Innovation in Power Electronics

Dr. Ahmad Bahai
CTO, Texas Instruments
Semiconductor market continues to grow

Worldwide semiconductor market, 2002-2014

Source: WSTS
Semiconductor market (units)

Worldwide semiconductor market, 2002-2013

Source: WSTS
**Power management Growth**

**Worldwide power semiconductor market, 2002-2014**

- **Source:** WSTS
More chips are coming into our lives

In 2015, each person on the planet purchased 109 chips

- Semantic Units: 7.2% CAGR (787B units in 2015)
- World Population: 1.2% CAGR (7.2B in 2015)
- Gross World Product: 4.7% CAGR ($73T in 2015)

Sources: WSTS, International Monetary Fund, U.S. Census Bureau
Power Management for old and new apps

Distributed (Local)
Renewable (Clean)
Conventional (Fossil)

Real-Time Monitoring
Smart Meters
2-way
Price signaling
Demand response
Supply response

Transmission & Distribution

Appliances
Power Supplies & zero stand-by

Real-Time Monitoring
HVAC

Smart Meters
Lighting

Transmission & Distribution
Motors

Make It
Move It
Use It

Transportation

The Internet of Power & Energy...

**Internet of Power**
- Central large-scale power plants
- Decentralized production – prosumers

**Internet of Data**
- Central/regulated generation of information
- Distributed & integrated storage devices

**Generation**
- Central

**Storage**
- Central/regulated

**Distribution**
- Ubiquitous Interconnectivity

**Flow**
- Data flow known and controllable
- Adaptive/fluctuating

- Active Balancing
- Bi-directional flow of energy

- One-directional flow through transmission and distribution grid
- Highly fluctuating resources (solar, wind) & loads

- Stable base load
Energy efficiency

In 2005, only 30 percent of electricity in the U.S. flowed through power converters of a smart grid; but by 2030, 80 percent will flow through power converters.


Yole Report
Smart Grid: Less than 40% of Power is going through solid state devices

- Enabling nationwide use of plug-in hybrid electric vehicles...
- Allowing the seamless integration of renewable energy sources like wind...
- Semi conductor
- Software
- Battery
- Network
- Use of solar energy – 24 hours a day...
- Exploiting the use of green building standards to help “lighten the load”...
- Ushering in a new era of consumer choice...

DoE Report
10X better storage technology!

Zn/Air Rechargeable 1370Wh/kg

Flow Batteries

Li/Air 11kWh/kg

Li-Sulfur

Theoretical Specific Energy (Wh/kg)

<table>
<thead>
<tr>
<th>Li-ion Battery Systems</th>
<th>410</th>
<th>385</th>
<th>630</th>
<th>508</th>
<th>952</th>
<th>1550</th>
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<tbody>
<tr>
<td>LiCoO₂ Graphite</td>
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<td>LiFePO₄ Graphite</td>
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<tr>
<td>LiS Silicon</td>
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</tbody>
</table>
Energy Micro Harvesting

- Low standby current
- Low active current
- Low operating voltage
- Low pin leakage...

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Harvested Power</th>
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<tbody>
<tr>
<td>Vibration/Motion</td>
<td></td>
</tr>
<tr>
<td>Human</td>
<td>4 μW/cm²</td>
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<tr>
<td>Industry</td>
<td>100 μW/cm²</td>
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<tr>
<td>Temperature Difference</td>
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<tr>
<td>Human</td>
<td>25 μW/cm²</td>
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<tr>
<td>Industry</td>
<td>1–10 mW/cm²</td>
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<tr>
<td>Light</td>
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</tr>
<tr>
<td>Indoor</td>
<td>10 μW/cm²</td>
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<tr>
<td>Outdoor</td>
<td>10 mW/cm²</td>
</tr>
<tr>
<td>RF</td>
<td></td>
</tr>
<tr>
<td>GSM</td>
<td>0.1 μW/cm²</td>
</tr>
<tr>
<td>WiFi</td>
<td>0.001 mW/cm²</td>
</tr>
</tbody>
</table>

![Energy Harvesting System Diagram](diagram.png)
What would the world look like if power converters were 10X more dense?
Data Utilities!

Growing exponentially
- 2.5 Quintillion $10^{18}$ bits of data/day
- Checking your phone 150 times/day
- 43600 sq. ft. (10 football fields), sized for 48 MW with more than 100000 servers
- Dedicated power plants with growing carbon footprint (620m tons CO2)

30TWh just for wireless data infrastructure, 1W saving equates to ~$2 annual utility saving

Tremendous room for growth!

Doing nothing well so poorly!

IEEE

IT footprints
Emissions by sub-sector, 2020

Total emissions: 1.43bn tonnes CO₂ equivalent
In search of Ideal Switching Function

FOMs:
- $R_{ON} \times \text{Area}$
- $R_{ON} \times Q_{GD}$
- $BV_{DSS}$
- $Q_{OSS}$
- Switching Frequency

Technology positioning
2015 forecast by Yole Développement
(Source: Super Junction MOSFET report - To be released in March 2011 - Yole Développement)

Texas Instruments
HV Technology Choices

GaN vs. Silicon – Device Structure

Intrinsic limitations of silicon FETs:
- Much higher Qrr
- Higher Ron for a given BV
- Worse switching metrics
  - Higher Qg*Ron
  - Higher Qoss*Ron
- Temperature limited (typ. 125C-150C)
- Non-integrated (for vertical device)

Conducting channel (2DEG) between drain and source → D-mode is the “natural” state.
2DEG=2-Dimensional Electron Gas

For an e-mode, the gate region is constructed to deplete the 2DEG underneath at zero gate bias.
Challenges

Lattice mismatch introduces stress

GaN:
Wurtzite lattice

• 17% lattice mismatch
• Diamond → hexagonal

Silicon:
Diamond lattice
(111) surface is hexagonal
(100) is cubic

GaN contracts 2X as fast as Si

If the wafer is flat at 1100°C (growth temperature)

Then it is flatter when cooled
Use thicker wafers: 6” - 30 mils

Then it will be bowed with cooled to room temperature. The GaN can also crack (bow exaggerated)

So it is compensated by strain management techniques

In-situ monitoring of wafer bow

Growth time

Heating Up
AlN Buffer
AlGaN Layer
GaN Layer
Cooling Down
Shrinking Power Blocks

- Low Losses
- Hi Temp Operation
- No Switching Recovery Time
- Faster switching
- Smaller passives

Source: http://energy.gov/eere/amo
In pursuit of 10X better power density-
Direct Conversion in Data Centers

Baseline AC Distribution System

AC Distribution System without PDU

DC Distribution System with SST
Power Package Challenges

Majority of the heat is dissipated through the board.

Heat-sink, airflow and system will define the limits.
III-V Power Devices and Others

2015 projection GaN device state-of-the-art
(V & Amp) vs. application requests

SIC diode only vs. SIC diode & transistor

Advancing power supply solutions through the promise of GaN

Yole Report

Bipolar

Unipolar

Field Effect Transistors

Diode

Thyristor

GTO

IGCT

BJT

IGBT

MOSFET

SJ MOSFET

SiC diode

SiC MOSFET

GaN HEMT

1970

1990

2010

2020

Texas Instruments
Power and energy efficiency is an ongoing challenge.

Innovation in power semiconductor is critical.

New devices and alternative energy sources have enabled new architectures.

More innovation in device, circuit, and systems is critical for us and our environment.

Conclusion