Power Packaging for Computer Applications

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Agenda

- Objectives

- Trend in power modules
  - Prior Art

- GT’s advances:
  - 3D (Doubleside)
  - Panel fan-out integration

- Advanced Components

- Shielding
Objectives

- Modules
  - 1-250 W
  - Single-stage power conversion:
    - 400 V to 1V; 48 V – 1V
  - 1- 140 MHz and beyond
  - Power density:
    - 1-5 W/mm³
    - 1 W/mm²
  - <1% losses from passive components
  - Module thickness: <0.5 mm

- Thinfilm-integrated passives for IVR:
  - Inductors:
    - L/R: 20000 nH/ohm
    - 1-150MHz
    - 1-2 A/mm²
    - 200-400 microns for composite films
    - 75 microns for sputtered films on glass
  - Capacitors:
    - 1000 nF/mm² at 1-10 MHz
    - 100 nF/mm² at 10-150 MHz
    - ESR: 25-50 milliohms
    - <75 microns
    - Substrate-embedded transformers:
      - > 1W/mm³
      - <2% losses from the component
Technology Trends and Drivers

- Minimize stages of power conversion to suppress losses
- Integrated power conversion with the load:
  - Suppress $I^2R$ losses
  - Minimize the need for decoupling capacitors
- Integration of storage elements that won’t offset the benefits or interconnection losses
- Better Power distribution network designs

- Short PDN path
- Low impedance
- Less voltage drop
- Less voltage variation
- Less de-caps
- More efficiency

Component Density vs. Interconnection Length

Discrete Modules

- PCB
- Inductor
- Cap
- Processor
- Substrate

Embedded Actives and Passives

- EMBEDDED ACTIVES
- EMBEDDED ACTIVES AND PASSIVES
- EMBEDDED ACTIVES
- EMBEDDED ACTIVES AND PASSIVES

- IC
- L
- C

Embedded in IC

Minimize stages of power conversion to suppress losses

Integrated power conversion with the load:

- Suppress $I^2R$ losses
- Minimize the need for decoupling capacitors

Integration of storage elements that won’t offset the benefits or interconnection losses

Better Power distribution network designs
Fully Integrated Voltage Regulator (FIVR) from Intel

**Strategy**

- Package embedded air core inductors
- Air core inductors with low DC resistance below ICs for low parasitic losses
- FIVR for high frequency applications (140 MHz)

**Components**

- Air core inductors with various topologies
  - Solenoids, plated through holes (PTHs)
- Die-side and land-side MLCCs

**Metrics**

- Inductance: $1 - 6.7$ nH
- Current handling: $5 - 20$ A
- $R_{dc}$: $6 - 36$ mΩ
- Area: $\sim 2.4$ mm$^2$
- Thickness: $200 - 700$ μm

**Cons**

- Air core inductors only have DC loss
- DC loss can be adjusted by changing the DC resistance

**Pros**

- For high inductance, air core inductors need more space and larger number of turns resulting high DC resistance
Fan-out Voltage Regulator (VR) from TSMC & Ferric

**Strategy**
- InFO™ with SoC and VR
- Silicon-integrated inductors

**Components**
- Magnetic thin-film inductors
  - Single inductors
  - Coupled inductors

**Metrics**
- Inductance: ~300 nH/mm²
- Current handling: ~1.5 A for single inductors
- Current handling: > 12A/mm²
- L/Rdc: > 200 nH/Ω for L > 100 nH
- L/Rdc: ~ 120 nH/Ω for L~ 10 nH
- Rdc: < 100 mΩ

**Pros**
- Magnetic cores can provide more inductance with less number of turns resulting in low DC resistance
- Low hysteresis and eddy current loss

**Cons**
- Magnetic saturation limits current handling
- Thicker films – reduce throughput and increase cost
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<tbody>
<tr>
<td>Inductors</td>
<td>L comes for free</td>
<td>Good properties</td>
<td>Good properties</td>
<td>Good properties and</td>
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<td></td>
<td>MLCCs getting</td>
<td>and performance</td>
<td>Power losses</td>
<td>performance</td>
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<tr>
<td></td>
<td>thinner</td>
<td></td>
<td></td>
<td>Low cost</td>
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<tr>
<td>Large footprint</td>
<td>Cost</td>
<td>Process-integration</td>
<td>IPD assembly or embedding</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power handling</td>
<td></td>
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Power Converters with high volumetric density

**ECP (AT&S)**
- Embedded component packaging (ECP™)
- Discrete components embedded in substrates

**MicroSIP (TI)**
- Low-power DC-DC converters with embedded IC

**Shinko**
- Discrete inductors
- Discrete capacitors

**TDK-EPC**
- Capacitor
- Inductor
- Capacitor
- PCB
- IC
- Solder Ball
- MicroSIP™ Module Cross-Section (Courtesy of System Plus Consulting)
## Competitiveness of GT Approach with Embedding Si Integrated Ta Capacitors

<table>
<thead>
<tr>
<th></th>
<th>• Discretes</th>
<th>• Embedded ICs</th>
<th>• 3D Packages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inductors</strong></td>
<td>• Ferrites;</td>
<td>• Embedded or</td>
<td>• Thinfilm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SMDs</td>
<td>inductors</td>
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<tr>
<td><strong>Capacitors</strong></td>
<td>• MLCCs</td>
<td>• MLCCs</td>
<td>• Thinfilm</td>
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<tr>
<td></td>
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<td>capacitors</td>
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<thead>
<tr>
<th></th>
<th>EFFICIENCY</th>
<th>POWER HANDLING</th>
<th>SIZE</th>
<th>COST</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Yellow</td>
<td>Green</td>
<td>Red</td>
<td>Yellow</td>
</tr>
</tbody>
</table>
LC Integration with Film Capacitors and Inductors

- Both capacitors are inductors are made as large-area free-standing films
- Can be pre-tested for yield and performance
- Laminated onto substrate or wafer
  - (Or Diced into IPDs and embedded or surface-assembled)

Capacitor Layer at panel scale

Inductor layers at panel scale

Large panel LC integration process
Silicon-Integrated Nanoscale Ta Capacitors

Component Manufacturer (Ex. AVX)

Ta foil

Anode  Cathode

TI Wafer

Use standard infrastructure with “next-generation” standard materials
# Competitiveness of GT capacitors

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Si deep trench</th>
<th>Discrete MLCC</th>
<th>Foil Capacitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component thickness (µm)</td>
<td>~ 200-300</td>
<td>200</td>
<td>75</td>
</tr>
<tr>
<td>Capacitance (µF/mm²)</td>
<td>1-2</td>
<td>2-3</td>
<td>2-3</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>-</td>
<td>150</td>
<td>1 - 150</td>
</tr>
<tr>
<td>Leakage current (µA/µF)</td>
<td>0.1</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

![Image of GT capacitors](image_url)
Capacitor Reliability

65°C/95%RH for 500 hours

- Capacitance response to frequency similar before and after exposure to elevated temperatures and moisture
- Improved ESR after testing
- Parylene sufficient hermetic seal that removes need for casing

65°C/95%RH for 1000 hours

- 1.15 µF/mm² at 1 MHz
- 1.34 µF/mm² at 1 MHz
- 1.19 µF/mm² at 1 MHz
- 1.09 µF/mm² at 1 MHz

80 kA-8V
200 nm Parylene
GT Program in Silicon-Integrated Foil Capacitors

Component Manufacturer (Ex. AVX)

Ta foil

H.C. Starck

Heraeus

Power modules with passive-active integration

Anode

Cathode

Wafer or substrate
Why high-voltage and high-temp capacitors:

High-power inverter and battery chargers:

- DC link capacitors;
  *supress noise from pulsed inverter current and stray DC bus inductance*

Key challenges:
- Higher voltage (200-900 V)
- High-temperature stability (115-175)
- Higher volumetric density for miniaturization
High-Temperature and High-Voltage Capacitors

<table>
<thead>
<tr>
<th>Operating voltage</th>
<th>Capacitance</th>
<th>Case-size (in mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 V</td>
<td>120μF</td>
<td>Diameter: φ25 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Length: 30 mm</td>
</tr>
<tr>
<td>400 V</td>
<td>68μF</td>
<td>Diameter: φ20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Length: 30 mm</td>
</tr>
</tbody>
</table>

AMS’ metallized polymer film capacitors

700 V; 625 A current;
68 mm x 34 mm x 30 mm

Safron’s polymer film capacitors

EPCOS: MLCCs with PLZT
11 microfarad/cc; 350 V

400 V formed dielectric

Electrolytic caps Vishay
Theoretical versus Achieved Volumetric Density for 450 V Applications

<table>
<thead>
<tr>
<th>Material</th>
<th>Capacitance Density (nF/mm³ or microfarad/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer film</td>
<td>10,000</td>
</tr>
<tr>
<td>Al Foil</td>
<td>40,000</td>
</tr>
<tr>
<td>Cu with hybrid</td>
<td>70,000</td>
</tr>
<tr>
<td>HV MLCC (CZT)</td>
<td>50,000</td>
</tr>
<tr>
<td>HV MLCC (PLZT)</td>
<td>30,000</td>
</tr>
</tbody>
</table>

Technology Gap (between current status and theoretically achievable)
Thin Planar HV and HT Capacitors

- Porous copper electrodes with hybrid dielectrics
- Layering with high thermal conductivity adhesives
- High thermal-stability adhesives
- Vias and metallization
- Solder termination with through-vias
- 3D stacking for unlimited scaling up in capacitance

8-9 microfarad/cm³
450 V
85-115 C

40 microfarad/cm³
450 V
>175 C

Porous copper Electrode

Conformal counter electrode
## Inductors - Prior Art

<table>
<thead>
<tr>
<th>Parameters</th>
<th>On-chip inductor</th>
<th>Discrete inductor</th>
<th>GT-PRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>L/R (nH/mΩ)</td>
<td>0.18</td>
<td>23</td>
<td>~20</td>
</tr>
<tr>
<td>Overall losses</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Current handling (A/mm^2)</td>
<td>3-4</td>
<td>0.6</td>
<td>2</td>
</tr>
<tr>
<td>DC resistance (mΩ)</td>
<td>1200</td>
<td>5.2</td>
<td>5</td>
</tr>
<tr>
<td>Thickness (μm)</td>
<td>~100</td>
<td>900</td>
<td>100-700</td>
</tr>
</tbody>
</table>

Sputtered nanomagnetic on Si

Ferrite inductors- Discrete

TSMC on-chip inductors

Coilcraft inductors
Advanced Magnetic Substrates

**Graph:**
- Sheet A
- Sheet B
- Sheet C
- Sheet D

**Table:**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Frequency [MHz]</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Sheet A</td>
<td>182</td>
</tr>
<tr>
<td>Sheet B</td>
<td>141</td>
</tr>
<tr>
<td>Sheet C</td>
<td>92</td>
</tr>
<tr>
<td>Sheet D</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>&lt;0.2</td>
</tr>
</tbody>
</table>

*Nitto Denko Corporation*

**Diagram:**
- Polymer insulation
- Magnetic sheets
- Copper winding
- Laminate substrate
- Substrate
- IC

**Micrograph:**
- Magnetic film
- Copper winding
Inductors IPDs with Nanomagnetic Films on 50 microns glass

Solenoid inductors

Potcor or racetrack inductors

Nanomagnetic film
: T=0.2um

Inductor: T=10um

Oxide: T=0.1um

Glass: T=100um

3 layers at the top
: 3 nanomagnetic films & 3 Oxides

1 layer at the center
: 1 nanomagnetic film

3 layers at the bottom
: 3 nanomagnetic films & 3 Oxides

Inductance (nH)

Magnetic inductors

~10X enhancement in inductance

Permeability
Frequency (MHz)
Component- and Package-Level Shielding

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shielding</td>
<td>60 - 120 dB</td>
</tr>
<tr>
<td>Frequency</td>
<td>1 MHz – 40 GHz</td>
</tr>
<tr>
<td>Distance of separation</td>
<td>0.1 – 10 mm</td>
</tr>
<tr>
<td>Shield metal thickness</td>
<td>~5-50 um</td>
</tr>
</tbody>
</table>

**Component-level shielding:**
- Plated copper
- Multilayered metallic structures

**External shielding:**
- Spray-coated, plated, sputtered

*Materials beyond copper are needed to shield magnetic fields*

Field patterns for TL

Field patterns for circular loop
Package-Level Shielding Beyond Copper and Mu metal

Shielding effectiveness
1. Absorption loss (A)
2. Reflection loss (R)

Multilayered shields
- Multiple reflections inside the shield
  - More effective shielding lower shield thickness
  - Effective at lower frequencies when absorption is not effective

- Magnetic films and magnetic absorption materials
Better EMI isolation Over Cu with Cu-Magnetic structures

(a) NiFe+Ti
Cu(7)NiFe(3)
Cu(3)NiFe(7)Ti
NiFe
Cu
No shield

(b) Isolation (dB) vs. Separation Distance (mm)

Port 1
Port 2

(b) Isolation (dB) vs. Separation Distance (mm)

Port 1
Port 2

NiFe+Ti
Cu(7)NiFe(3)
Cu(3)NiFe(7)Ti
NiFe
Cu
No shield
Summary

GT-PRC is innovating power packaging technologies and also creating an industry ecosystem of material suppliers, component manufacturers and end-users:

• Capacitors in consumer power modules:
  • Silicon-integrated nanoscale tantalum capacitors

• High-temperature and high-voltage capacitors with:
  • Porous copper electrodes
  • Nanoscale inorganic – organic hybrid dielectrics

• Inductors and capacitors in integrated voltage regulators:
  • Low-cost polymer nanocomposite inductors
  • Panel-scale inductor and capacitor integration

• Integrated shielding at component and package-level
  • Materials beyond copper