on high voltage is an issue; data is not there to convince users; initial field data is critical, then customers are comfortable
- Test bed is key for US companies; don’t want to set up their own;
- 600V – 1200V as cross-over point for different technologies; Si good at lower voltages; automotive applications need devices at 1200V (or below); want better performance than Si at Si price; can do it today with Si, but have to accept current performance limitations

What are the critical performance metrics for switch materials for high switching frequency (>10 MHz) converters at 10 W (SSL), 50 W (SSL/PV), 250 W (PV)?

- Mobility
- Bandgap
- Permittivity
- Material quality (defect): Defects and Wafer size issues

Low defect thick epi is a critical issue

1C Screw dislocation banishment

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What are the critical performance metrics for switch materials for high blocking voltage (1kV, 10kV, 100 kV)?

- Mobility
- Bandgap
- Permittivity
- Material quality (defect)

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- Above 3kV only one source for epilayers; non-economical; have been advances in this area that are not commercially-available; not a lot of volume in “thick” epilayers, resulting in poor utilization of Cree’s operation to produce this material; [disagreement about whether this is inherently more expensive than 1200V material]; Cree says "hot wall" process is inherently more expensive; 10-20X reduction in cost needed; low-defect thick epilayer is critical

- Make 3kV devices light triggered; results in large machine (wind turbine) and direct interface of device with coils in machine; light triggering for HV devices is a game changer
- High-temperature operation; valuable for transportation – decreases thermal management requirements
- Discussion of past experience developing 150MW converters; had to band GTOs in series operation themselves; recommendation is to develop specification for HV devices so they can be used across a platform
- Cree says its cost of system, not module; if you can eliminate cooling system for power electronics in Prius, what is value of that? Increase in fuel efficiency, decrease in cooling system cost.
- Gains in power factor correction with SiC have value in some applications; systems-level view; power supply company doesn't care about efficiency, they care about price; but end user (Google – buyer of computer that uses power supply) cares about efficiency

What level of investment would be required to develop and deploy these technologies? What is the return on investment?

- 1 good pilot project is a good stating project
- GaN and SiC have received > $500M from DoD, etc.   Starting at the materials level.
- Example: Phase 1-3 RF Program ~ $175M (DARPA only)
  - – Need Portfolio of Interlocking Programs

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- What level of investment is needed? 6.5-20kV –1 pilot project is good starting point (build inverter); Phase 1-3 RF Program $175M from DARPA alone (P1:materials – P2:devices – P3:circuits)
- Where to invest depends on application; SiC has $100M+; GaN on Si investment has been more limited (debate about this – Cree suggests $120M invested by single player in past)
- Has there ever been a successful HV heteroepitaxial device? LEDs are most successful technology in this area

- Some GaN on Si HV devices (1800V, 120A device from Fujitsu); tremendous investment by private firms, but not much government investment (IR spent $60M for device below 50V, not clear what they're doing in HV space); International Rectifier has not released device
- GaN on Si is on fast trajectory; but not commercialized -
- Diamond also discussed briefly as a material
- Need critical mass of investment in materials; $500M in SiC materials, then work could begin on device-level issues; what materials investments do we make now? GaN on Si getting traction, but may not be right place to invest for ARPA-E (debate over whether GaN on Si is right place to invest – GaN on Si proponents explain that we are not that far behind Japan yet in this technology)
- Opponents suggest GaN on Si is too near-term; private companies investing in this already
- Switches are building blocks for devices (can develop new circuit architectures in these); we need to look at HV reliability of GaN (and other substrates)
- Current investments in HV devices using SiC for specific missions; these devices need to be deployed

For power converter technology (AC/DC & DC/AC), what are the drivers for integration?

- Packaging costs
- Footprint
- Efficiency
- Ease of use

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For power converter technology (AC/DC & DC/AC), what are the <u>barriers</u> for integration?

- Performance
- Yield
- Thermal management
- Design complexity

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- ○ Are there integration opportunities? "System on a chip" approach? Cree is making discrete chips to get used in parallel for PV inverter; issue with integrated devices
- ○ Integrating several power devices in same die is important; difficult in vertical approach, lateral devices may be needed here Integrated circuits; higher frequency of GaN decreases size
- ○ If we go to lateral device design, SiC advantages are less clear
- ○ GaN really good in 600-1200V, but outside of that range, SiC is just as good, even in lateral devices; assumes GaN on Si (big assumption)
- ○ Reliability of GaN on Si to match SiC; not sure this is possible
- ○ GaN on Si can use fully depreciated fabs; 6" wafer (SiC can do this in the future)
- ○ Companies are investing in GaN on Si; International Rectifier (30V, 70V)
- ○ New devices have to be game changes; hard to compete with Si
- ○ High voltage devices (above 1200V – SiC needs to do this)
- ○ SiC can be combined with Si; use each where it is most effective
- ○ Is batch processing of heterogeneous materials (SiC and Si) feasible for high-volume application? Integrated on small board – multi-chip module (packaging approach)
- ○ 10kV+ devices: changes grid to new architecture; materials challenges for both SiC and GaN at high voltages
- ○ Invest in Si thyristors; reliable, rugged, easy to use; surge current capability and gate control, light triggered; useful to power electronics engineers
- ○ From application-point of view, SiC can make major changes on grid; switch fast and accommodate high-voltage (13.6kV) in small form factor;

- For HV apps, we cannot use GaN thyristors; can't use direct bandgap material; DARPA has funded this, but it doesn't work well

Final Conclusions (High-Impact Areas to Focus)

- Bi-polar SiC; thick epi; 5kV+ (DARPA was unipolar)
- GaN on Si; validate reliability at 1200V; normally-off technology; GaN devices are reliable today because they operate at 1/3 of breakdown voltage; US companies need help proving device performance (test bed) to compete with Japanese; also need GaN on Si for high switching frequency at lower voltages; but apps vary (some need small footprint, some need high temp operation) and little articulation of who needs what
- GaN (bulk) – fundamental materials issues; large-area cost-effective substrates; for apps with voltage in between SiC and GaN on Si
- You won't change much in the 1200V area; invest in higher voltages because industry won't do this on their own – Cree won't do 12kV MOSFETs on their own
- Transformer-less connection to grid is huge (using power electronics instead)