MACOM P-I-N Diode Modules and MMICs Enable 5G Implementation

James J. Brogle, Senior Principal Engineer
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Technology: Hybrid, HMIC & AlGaAs
P-I-N Diode Integration Technologies
MACOM’s Technology Portfolio

MACOM’s Proprietary Semiconductor Technologies
- Si Diodes: PIN, Schottky, Varactor, HMIC
- AlGaAs Diodes
- GaN
- GaAs MESFET
- GaAs pHEMT
- Si Power: Bipolar, MOSFET
- InP Lasers
- Photodetectors

Internal Assembly
- Chip and Wire
- SMT

Partner Technologies
- CMOS (down to 16nm node)
- SiGe
- SOI
- InP HBT

Packaging and Assembly
- Plastic (Small Signal and Power)
- Ceramic
- Laminate
- Bump/Bare Die
- SMT
- Chip and Wire
Diode Overview

> Diode Technology Platforms – all M/A-COM Tech wafer processes
  
  • Traditional Si & GaAs Processes – Discrete Die & Hybrid/Multichip Modules
    • PIN, Limiter, Varactor and Schottky Diodes, Chip Capacitors
    • Many formats including die & leaded and surface-mount plastic and ceramic packages
  
  • HMIC™ - “Heterolthic Microwave Integrated Circuit” Process – Si-Glass RFIC
    • Si PIN or Schottky diodes integrated with passive elements, apps typ to 26GHz.
    • Formats include chipscale wire-bondable, surface-mount & flip-chip, and QFN plastic.
  
  • AlGaAs Diode Process – Unique Heterojunction MMIC
    • Patented AlGaAs PIN or GaAs Schottky diodes with passives, apps typ to 50, 77, >100GHz.
    • Wire-bondable format. Exploring flip-chip, surface-mount & packaged versions.

> Products

  • PIN diode switches, attenuators, phase shifters, limiters; Schottky diode mixers, detectors, limiters;
  passive filters, matching networks, bias networks.
Traditional Si & GaAs Diode Processes

- PIN, Limiter, Varactor and Schottky Diodes, Chip Capacitors

- Cermachip PIN Diodes (Moat process enables volume assembly)

- 50-200W Hybrid PIN Diode Switches
  - Infrastr. 2-3.5GHz, Mil/PS Radio 30MHz-6GHz
    - Si PIN, Cap, ALN – QFN
  - 125W S Band Radar Switch-Limiter
    - Si PIN, Schottky, Cap, HMIC™ Passive, ALN – QFN
  - 100-300W UHF-C Band Family of Hybrid Limiters
    - HMIC™/Ceramic Hybrid Platform Si PIN, Schottky, Cap
HMIC™ RFIC Diode Process

> Two Materials In ONE Structure, Matched TCE ~3ppm/°C
  • Glass (Low Dielectric εr & Low Loss tanδ)
  • Silicon (High Therm κ & Low El ρ)

> Monolithic Circuit Solutions
  • Monolithic P-I-N/Schottky Diodes
    • Switches, Attenuators, Limiters, Mixers
  • High Q Capacitors & Inductors
  • 3-D RF Micro-machined Si
  • Wafer Scale Fabrication

> 10-80W 0.9-3.5GHz Infrastructure Switches
  • HMIC™ PIN RFIC & Si Chipcaps – QFN

> 2W 50MHz-26GHz Broadband Switches
  • HMIC™ PIN – Surface-mount & Bondable RFICs

> 20W X Band Mil/Weather Radar Switches

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**European Microwave Week 2019**

**PORTE DE VERSAILLES PARIS, FRANCE**

29th September - 4th October 2019
AlGaAs MMIC Diode Process

- **Patented Heterojunction AlGaAs PIN Diode**
  - PIN Diodes – Switches, Attenuators, Limiters
  - AlGaAs has a wider bandgap than GaAs
    - Therefore higher P+/N- barrier than GaAs
  - Improves forward bias RF diode characteristics
    - Therefore lower RF on-state resistance Rs
  - Maintains reverse bias RF diode characteristics
    - Therefore RF off-state capacitance C_t maintained
  - Confirmed by simulations & measurements
  - IEEE peer-reviewed published results

- **GaAs Schottky Diodes - Mixers, Detectors, Limiters**

- **SatCom/MilCom/ISM/Auto Switches MHz-80GHz**
  - AlGaAs PIN – Broadband MMICs to 26dBm

- **10-40W Ku/Ka Band SatCom/MilCom Switches**
  - AlGaAs PIN – MMICs & SMTs to >46dBm

- **AlGaAs W-Band Switches, 60-110GHz**
  - AlGaAs PIN – Broadband MMICs to 23dBm
Unique, Patented Heterojunction PIN Diode

> Idea Borrowed from GaAs HBT’s
  • AlGaAs has a wider bandgap than GaAs
  • P+ AlGaAs Anode/N- GaAs I-region Creates a Larger Barrier Height

> Improves Forward Bias RF diode characteristics
  • Enhances Forward Injection of Holes into I-region
  • Retards the Back Injection of Electrons into P+ Anode
  • Results in Higher Charge Concentration in I-region
  • Reduces RF On-State Resistance

> Maintains Reverse Bias RF Diode Characteristics
  • I-region Thickness and Resistivity Remain Unchanged
  • Off-State Capacitance Unchanged

> Confirmed by Simulations & Fabricated Device Measurements
  • 37% Reduction in Rs, and No Change in Ct
Improved Metric Required to Evaluate/Rank Active Components for Switch Applications

- Technology/Topology Agnostic
- On Resistance/Off Capacitance are Key Limiting Parameters Regardless of Technology/Topology
- Switch Figure of Merit
- FET Technologies - $R_{ON} \times C_{OFF}$ Product in femtosec
- PIN Diode Structures - $R_{S} \times C_{T}$ Product in femtosec

Active Switch Device Technology/Rankings Unmistakably Jump Off the Page

- Figure of Merit Clearly Tracks with Switch Parametric Results
- PIN Diodes Solutions are Plainly the Best Choice for High Power mmW Switch Technology Applications
- AlGaAs/GaAs VPIN Based Switches are Best Choice for mmW POWER

<table>
<thead>
<tr>
<th>Process Figure of Merit</th>
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</thead>
<tbody>
<tr>
<td>Switch Technology</td>
<td>Frequency (GHz)</td>
<td>$1000/(R_{ON} \times C_{OFF})$ (fsec)</td>
<td>IL (dB)</td>
<td>ISO (dB)</td>
<td>IIP3 (dBm)</td>
<td>CW Power Handling (watts)</td>
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<td>AlGaAs PIN Diode</td>
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<td>94</td>
<td>0.40</td>
<td>48</td>
<td>60</td>
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<td>Si FET</td>
<td>DC-18</td>
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<td>GaAs pHEMT</td>
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<td>DC-60</td>
<td>485</td>
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<td>GaN HEMT</td>
<td>DC-18</td>
<td>2500</td>
<td>1.59</td>
<td>25</td>
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</tbody>
</table>

NS = Not Specified

Best Insertion Loss vs Frequency
Sub-6GHz P-I-N Diode MMICs & Modules
Silicon HMIC and Hybrid Technologies
MACOM Advantages

- Market leader for High Power Switches for TDD Base Stations.
- Long heritage of high performance high isolation switches, digital step attenuators, and driver amplifiers, etc. for the next gen TRx FEMs
- High Gain and Super Low NF Low Noise Amplifiers
- Integrated Switch and LNA Rx modules for significant PCB size reduction.
MACOM High Power Diode Switches for TD-BTS

- Discrete Diode and HMIC switches
  - Broadband: 10 – 6000 MHz
  - Asymmetrical Design: Low IL on Tx; High Isolation on Rx
  - Shipped millions of parts to Tier 1 OEMs. Excellent Reliability!

<table>
<thead>
<tr>
<th>@ 2.7 GHz</th>
<th>10 Watt SPDT MASW-000822</th>
<th>20 Watt SPDT MASW-000825</th>
<th>50 Watt SPDT MASW-000834</th>
<th>120 Watt SPDT MASW-000936</th>
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<tbody>
<tr>
<td>Tx IL</td>
<td>0.35 dB</td>
<td>0.29 dB</td>
<td>0.30 dB</td>
<td>0.20 dB</td>
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<tr>
<td>Rx IL</td>
<td>0.55 dB</td>
<td>0.42 dB</td>
<td>0.38 dB</td>
<td>0.50 dB</td>
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<tr>
<td>Tx ISOL</td>
<td>24.5 dB</td>
<td>24.2 dB</td>
<td>18.7 dB</td>
<td>13.0 dB</td>
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<tr>
<td>Rx ISOL</td>
<td>29.5 dB</td>
<td>28.6 dB</td>
<td>41.8 dB</td>
<td>50.0 dB</td>
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<tr>
<td>Tx P1dB</td>
<td>&gt;41 dBm</td>
<td>&gt;43 dBm</td>
<td>&gt;47 dBm</td>
<td>50 dBm</td>
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<tr>
<td>Tx IIP3</td>
<td>&gt;65 dBm</td>
<td>&gt;65 dBm</td>
<td>&gt;66 dBm</td>
<td>72 dBm</td>
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<td>SW Speed</td>
<td>&lt;500 ns</td>
<td>200 ns</td>
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<td>200 ns</td>
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<td>Package (RoHS)</td>
<td>3mm 16L PQFN</td>
<td>3mm 16L PQFN</td>
<td>4mm 16L PQFN</td>
<td>4mm 16L PQFN</td>
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</tbody>
</table>
High Power HMIC™ Switch – MASW-000834
50 Watt Switch for 0.05 - 6.0 GHz Higher Power Applications

> Exceptional Broadband Performance

> Low Loss:
  - TX = 0.33 dB @ 2010 MHz, 5 V / 20 mA
  - TX = 0.38 dB @ 3.5 GHz, 5 V / 20 mA

> High Isolation:
  - RX = 44 dB @ 2010 MHz, 20 mA / 5 V
  - RX = 36 dB @ 3.5 GHz, 20 mA / 5 V

> High TX RF Input Power: 50 W CW @ 2010 MHz (25C)

> High TX RF Input Peak Power: >1000 W

> Suitable for Very High Power TD-SCDMA & WiMAX Applications

> Surface Mount 4 mm PQFN Package

> 12.3 million parts shipped!
High Power Hybrid Switch – MASW-000936
120 Watt Switch for 0.05 - 6.0 GHz Higher Power Applications

- Exceptional Broadband Performance
- Low Insertion Loss: TX = 0.20 dB @ 2.7 GHz
- High Isolation: RX = 50 dB @ 2.7 GHz
- High TX RF Input Power = 120 W CW @ 2.0 GHz, 85°C
- High TX RF Input Peak Power: 1000 W
- Suitable for High Power LTE, TD-SCDMA, WiMAX, and Military Radio Applications
- Surface Mount 4 mm PQFN Package
- 9.5 million parts shipped!
MAIA-011004
High Power Switch + LNA Module, 0.4 – 5GHz

> Features:
- Bias LNA: 3V – 5V, 70mA/branch
- Bias Switch: 0 or 28V, 5mA to 100mA
- RF Input Power: 100W CW @ 85°C
- Gain: 33 dB @ 2.7GHz, 31dB @ 3.5GHz
- NF: 1.2 dB @ 2.7 GHz, 1.3dB @ 3.5GHz
- Output IP3: 36 dBm
- Isolation LNA2 to LNA1: 40dB @ 2.7GHz
- Isolation RF to LNA1: 35dB @ 3.5GHz
- 50 Ohm Internally Matched Input & Output
- 5x5mm 32-Lead HQFN Package

> Additional Information:
- Export Compliance; ECCN EAR99
- Demo Boards Available

> Target Markets and Applications:
- 5G mMIMO, Wireless Infra, MilCom
MAMF-011070
High Power Switch + DC-DC/Switch Driver

Features:
• Broadband Performance: 0.7 – 6.0 GHz
• Low Loss: Tx = 0.3 dB, Rx = 0.4 dB at 2.7 GHz
• High Isolation: Rx = 43 dB at 2.7 GHz
• Up to 125 W CW Power Handling at 85 °C
• Single +5 V DC supply
• Compatible with 1.8 V and 3.3 V logic
• Lead-Free 5 mm 20-Lead HQFN Package

Additional Information:
• Export Compliance; ECCN EAR99
• Demo Boards Available
• Production Release in Q3’18

Target Markets and Applications:
• 5G mMIMO, Wireless Infra, MilCom
5G High Power Switches and Bias Controller

- Working on new high switches for the 2.6 and 3.5 GHz Macro and Indoor applications.

<table>
<thead>
<tr>
<th>Switches</th>
<th>CMOS Controller</th>
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<tbody>
<tr>
<td>MASW-011120</td>
<td>MADR-011028:</td>
</tr>
<tr>
<td>2.6GHz: 100W @120C</td>
<td>For both switches</td>
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<tr>
<td>3.5 GHz: 80W @120C</td>
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<tr>
<td>MASW-011121</td>
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<tr>
<td>2.6GHz: 120/160W @120C</td>
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<tr>
<td>3.5 GHz: 100W @120C</td>
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</table>

**Features:**
- 10 V to 60 V Back Bias
- 300 mA Sinking Current
- 100 mA Sourcing Current
- Propagation Delay <200 ns Driving 1000 pF Capacitive Load
- Low Quiescent Current
- Compatible with 1.8 V and 3.3 V logic
- 4 mm 16-Lead PQFN Package
mmW P-I-N Diode MMICs & Modules

AlGaAs MMIC Technology
Switching/Control Solutions for mmW BTS

MACOM Advantage

- Unique/Patented AlGaAs Technology
- Low Loss
- High Isolation
- High Power
- Passive Integration
MASW-010646
Ka-Band High Power Reflective AlGaAs SPDT PIN Switch

- Broadband Performance, 26 to 40 GHz
  - Low Loss: 0.6 dB
  - High Isolation: 32 dB
  - Up to 13 W CW Power, +85°C
- Die with G-S-G RF Pads and DC Bias Pads
- Includes DC Blocks and RF Bias Networks

Electrical Specifications: Freq. = 28 - 38 GHz, $T_a = +25°C$, +25 mA, -15 V, $Z_0 = 50 \Omega$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Test Conditions</th>
<th>Units</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion Loss</td>
<td>26 GHz</td>
<td>dB</td>
<td>0.60</td>
<td>0.60</td>
<td>0.90</td>
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<td>25 GHz</td>
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<td>35 GHz</td>
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<td>38 GHz</td>
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<td>Isolation</td>
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<td>40 GHz</td>
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<td>42</td>
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<tr>
<td>$RF_{COMON}$ Return Loss, On state</td>
<td>26 GHz</td>
<td>dB</td>
<td>16</td>
<td>16</td>
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<td>25 GHz</td>
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<td>40 GHz</td>
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<td>16</td>
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<tr>
<td>$RF_{1}, RF_{2}$ Return Loss, On state</td>
<td>26 GHz</td>
<td>dB</td>
<td>16</td>
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<td>25 GHz</td>
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<td>40 GHz</td>
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<tr>
<td>Switching Speed-Ton</td>
<td>50% DC to 90% RF</td>
<td>ns</td>
<td>50%</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Switching Speed-Off</td>
<td>50% DC to 10% RF</td>
<td>ns</td>
<td>50%</td>
<td>23</td>
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<tr>
<td>Rise Time -Tr</td>
<td>10% to 90% RF</td>
<td>ns</td>
<td>10%</td>
<td>9</td>
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<td>Fall Time - Tf</td>
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<td>90%</td>
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<td>CW Input Power</td>
<td>-25 V</td>
<td>dBm</td>
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<td>-25</td>
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<td>Reverse Bias Voltage</td>
<td>-32 V</td>
<td>mA</td>
<td>-32</td>
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<td>Reverse Bias Current</td>
<td>+10 V</td>
<td>mA</td>
<td>+10</td>
<td>+10</td>
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</table>

Insertion Loss (On State)

Isolation (Off State)
MASW-011098
High Power Reflective SPDT AlGaAs PIN Switch
26-40 GHz

> Features

• Typical Loss: 1 dB
• High Isolation: 37 dB
  • Up to 7 W CW Power, +85°C
• 5x5mm 20-lead Laminate Package
• RoHS Compliant and 260°C Reflow Compatible
MASW-011098
High Power Reflective SPDT AlGaAs PIN Switch
26-40 GHz
MASW-011036
Ka-Band High Power Terminated AlGaAs SPDT PIN Switch

- Broadband Performance, 26 to 40 GHz
- Low Loss <1 dB; High Isolation >38 dB
  - Up to 13 W CW Power, +85°C
- Die with G-S-G RF Pads and DC Bias Pads
- Includes DC Blocks and RF Bias Networks
- 23 dBm power handling in terminated port

Freq. = 28 - 30 GHz, $T_a = +25°C$, +4.0 V @ +25 mA / -15 V @ 0 mA, $Z_0 = 50 \Omega$

<table>
<thead>
<tr>
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<th>Units</th>
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<th>Typ.</th>
<th>Max.</th>
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<td>32 - 36 GHz</td>
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<td>1.5</td>
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<td>36 - 40 GHz</td>
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<td>36 - 40 GHz</td>
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<td>Input / Output Return Loss</td>
<td>26 - 28 GHz</td>
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<td>On state</td>
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<td>36 - 40 GHz</td>
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<td>RF1, 2 Return Loss, Off state</td>
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<td>Switching Speed-Ton</td>
<td>50% DC to 90% RF</td>
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<td>Rise Time - Tr</td>
<td>10% to 90% RF</td>
<td>ns</td>
<td>—</td>
<td>10</td>
<td>—</td>
</tr>
<tr>
<td>Fall Time - Tt</td>
<td>90% to 10% RF</td>
<td>ns</td>
<td>—</td>
<td>8</td>
<td>—</td>
</tr>
<tr>
<td>CW Input Power</td>
<td>25 V @ +85°C</td>
<td>dBm</td>
<td>—</td>
<td>41</td>
<td>2</td>
</tr>
<tr>
<td>Reverse Bias Voltage</td>
<td>—</td>
<td>V</td>
<td>—</td>
<td>-32</td>
<td>-15</td>
</tr>
<tr>
<td>Reverse Bias Current</td>
<td>-15 V</td>
<td>mA</td>
<td>—</td>
<td>25</td>
<td>—</td>
</tr>
<tr>
<td>Forward Bias Current</td>
<td>+4 V</td>
<td>mA</td>
<td>—</td>
<td>25</td>
<td>—</td>
</tr>
</tbody>
</table>
MASW-011036
Kα-Band High Power Terminated AlGaAs SPDT PIN Switch

Insertion Loss

Input/Output Return Loss

On Wafer Measured
HFSS

Input

Output

On Wafer Measured
HFSS
MASW-011036 in SMT Package
Packaged Die vs Probed Die (no wirebonds)

Insertion Loss

Input Return Loss

Isolation

Output Return Loss

Terminated Return Loss
MASW-011087
AlGaAs SP4T Reflective PIN Diode Switch
14 - 38 GHz

- Low Loss: 0.9 dB, 16 to 35 GHz
- High Isolation: 32 dB, 16 to 35 GHz
  - 30 dBm CW Power Handling @ +85°C
    - Switching Speed <34 ns
- Integrated DC Blocks and RF Bias Networks
- Die with G-S-G RF Pads and DC Bias Pads
  - RoHS* Compliant
  - Pt-Pt Backhaul; SatComm
- Bare Die; Wirebondable
MASW-011087
AlGaAs SP4T Reflective PIN Diode Switch 14 - 38 GHz
High Power Ka-Band
Shunt Switch Diode Design Optimization

> Increase Power Handling - $P_{\text{incident}} > 40$ watts (+46 dBm)
> Maintain/Reduce Insertion Loss
> Maintain/Improve Isolation

> Shunt Diode Structure Modification
  • Lateral Stacking of One “Series” Diode with Two Shunt Diodes
  • All Diodes in Shunt
  • Effectively Doubles the “I” Region Thickness
  • Enables Application of 60 volt Back Bias
  • Supports Power Handling of 523 watts (without Thermal Constraints)

> Thermal Considerations
  • Parallel/Combine Two Modified Diode Structures per Arm
  • Spread Dissipated Power Over Six Diodes per Arm
  • 4x Improvement in $\Theta$ => 52 watts (+47.2 dBm) Power Handling (Baseplate = 85°C & $T_{\text{max}} = 150°C$)
Features

- Low Loss: 0.6 dB, 28 to 34 GHz
  - High Isolation > 26 dB
- >40W CW Power Handling, +85°C
- Switching speed less than 65 ns
- Integrated DC Blocks and RF Bias Networks
- Die with G-S-G RF Pads and DC Bias Pads
  - RoHS* Compliant
MASW-011094
Ka-Band High Power Terminated SPDT AlGaAs PIN Switch
24 - 37 GHz

Ka-Band Power Handling

- Input Power to Switch
- Switch Output Power
- Insertion Loss

Test Amplifier Input Drive Power (dBm)

Switch Input/Output Power (dBm)

Insertion Loss (dB)

25°C, 60°C, 80°C, 90°C
4 & 6-bit Ka Band Phase Shifters

Simulation and Layout
- In order to achieve a good impedance match and low phase and amplitude error for each phase state, extensive simulation and tuning was required.
- Simulation was done with a combination of models for diodes and vias and ADS Momentum simulations for passive structures.
- The challenge of tuning all 16 or 64 states simultaneously was accomplished by looking for patterns to isolate mismatched bit paths and adjusting the layout accordingly.
- Chip Sizes: 4.21 x 4.41 mm (4-bit) and 7.34 x 4.41 mm (6-bit).

Test Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Test Conditions</th>
<th>4-Bit</th>
<th>6-Bit</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion Loss</td>
<td>0 dBm, 27.5 - 29.5 GHz</td>
<td>3.0 - 3.5</td>
<td>5.1 - 5.6</td>
<td>dB</td>
</tr>
<tr>
<td>Return Loss</td>
<td>0 dBm, 27.5 - 29.5 GHz</td>
<td>&gt;12</td>
<td>&gt;15</td>
<td>dB</td>
</tr>
<tr>
<td>Max CW Input Power</td>
<td>28.5 GHz, +85°C Baseplate</td>
<td>&gt;32</td>
<td>&gt;32</td>
<td>dBm</td>
</tr>
<tr>
<td>Switching Speed</td>
<td>T-rise/T-fall, 28.5 GHz, 0° to 180°</td>
<td>20/200</td>
<td>25/220</td>
<td>ns</td>
</tr>
<tr>
<td>IIIP</td>
<td>28.5 GHz, 10 MHz offset, -10 dBm Pin</td>
<td>43</td>
<td>43</td>
<td>dBm</td>
</tr>
<tr>
<td>RMS Phase Error</td>
<td>27.5 - 29.5 GHz</td>
<td>2 - 7</td>
<td>1 - 7</td>
<td></td>
</tr>
<tr>
<td>RMS Phase Error 180°</td>
<td>27.5 - 29.5 GHz</td>
<td>3.5 - 5.5</td>
<td>1 - 4</td>
<td></td>
</tr>
<tr>
<td>RMS Amplitude Error</td>
<td>27.5 - 29.5 GHz</td>
<td>0.1</td>
<td>0.15</td>
<td>dB</td>
</tr>
</tbody>
</table>

Reverse bias = -10 V, Forward bias = +20 mA per bit, Temp = +25°C unless otherwise specified.

Acknowledgments
- Jaime Boyce – Manager/Guidance
- Joe Biskowski – Guidance
- Mark Russo – Test Measurements
- Belinda Pierns – Diode Models
MACOM’s Portfolio includes multiple Semiconductor, Assembly & Packaging Technologies

- Si and AlGaAs P-I-N Diode technologies have superior figures-of-merit as control devices
- Si Hybrid & HMIC P-I-N technologies enable high-power low-loss <6GHz 5G TDD switching
- AlGaAs P-I-N technology enables high-power low-loss mmW 5G TDD switching

Switches and other control functions (passives, phase-shifters, attenuators) have been demonstrated:
- Si Hybrid & HMIC P-I-N, 1MHz through 26GHz
- AlGaAs MMIC P-I-N, 1GHz through 110GHz