Galvanic Isolating Power Supplies – From PCB to Chip & from Analogue to Digital

Matthias Radecker, Yujia Yang, Torsten Reich, René Buhl, Hans-Joachim Quenzer, Shan-Shan Gu-Stoppel
Outline

- Galvanic Isolation versus Miniaturization
- Size Reduction at PCB
- Integration on Silicon versus Passive Process
- Piezo Transformer: Discrete and on Silicon
- GaN on Silicon
- Interleaved Driving for Matching Modules
- Digital Driving for Flexible Programming
- Sequence Based Control & Transient Control
- Conclusion
Outline

- Galvanic Isolation versus Miniaturization
- Size Reduction at PCB
- Integration on Silicon versus Passive Process
- Piezo Transformer: Discrete and on Silicon
- GaN on Silicon
- Interleaved Driving for Matching Modules
- Digital Driving for Flexible Programming
- Sequence Based Control & Transient Control
- Conclusion
Galvanic Isolation versus Miniaturization

Isolation by discrete components

- **Magnetic transformer**: Winding Isolation and Pin Distance on PCB large (8 mm creepage distance)
- **Capacitor**: Large Coupling Capacitance, maximum power limited, 8 mm creepage distance
- **Piezoelectric transformer**: Size must allow for 8 mm creepage distance, pin distance on PCB large
- **High power density with galvanic isolation** is only possible with integrated technology
Galvanic Isolation & Miniaturization

Isolation by passive technology: **114 W/cm³**

- Integrated magnetic transformer: Isolation by material, no air creepage distance, **V = 10.5 cm³**
- + multilevel input stage -> reduce blocking voltage
- + low Q -> unregulated
- + high frequency

= Miniaturization

Source: VICOR

BCM® Bus Converter

BCM380y475x1K2A30
Outline

- Galvanic Isolation versus Miniaturization
- **Size Reduction at PCB**
- Integration on Silicon versus Passive Process
- Piezo Transformer: Discrete and on Silicon
- GaN on Silicon
- Interleaved Driving for Matching Modules
- Digital Driving for Flexible Programming
- Sequence Based Control & Transient Control
- Conclusion
Size Reduction at PCB

LED Off-Line 12 Watts: 0,7 W/cm³ - Transformer Size:

- PCB: 78x34x15 mm³=39,78 cm³ (opt.) 24,3 cm³ (low cost)164 %
- PCB: 60x27x12 mm³=19,44 cm³ (optimized) 80 %
- PCB: 60x7x10,5 mm³=17,01 cm³ (optimized) 70 %

Flyback
H=8,5 mm
2,04 cm³ 100 %

Piezo Radial H=5,2 mm
1,47 cm³ 72 %

Piezo Quad. H=3,75mm
0,85 cm³ 42 %

Size Reduction at PCB depends mainly on height of transformer
Size Reduction at PCB

Off-Line Power Supply 4 Watts: **0,68 W/cm³** - Frequency:

- PT Radial 200 kHz
  - D=14 mm; H=4 mm (V=0,62 cm³)

- PT Radial 280 kHz
  - D=10 mm; H=3.5 mm (V=0,28 cm³)

Multi-leaded Power package
- PCB: 40x25x8 mm³
- Power package (e.g. SDIP-38L = 5,9 cm³)
- RAC04-C (RECOM)
  - = 10,7 cm³ 134 %
  - = 8,0 cm³ 100%
  - = 8,0 cm³ 74%

Power package for small height converter components suitable
Outline

- Galvanic Isolation versus Miniaturization
- Size Reduction at PCB
- Integration on Silicon versus Passive Process
- Piezo Transformer: Discrete and on Silicon
- GaN on Silicon
- Interleaved Driving for Matching Modules
- Digital Driving for Flexible Programming
- Sequence Based Control & Transient Control
- Conclusion
Integration on Silicon versus Passive Process

“emPIC“ (embedded passives integrated circuit)


Ballast-on-a-chip: Di-electric Isolation

EZ-HV™, Philips Semiconductors (SOI-technology)

Silicon Technology and Passive Technology with L in range of μH not compatible
Outline

- Galvanic Isolation versus Miniaturization
- Size Reduction at PCB
- Integration on Silicon versus Passive Process
- Piezo Transformer: Discrete and on Silicon
- GaN on Silicon
- Interleaved Driving for Matching Modules
- Digital Driving for Flexible Programming
- Sequence Based Control & Transient Control
- Conclusion
Topology Off-Line Piezo Power Supply

IF + Boost Converter (PFC) + Serial Inductor HB + Piezo Transformer + Synchronous Rectifier FB + OF
Topology Off-Line Piezo Power Supply

Input Filter + Boost Converter (PFC)
Topology Off-Line Piezo Power Supply

Serial Inductor HB + Piezo Transformer + Synchronous Rectifier FB + Output Filter

$L_f = 2700 \, \mu H \ @ \ 260 \, kHz \ & \ 3Watts$
Experimental Results 3 Watts

Input Filter + Boost Converter (PFC) $V_{IN} = 90V_{rms}$

![Graph showing waveforms for I_Line, V_Line, and V_Bus]
Experimental Results 3 Watts

SIHB + PT + Rectifier + Output Filter: $V_{BUS} = 450V$
## Experimental Results 3 Watts

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching Frequency</td>
<td>261.86 kHz</td>
</tr>
<tr>
<td>Average output voltage</td>
<td>4.947 V</td>
</tr>
<tr>
<td>Average output power</td>
<td>3.138 W</td>
</tr>
<tr>
<td>Half-Bridge Lf rms current</td>
<td>55 mA</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>28 °C</td>
</tr>
<tr>
<td>PT maximum temperature</td>
<td>62 °C</td>
</tr>
<tr>
<td>Lf maximum temperature</td>
<td>46 °C</td>
</tr>
<tr>
<td>S1, S2 maximum temperature</td>
<td>38 °C</td>
</tr>
</tbody>
</table>
Goal: All Components **Integrated on Silicon**

Simple and Reliable Packaging!
Integrated Synchronous Rectifier

3.5 mm² @ $P_{\text{out max}} = 5$ Watts (CMOS)
Integrated Piezo Transformer

Discrete Device
(PZT Power Density = 20 ... 40 W/cm³)

Single Integrated Device

- How to integrate a PT on Silicon?

Integrated Array
(Goal: PZT Power Density = 20000 ... 40000 W/cm³)
Integrated Piezo Transformer

- Thickness PZT: $T_p = 4 \, \mu m$
- Thickness Silicon: $T_{si} = 400 \, \mu m$
- Input Voltage = 100 V
- Output Voltage = 11.3 V
- Strain Output Electrode-Membrane:
  - maximum planar: 0.14 $\mu m$
  - maximum vertical: 2.5 $\mu m$
  - average planar: 0.08 $\mu m$
  - average vertical: 1.6 $\mu m$
- average stress: $2.89 \times 10^8 \, Pa$

- Dumbbell-shaped Hollow-Out U Device
Integrated Piezo Transformer

- Thickness PZT: $T_p = 2 \, \mu\text{m}$
- Thickness Silicon: $T_{si} = 20 \, \mu\text{m}$
- Input Voltage = 100 V
- Output Voltage = 22.3 V
- Strain Output Electrode-Membrane:
  - maximum planar: 1.1 $\mu\text{m}$
  - maximum vertical: 1.2 $\mu\text{m}$
  - average planar: 0.77 $\mu\text{m}$
  - average vertical: 1.0 $\mu\text{m}$
- average stress: $6.23 \times 10^8$ Pa

- Double Ring Device
Integrated Piezo Transformer

- Thickness PZT: $T_p = 2 \, \mu m$
- Thickness Silicon: $T_{si} = 20 \, \mu m$
- Input Voltage = 100 V
- Output Voltage = 16.8 V
- Strain Output Electrode-Membrane:
  - maximum planar: 0.5 $\mu$m
  - maximum vertical: 1.9 $\mu$m
  - average planar: 0.3 $\mu$m
  - average vertical: 1.1 $\mu$m
- average stress: $5.06 \times 10^8$ Pa

- Drum-shaped Device
### Integrated Piezo Transformer

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement vertical (µm)</td>
<td>6e-4</td>
<td>0,87e-2</td>
<td>1,6</td>
<td>1</td>
<td>1,1</td>
</tr>
<tr>
<td>Average Stress (Pa)</td>
<td>1,08e8</td>
<td>2.29e7</td>
<td>2,89e8</td>
<td>6,23e8</td>
<td>5,06e8</td>
</tr>
<tr>
<td>Input Voltage (V)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Output Voltage (V)</td>
<td>29</td>
<td>1,45</td>
<td>11,3</td>
<td>22,3</td>
<td>16,8</td>
</tr>
</tbody>
</table>

- **Decision:** Hollow-Out U Design
Integrated Piezo Transformer

- Top Layer (Au) with Bottom Layer (Pt) has large conduction resistance and capacitive shorts
- Interdigital Structure for only Top Layer (Au) has minimum conduction resistance and small capacitances
Sputtering of PZT

Choice of Sputtering Process: High Power Density achieved by unique crystal structure

PZT-Schicht auf Si durch
PZT on Si through hollow cathode sputtering 13,3 µm thickness,
(100 µm thickness possible)

Magnetron Sputtering of PZT
• 8” Siliziumwafer
• hot sputtering process T = 550°C
• metallic targets
• Sputtering rate 100 nm/min
Integrated Piezo Transformer Application

Conventional Inductor → LTCC Inductor or Integrated

Discrete PT → Integrated PT

Input Rectifier

Conventional Analog Driver ICs

Si Mosfets for HB

Digital Driver Plattform

GaN Mosfets for HB
Outline

- Galvanic Isolation versus Miniaturization
- Size Reduction at PCB
- Integration on Silicon versus Passive Process
- Piezo Transformer: Discrete and on Silicon
- GaN on Silicon
- Interleaved Driving for Matching Modules
- Digital Driving for Flexible Programming
- Sequence Based Control & Transient Control
- Conclusion
GaN Integrated on Silicon

- GaN has high blocking voltage
- High temperature capability
- Small On-Resistance
- High switching frequencies
- GaN on large and cheap silicon substrates
- Arrays feasible (Half-Bridge)

But: For Voltages over 100 V no benefit compared to Silicon (e.g. Coolmos)
Outline

- Galvanic Isolation versus Miniaturization
- Size Reduction at PCB
- Integration on Silicon versus Passive Process
- Piezo Transformer: Discrete and on Silicon
- GaN on Silicon
- Interleaved Driving for Matching Modules
- Digital Driving for Flexible Programming
- Sequence Based Control & Transient Control
- Conclusion
Interleaved Driving for Matching Modules

- Modules operate on demand
- Master: Voltage Control
- Slaves: Current Control

- Phase Shifting: $\phi = \frac{2 \pi}{n}$
- Reduces Output Filter
- Reduces Input Filter
Granular Structure for Matching Modules

- Control Chipset: Nano-DSP, Low-Side- and High-Side Driver
- GaN on Si or Si Half-Bridge Multi-level Chipset
- Integrated Inductors (nH -> MHz !)
- Modul of integrated Micro-Piezo-Trafo-Strings (PZT-MEMS)
- Integrated Synchronous Rectifier Chip

Input Source with Rectifier

Load With Filter
Outline

- Galvanic Isolation versus Miniaturization
- Size Reduction at PCB
- Integration on Silicon versus Passive Process
- Piezo Transformer: Discrete and on Silicon
- GaN on Silicon
- Interleaved Driving for Matching Modules
- Digital Driving for Flexible Programming
- Sequence Based Control & Transient Control
- Conclusion
Digital Driving for Flexible Programming

- Chip by Chip
- Nano-DSP for Digital Control
- Low-Side Driver
- High-Side Driver up to 1 MHz
- Programmable Pins
- Interleaving by GPIO

Source: DP2 of Infineon Technologies AG
Outline

- Galvanic Isolation versus Miniaturization
- Size Reduction at PCB
- Integration on Silicon versus Passive Process
- Piezo Transformer: Discrete and on Silicon
- GaN on Silicon
- Interleaved Driving for Matching Modules
- Digital Driving for Flexible Programming
- Sequence Based Control & Transient Control
- Conclusion
Sequence Based Control and Transient Control

- Sequence Based Control (SBC) means extended sliding mode control considering linear and saturated areas
- SBC can improve transient behaviour significantly and avoid instability of PWM converters
- Modular topology with interleaved cells controllable by SBC
- SBC requires Digital Control (DSP)

---

- Transient Control (TC) will control switching slopes at power switches for improving EMI suppression and reducing filter expense
- Transient Control (e.g. dV/dt of Drain-Source Voltage) will improve interleaving ripple reduction (avoid spikes)
- TC requires Digital Control (DSP)
Outline

- Galvanic Isolation versus Miniaturization
- Size Reduction at PCB
- Integration on Silicon versus Passive Process
- Piezo Transformer: Discrete and on Silicon
- GaN on Silicon
- Interleaved Driving for Matching Modules
- Digital Driving for Flexible Programming
- Sequence Based Control & Transient Control
- Conclusion
Conclusion

- Power density of galvanic isolating off-line supplies for several Watts is not satisfying today
- Magnetic transformer technology is not compatible yet with silicon integration, only at > 100 MHz
- Piezoelectric transformers have larger power density than magnetics and can be integrated on silicon
- High efficient power switches as GaN transistors can be integrated on silicon to reduce switching losses, only with granular structure for $V_{BR} < 100$ V
- Interleaved driving reduces filter expense
- Integrated arrays of piezo transformers improve matching
- Digital driving provides functional flexibility and enable appropriate control methods (SBC, TC)
Thank you!