Intelligent Electricity

Rajeev Ram, Program Director, ARPA-E

2010: 30% of all electric power flows through power electronics
2030: 80% of all electric power will flow through power electronics
ROLE OF POWER ELECTRONICS

2010: 30% of all electric power flows through power electronics
2030: 80% of all electric power will flow through power electronics
## POWER MAGNETICS WHITE SPACE

<table>
<thead>
<tr>
<th>Frequency</th>
<th>10 W</th>
<th>1000 W</th>
<th>100 kW</th>
<th>10 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 kHz</td>
<td>N/A</td>
<td>Now: ferrite, amorphous</td>
<td>Now: amorphous, ferrite, nanocrystalline</td>
<td>Future: existing and new materials</td>
</tr>
<tr>
<td>500 kHz</td>
<td>Now: ferrite</td>
<td>Now: ferrite</td>
<td>Future: new materials</td>
<td></td>
</tr>
<tr>
<td>5 MHz</td>
<td>Now: thin-film</td>
<td>Future: new materials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 MHz</td>
<td>Future: thin-film and air core</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

>92% Dimmable LED Driver

1MW PV Inverter
HV SWITCHES AND HI-FREQUENCY TRANSFORMERS
(3~5 nm Co Particles)

(Al₂O₃, ZrO₂, etc.)

100 nm

3 mm

Deposit Material Layers  Fabricate Toroidal Component  Wind Wire
MINIATURE (FAST) MAGNETICS NEEDS FAST SWITCHES

Bandgap (energy to ‘free electron’) increases

- Breakdown voltage increases
- Drift region can be decreased

- Reduces transit time
- Increases frequency
- Reduces on-resistance

Wide Bandgap Materials: SiC, GaN, etc.

Operation Frequency (Hz)

Power (VA)
AUTOMOTIVE ELECTRONICS
- 600V GaN-on-Si with sintered interconnects & double-side cooling.
- Reduce energy losses and cost by at least 50% relative to Si IGBT

\[
(W_g=100 \text{ mm}, \ L_g=2 \text{um})
\]

\[
\text{Ion/loff(600 V) > 10^6}
\]

\[
V_g=-10 \text{V} \quad I_{BV} = 0.1 \text{ uA} / \text{mm}
\]
• Develop a Mult-Chip Power Module for >500 kHz
• Develop 1200V, 20A SiC MOSFET with isolated, integrated SiC gate drive
• Small, lightweight, few materials, low cost
• >94% efficiency, > 5kW/kg, > 100W/in3
• Integrate into Prius vehicle and demonstrate operation
HIGH EFFICIENCY MOTOR DRIVE GAN-SIC

Sub 20 KHz

GaN/SiC 3-ph inverter with Integrated Filter, 100 KHz

2 kW-98.5% (including Filter and drive losses)

Line output Pure-Sine

Program goal

Efficiency (%) vs. Load (W)
ENHANCEMENT-MODE GaN-Si

40 µA / 1100 V Program
ADEPTTarget

>1000V GaN on Si Material
(Buffer structure)

Transfer characteristic of GaN on
Silicon E-mode HEMT, Vt>4V
• 30-50% of cost for dimmable LED luminaire (ADEPT: MIT, Teledyne, CUNY)
• 20% energy loss in industrial motors due to mechanical throttling (ADEPT: Transphorm)
• 20% of material cost for HEV is power electronics (ADEPT: Delphi/IR, HRL/GM, APEI/Cree, CWRU)
• Negligible storage - just in time delivery of power

• Centrally controlled

• Negligible control of path - Joules are indistinguishable

Not the internet
STATE OF THE GRID

- Congested Lines
- Aging Infrastructure
- Increasingly unreliable
- Increasingly unpredictable
LOCATION MARGINAL PRICING

This image will be refreshed in 3 Minutes, 4 Seconds. Please hit ctrl-F5 to manually refresh this page.
CONTROL AND ACTUATION OF THE GRID

Control in the Grid
Flexible AC Transmission System:
- Static VAR
- STATCOM
- UPFC

Demand Response
Schedule demand
(eg. large industrial loads)

Grid Storage
Dispatch of intermittent generation
**ROUTING ELECTRICAL POWER**

GA Tech study of simplified IEEE 39 Bus system with 4 control areas, operation simulated for 20 years, 20% RPS phased in over 20 years, sufficient transmission capacity added each year to eliminate curtailment of renewable generation.

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**Today: Uncontrolled Flows**

**Power Routing**

Base Case: 3.4 MW sent; 0.34 MW recd

- BAU case requires upgrade of 3 inter-regional paths, for a total of 186,000 MW-MILES
- Power flow control to route power along underutilized paths, 36,000 MW-miles of new lines needed, only 20% of BAU
SOLID-STATE TRANSFORMERS

- Significantly improved SiC IGBTs
  - High voltage (20kV)
  - Extremely efficient (>98%)
  - Fast switching (50kHz)

Efficient, high-temperature silicon carbide switches could slash power losses from silicon-based FACTS controllers by more than 50 percent. Cree leads a US $3.7 million project with the U.S. government's ARPA-E high-risk energy R&D fund to engineer 15- to 20-kilovolt silicon carbide power modules ready for grid-scale power flows.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Mass</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Today</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60 Hz</td>
<td>8,160 lb</td>
<td>4.80m³</td>
</tr>
<tr>
<td>Tomorrow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 kHz</td>
<td>100 lb</td>
<td>0.14m³</td>
</tr>
</tbody>
</table>
**15 kV SiC P-IGBT**

Highest Breakdown Voltage Ever Reported for a Semiconductor Switch

\[
V_F = 5.8 \text{V} @ 5 \text{A}, V_{GE} = -20 \text{V} \\
= 11.2 \text{V} @ 32 \text{A} (200 \text{ A/cm}^2)
\]

\[
R_{on,sp} = 24 \text{ m}\Omega \cdot \text{cm}^2 \\
(V_{GE}=-20\text{V}, V_{CE}=-11.2\text{V})
\]

**SiC P-IGBT Structure**

- **Emitter**
- **Gate**
- **P+**
- **N-well**
- **P drift**
  \(2 \times 10^{14} \text{ cm}^{-3}, 140 \mu\text{m}\)
- **P field-stop buffer**
  \(2 \mu\text{m}, 1 – 5 \times 10^{17} \text{ cm}^{-3}\)
- **N+ injector/Substrate**

**Room Temperature Device Characteristics**

- 15 kV Blocking (\(V_{GE}=0\text{V}\))

**15 kV, 0.6 \mu\text{A}**
In today’s integrated and digitized global market, where knowledge and innovation tools are so widely distributed. . . . :whatever can be done, will be done. The only question is will it be done by you or to you.

Thomas L. Friedman, Author, “The World Is Flat”

“Here, you see, it takes all the running you can do to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that.”

The Red Queen, Through the Looking Glass
PV POWER ELECTRONICS

BASE CASE

PV Strings

Combiner

Central Inverter

Transformer

Utility Grid

Source: Rocky Mountain Institute

PV System

Balance of System

Module

Ground-Mounted System

Rooftop System

BoS Detail

Business Processes

Structural System

Electrical System

$3.50

$3.75

$1.60

$1.85

$1.00

0.5

0

3

2

1

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<table>
<thead>
<tr>
<th>System Categories</th>
<th>Cost</th>
<th>Voltage &amp; Power</th>
<th>CEC Efficiency</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category 1</td>
<td>$0.05/W</td>
<td>&gt;3 converters/module</td>
<td>&gt;98% cell-to-AC MPPT</td>
<td>Single-chip DC/DC Inside Module Frame</td>
</tr>
<tr>
<td>Category 2</td>
<td>$0.20/W</td>
<td>&gt;600 V &gt;250 W</td>
<td>&gt;98% cell-to-AC</td>
<td>&lt; 2 lbs Integrated: &lt; 10 parts</td>
</tr>
<tr>
<td>Category 3</td>
<td>&lt;$0.10/W</td>
<td>100kW</td>
<td>&gt;98% cell-to-AC</td>
<td>&lt; 50 lbs</td>
</tr>
<tr>
<td>Category 4</td>
<td>$0.10/W</td>
<td>&gt; 2 MW scalable</td>
<td>&gt;98% module-to-grid</td>
<td>&lt; 1000 lbs</td>
</tr>
</tbody>
</table>
12.5 kV SiC N-IGBT

12.5 kV SiC N-IGBT With Specific On Resistance ($R_{on,sp}$) of Only 5.3 mΩ-cm²!

$V_F = 4.1\text{V} @ 5\text{ A}, V_{GE} = 20\text{V}$

$= 6.1\text{ V} @ 32\text{ A} (200\text{ A/cm}^2)$

$R_{on,sp} = 5.3\text{ mΩ-cm}^2$

($V_{GE} = 20\text{V}, V_{CE} = 6.1\text{V}$)

12.5 kV blocking ($V_{GE}=0\text{V}$)

Room Temperature Device Characteristics