ARPA-E Initiatives in High Efficiency Power Conversion

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U.S. Department of Energy

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ARPA-E Mission

- Reduce Energy-Related Emissions
- Reduce Energy Imports
- Improve Energy Efficiency
The ARPA-E Approach

Transformational & disruptive technologies that lead to new learning curves.
Focused Programs

Transportation Energy Technologies

Stationary Energy Technologies

- BEEEST
- PETRO
- Electrofuels
- MOVE
- RANGE
- REMOTE

- HEATS
- AMPED
- REACT
- SBIR/STTR
- METALS
- SWITCHES

- Solar ADEPT
- BEETIT
- GRIDS
- IMPACCT
- ADEPT
- GENI
- FOCUS
Electricity is \sim 40\% of U.S. Energy Consumption

- In 2005, 30\% of electricity in the U.S. flows through power converters.
- By 2030, 80\% of electricity could flow through power converters.
Power Conversion is Ubiquitous

- Universal Goals:
  - High Power Density
  - Low Cost
  - High Efficiency

Tradeoffs often required between these objectives.
High Power Density, Low Cost, High Efficiency Requires New Magnetic Components

Magnetic components are often the largest, most expensive parts in converters.

Higher frequencies reduce the amount of material (lower cost) but reduces efficiency.

High Frequency Difficult at High Voltages/Powers

1200 V Silicon IGBTs Switching Performance

![Current vs. Frequency Graph](image)

- IRG7PH42UPbF
- IRG7PH35UPbF
- IRG4PH50UPbF

**X-axis:** Frequency (kHz)

**Y-axis:** Current (A)
High Power, High Frequency Requires New Switches

New device technologies needed for high power, high frequency power conversion.

- Reduced carrier transit time
- Increased frequency
- Reduced on-resistance

Semiconductor bandgap increases
Critical electric field increases
Drift region thickness can be decreased
## Semiconductor Materials Properties

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Wide band-gap</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Si</td>
<td>GaAs</td>
</tr>
<tr>
<td><strong>Band Gap</strong></td>
<td>Eg (eV)</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Electron</strong></td>
<td>n&lt;sub&gt;i&lt;/sub&gt; (cm&lt;sup&gt;-3&lt;/sup&gt;)</td>
<td>1.5×10&lt;sup&gt;10&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Concentration</strong></td>
<td>μ&lt;sub&gt;n&lt;/sub&gt; (cm&lt;sup&gt;2&lt;/sup&gt;/V s)</td>
<td>1350</td>
</tr>
<tr>
<td><strong>Electron</strong></td>
<td>μ&lt;sub&gt;n&lt;/sub&gt; (cm&lt;sup&gt;2&lt;/sup&gt;/V s)</td>
<td>1450</td>
</tr>
<tr>
<td><strong>Mobility</strong></td>
<td>v&lt;sub&gt;sat&lt;/sub&gt; (10&lt;sup&gt;7&lt;/sup&gt;cm/s)</td>
<td>1</td>
</tr>
<tr>
<td><strong>Breakdown</strong></td>
<td>E&lt;sub&gt;br&lt;/sub&gt; (MV/cm)</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Electric Field</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Conductivity</strong></td>
<td>Θ (W/cm K)</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Maximal Operation</strong></td>
<td>T&lt;sub&gt;max&lt;/sub&gt; (°C)</td>
<td>125</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Figure of Merit</strong></td>
<td>FOM = (E&lt;sub&gt;br&lt;/sub&gt; * v&lt;sub&gt;sat&lt;/sub&gt;) / 2π</td>
<td>1</td>
</tr>
</tbody>
</table>

Power Electronics R&D Whitespaces (2010)

**Switches**
- Unipolar SiC
- Si
- Integrated WBG
- >13kV WBG

**Magnetics**
- Hard Magnets
- High Flux Soft Magnets

**Converters**
- >10 W, >95%
- Single-Chip
- Single Chip AC

**Capacitors**
- High Efficiency
- Reliable + fast + high energy density
ADEPT
EFFICIENT POWER CONVERSION

- **Goals**
  - Improve the energy efficiency of electronic devices and power systems
  - Enable high efficiency, high power density power electronics
  - Contribute to the development of a smart grid

<table>
<thead>
<tr>
<th>Program Director</th>
<th>Dr. Tim Heidel (Dr. Rajeev Ram)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kickoff Year</td>
<td>2010</td>
</tr>
<tr>
<td>Projects</td>
<td>13</td>
</tr>
<tr>
<td>Total Investment</td>
<td>$37.7 Million</td>
</tr>
</tbody>
</table>

**Highlights**
- Advanced charge storage devices
- Magnetic materials
- Advanced solid-state switch technologies
- Advanced circuit topologies and converter architectures
# ADEPT Program Technical Targets

<table>
<thead>
<tr>
<th>Category</th>
<th>Voltage &amp; Power</th>
<th>Efficiency</th>
<th>Switching Frequency</th>
<th>Power Density</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully Integrated, Chip-scale power converters</td>
<td>&gt;100V 10-50W</td>
<td>&gt;93%</td>
<td>&gt;5 MHz</td>
<td>&gt;300 W/in³</td>
<td></td>
</tr>
<tr>
<td>Package integrated power converters</td>
<td>&gt;600V 3-10kW</td>
<td>&gt;95%</td>
<td>&gt;1 MHz</td>
<td>&gt;150 W/in³</td>
<td></td>
</tr>
<tr>
<td>Lightweight, solid-state, medium voltage energy conversion</td>
<td>13kV 1MW</td>
<td>&gt;98%</td>
<td>&gt;50 kHz</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>
ADEPT Integrated Magnetics

**Air-core inductors**
- Fast models, verified by simulation, used for optimization.

**Magnetic-core inductors**
- Nano-magnetic materials

**Modeling and design**

**Micro-fabricated inductors**

300 CoNiFe laminations (t < 0.3μm), Surface roughness < 30nm

Converter efficiency vs Inductor power density (W/mm²)
μ-Fabrication of Magnetic Components

Fabrication Technologies

- High aspect ratio micro pillar array, 70 µm – 1mm tall
- Cu Electroplating for inductor winding
- Metal encapsulated polymer core vertical inductor winding
- Magnetic cores integration to μfabricated windings
- Nanogranular powder (Upenn) to toroid by pressing
- 70 µm feature size, 1mm tall vertical winding connected to bottom and top winding

Inductors

- 70 turn air core inductor
  - ID: 4 mm, OD: 8 mm, H: 1mm
  - $L_{ave}$: 650 nH, Q: 14 @10MHz
  - Power converter efficiency: 76-81%
- Silicon-embedded inductor
  - 25 turns, ID: 2 mm, OD: 6 mm, H: 0.3 mm
  - Iron-powder core integrated
  - $L_{ave}$: 180 nH, Q: 20 @10MHz
- Magnetic core integrated inductor
  - 25 turns, ID: 2 mm, OD: 6 mm, H: 1mm
  - CoZrO core (Dartmouth)
  - $L_{ave}$: 640 nH, Q: 53 @10MHz
- Hand wound inductor
  - Iron oxide power core (Upenn)
  - $L_{ave}$: 900 nH Q_{3MHz}: 8
  - Power converter efficiency: 91%
High Power Density Point of Load Converter

10x Power Density
High Efficiency (88%)

1-phase module with IR GaN 5 MHz
2-phase module with IR GaN 5 MHz

Power density (W/in³)

1000
700
500
300

1A 5A 10A 15A 20A 30A current

3D Integrated Converter
SiC Bi-Directional Vehicle Battery Charger

Highly integrated full bridge, high frequency (>500kHz) 1200V SiC multi-chip power module

SiC gate driver IC integrated into power module

Two-stage bi-directional vehicle battery charger with galvanic isolation

Module 1 with gate driver

DC-bus capacitors

Resonant inductor

Output inductor

Control board (transparent)

Output capacitors

Module 3
SiC Bi-Directional Vehicle Battery Charger

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volumetric Power Density</td>
<td>7.4 W/in³ (387.5 in³)</td>
<td>83.3 W/in³ (73.2 in³)</td>
</tr>
<tr>
<td>Gravimetric Power Density</td>
<td>0.44 kW/kg (6.6 kg)</td>
<td>3.8 kW/kg (1.6 kg)</td>
</tr>
<tr>
<td>Power</td>
<td>2.88 kW</td>
<td>6.1 kW</td>
</tr>
<tr>
<td>Efficiency</td>
<td>-</td>
<td>95% peak</td>
</tr>
</tbody>
</table>

The charger was integrated into a 2010 model Toyota Prius Plug-in Hybrid

10x Increase in Power Density and Increased Efficiency
GaN/Si Bidirectional Vehicle Battery Charger

Normally-off 600V GaN-on-Si devices with operation up to 200°C

Low dynamic Ron @ HV with optimized electric field management

![Graph showing current (A/mm) vs. VDS (V) for different conditions.](Image)

- ![Graph showing dynamic Ron vs. bias (V) for different devices.](Image)
  - HRL GaN FET w/ 3FP
  - HRL GaN FET w/ 2FP
  - Vendor A Si MOSFET
  - Vendor B GaN FET
  - Commercial GaN (circa 2010)
  - Commercial Si MOSFET

*HRL's GaN Device Technology: Insulating Gate Normally-off Switch...*
GaN/Si Bidirectional Vehicle Battery Charger

1kW Breadboard
(165Vac, 250Vbatt, 500kHz)
94.2% efficiency, PF=0.998

Charger Design (To be built in 2014.)

: 6.6kW power
> 120 W/in³
>95% Eff.

2x faster charging, 2x more efficient,
10x more compact
Dynamic PWM Enables GaN Circuits to Maintain High Efficiency Using Frequencies up to 1 MHz

- GaN-on-Silicon HEMTs with >1100V breakdown
- E-mode GaN-on-Si HEMTs demo (Gate drive 0~12V, 230:400V boost converter with h=98.9%)
- 3-phase GaN power modules (600-900V, 14-25A CW current)
- Pure sine-wave motor drive test by customer (2-8% EM efficiency gain)
- 1MHz motor drive demo
10kV+ SiC PiN Rectifiers, Anode Switched Thyristors

- Commercial 4H SiC substrates show very low crystal dislocations (micropipe, screw, basal) and epitaxial films have very long carrier lifetime.

- Breakdown voltage as high as 11kV demonstrated on 6.4mm x 6.4 mm PiN rectifier fabricated on 94 μm/6.6x10^{14} cm^{-3} n-base layers. (117 V/μm, 86% of avalanche breakdown limit).
15kV+ SiC IGBTs, Solid State Transformers

19 kV/20 A SiC n-IGBT

15kV/40A SiC IGBT Copack

19 kV/20A SiC n-IGBT Reverse Blocking

$V_{GE} = 0$ V

$I_c = 1.43 \mu A$ at $V_{ce} = 19$ kV

Transformerless Intelligent Power Substation (TIPS)

AC to DC Converter

DC to DC Dual Active Bridge

DC to AC Converter

HV Grid

LV Grid

AC

HV DC Link

High Freq Transformer

LV DC Link

DC

AC

DC

AC
Barriers to Ubiquitous Adoption

- Long Term Device Reliability?
  - 15 V dielectric gate
  - Normally-off operation
  - Threshold stability
  - Threshold hysteresis
  - Carrier trapping
  - Leakage currents
  - Breakdown mechanisms
  - Accelerated life tests
  - High dV/dt gate drive

- High cost!
  - Proving business cases:
    - System costs vs. Device costs

- Applications and Demonstrations
  - Higher voltages, Higher dV/dts, new circuit topologies…
  - Success will only come through experience…
  - Get the devices into the hands of engineers as quickly as possible.
Widespread adoption will require functional cost parity with Si devices

- No 100A GaN or SiC devices commercially available.
- No 1200V GaN devices commercially available.
- 1200V SiC MOSFETs (<40A) currently $0.50-3.00/A.
SWITCHES Program Builds on ADEPT Success

- Key Device Parameters:
  - Breakdown voltage
  - Junction temperature
  - Switching speed
  - Ease of driving
  - Current rating
  - $/Amp

- About $6B market today for devices between 400 and 900 V (mostly inverters and motor drives)
SWITCHES
Low Cost, High Current Wide Bandgap Switches

Goals
• High voltage (1200V+), high current (100A) single die power semiconductor devices at functional cost parity with silicon power transistors.
• Reduce the barriers to widespread deployment of low-loss WBG power semiconductor devices in stationary and transportation energy applications.

Highlights
• Low Cost (Foundry) SiC Device Fabrication
• Vertical GaN Transistors
• Diamond Semiconductor Devices

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<td>$27 Million</td>
</tr>
</tbody>
</table>
SWITCHES primary technical targets were set to achieve high performance and market viability

<table>
<thead>
<tr>
<th>ID</th>
<th>Parameter</th>
<th>Primary targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Discrete Device Cost (Packaged)</td>
<td>&lt;= $0.10 /A</td>
</tr>
<tr>
<td>1.2</td>
<td>Drain-Source Breakdown Voltage</td>
<td>&gt;= 1200 V ($V_{DSS} @ T_C = 25\degree C$ and $V_{GS} = 0$)</td>
</tr>
<tr>
<td>1.3</td>
<td>Continuous Drain Current Rating (Single Die)</td>
<td>&gt;= 100 A ($I_D @ T_C = 25\degree C$ and $V_{GS} &lt;= 20$ V)</td>
</tr>
<tr>
<td>1.4</td>
<td>Operating Junction Temperature</td>
<td>-55 \degree C to 150 \degree C</td>
</tr>
<tr>
<td>1.5</td>
<td>$I_{OFF}/I_{ON}$ Ratio</td>
<td>&gt; 10^6</td>
</tr>
<tr>
<td>1.6</td>
<td>Vth (not applicable to diodes)</td>
<td>&gt; 2 V @ $I_D = 5$ mA</td>
</tr>
<tr>
<td>1.7</td>
<td>Dynamic Performance</td>
<td>Hard switched boost (PFC) converter at $f &gt;= 40$ kHz, $V_{OUT} = 800$ V, $I_{MAX} = 50$ A.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ID</th>
<th>Parameter</th>
<th>Secondary targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Specific $R_{DSON}$</td>
<td>&lt; 3 mΩ*cm^2 @ $V_{GS} = 15$ V</td>
</tr>
<tr>
<td>2.2</td>
<td>Switching Loss $E_{ON}+E_{OFF}$</td>
<td>&lt; .5 mJ @ 800 V and 50 A</td>
</tr>
</tbody>
</table>
SiC MOSFETs

- SiC MOSFETS are the device of choice for 1200-2000V applications.
- 1200V devices now commercially available, but with relatively low current ratings (<40A).
- SiC MOSFETs currently 5-8X the $/A cost relative to Si.

Challenges:
- Carrier mobilities remain substantially below theoretical maximum due to interface challenges.
- High temperature processing steps require use of dedicated, custom SiC device fabrication facilities.
GaN Device Challenges

- Lateral GaN HEMT current density/die area is relatively low and die size increases directly with breakdown voltage.
- Material quality requirements make high current devices (>100A) requiring large die sizes extremely challenging.
- Lateral GaN HEMTs will struggle to reach cost parity with Si power semiconductor devices on a $/A basis at >1200V and >100A.

Cross-section and electric field distribution at breakdown.
Vertical (Bulk) GaN Devices

- Utilize more of the material for conduction, allowing for higher current densities.
- Breakdown voltage must only be handled vertically.*
- Allows much higher breakdown voltages and higher current devices.
- Requires compatible (non-Si) substrate.

Diamond Power Devices

- Diamond advantages:
  - Very high bandgap (5.45 eV)
  - Superb thermal conductivity
  - High electron mobility

- Why now?
  - Availability of single crystal substrates.
  - p-type (boron-doped) and n-type (phosphorus-doped) epi growth.
  - Improved low resistance contacts
  - Demonstration of (low current) BJT and other devices in literature.

Single crystal CVD diamond substrates.
(Element 6)

Kato et al., Diamond & Related Materials 34 (2013), 41-44
Conclusion

- Technical advances in magnetics, capacitors, and switches are enabling high efficiency, high power density, low cost power electronics.

- These advances offer enormous energy efficiency gains for the U.S. and the rest of the world.

- Initial application demonstrations are producing impressive results. However, the path to large scale adoption remains unclear.
  - How will the reliability of new components be fully validated?
  - How will these components reach cost parity with conventional components?
  - How will engineers learn to fully utilize the capabilities of all of these new components.

- The APEC community is critically important to enabling these technical advances to realize their full potential.