Rensselaer

Integrated High Frequency Power Conversion using GaAs pHEMTs

T. Paul Chow, Mona Hella, Vipindas Pala, Han Peng

Rensselaer Polytechnic Institute,

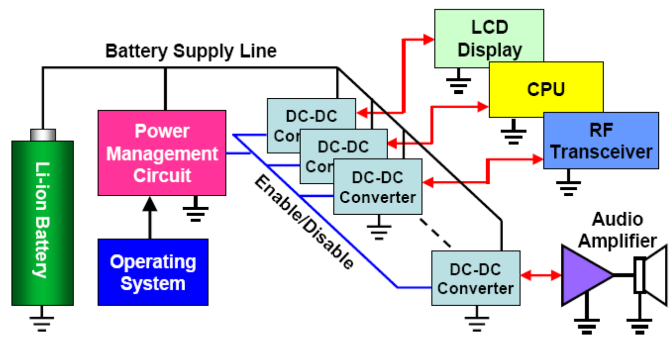
Troy, NY

Power Converters for Portable Electronics

- Battery Capacity
- IC Voltage Scaling
- Miniaturization
- Integration

System Trends

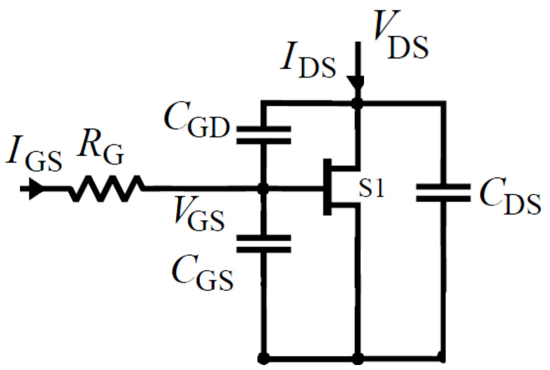
Efficient POL Power Conversion



- Bandwidth +
- Efficiency +
- Footprint

SMPS

Switch Power Losses for Hard Switched Converters



- Gate capacitance charging loss and output switching loss limit the switch gate width
- Product of R_{ON} and Q_G still determines minimum switch power loss

$$P_{CON} = I_{DS}^2 R_{DS,ON}$$

$$P_{SW} = \frac{1}{2} V_{Batt}\ I_{DS}\ (t_{ON} + t_{OFF}) \times Freq$$

$$\approx V_{Batt}\ I_{DS} \frac{Q_G}{I_G}\ Freq$$

$$P_{GD} = Q_G V_{GS,ON} Freq$$

$$P_{OSS} = \frac{1}{2} Q_{DS1} V_{Batt} Freq$$

$$P_{Min} = 2\sqrt{\overline{I_L^2} R_{ON,SP} Df \left(\frac{\overline{I_L}}{I_G} Q_{G,SP} V_{Batt} + Q_{G,SP} V_{DD} + \frac{1}{2} Q_{DS,SP} V_{Batt} \right)}$$

$$\Rightarrow FOM = R_{ON} \times Q_G$$

Rensselaer

FOM : Low-Voltage High Frequency Switches

$$FOM = R_{ON} \times Q_G$$

$$(R_{CH} + R_D + R_{EXT}) * (Q_{CH} + Q_D) = \left(R_{EXT} + \frac{L_{CH}}{W\mu_{CH}Q_{CH}} + \frac{L_D}{W\mu_D Q_D}\right) \times (Q_{CH}L_{CH}W + Q_D L_D W)$$

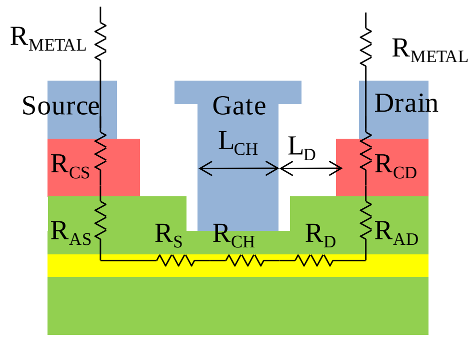
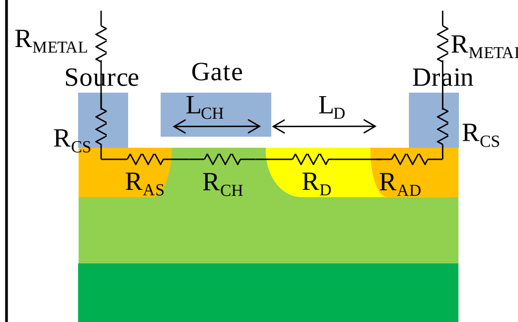
Channel Scaling to improve these

- R_{EXT} : Contact, Access, Metallization resistance become critical

Wide Bandgap Advantage limited to these two terms only

Comparison of Device Technologies

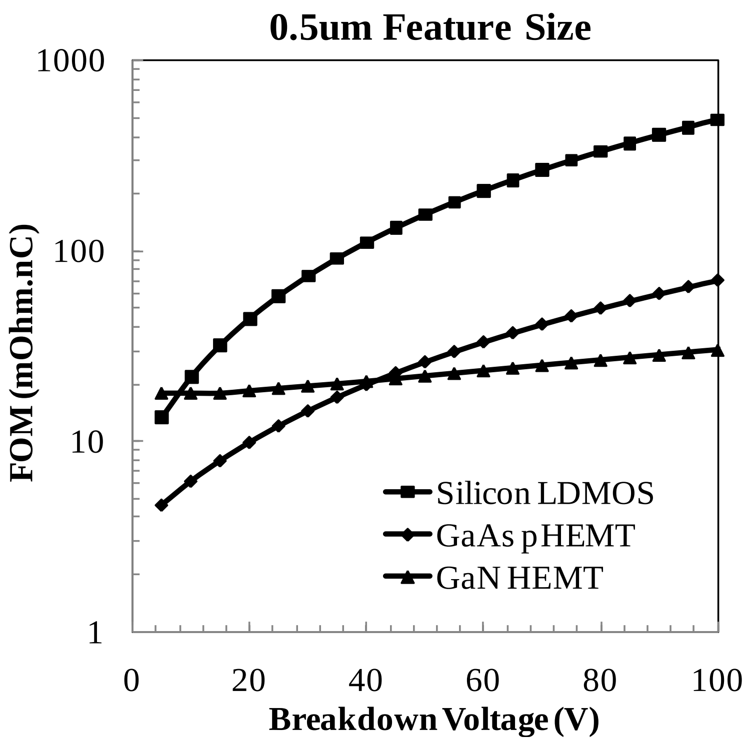
- HEMT : Higher mobility, NMOS : Smaller access resistance
- GaAs : Higher channel and drift mobility compared to GaN, Si
- GaN : Higher voltage supporting capability, but for low voltages, the drift region contribution is small, so other resistance components dominate

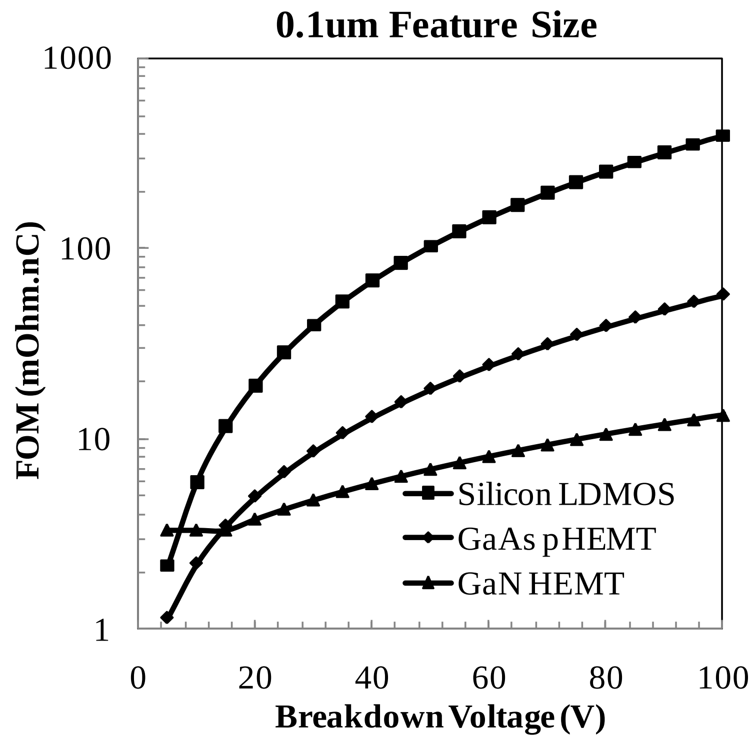
Device	**HEMT**		**Lateral NMOS**
Structure			
Material	**AlGaAs/InGaAs/ AlGaAs**	**GaN**	**Silicon**
μ_{CH} ($cm^2V^{-1}s^{-1}$)	6000	1500	500
μ_D ($cm^2V^{-1}s^{-1}$)	6000	1500	1200
$E_{C,Lat}$ = BV/ L_D	25V/µm	150V/µm	15V/µm
Contact + Access Res.	0.2 Ω.mm	0.2 Ω.mm	0.1 Ω.mm

Power Device for High Frequency Switching

- Silicon approach :
  - Migrate to Nanometer gate lengths to reduce capacitance
  - Below 5V : Cascoded nm-CMOS
  - Below 20V : LDD NMOS
  - Above 20-30V: LDMOS
- Our approach : Schottky gated AlGaAs/InGaAs/AlGaAs pHEMTs on GaAs substrates
  - Bandgap + Mobility Advantage
  - Low FOM without small feature size processes

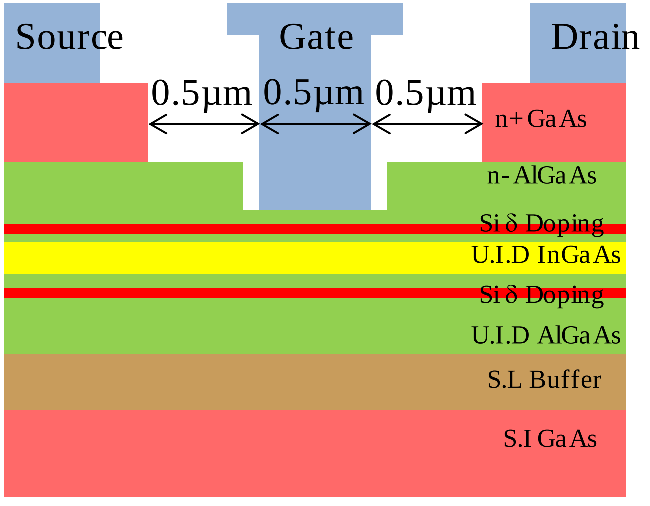
First Order Comparison of FOM





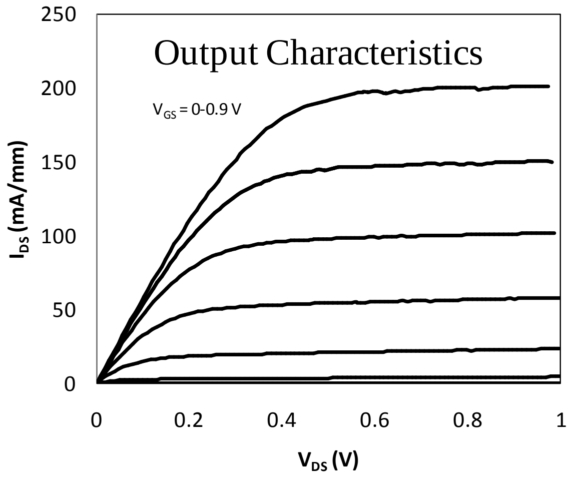
- Mobility and Bandgap advantage for GaAs pHEMTs
- Best for under 20V

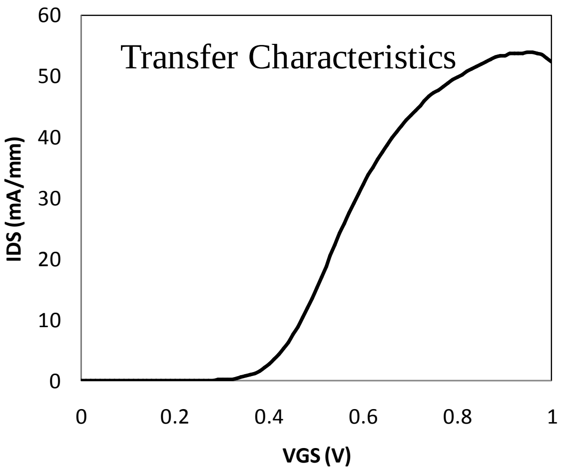
0.5µm E-Mode GaAs pHEMT Switch



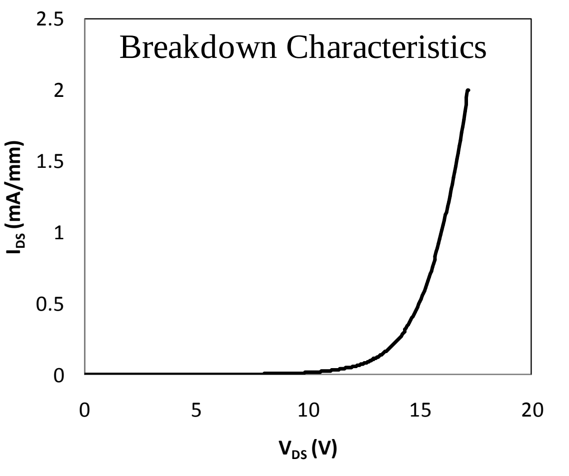
- pHEMTs ubiquitous in RF MMICs
- Mature Process technology
- Double recessed commercially available E-pHEMT process (TriQuint TQPED)
  - For RF switches and front ends : Not-optimized for power swtiching
- InGaAs 2DEG Channel
- Threshold Voltage = +0.36V, Maximum $V_{G,ON}$=0.8V
- Semi-insulating substrate : High side operation

Device Characteristics





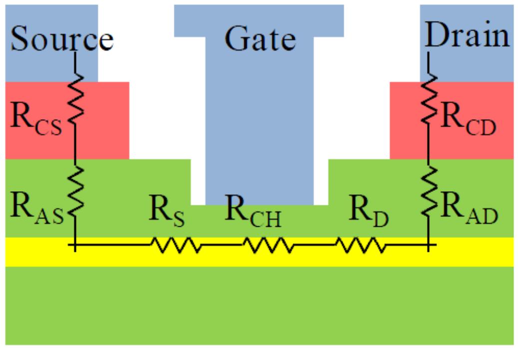
- Threshold Voltage = +0.36V, Maximum $V_{G,ON}$=0.8V
  - Low Leakage at V_G=0V, V_{DS}=5V : 20nA/mm
  - No negative voltage generator required in standby mode
  - P_{ON} / P_{OFF} = 10^5
- Breakdown Voltage 11V (at V_{GS}=0V) (10uA/mm)
  - Limited by leakage
  - Avalanche breakdown only at ~25-30V

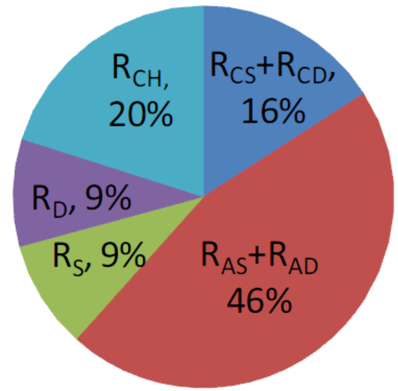


Rensselaer

Intrinsic FET Characteristics

TLM Measurements : Single Finger FET (100um)

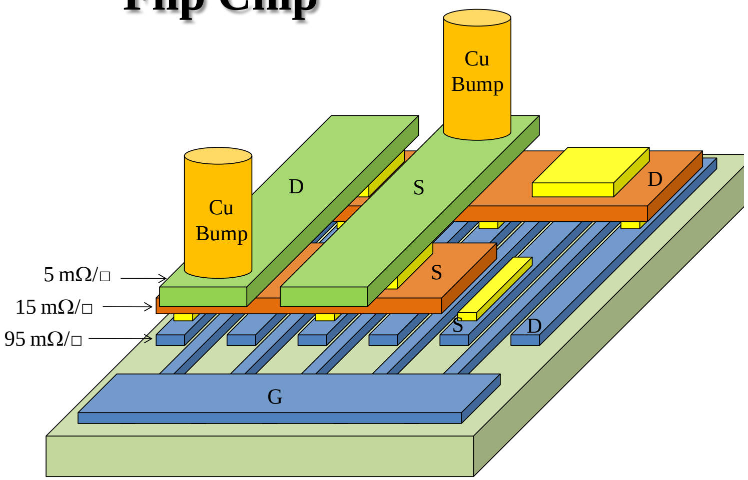


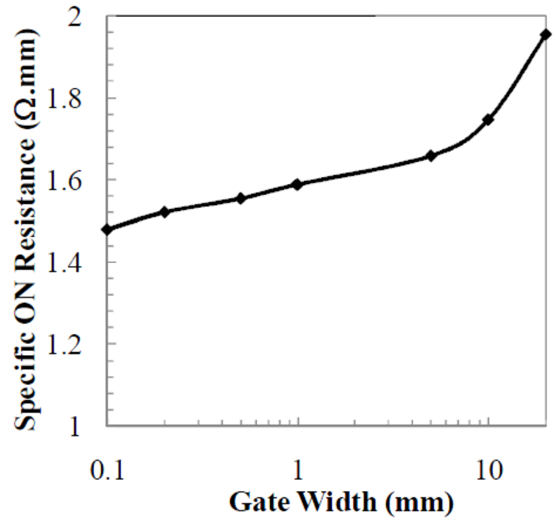


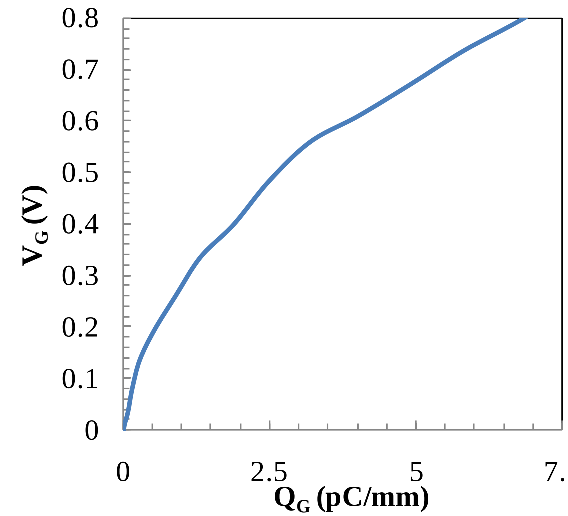
- Intrinsic Specific R_{ON} (Measured on single Finger 100µm wide FET= 1.48 Ohm.mm
  - Dominated by Contact and Access
  - Intrinsic Specific R_{ON} (Measured on single Finger 100µm wide FET= 1.48 Ohm.mm
- Specific Gate Charge (From Capacitance Models) : 3.1pC/mm
- Intrinsic FOM : 4.6 mΩ.nC

Metallization and Packaging Effects

Three Level Interconnect + Flip Chip



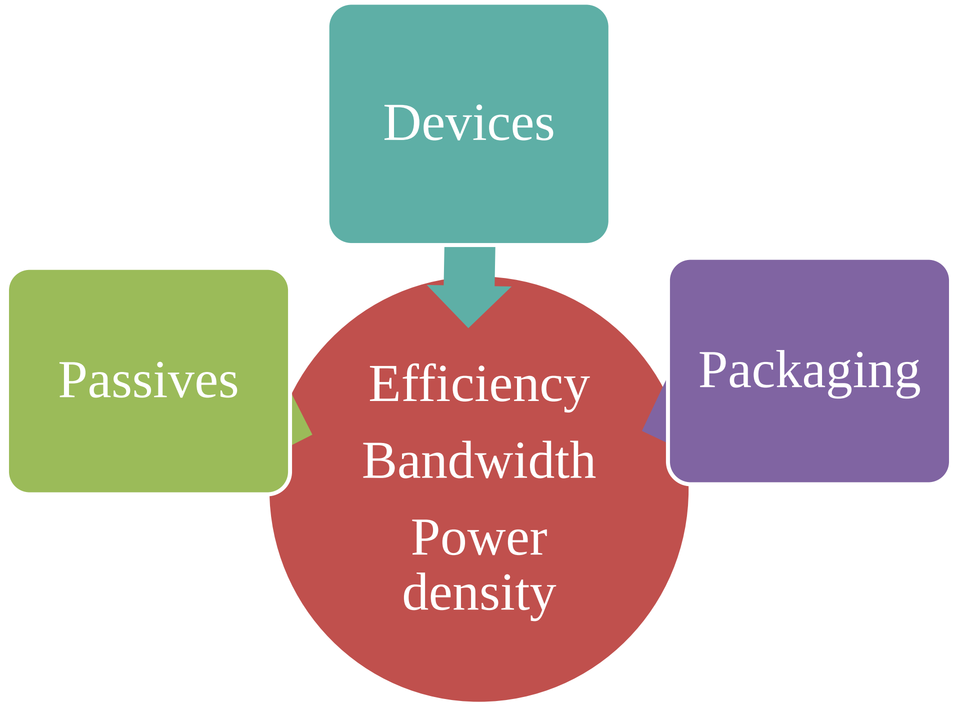




- Metallization resistance further degrades resistance for multi-fingered devices
- 10mm gate width: R_{ON} = 1.75mΩ, Q_G = 70pC
- <u>FOM=12 mΩ.nC</u>
  - Compared to 27.5 mΩ.nC for Silicon 0.5um, 11V LDMOS (GWS24N07)

Rensselaer

Key Technologies for High Frequency Power Conversion

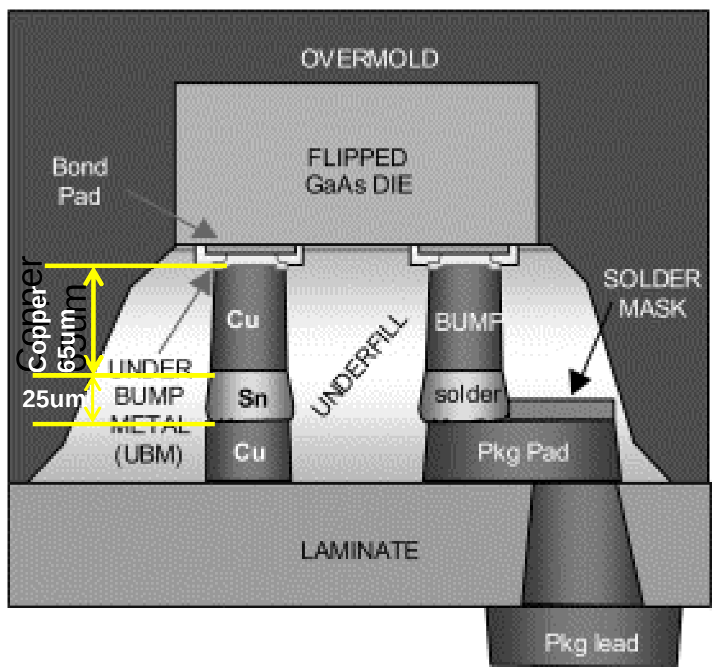


Device is only part of the story !!

Rensselaer

Passive Technology : Thick Cu Inductors on GaAs

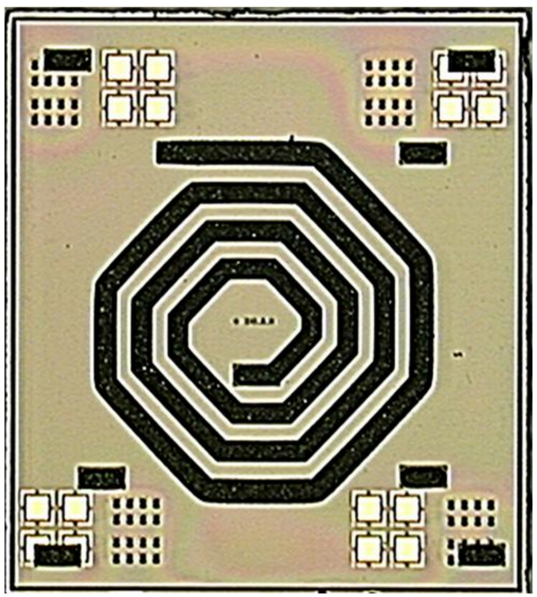
- Air core inductors for switching above 100 MHz
- Thick Cu (65μm tall) spirals with spacing of 30-45μm
- Solder bumps on top, flip chipped to laminate
- Bump height (25um) prevents Eddy current losses to laminate interconnect

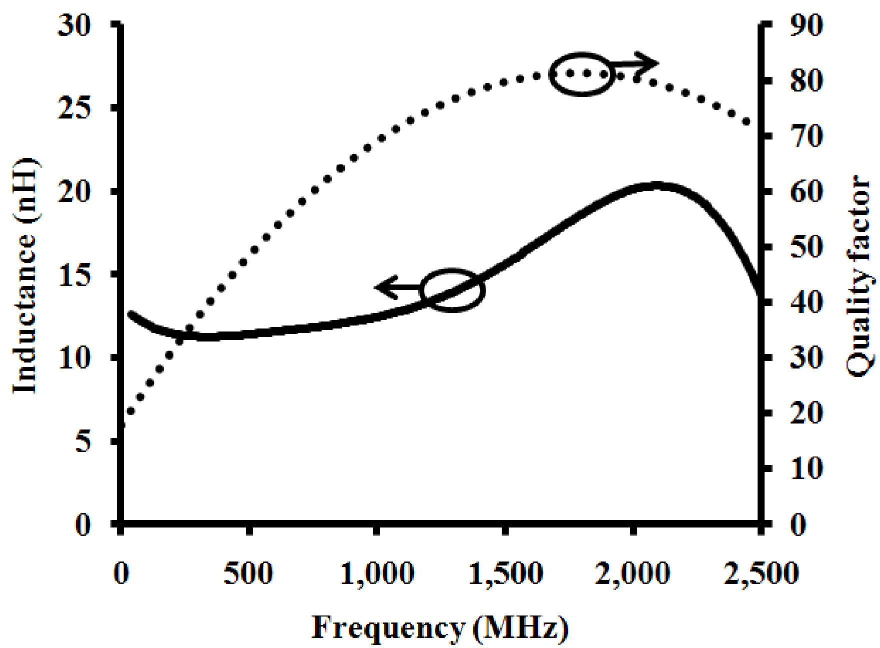


Rensselaer

Passives for DC-DC Conversion

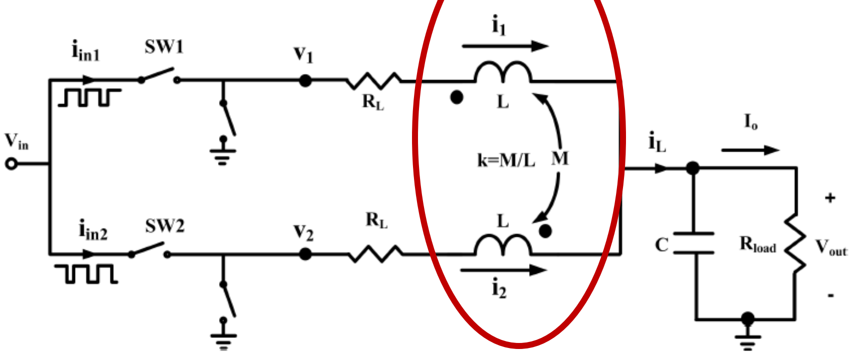
- Tall Cu : Low DCR, High Q

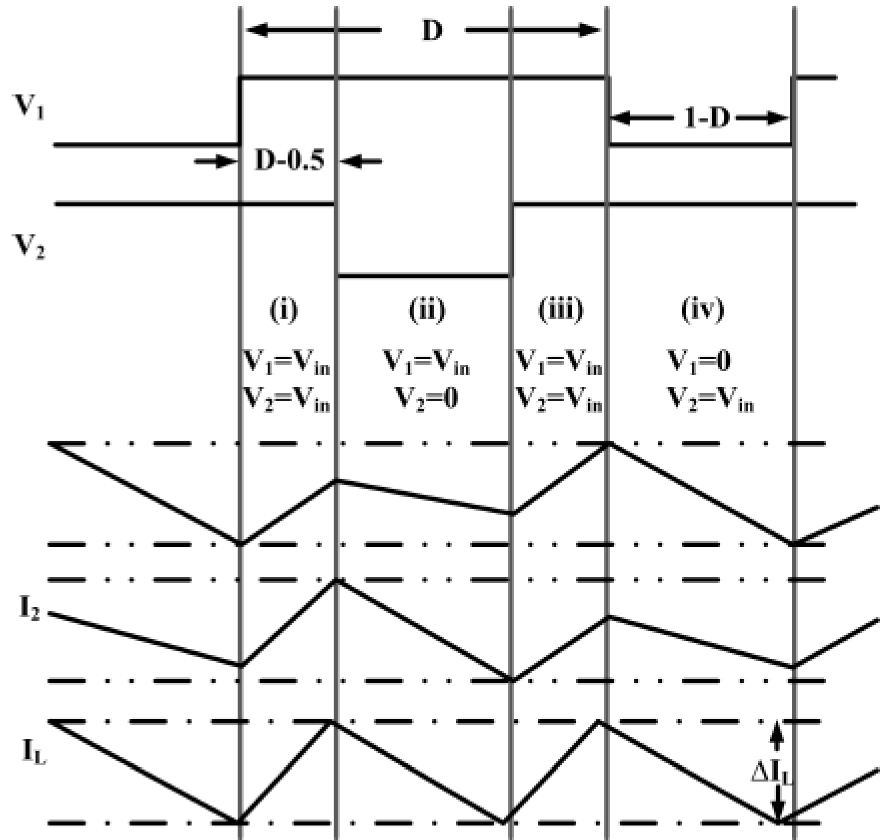




Inductor Coupling for Multiphase Converters

- Can use smaller inductors for same ripple : improved efficiency, bandwidth





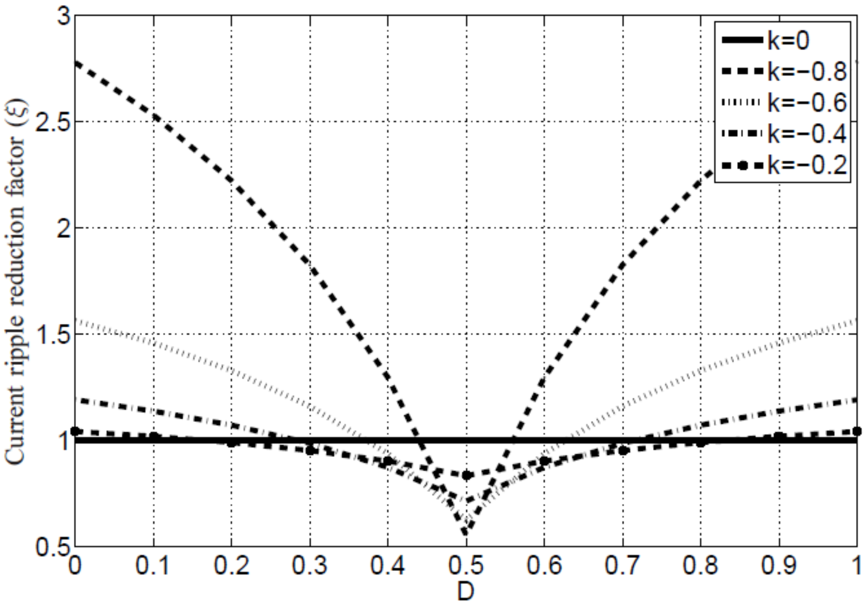
Optimal Coupling Factor

$$k_{opt} = \begin{cases} \frac{1-D}{D}\left(\sqrt{1-\left(\frac{D}{1-D}\right)^2}-1\right) & \text{for D} \le 0.5 \\ \frac{D}{1-D}\left(\sqrt{1-\left(\frac{1-D}{D}\right)^2}-1\right) & \text{for D} > 0.5 \end{cases}$$

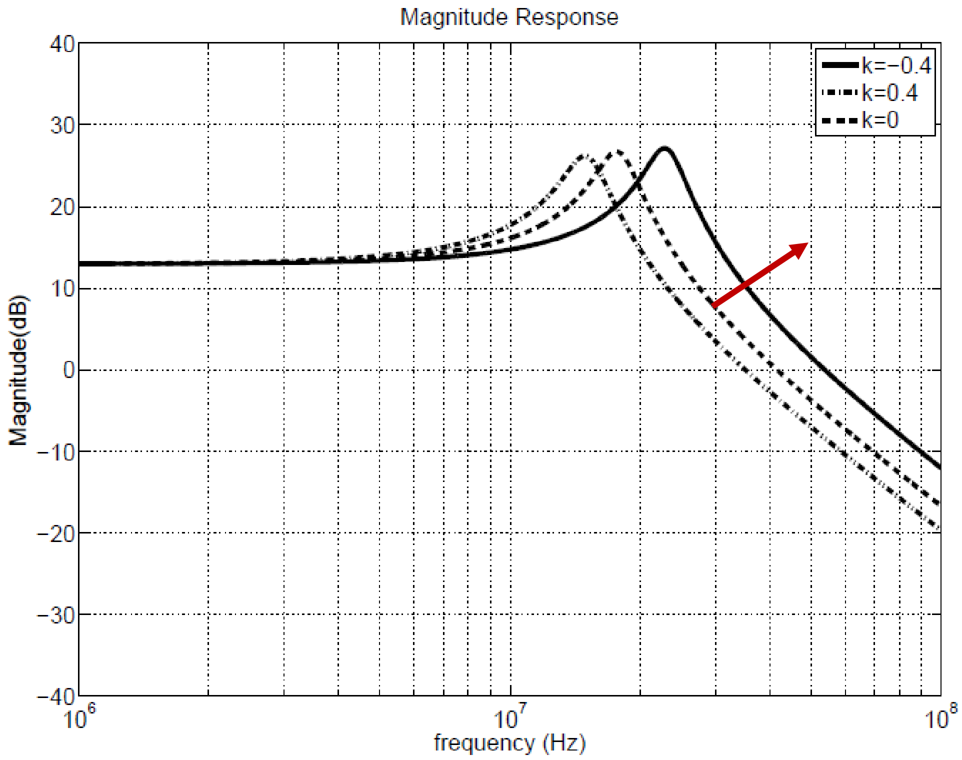
Rensselaer

Coupling : Ripple and Bandwidth enhancement

Current Ripple Reduction with Duty Ratio

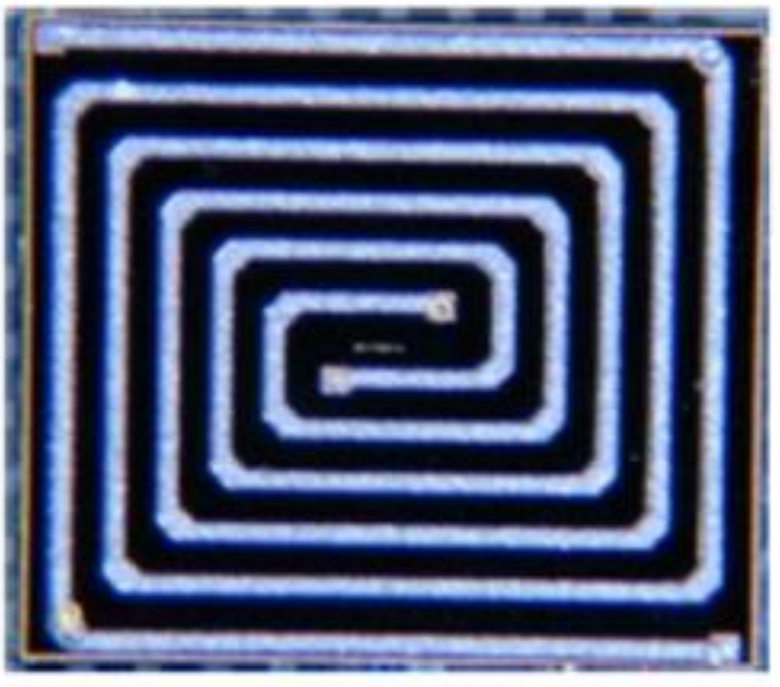


Bandwidth enhancement with negatively coupled spirals

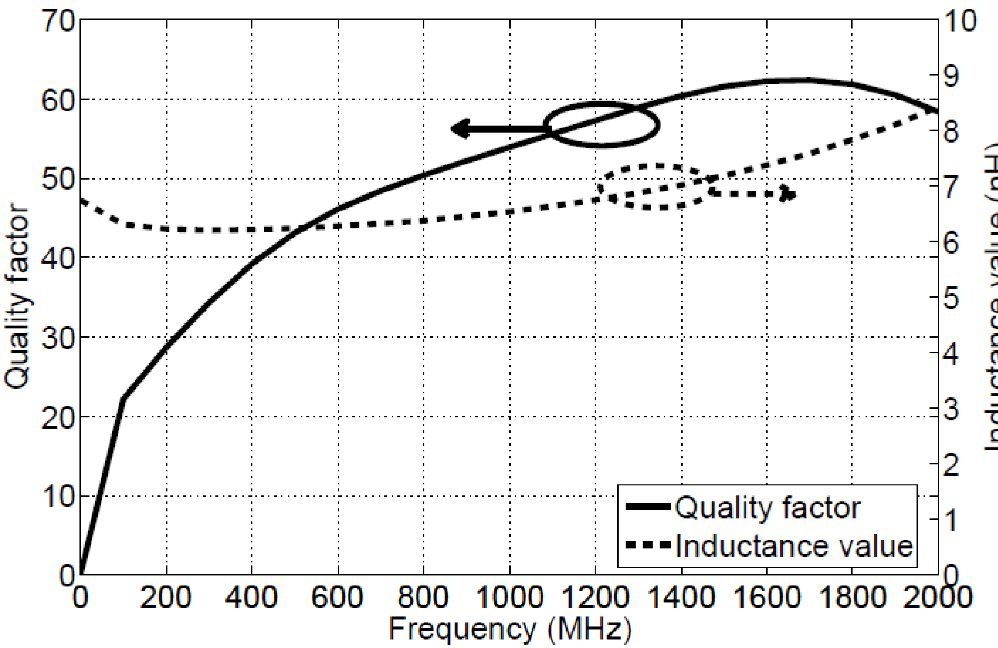


Coupling : Ripple and Bandwidth enhancement

- Coupled Thick Cu Inductors on GaAs

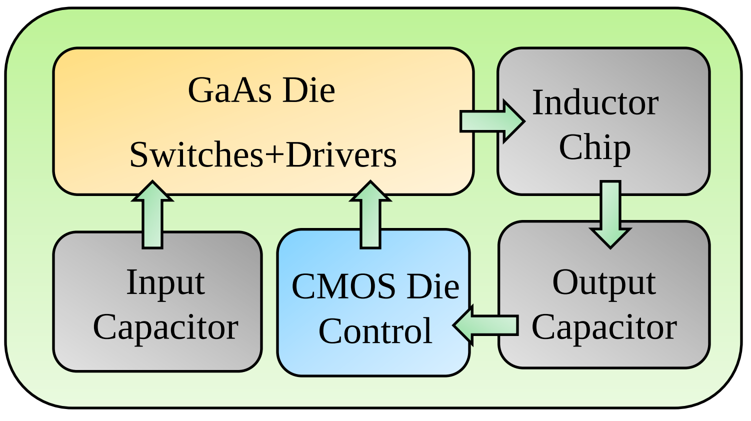


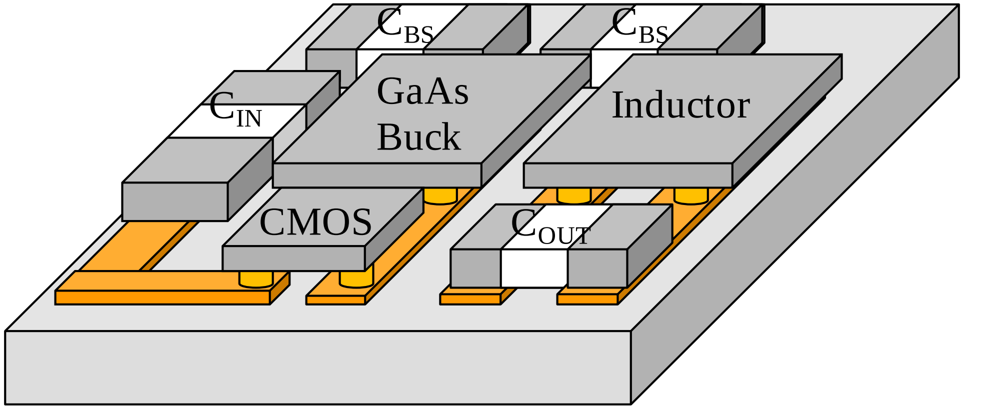
Coupling Factor : -0.4 for 65% conversion Ratio



Packaging : Multi-chip Module

- Use best technology for each component :
  - GaAs pHEMT– High Frequency Switch + Drivers
  - Inductor Chip– Thick Cu on bare semi-insulating GaAs / SMD
  - CMOS – Control and Logic

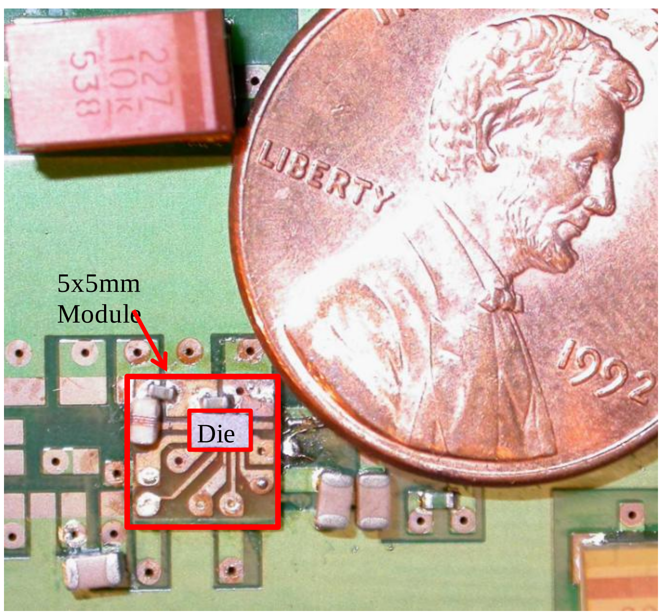


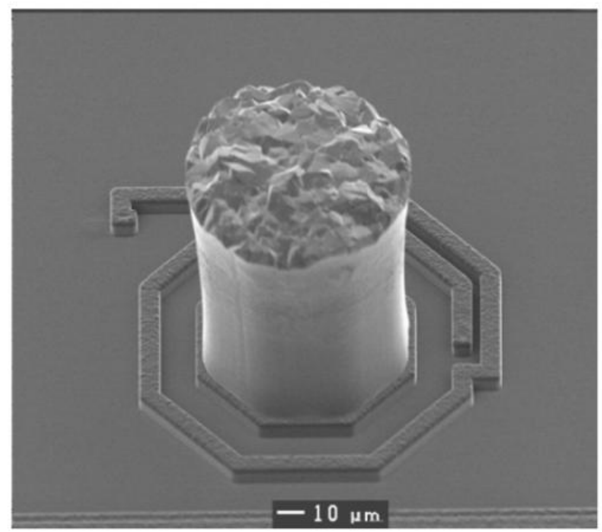


Rensselaer

Flip Chip Bonding

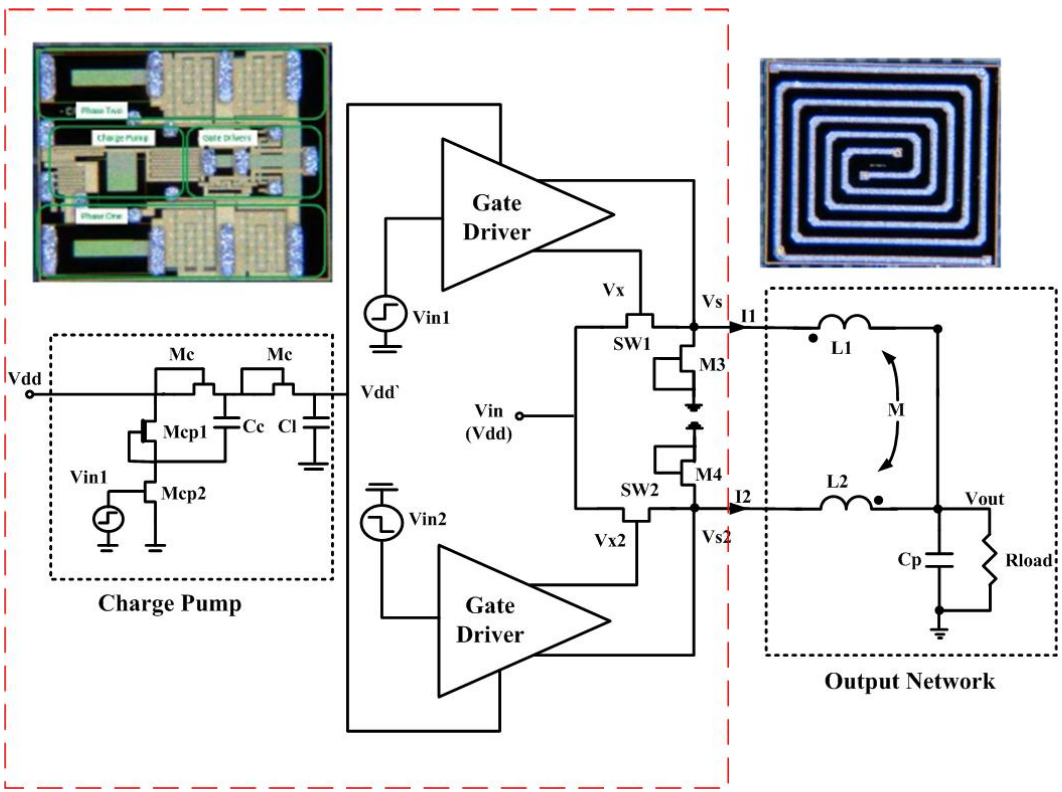
- Solder on Copper bumps
- Can place bumps on active FET area : spreading resistance reduced
- No bondwire parasitics : lower wire inductance, resistance
- Eliminates the need for ON-chip de-coupling
- High throughput, low assembly cost

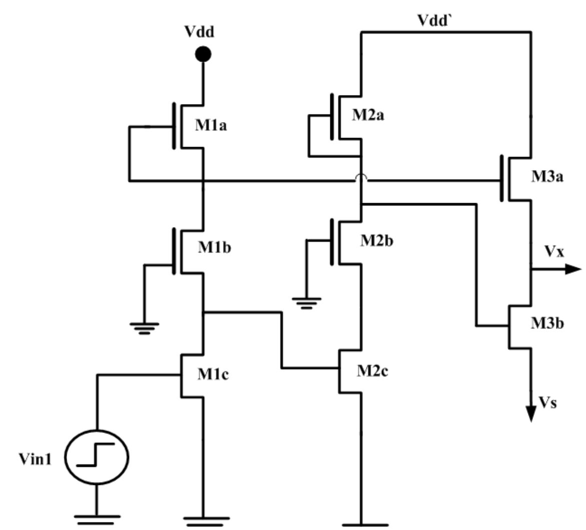




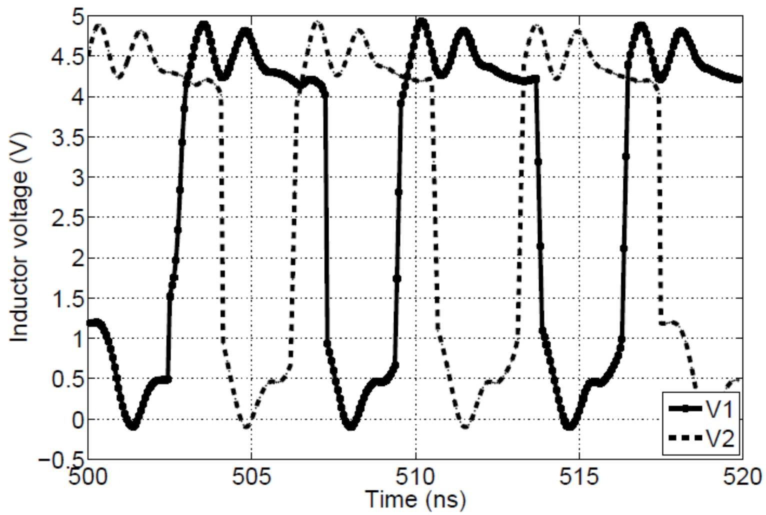
Design Example A

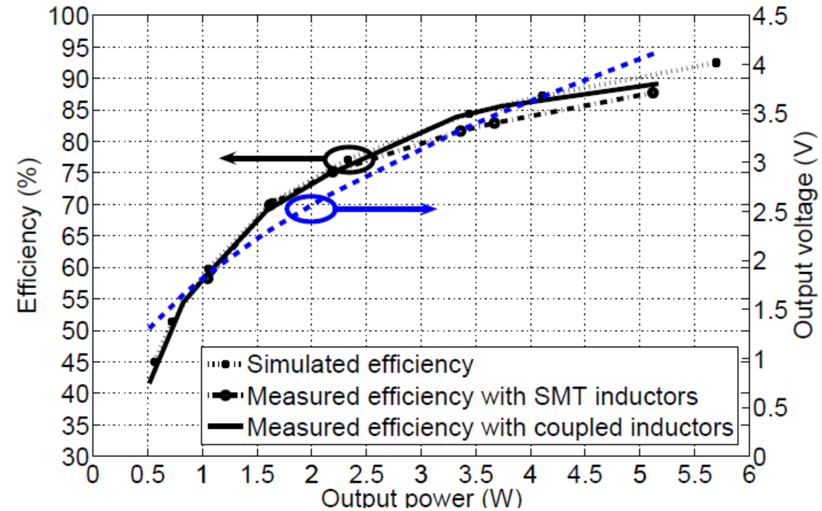
- 150 MHz 2 Phase Interleaved Buck with Coupled Inductors
- Switches + Drivers on GaAs pHEMT
- 4.5V Input : 1.5-3.3V Output, 0.5A per Phase





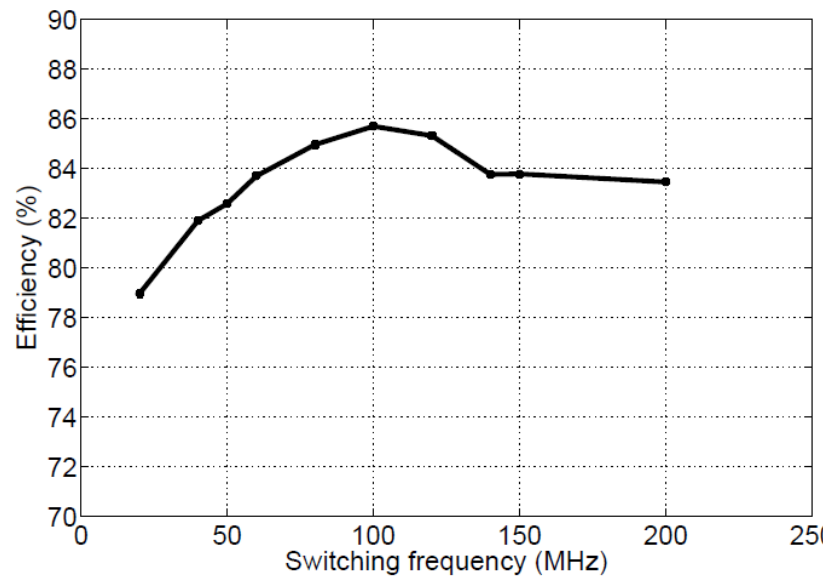
Measurements





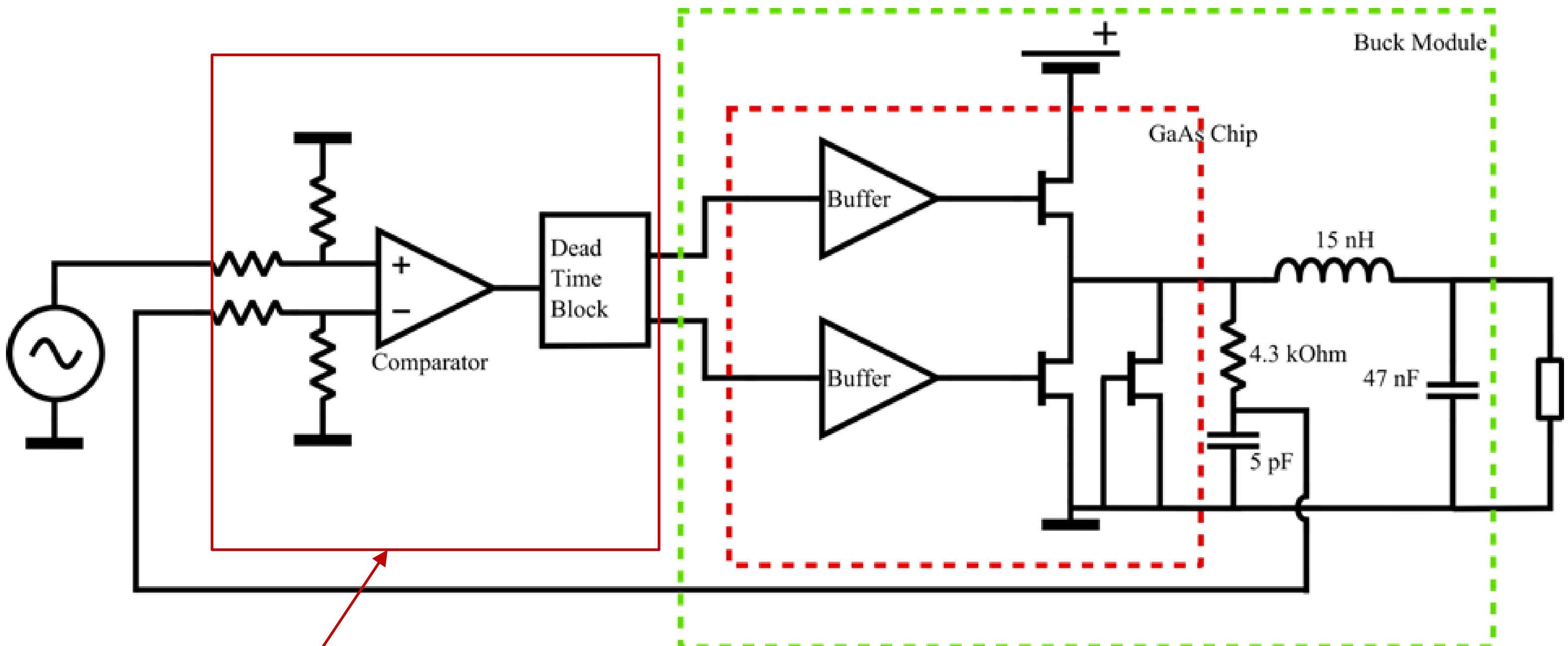
MEASURED PERFORMANCE SUMMARY

Technology	0.5μm GaAs p-HEMT
Circuit Area	$4.22mm^2$
Inductor Area	$5.94mm^2$
Inductance Value	8.77 nH
Coupling Factor	0.46
Q at 150MHz	26
Input Voltage	4.5 V
Output Voltage	3.3 V
Output Current	1 A
Switching Frequency	150 MHz
Peak Efficiency	84%
Voltage Ripple	116 mV



Design Example B

- ~100MHz DC-DC Converter for Power Amplifiers
- Single Phase , GaAs pHEMT Output Stage + 0402 Air Core inductors from Coilcraft



GaAs pHEMT "Dummy CMOS" Chip

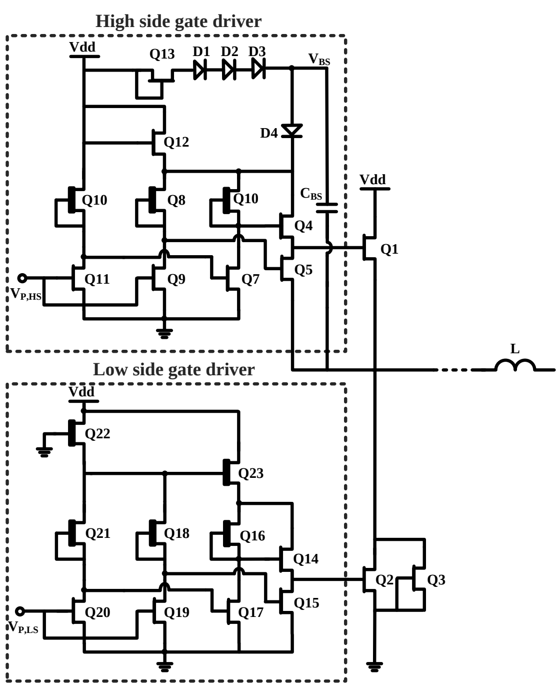
Power Converter Module

Rensselaer

Design Example B : GaAs Output Stage

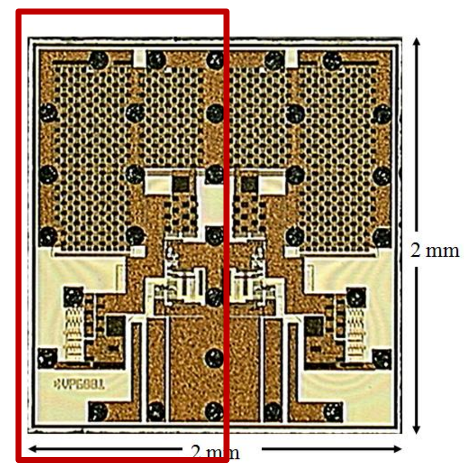
- Synchronous Buck Converter
- High Side Bootstrapped driver for N-type device
- 100MHz switching frequency at full power (switching frequency varies with load)

GaAs Buck Circuit + Bootstrapped Gate Driver



Chip Photograph

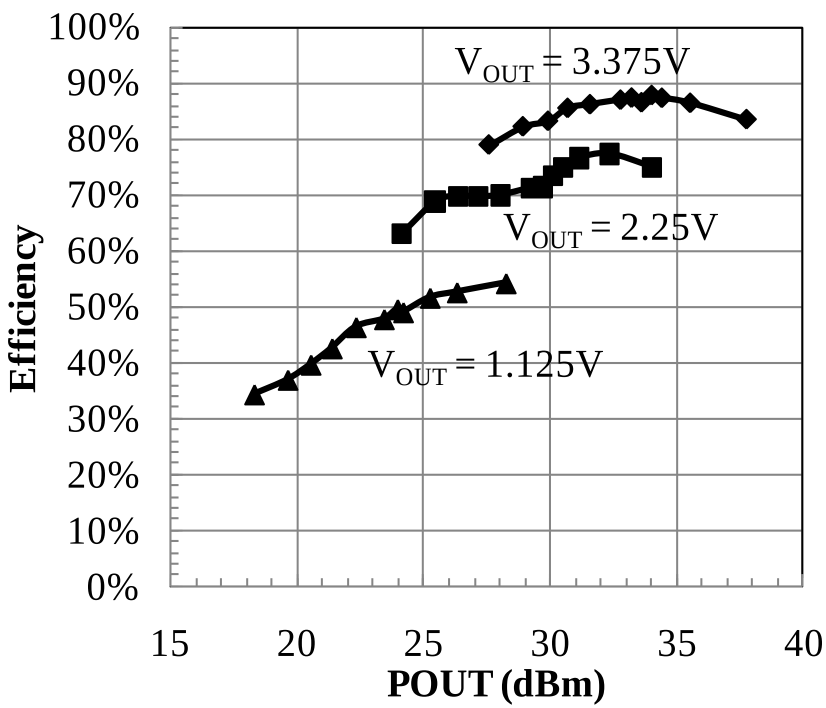
Single Phase Used



Rensselaer

Measurements

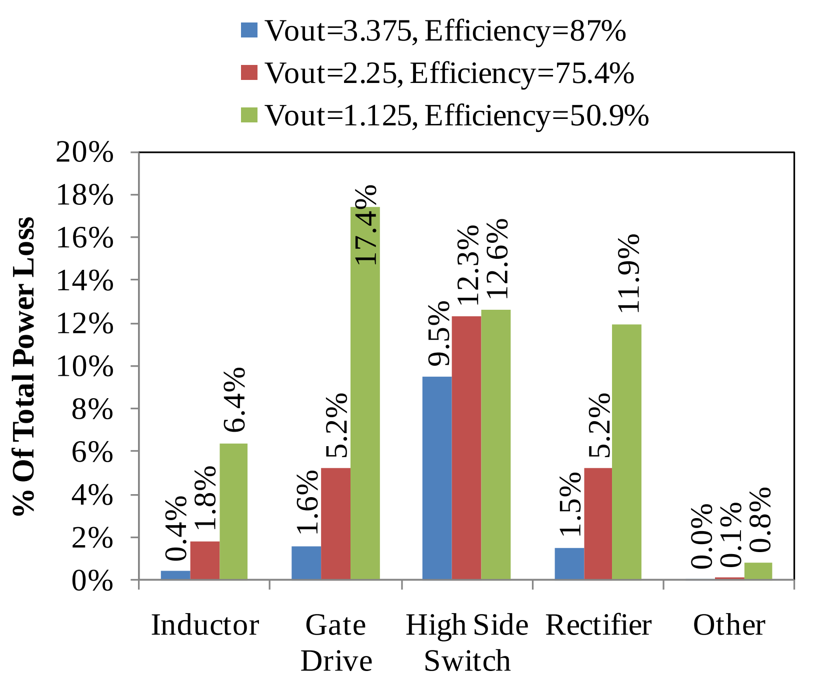
- Efficiency : 88% at 4.5V input, 3.375V output, 1A
- Efficiency degradation at low power due to GaAs gate driver power loss



Rensselaer

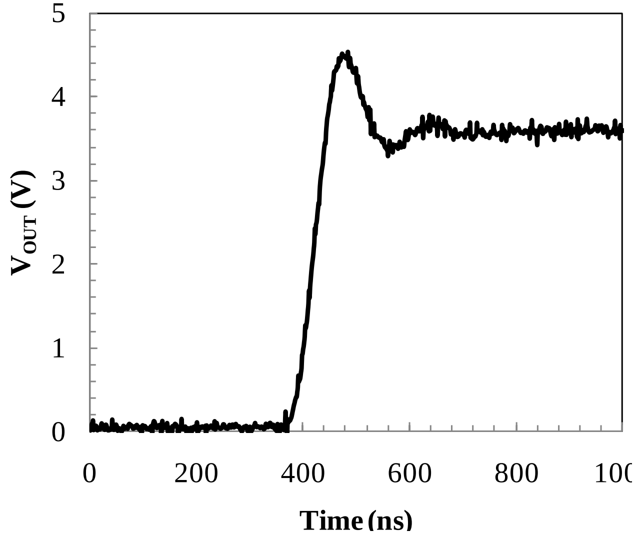
Simulated Power Loss Components

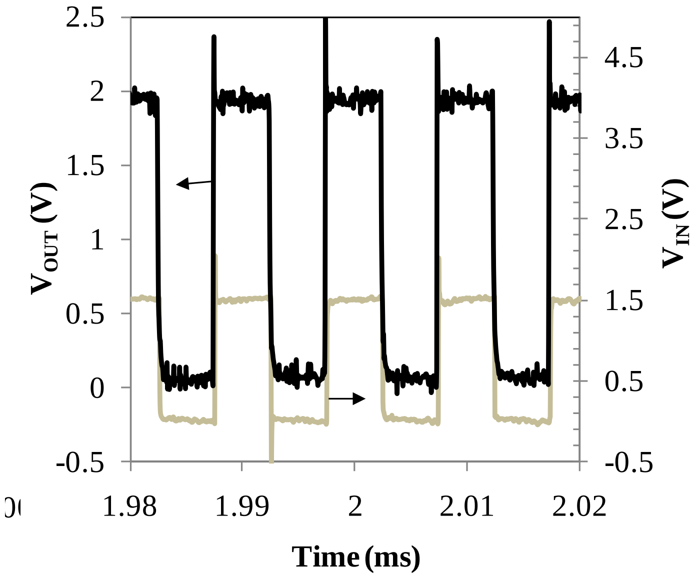
- At low power, GaAs gate driver loss degrades efficiency considerably
- GaAs has no PMOS like device, hard switched drivers are lossier than CMOS

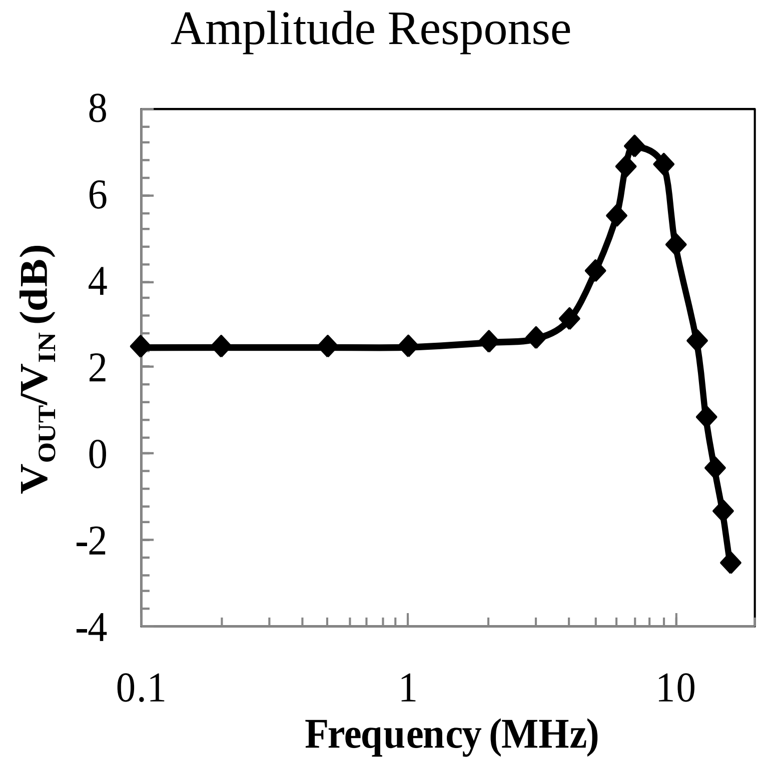


Rensselaer

Transient Response and Bandwidth







Summary

- GaAs Technology platform for high frequency switching
  - Device :
    - E-pHEMTs with superior FOM, Breakdown and Ruggedness
    - 3 Layer Interconnect
    - Thick Cu Air core planar inductors for integration
  - Passive
    - Thick Cu high Q air core planar inductors on GaAs
    - Coupling to achieve bandwidth + efficiency improvement
  - Packaging
    - Flip Chip Interconnects : Low parasitic inductances, reduced de-coupling, integration
    - Multi-chip modules : pHEMT Power + GaAs Passive + CMOS Control
- Design Examples
  - 150MHz interleaved Converter with coupled inductors, 84% Efficient
  - 100 MHz Single Phase, 1A output – 88% Efficient, 3dB bandwidth – 14.5 MHz

Future Work

- Output Stage :
  - 0.25µm GaAs E-pHEMT process : Gate Charge Advantage
  - Resonant drivers : Reduce driver loss, improve switching time and thus reduce switching loss
- Adding CMOS based controller for PA power supply modulation up to 10-15 MHz
- E-Mode power pHEMT processes for higher voltages : 20V, 30V rated devices

chowt@rpi.edu
palav@rpi.edu
hellam@ecse.rpi.edu
pengh2@rpi.edu