Power Converters: Why commercial world is betting on Gallium Nitride (GaN) to replace Silicon

Satish K Dhawan
Yale University
Agenda

- CMS ECAL Powering 2.5 V @ 50,000 amps
- DC-DC Converters
- Commercial Device 100 Mrads- Beginners luck
- ATLAS Upgrade work. Embedded Air Coil PCB
- Why Thin Oxide for Radiation
- Why go beyond Silicon. 15 V LDMOS
- GaN Wide band Gap material. RF & Power Switching
- Data Centers 400V DC distribution
- Companies involved with GaN Product Development
- Advantage of this development
- Conclusions

Collaborators:
Yale University: Keith Baker, Hunter Smith
Brookhaven National Laboratory: Hucheng Chen, James Kierstead, Francesco Lanni, David Lynn, Sergio Rescia,
CMS ECAL: Electromagnetic Calorimeter

80 Amps Power supply for 4 LVR Boards
Power Supply @6.3V  30 meters away
3K Boards x 16 amps = 48 Kamps
Magnetic Field 4T in CMS
CMS ECAL: 5 Oodles (50 Kamps).  
- Power Supply output = 315 KW
- Power loss in Leads to SM = 100 KW
- Power loss in Regulator Card = 90 KW
- Power Delivered @ 2.5 V = 125 KW

1 Oodle = 10,000 amps

Yale: Designed, built, burn-in and Tested.

- # of Power Supplies ~ 700
- # of ST LDO Chips = 35 K
- LHC Radiation Hard made by ST Microelectronics
- # of LVR Cards = 3.1 K.

Power Supply 6.3 V
- 64 Amps
- 30 m

- Vdrop = 2V
- Pd = 128 W

SM: Super Module
- 4.3 V
- 2x16 mm² (AWG 6)
- 1 to 3 m

Junction Box

4 LVR Boards

2.5V
- 64 amps
- 160 W

4 Oodles
Power Chain Efficiency for CMS ECAL

- Transformer:
  - 99.5%
  - 5-6 Km

- Power Grid:
  - 600 KV 50 MW 300 KM
  - 80% 100 Km

- Transformer:
  - 99%
  - 33 KV
  - Nuclear Generating Plant

- UPS Batteries:
  - 97%
  - 380 V 3 Phase
  - 50-100 m

- Isolation Transformer:
  - 98%
  - 220 V 3 Phase
  - 40 m

- AC to DC Rectifier & PFC:
  - 99.5%
  - 230 V 3 Phase
  - 140 m Cable Loss = 3%
  - 385 V

- Wiener Maraton PS:
  - 75-79%
  - 6.3 V

- Load:
  - 40%
  - 125 KW

- Power delivery Efficiency:
  - = 30%

- Power for Heat Removal:
  - = 20%

- From Experts Efficiency %
- Guess work Efficiency %

Represents the efficiency of power delivery to a physics detector, e.g. ECAL

It takes 2 watts of power to remove 1 watt of heat load
Can we do better?

• Is there a better way to distribute power?
• High Radiation
• Magnetic Field 4 T
• Load ~1 V Oodles of current
• Feed High Voltage and Convert - like AC power transmission
• Commercial Technologies — No Custom ASIC Chips
• Learn from Semiconductor Industry
• Use Company Evaluation Boards for testing
Power Stage - High Volts

Controller Low Voltage

Synchronous Buck Converter

Control Switch 30 mΩ

Synch Switch 20 mΩ

Power Stage Drivers

PWM: Pulse Width Modulator

Error Amp

V reference

Buck Safety

Minimum Switch ON Time Limits Max Frequency
10 nsec @ 10 MHz

Vout = 11%

Control
Synch

Vout = 50%

Control
Synch

Control Switch: Switching Loss > I^2
Synch Switch: Rds Loss Significant
Buck Regulator Efficiency after 100 Mrad dosage

Found out at Power Technology conference 0.25 µm Lithography

- Irradiated Stopped on St. Valentines Day 2007
- We reported @ TWEPP 2008 - IHP was foundry for EN5360
ATLAS Si Tracker

LHC Solution
10 Chip Hybrid – SCT Module for LHC
3.5 V
1.5 amps
Cable Resistance = 4.5 Ohms

4088 Cables
10.25 V
Voltage Drop = 6.75 V

Counting House

sLHC Solution
20 Chip Hybrid – Si Tr Module for Hi Luminosity
1.3 V
2.4 amps
X 4 DC-DC Power Converter
5.2 V
Current Reduced by 4 (losses by 16)

Commercial Solution
EN5360
It is still available

Silicon Technology Limit
(Radiation limited)
20 Chip Hybrid – Si Tr Module for Hi Luminosity
1.3 V
2.4 amps
X 10 DC-DC Power Converter
13 V
0.24 amps
Voltage Drop = 1.08 V

Current Reduced by 10 (losses by 100)

> X 40 with Gallium Nitride Transistors
Power Delivery with Existing SCT Cables (total = 4088)

Resistance = 4.5 Ohms

- 3.5 V @ 1.5 amps
- 1.3 V @ 2.4 amps
- 1.3 V @ 2.4 amps with x10 Buck switcher. Efficiency 90%

Power Efficiency %

Voltage @ Load
Coupled Air Core Inductor Connected in Series

Plug In Card with Shielded Buck Inductor

Different Versions
- Converter Chips
  Max8654 monolithic
  IR8341 3 die MCM
- Coils
  Embedded 3oz cu
  Solenoid 15 mΩ
  Spiral Etched 0.25mm

Noise Tests Done: sLHC SiT prototype, 20 µm AL Shield
Threshold Shift vs Gate Oxide Thickness

Threshold Shift vs Gate Oxide Thickness

\[ \Delta V_{FB} = \frac{10^{6} \text{ RAD (Si)}}{VOLT/RAD(Si)} \]

- **T** = 80\(^\circ\)K
- **\(E_{ox}\)** = +2.0 MV/cm

- **TO 3C** - PHOS-DOPED
- **TO 1C** - POLY-SI
- **TO 8** - GATE
- **OTHER** - ALUMINUM GATE

- **BOESCH & McGARRITY** (1976)

\[ \Delta V_{FB} \propto t_{ox}^2 \]

Hole removal process by tunneling in thin-oxide MOS Structures

**Poly- Si**

**SiO\(_2\)**

**Si**

\[ e^- \]

**Tunneling Region**


Can We Have
High Radiation Tolerance & Higher Voltage Together ???

Higher radiation tolerance needs thin oxide
while higher voltage needs thicker oxide – Contradiction?

Mixed signal power designs from TI, TSMC, IBM etc - 0.18 μm & 0.13 μm
Automobile Market. Voltage ratings 10 - 80 Volts
Deep sub-micron but thick oxide

Controller : Low Voltage

High Voltage: Switches – some candidates HV & Thin oxide

RF Process LDMOS, Drain Extension, Deep Diffusion etc

>> 20 Volts  HEMT GaN on Silicon, Silicon Carbide, Sapphire
**IHP NMOS Transistor**

$V_G$ versus $I_D$ at Selected Gamma Doses

**IHP PMOS Transistor**

$V_G$ versus $ID$ at selected Gamma Doses

**XY Semi (VD = 12V)**

2 Amp FET- HVMOS20080720 Process
## Thin Oxide Devices (non IBM)

<table>
<thead>
<tr>
<th>Company</th>
<th>Device</th>
<th>Process</th>
<th>Foundry</th>
<th>Oxide</th>
<th>Dose before</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Name/ Number</td>
<td>Name</td>
<td>nm</td>
<td>Damage seen</td>
<td>Damage Mode</td>
</tr>
<tr>
<td>IHP</td>
<td>ASIC custom</td>
<td>SG25V GOD</td>
<td>IHP, Germany</td>
<td>5</td>
<td>Minimal Damage</td>
<td></td>
</tr>
<tr>
<td>XySemi</td>
<td>FET 2 amps</td>
<td>HVMOS20080720</td>
<td>China</td>
<td>7</td>
<td>Minimal Damage</td>
<td></td>
</tr>
<tr>
<td>XySemi</td>
<td>XP2201</td>
<td>HVMOS20080720</td>
<td>China</td>
<td>12 / 7</td>
<td>2Q2010</td>
<td></td>
</tr>
<tr>
<td>Enpirion</td>
<td>EN5365</td>
<td>CMOS 0.25 µm</td>
<td>Dongbu HiTek, Korea</td>
<td>5</td>
<td>64 Krads</td>
<td></td>
</tr>
<tr>
<td>Enpirion</td>
<td>EN5382</td>
<td>CMOS 0.25 µm</td>
<td>Dongbu HiTek, Korea</td>
<td>5</td>
<td>111 Krads</td>
<td></td>
</tr>
<tr>
<td>Enpirion</td>
<td>EN5360 #2</td>
<td>SG25V (IHP)</td>
<td>IHP, Germany</td>
<td>5</td>
<td>100 Mrads</td>
<td></td>
</tr>
<tr>
<td>Enpirion</td>
<td>EN5360 #3</td>
<td>SG25V (IHP)</td>
<td>IHP, Germany</td>
<td>5</td>
<td>48 Mrads</td>
<td></td>
</tr>
</tbody>
</table>

### Necessary condition for Radiation Hardness - Thin Gate Oxide

**But not sufficient**

- IHP: Epi free, High resistivity substrate, Higher voltage, lower noise devices
- Dongbu: Epi process on substrate, lower voltage due to hot carriers in gate oxide
Why we got into GaN?

This paper

The aim of our investigation was the test of our standard AlGaN/GaN HFET devices for reliability simulating a mission of **10–100 years in space environment**. This paper describes the results of irradiation with protons and heavy ions like carbon, oxygen and iron at 68 MeV and 2 MeV on a series of devices from the same wafer. The fluences were varied in a wide range between and cm.

Proton and Heavy Ion Irradiation Effects on AlGaN/GaN HFET Devices
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 53, NO. 6, DECEMBER 2006

A few days after reading this paper in early 2008, there was IMWS in Boston. There were many companies pedaling GaN RF transistors - Cellular Market. **We could not pass up an opportunity to test GaN for physics**
Gallium Nitride Devices Tests 2009

**RF GaN**  20 Volts & 0.1 amp
- 8 pieces: Nitronex NPT 25015: GaN on Silicon
- ✔ Done Gamma, Proton & Neutrons
- ✔ 65 volts Oct 2009  

**Gallium Nitride Devices Tests 2009**

- 2 pieces: CREE CGH40010F: GaN on SiC
- 6 pieces: Eudyna EGNB010MK: GaN on SiC
- ✔ Done Neutrons

**Switch GaN**
- ✔ International Rectifier GaN on Silicon
  - Under NDA. Good efficiency to >12 MHz Driver limited

- Oscillations in SPA @ >>1 GHz
Electrical Properties of Wide Bandgap Semiconductors Compared With Si and GaAs

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_g$ (eV)</th>
<th>$\varepsilon_s$</th>
<th>$\mu_n$ (cm$^2$/Vs)</th>
<th>$E_c$ (MV/cm)</th>
<th>$v_{sat}$ ($10^7$ cm/s)</th>
<th>$n_i$ (cm$^3$)</th>
<th>BFOM*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.12</td>
<td>11.8</td>
<td>1350</td>
<td>0.3</td>
<td>1.0</td>
<td>1.5x10^{10}</td>
<td>1</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.42</td>
<td>13.1</td>
<td>8500</td>
<td>0.4</td>
<td>2.0</td>
<td>1.8x10^{16}</td>
<td>17</td>
</tr>
<tr>
<td>4H-SiC</td>
<td>3.26</td>
<td>10</td>
<td>720</td>
<td>2.0</td>
<td>2.0</td>
<td>8.2x10^{-9}</td>
<td>134</td>
</tr>
<tr>
<td>6H-SiC</td>
<td>2.86</td>
<td>9.7</td>
<td>370</td>
<td>2.4</td>
<td>2.0</td>
<td>2.4x10^{-5}</td>
<td>115</td>
</tr>
<tr>
<td>2H-GaN</td>
<td>3.44</td>
<td>9.5</td>
<td>900</td>
<td>3.0</td>
<td>2.5</td>
<td>1.0x10^{-10}</td>
<td>537</td>
</tr>
</tbody>
</table>

$E_g$: bandgap; $\varepsilon_s$: dielectric constant; $\mu_n$: electron mobility; $E_c$: critical electric field; $v_{sat}$: saturation velocity; $n_i$: intrinsic carrier density.

*BFOM* = $\varepsilon \mu E_c^3$, BFOM was normalized by the BM of Si.

Table I: Physical characteristics of Si and main wide bandgap semiconductors [1-3].

<table>
<thead>
<tr>
<th>Property</th>
<th>Si</th>
<th>GaAs</th>
<th>6H-SiC</th>
<th>4H-SiC</th>
<th>GaN</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap, $E_g$ (eV)</td>
<td>1.12</td>
<td>1.43</td>
<td>3.03</td>
<td>3.26</td>
<td>3.45</td>
<td>5.45</td>
</tr>
<tr>
<td>Dielectric constant, $\varepsilon_r$</td>
<td>11.9</td>
<td>13.1</td>
<td>9.66</td>
<td>10.1</td>
<td>9</td>
<td>5.5</td>
</tr>
<tr>
<td>Electric Breakdown Field, $E_c$ (kV/cm)</td>
<td>300</td>
<td>400</td>
<td>2500</td>
<td>2200</td>
<td>2000</td>
<td>10000</td>
</tr>
<tr>
<td>Electron Mobility, $\mu_n$ (cm²/V·s)</td>
<td>1500</td>
<td>8500</td>
<td>500</td>
<td>1000</td>
<td>1250</td>
<td>2200</td>
</tr>
<tr>
<td>Hole Mobility, $\mu_p$ (cm²/V·s)</td>
<td>600</td>
<td>400</td>
<td>101</td>
<td>115</td>
<td>850</td>
<td>850</td>
</tr>
<tr>
<td>Thermal Conductivity, $\lambda$ (W/cm·K)</td>
<td>1.5</td>
<td>0.46</td>
<td>4.9</td>
<td>4.9</td>
<td>1.3</td>
<td>22</td>
</tr>
<tr>
<td>Saturated Electron Drift Velocity, $v_{sat}$ ($\times 10^7$ cm/s)</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2.2</td>
<td>2.7</td>
</tr>
</tbody>
</table>

$\varepsilon = \varepsilon_r \cdot \varepsilon_0$ where $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m

Burak Ozpine et al Comparisson of Wide bandgap Semiconductors for Power Applications ONRL epe 2003 wide bandgap
Table II: Main figures of merit for wide-bandgap semiconductors compared with Si [2].

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>GaAs</th>
<th>6H-SiC</th>
<th>4H-SiC</th>
<th>GaN</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>JFM</strong></td>
<td>1.0</td>
<td>1.8</td>
<td>277.8</td>
<td>215.1</td>
<td>215.1</td>
<td>81000</td>
</tr>
<tr>
<td><strong>BFM</strong></td>
<td>1.0</td>
<td>14.8</td>
<td>125.3</td>
<td>223.1</td>
<td>186.7</td>
<td>25106</td>
</tr>
<tr>
<td><strong>FSFM</strong></td>
<td>1.0</td>
<td>11.4</td>
<td>30.5</td>
<td>61.2</td>
<td>65.0</td>
<td>3595</td>
</tr>
<tr>
<td><strong>BSFM</strong></td>
<td>1.0</td>
<td>1.6</td>
<td>13.1</td>
<td>12.9</td>
<td>52.5</td>
<td>2402</td>
</tr>
<tr>
<td><strong>FPFM</strong></td>
<td>1.0</td>
<td>3.6</td>
<td>48.3</td>
<td>56.0</td>
<td>30.4</td>
<td>1476</td>
</tr>
<tr>
<td><strong>FTFM</strong></td>
<td>1.0</td>
<td>40.7</td>
<td>1470.5</td>
<td>3424.8</td>
<td>1973.6</td>
<td>5304459</td>
</tr>
<tr>
<td><strong>BPFM</strong></td>
<td>1.0</td>
<td>0.9</td>
<td>57.3</td>
<td>35.4</td>
<td>10.7</td>
<td>594</td>
</tr>
<tr>
<td><strong>BTFM</strong></td>
<td>1.0</td>
<td>1.4</td>
<td>748.9</td>
<td>458.1</td>
<td>560.5</td>
<td>1426711</td>
</tr>
</tbody>
</table>

**JFM**: Johnson’s figure of merit is a measure of the ultimate high frequency capability of the material.

**BFM**: Baliga’s figure of merit is a measure of the specific on-resistance of the drift region of a vertical FET.

**FSFM**: FET switching speed figure of merit.

**BSFM**: Bipolar switching speed figure of merit.

**FPFM**: FET power handling capacity figure of merit.

**FTFM**: FET power switching product.

**BPFM**: Bipolar power handling capacity figure of merit.

**BTFM**: Bipolar power switching product.
Fig. 6. AlGaN/GaN heterostructure and its band diagram. When the AlGaN layer is under tensile strain, free carriers are accumulated at the heterointerface owing to the piezoelectric effect caused by the strain, and a spontaneous polarization effect.

Fig. 7. Restrictions of HF devices in terms of output power and frequency. The limiting factors for HF device operation are thermal restriction, material property restriction and current gain restriction, for the respective regions shown in the figure.

Fig. 8. Dependence of drift velocity of semiconductors on electric field. GaAs and InP have high mobilities (slope of drift velocity–electric field relation in the low-electric-field region); however, their drift velocities decrease in the high-electric-field region. On the other hand, GaN shows high drift velocity in the high-electric-field region.

**GaN History**

1975: A Phenomenon lead to HEMT. T. Mimura et.al.
2005: Nitronex GaN on Si RF Power amplifier Cellular Base stations

June, 2009: EPC announced GaN on Si for power. 20 - 200 V. E-mode
March, 2010: Start selling thru Digikey
Feb 2010: IR announced GaN on Si for power 12 V parts- Engineering samples

2010: Single Crystal by Ammono - IEEE Spectrum July 2010
3 inch GaN substrates becoming available in Japan

GaN RF transistors have been displacing Si LDMOS transistors
- Cellular base stations
EPC: First supplier of GaN for DC-DC converters. Available thru Digikey
International Rectifier: d-Mode with driver
HFET device structure on Si substrate. R&D Association Fuji Electric and Furukawa Electric

Recently Published Devices

Uemoto, Panasonic IEDM 09-168
Inverter for Air Conditioning Motor
e- Mode

Velox Semiconductor: (Being acquired by Power Integrations - $300M company)
IEEE ELECTRON DEVICE LETTERS, VOL. 30, NO. 10, OCTOBER 2009
600 V @ 5.5 A

K. Ota: Nano Electronics Res Lab. NEC IEDM 09- 154
**2 Commercial Device Companies**

**Half bridge Power Stage with Driver**

Vin = 7 - 13.2 V  Vout = 0.6 – 5.5 V

*Status: Sampling Special Customers*

*Delivery 2Q2011*

- iP2010 30A $9 @ 2.5K
- iP2011 20A $6 @ 2.5K

---

**International Rectifier Corp.**

**d-mode**

**AlGaN Electron Generating Layer**

**Dielectric**

- **Si**
- **GaN**
- **AlGaN**

Piezoelectric effects create 2 DEG electron sheet $n_e = 10^{13} \text{ cm}^{-2}$

**e-mode**

**EPC:** Efficient Power Conversion Corp.

Distributor: [www.Digikey.com](http://www.Digikey.com)

**Aluminum Nitride Isolation Layer**

- **33 amps:** 4.1mm x 1.3mm
- **$2.48 @ 1 K**

- **6 amps:** 1.7mm x 0.7mm
- **$1.31 @ 1 K**

- **3 amps:** 1.7mm x 0.7mm
- **$2.10 @ 1 K**

---
Depletion & Enhancement Mode Devices

Enhancement Mode – Normally OFF

Depletion Mode – Normally ON

GaN No Reverse Recovery

D-mode Rds lower by 2 but need to drive gate with Negative voltage drive

A comparison between Silicon and GaN characteristics

<table>
<thead>
<tr>
<th></th>
<th>Typical 100V Silicon</th>
<th>100V eGaN™</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum gate-source voltage</strong></td>
<td>±20 V</td>
<td>+6 V and -5 V</td>
</tr>
<tr>
<td><strong>Avalanche capable</strong></td>
<td>Yes</td>
<td>Not rated</td>
</tr>
<tr>
<td><strong>Reverse-direction 'diode' voltage</strong></td>
<td>~1 V</td>
<td>~1.5 V to 2.5 V</td>
</tr>
<tr>
<td><strong>Body-diode reverse-recovery charge</strong></td>
<td>High</td>
<td>None</td>
</tr>
<tr>
<td><strong>Gate-to-source leakage</strong></td>
<td>A few nanoamps</td>
<td>A few milliamps</td>
</tr>
<tr>
<td><strong>Gate threshold</strong></td>
<td>2 V to 4 V</td>
<td>0.7 V to 2.5 V</td>
</tr>
<tr>
<td><strong>Internal gate resistance</strong></td>
<td>&gt;1 Ω</td>
<td>&lt;0.6 Ω</td>
</tr>
<tr>
<td><strong>dV/dt capacitance (Miller) ratio</strong> Q_{GD}/Q_{GS}</td>
<td>0.6 to 1.1</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Change in R_{DS(ON)} from 25°C to 125°C</strong></td>
<td>&gt;+70%</td>
<td>&lt;+50%</td>
</tr>
<tr>
<td><strong>Change in V_{TH} from 25°C to 125°C</strong></td>
<td>-33%</td>
<td>-3%</td>
</tr>
</tbody>
</table>

Better current sharing in parallel devices
**Typical Application**

**International Rectifier**

**MCM: Driver + FETs**

**Sampling**

**For Buck Converter Add**
- PWM
- Inductor
- Caps

---

**eGaN friendly interface gate driver in 6-pin DFN package (bottom view)**
Who is this EPC Company- Never heard of it?

- Startup near Los Angeles, CA airport – 11 employees + Consultants ~ 20
- Started by Alex Lidow. Ex CEO of International Rectifier. His father founded IR
- Foundry – Episil Inc – is well established in Taiwan
- Process: Epitaxial growth on standard CMOS Silicon substrate
- Location: El Segundo, CA, 909 N. Sepulveda Blvd

1 mile away
- International Rectifier: 101 N. Sepulveda Blvd. - GaN for power conversion
- Anagenesis Inc: 222 N. Sepulveda Blvd – Market Strategy Development

100 miles away
- Transphorm Inc Developing 600 V GaN Switches
- CREE: Santa Barbara Technology Center GaN BlueLED’s
- University of California, Santa Barbara
- In San Jose: Eudyna – RF GaN on SiC (Technical Support & Marketing)

3000 miles away
- Nitronex – RF GaN-on-silicon
- Velox: 600 V GaN-on-sapphire Switches
- CREE: RF GaN on SiC, SiC FETs, Blue LEDs,
- North Carolina State University
During Gamma Irradiation DC BIAS 4 VOLTS, VDS = 0
Fluence rate= 5 mega M rad/day

Proton Irradiation
The run went well, we left your board in the beam until it reached approximately 1x10^15 p/cm^2 (800 MeVp). The initial measurement over voltage across the 50 ohm resistor was 0.645V, and the final measurement was 0.643V. Readings were taken after every entry to remove samples from the blue room (7 times) and they were always between 0.643V - 0.645V. I'm sure Leo Bitteker has your shipping information but you may want to send him a reminder in a couple of weeks.
No SEB: but the drain current leakage is increased after irradiation with Au ions with a bias of $V_{ds} = 100V$ and $V_{gs} = 0V$.

No SEGR, but the drain current leakage is increased after irradiation with Au ions with a bias of $V_{gs} = 6V$ and $V_{ds} = 0V$. It is believed increased leakage is caused by the large gate bias, not by heavy ion irradiation.
Die Cost: Ω / Area

BFOM: Conduction Loss

- Si-SJMOSFET
- SiC transistors
- GaN-HFET
- eGaN

Production Device
Best- Academic- made one transistor work
Company: Can produce but does not meet all target product specifications
Why so much interest in GaN?

Power Efficiency

IBM Challenge
Data Center Usage
Consumer
Portable Gadgets
# Telecom Central Office Energy Consumption

<table>
<thead>
<tr>
<th>Country</th>
<th>Network</th>
<th>Energy Consumption</th>
<th>% of Country Total Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>Verizon 2006</td>
<td>8.9 TWh</td>
<td>0.24%</td>
</tr>
<tr>
<td>Japan</td>
<td>NTT Group 2007</td>
<td>5.54 TWh</td>
<td>1%</td>
</tr>
<tr>
<td>Italy</td>
<td>Telecom Italia 2005</td>
<td>2 TWh</td>
<td>1%</td>
</tr>
<tr>
<td>France</td>
<td>France Telecom-Orange 2006</td>
<td>2 TWh</td>
<td>0.4%</td>
</tr>
<tr>
<td>Spain</td>
<td>Telefonica 2006</td>
<td>1.42 TWh</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

Global electricity consumption of telecom industry estimated at 1%:

164 billion kWh

More than the total electricity consumption of Iran, Turkey or Sweden

Enough to power 1.6 million homes

110.7 million tons of CO2 (equivalent to the annual emissions of 29 million cars !)

Source: Emerson Network Power and NTT

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GaN High Efficiency Power Switching Applications

- Data Center: Efficiency sensitive / More CPU power in same vault
  400 V DC (+/-200 V) Power distribution: 12 V – 1 V converters.
  - IEC SMB SG4, IEC TC64, ETSI EE, The Green Grid - Power sub working group
- AC Line > DC power converters 600V 5 - 20 amps. Low vampire power
- Electric Vehicles 600 /900 V 100 kwatts
- Railways 8 KV SiC FETs, SiC diodes

Potential LV DC-DC Power Stage Roadmap

Optimized Performance – Without tradeoff

For high frequency Integrate a GaN Driver into Power Stage!
## Status of GaN player

<table>
<thead>
<tr>
<th>Company</th>
<th>Detail of Target or status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fujitsu Laboratory</td>
<td>Mass-production level in 2011(fiscal)~2012 in the medium Vb over 600V using Si or SiC substrate (representative by Fujitsu Micro-elect.)</td>
</tr>
<tr>
<td>Furukawa and Fuji Electric</td>
<td>Commercial use at 2011(fiscal)</td>
</tr>
<tr>
<td>International Rectifiers</td>
<td>Commercial use from 2010</td>
</tr>
<tr>
<td></td>
<td>Beginning of product is lower Vb such several tens of voltage</td>
</tr>
<tr>
<td>NEC (Renesus)</td>
<td>Deliver Sample at 2011(fiscal)</td>
</tr>
<tr>
<td>Panasonic</td>
<td>Commercial use at 2011(fiscal)</td>
</tr>
<tr>
<td>Rohm</td>
<td>Deliver Sample at 2011(fiscal), also developing GaN native substrate</td>
</tr>
<tr>
<td>Sanken Electric</td>
<td>Trial manufacture of Vb over 800 V</td>
</tr>
</tbody>
</table>

**Timeline**

- 2006
- 2007
- 2008
- 2009
- 2010
- 2011
- 2012

* Velox (Developing SBD with STMicro)
* IR (Announcement of establish 6in-line)
* EPC announced GaN devices on Si
  - Fujitsu (At DRC2009, masproduction at 2011 using 6in-line)
  - NEC (paper at IEDM2009)
  - Advanced power device research association (Furukawa & Fuji)
* Sanken-electric or Panasonic have been developing the GaN devices going to masproduction at 2012

*Prepared by Dr. Nariaki Ikeda of Advanced Power Device Research Association*

*From Nikkei electronics (2010.1.11 in Japanese)*
Panasonic
New President: Mr. Ishiguro
Deliver Products FY2010

Market: White Appliances
Air Conditioners, Washer, Dryers

Fujitsu
President H. Okada
GaN Power Devices.
150/200 mm Fab lines
Ship samples mid 2010
Production start end 2010

Factory: Aizuwakamatsu

Market:
Mobile, Auto, TV & Industrial
Enable Gate
ON: 0.8 µs
OFF: 10 µs

Yale University
May 30, 2010

Air Coil DC-DC Converter
Vin 12 V
Plug in card
Maxim / IR
3 meters Twisted pair AWG 24

Load Resistor
2.5 Ω 10 W

Gate
+5V

Gnd

Load = 3 amps (Electronic)

Pulsing Load

Turn off Spike with
1 amp load = 27 V
FWHM = 80 nS

+2.5 V, Bump = 200 mV

Enable Gate
ON: 0.8 µs
OFF: 10 µs

Pulsing Converter

Vout = 2.5 V

Charging Cout

ILC SiD Powering Pulsing Development

KPiX
ASIC Chip

Vin
Analog-Long Time constants, Slow Settling

Vin P
Analog-Fast Settling

Gate
Power Switch

Power Switch

Digital
What can be achieved by this Development?

- Current Reduction from Power Supply by DC-DC near Load Losses > Current^2 x Resistance

- Silicon ÷10 Current Reduction
  \[\text{Power Loss reduced by 100}\]

- GaN ÷ 50 Current Reduction
  \[\text{Power Loss reduced by 2500}\]

Thermal Challenge

A grain of Basmati Rice
4 watts

GaN FETs
40 V 33 A 4mΩ
FET Solder side
Summary: Power Delivery for HEP Detectors & Colliders

- Early work at Intel central research lab’s AIR Core Coils.
- Bell labs / Lucent investigators started Enpirion (maker of the commercial chip that happens to be Radiation Hard)
- Radiation Hardness: Silicon LDMOS 15 V Few amps
- Gallium Nitride could be a game changer: 100 Volts, tens of amps.
- Opportunity for Linear Collider Beam line power supplies
- Gallium Nitride: US companies developing for Power switching market.
  - Japanese companies - Consumer, Auto, Industrial
  - Europe companies – IGBT Replacement, Device R&D - EMEC
- Yale Ideas: Physics Converters to run in radiation and magnetic fields.
Top of the World is Cool but lonely!
Let us keep it cool with highly efficient PS
Swimming is Great at the North Pole
Last month Fairbanks was 33 C - Bye Bye Glaciers!

More Details: http://shaktipower.sites.yale.edu/
Backup Slides
Bias during Radiation
Max operating V & I Limit Power by duty cycle

30 m

Source
FET
Gate
100

Power Supply
V out = 20 Volts

330 2 Watts

DMM
DC mV

1 Ω

~ 0.070 Amps

GND

30 m

50 Ω Terminator

Pomona Box

Powered FET

G

D

S

2 Shorted FETs
Rad vs wo Bias

FET Setup for Proton Radiation Exposure

Satish Dhawan, Yale University
July 28, 2009