Thin Film Inductors for Integrated Power Conversion
Ferric, Inc.
Noah Sturcken, PhD - CEO
INTEGRATED VOLTAGE REGULATION (IVR)

Switched inductor DC-DC power conversion with On-chip Magnetic Thin-Film Inductors Save Power, Space And Cost
FERRIC | Package Integrated Voltage Regulator (PIVR)

- Shrink power converters so they can be integrated with the IC
- Reduce $I^2R$ losses associated with high current levels in board + socket + package
- Enable delivery of many independently scalable supplies
**POWER SAVINGS: 20 – 50%**

- **Lower Distribution Losses**: Ferric’s Package Voltage Regulators (PVR) reduce losses in the power distribution network since they are placed at the true Point of Load.

- **Improve Power Management**: Ferric’s integrated solution improves spatial and temporal granularity for power management, significantly reducing power consumption.

![Graph showing voltage and PDN impedance over years](image)

![Diagram showing spatial voltage scaling](image)
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  Total power delivered to DC-DC converter

  More than 50% reduction in overall power consumption from power management.

  ![Power Loss Analysis for FPGA](image)

  **Temporal Voltage Scaling with Discrete VR**

  **Temporal Voltage Scaling with IVR**
**IMPROVED POWER INTEGRITY**

**Conventional Power Delivery Network (PDN)**

![Conventional PDN Diagram]

**Integrated Power Delivery Network (PDN)**

![Integrated PDN Diagram]

Ferric IVRs utilize high bandwidth (UGBW > 50MHz) feedback control and are placed in immediate proximity to the processor load:

- Regulate resonant impedance peaks from upstream PDN
- Reducing maximum broadband supply impedance to <1mΩ
- Reduce processor supply voltage margins for improved efficiency
### IVR TECHNOLOGY ELEMENTS

**Integrated Inductors**
- Inductance density
  - $> 300 \text{nH/mm}^2$, $> 8,500 \text{nH/mm}^3$
- Current density $> 12 \text{A/mm}^2$
- DC Resistance $< 40 \text{m\Omega}$
- Magnetic Coupling $k > 0.9$
- Available monolithically at TSMC or on IPDs

**Integrated Circuit Designs**
- High switching frequency ($>10 \text{MHz}$)
- High bandwidth controller
- Optimization for high efficiency
- Optimization for high density

**Array of thin-film power inductors**

**Example high-frequency buck converter architecture**
OUTLINE

- Ferric Thin-Film Power Inductors & Transformers
- Ferric Device Libraries, Design and Models
- Ferric Power Converters
**FERRIC INDUCTORS**

*Ferric* CMOS integrated magnetic thin-films enable high-quality, high density, low-profile, on-chip/in-package inductive components

- Integrated with TSMC CMOS
  - Inductor layers available as Back-End-of-Line process option (similar to MIM Cap)
  - Circuit models, LVS, DRC
  - Inductor Cell Library

![Image of magnetic thin-film inductors monolithically integrated with CMOS IC](image-url)
BH Loops

- Non-patterned film
- Full Ferric magnetic process
- Measured on BH-Looper at 16Hz
- Ms ~ 1.5T
- Hc ~ 0.39Oe
FERRIC INDUCTORS | Magnetic Cores

Complex Permeability Measurement

- Full Ferric magnetic process (~5μm thick)
- Film patterned into array of 100μm strips
- Measurement power at 10dbm on PNA

![Complex Permeability Measurement Graph]

Effective Permeability vs Frequency (MHz)
FERRIC INDUCTORS | Highlights

- Peak Q Factor > 20 @ ~100MHz
- Peak Inductance Density ~300nH/mm²
- $L/R_{DC} > 200\text{nH}/\Omega$ for $L > 100\text{nH}$
- $L/R_{DC}$ of 120nH/Ω for $L \sim 10\text{nH}$
- Current Density exceeding 12A/mm² for coupled inductors (balanced current)
- Saturation Current exceeding 1.5A for single inductors
- Cross wafer inductance variability $\sigma < 3\%$
- Other Devices in development:
  - Transformers, Baluns, transmission lines, antennas, improved inductor designs
Ratio of AC Inductance (at 100MHz) to DC Resistance for a family of integrated power inductors
Inductor performance for a representative single power inductor
Inductor performance for a representative coupled power inductor
Inductor coupling is used in two-phase buck converters to avoid magnetic saturation.
FERRIC DEVICES | Transformers Design

- Solenoid structure
  - Minimize capacitive/inductive coupling
- Elongated magnetic cores
  - Maximize permeability
- 24-turn primary coil
  - Number of secondary coil turns varies

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<th>Design (i)</th>
<th>Design (ii)</th>
<th>Design (iii)</th>
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<tr>
<td>Turns ratio</td>
<td>2:1</td>
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<td>Primary Turns</td>
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<td>24</td>
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<td>Secondary Turns</td>
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<td>Coil Width, μm</td>
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<td>Device Width, μm</td>
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<td>Device Length, μm</td>
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### Transformer Electrical Performance

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<td>Turns ratio</td>
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<td>3:1</td>
<td>12:1</td>
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<tr>
<td>DC resistance, Ω (primary, secondary)</td>
<td>1.35, 0.34</td>
<td>1.36, 0.17</td>
<td>1.39, 0.02</td>
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<td>Inductance, nH (primary, secondary)</td>
<td>175, 44</td>
<td>166, 19</td>
<td>151, 2</td>
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<tr>
<td>Peak Q</td>
<td>16</td>
<td>14</td>
<td>11</td>
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<tr>
<td>Frequency, MHz</td>
<td>up to 80</td>
<td>up to 80</td>
<td>up to 100</td>
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<tr>
<td>Coupling coefficient</td>
<td>0.96</td>
<td>0.95</td>
<td>0.74</td>
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<tr>
<td>Saturation current, mA</td>
<td>300</td>
<td>300</td>
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</table>

Inductance versus applied DC bias of transformer design (i). The saturation current is defined as current when L drops by 20%, which is around 300 mA in this plot.

Coupling coefficient and maximum available gain of transformer design (i).
OUTLINE

- Ferric Thin-Film Power Inductors
- Ferric Device Libraries, Design and Models
- Ferric Power Converters
Many electrical parameters controlled by design with single fabrication process

- Inductance, Resistance and saturation current
- Coupling coefficient and turns ratio for transformers
Wide inductor design space is covered with a single manufacturing process.
**FERRIC INDUCTOR MODELS**

- Measurements: S-parameter, DC...
  - Parameter extraction: Curve fitting
  - Iteration fitting
  - Genetic algorithm (GA)
  - Exponential gradient (EG) algorithm
  - Characteristic-function

- Equivalent Circuits: lumped or distributed

- Circuit Simulator: SPICE, Spectre...
  - Black-box in Simulators

- Layout and process parameters

- EM simulators: HFSS, ADS...

- Non-linear magnetic behavior
  - Verilog or VHDL

- Analytical Method

- Layout and process parameters
FERRIC INDUCTOR MODELS

L & R VS. FREQUENCY WITH $I_{\text{AVG}}$ SWEEP: MEASUREMENT & SIMULATION

Broadband compact circuit models are available for Ferric Library devices including magnetic saturation.

Measured inductor inductance data (dots) compared with SPECTRE model (lines)

Measured inductor resistance data (dots) compared with SPECTRE model (lines)
OUTLINE

- Ferric Thin-Film Power Inductors
- Ferric Device Libraries, Design Support and Models
- Ferric Power Converters
- >10 IVR Bucks with thin-film inductors on embedded PMIC (ePMIC)
  - Buck count increase to provide per-core DVFS
  - 1 Buck from master PMIC
  + Reduction in BOM, board area, power delivery losses
  + Improved power management → improved performance-per-watt
Fe01034D Power Converter
3A Chip Scale DC-DC Step-Down Power Converter with Integrated Inductor

The Fe01034D is an 8-phase Buck converter with fully integrated powertrain, including thin-film power inductors. The Fe01034D integrates interface, power management, voltage control and power train circuitry (including power FETs, inductor and capacitor) all in one die, 2.0mm x 3.2mm.

The Fe01034D is designed to meet the precise voltage and fast transient requirements of high-performance processor, DSP, FPGA, and memory in distributed power architecture. The power converter’s high-bandwidth regulation, coupled with high switching frequency powertrain driving magnetic composite integrated inductor technology deliver high-quality, small footprint power management for high performance loads.

High switching-frequency DC-DC power conversion with integrated power inductors greatly reduces board area, layout complexity, and BOM. The Fe01034D provides improved energy efficiency for true point of load (POL) applications and significantly reduced design cycle and overall system cost.

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- Integrated Thin-Film Magnetic Inductors
- Efficiency > 85%
- Multi-Phase Operation
- Single Input Supply Operation
  - 1.8V-2.5V
- Programmable Output Voltage
  - 0.6V-1.5V
- Output Current
  - 0mA – 3A
- Small footprint
  - 2.0mm x 3.2mm
  - 180µm IO Pitch
- Low Profile
  - 400µm
- Digital Power Management Interface
- High switching frequency
  - 100MHz
- Programmable soft start
- Load Regulation
- Line Regulation
- Fast Input Step
- Programmable Ramp Rates
- Auto Phase Shedding
- Output LDO
- Gang operation
- On-chip power monitor
- On-chip temperature monitor
- Under Voltage Lockout, Over Current, Over Voltage and Thermal Protection.

Application
Point of load regulation for processors, DSPs, FPGAs, and ASICS
Noise sensitive applications such as AV, RF and Gbit I/O
Blade servers, RAID storage systems, LANSAN adapter cards, wireless base stations, industrial automation.

Ordering Information

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<th>Part Number</th>
<th>Temp Rating (°C)</th>
<th>Package</th>
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<tbody>
<tr>
<td>Fe01034D</td>
<td>-40 to +85</td>
<td>FC Bare Die - 59 Cu Bump</td>
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<td>TDB</td>
<td>Evaluation Board</td>
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Figure 1: Application Schematic Total Area 6.4 mm²

Load Transient: VIN = 1.8V, VOUT = 1.2V, IOUT = 1.5A - 3A

Efficiency VIN = 1.8V, VOUT = 0.9V, 1.2V, 1.5V

Efficiency vs. Output Current
Vin: 1.8V
Inductors embedded in Wafer Level Package
Reduce board footprint by 400%!

- **Total Board Solution Size:** ~3.0mm²
  - 1x WLCSP Boost Converter Chip (1x 1.44mm²)
  - 2x 0402 Discrete Capacitors(2x 0.5mm²)
FERRIC | μVR BOOST | FE1004U

FE01004U Power Converter
0.1A Chip Scale DC-DC Step-Up Power Converter with Integrated Inductors

Description
The FE01004U is a synchronous step-up DCDC converter with integrated power FETs, inductor and capacitor. The nominal input voltage range is 1.8V to 6.0V. The output fixed voltages is 2.5V-5V in increments of 0.1V with ±2% accuracy. Up to 100mA of continuous output current can be drawn from this converter. Fast switching frequency allows for the use of small size input / output capacitors and enables wide loop bandwidth within a small footprint and low profile. The FE01004U solution offers greatly reduced board area, layout complexity and BOM. With a WL CSP package size of 1.2mm x 1.2mm, a total board solution of 2.5mm² can be achieved.

Features
- Integrated Magnetic Thin-Film Inductors
- Up to 90% Efficiency
- Internal Synchronous Rectification
- Input Voltage Range: 1.8V-5.5V
- Fixed Output Voltage: 2.5V-5V with ±2% accuracy (0.1V increment)
- Output Current: Up to 100mA OR 500mA
- Operating Quiescent Current: 0.5 µA
- Small Footprint: 1.2mm x 1.2mm
- Low Profile: 400µm
- Total Board Solution Size: 2.5 mm²
- Pulse Frequency Modulation
- Soft Start
- Under Voltage Lockout
- Over Current Protection
- Over Voltage Protection
- Load Disconnect
- Output LDO for VIN > VOUT

Applications
- Low-Voltage Li-ion Batteries
- Smart Phones, Tablets, Portable Devices
- Wearable devices
- PC Peripherals

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<td>-40 to +105</td>
<td>9-pin WL CSP</td>
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<td>TBD</td>
<td>Evaluation Board</td>
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Vin=3.6V, Vout=5V, Iout=6mA-50mA
Vin=3.6V, Vout=5V, Iout=6mA-100mA
Vin=3.6V, Vout=5V, Iout=50mA
FERRIC IPDs | SOC embedded Voltage Regulator (eVR)

- Ferric Power Inductor IPD integrated on SoC package ‘landside’
- Ferric SoC-IVR Die: IVR controller, half-bridge and cap – SoC and ‘slammer’ loads
- >85% efficiency for 1.5V to 0.85V conversion, 2A/mm² current density
FERRIC
THE COMPANY

- Fabless semiconductor technology company, founded in 2011
  - Located in New York
- Integrated magnetic component and power conversion technology
- Ferric integrated power inductors are available at TSMC now

Company Focus:
- semiconductor device manufacturing
- magnetic thin-films
- RF device design, characterization and modeling
- CMOS IC design for power conversion applications

Chip Sales, Design, IP and Process Licensing
QUESTIONS?