SiC MOSFETs
What it Takes to Create Cost-Effective and Highly Reliable High-Power Solutions

Power Electronics Conference 2018
Christophe Warin
Product Marketing Manager – SiC
Littelfuse / Monolith Semi. Timeline + Partnerships

December 2012
Monolith Semiconductor incorporated

December 2013
Inked agreement with XFab for high-volume manufacturing

August 2014
Demonstrated first SiC MOSFETs made in 150mm CMOS foundry

December 2015
Formed strategic partnership with Littelfuse

March 2017
Availability of fully qualified 1200V SiC diode platform in 150mm CMOS foundry

May 2013
Demonstrated 1700V, 5A SiC MOSFET at Cornell fab

April 2014
Demonstrated 1200V, 10A SiC diodes fabricated in 150mm CMOS foundry

November 2014
Delivered first engineering samples to select customers

March 2017
Littelfuse makes incremental $15 million investment in Monolith

Jan 2018
Purchases
Outline

- Motivation for SiC devices
- High-volume 150 mm process
- Performance / Ruggedness Validation
  - HTRB / HTGB
  - Gate Oxide Lifetime
  - Avalanche and short circuit
  - Switching performance
- SiC products
Reality: Ideal Switch Is Not Enough

Long-term Reliability
Voltage, Temperature, Moisture, Mechanical

Performance
Breakdown Voltage, On-resistance, Switching Loss

Ruggedness
Short-circuit, Avalanche, Surge, ESD

Cost

Manufacturability
Yield, Process Margin
Outline

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SiC MOSFET in High-Volume 150mm CMOS Fab

- Compatible material, similar process steps
- Handling challenges: semi-transparent wafer
- High temp. implantation – different species
- High temp. activation

Concurrent manufacturing of Si and SiC – reuse established CMOS processes – minimize special tools.
Design Specifications

- Epitaxial layer: Epi doping variation
- Termination design: Dose variation, high field in molding compound
- JFET design: High oxide field
- Channel design: On-resistance vs. device ruggedness
- Source/contact design: Design rule

Designed for manufacturability and ruggedness
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HTRB and HTGB Testing

Minimal shift observed for HTRB at 175°C, $V_{GS} = 0$ V, $V_{DS} = 960$ V

Minimal shift observed for HTGB at 175°C, $V_{GS} = -10$ V and $V_{GS} = +25$ V
• Observe +200 mV shift after HTGB+ for 5500hrs ($V_{GS} = +25V$, $T = 175^\circ C$), primary shift occurs at first readpoint
• No significant drift under HTGB- for 2700 hours ($V_{GS} = -10V$, $T = 175^\circ C$)
The oxide reliability of Littelfuse’s SiC MOSFETs are “silicon-like”
Accelerated Gate Oxide Lifetime test
LSIC1MO12E0080 1200V, 80 mOhm SiC MOSFET On-wafer Testing

$10^{10}$ sec=300 yrs

- Close agreement between TDDB data from test structures and fully processed 80mΩ DMOSFETs
- Predict life > 100 years when operating at $T=175^\circ\text{C}$ and $V_{GS}=25\text{V}$. 
In-Depth Study of Short-Circuit Robustness and Protection of 1200V SiC MOSFETs
Xuning Zhang, Gin Sheh, Levi Gant, Sujit Banerjee
PCIM 2018
Short Circuit Robustness

- Short circuit time characterized - Shorter withstand time compared to IGBT
  - Sensitive to dc link voltage and gate voltage
  - Device can be protected using Desat feature in gate driver Ics
Avalanche Ruggedness
Unclamped Inductive Switching 1200 V, 80 mΩ rated SiC MOSFETs

• Avalanche energy (Unclamped Inductive Switching, UIS) shows the ability of the MOSFET to survive transients sometimes incurred when driving inductive loads.

$I_{AS} = 20A$
$E_{AS} = 1100mJ$
$V_{DS,max} = 1793V$

PASS
Avalanche Ruggedness

Repetitive unclamped inductive 1200V, 160mΩ rated SiC MOSFETs

- UIS test solution with R-UIS test capabilities
- Waveforms during R-UIS cycle: each UIS period = 20msec.
- The energy of the unit UIS cycle = 125mJ

On-Resistance (mOhm)

Comparative Study on the R-UIS of 1200V 160mOhm SiC Planar Gate MOSFETs
In-Hwan, Sauvik Chowdhury, Blake Powell, Kiran Chatty, Sujit Banerjee, and Kevin Matocha
ECSCRM 2018
### Avalanche Ruggedness

Repetitive unclamped inductive 1200V, 160mΩ rated SiC MOSFETs

**LSIC1MO120E0160** demonstrated excellent R-UIS capabilities: no parametric shift on key electrical performances such as on-resistance, threshold voltage, breakdown voltage and drain leakage current after 100000 cycles of R-UIS stress.

<table>
<thead>
<tr>
<th>Design</th>
<th>Post stress parameter drift (R-UIS robustness)</th>
<th>DC Parameter shifts after 100,000 cycle of R-UIS stress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ΔVt [mV]</td>
</tr>
<tr>
<td>Competitor A #1</td>
<td>Negligible (Good)</td>
<td>-20.1</td>
</tr>
<tr>
<td>Competitor A #2</td>
<td>Negligible (Good)</td>
<td>-27.9</td>
</tr>
<tr>
<td>Competitor B #1</td>
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<td>N/A</td>
</tr>
<tr>
<td>Competitor B #2</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Competitor C #1</td>
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<td>N/A</td>
</tr>
<tr>
<td>Competitor C #2</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>LSIC1MO120E0160 #1</td>
<td>Negligible (Good)</td>
<td>-55.4</td>
</tr>
<tr>
<td>LSIC1MO120E0160 #2</td>
<td>Negligible (Good)</td>
<td>-38.0</td>
</tr>
</tbody>
</table>
Avalanche Ruggedness
Repetitive unclamped inductive 1200V, 160mΩ rated SiC MOSFETs

- Competitor A and LSIC1MO120E0160 were robust up to 100K cycle.
- Competitor B showed BV collapse during I-V measurement after 20K cycle
- Competitor C (80 mOhm trench gate) didn’t show any R-UIS capability
Avalanche Ruggedness
Repetitive unclamped inductive 1200V, 160mΩ rated SiC MOSFETs

- Gate oxide shielding capability is critical to ensure R-UIS robustness
- LSIC1MO120E0160: state-of-art ruggedness under repetitive UIS conditions

Electric field at Vds = 1600V
Highest e-field at gate oxide in JFET region:
\[ E_{ox} \approx 4 \text{ MV/cm} \]
SiC MOS reliability and ruggedness

• What is the wearout lifetime of SiO$_2$ grown on SiC? Gate oxide wearout for thick oxides can be extrapolated from constant voltage TDDB. Predict gate oxide wearout life > 100 years when operating at T=175°C and V$_{GS}$=25V.

• How does long-term stress impact the SiC MOSFET threshold voltage stability? We have shown stable operation under:
  $V_{GS} = +25V$ for 5500 hrs (+200mV) and $V_{GS} = -10V$ for 2700 hrs at T=175°C.

• Are SiC MOSFETs stable under unclamped inductive switching (simultaneous voltage+current)? Maximum UIS capability scales with die active area:
  $E_{AV} = 1000$ mJ for 1200V, 80 mOhm (~10 J/cm$^2$).
  No parametric change observed for:
    Single shots of 80% of Max UIS.
    100k shots of 25% of Max UIS
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  - HTRB / HTGB
  - Gate Oxide Lifetime
  - Avalanche and short circuit
  - Switching performance
- SiC products
## SiC MOSFET Standard Package Portfolio

<table>
<thead>
<tr>
<th>Voltage</th>
<th>R\text{\textsubscript{DS}} (m\textOmega)</th>
<th>TO247-3L</th>
<th>TO247-4L</th>
<th>TO263-7L (D2PAK)</th>
<th>TO268-2L (D3PAK)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1200V</strong></td>
<td>160</td>
<td>LSIC1MO120E0160</td>
<td>LSIC1MO120G0160</td>
<td>LSIC1MO120T160</td>
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<td></td>
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<td><strong>1700V</strong></td>
<td>750</td>
<td>LSIC1MO170E1000</td>
<td></td>
<td>LSIC1MO170T0750</td>
<td>LSIC1MO170H0750</td>
</tr>
</tbody>
</table>

- TO247-3L: Most common
- TO247-4L: With Kelvin connection
- TO263-7L: Surface mount with Kelvin connection
- TO268-2L: High creepage
- Other R\text{\textsubscript{DS}} and voltages being developed
- Bare die available on request.
- Competitive performance and price with best-in-class delivery in market
- Samples available for evaluation
### SiC Diode Standard Package Portfolio

- **Wide portfolio of 650V and 1200V diodes**
- **650V are AECQ-101**
- **Both surface mount and through-hole**
- **Other package options**: TO-247-2L, SOT-227, ISOPLUS, bare die etc.
- **Competitive performance and price with best-in-class delivery in market**
- **Samples available for evaluation.**

<table>
<thead>
<tr>
<th>650V (2018 Q4 release)</th>
<th>TO252-2L (DPAK)</th>
<th>TO263-2L (D2PAK)</th>
<th>TO220-2L</th>
<th>TO247-3L</th>
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</thead>
<tbody>
<tr>
<td>6A</td>
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<tr>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1200V (In Production)</th>
<th>TO252-2L (DPAK)</th>
<th>TO263-2L (D2PAK)</th>
<th>TO220-2L</th>
<th>TO247-3L</th>
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<tr>
<td>5A</td>
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<td>LSIC2SD120E40CC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SiC Offerings Cont. (Packaging Highlights)

- **SMPD packages**
  - High current capability
  - High creepage distances
  - Tape-and-reel packing option for pick-and-place

- **SOT-227 packages**
  - Superior cooling performance (AlN substrate)
  - Kelvin source connection to decouple gate loop

- **TO-268 HV packages**
  - Very high creepage distances

- **TO-247 HV packages**
  - For new 1700 V designs
  - >7.6 mm Drain-Source spacing

- **ISO-247**
  - DCB isolation
Summary

- SiC MOSFETs starting to gain customer acceptance
  - Multiple suppliers
  - Wider offering of voltage, current and package

- Littelfuse SiC MOSFETs have exhibited industry leading performance and reliability

- Littelfuse SiC MOSFETs are in strong position
  - Solid technology, extensive manufacturing resources, global distribution network
Thank You!

SPEED. FLEXIBILITY. POWER.

Fast and agile just got stronger

Come see us at Hall 9, Booth 305

PowerSemiSupport@Littelfuse.com
1200V, 80 mOhm MOSFET Comparison
Rdson versus Gate Drive voltage

Conditions:
- $I_D = 20A$
- $t_c < 400 \mu s$

20V: lowest Rdson
18V: Rdson is ~5% > @ 150°C

Flexible gate drive

Notes:
- Threshold voltage is high enough (typ 3V) for 0V gate drive. Good layout required
- -5V add noise margin and speed
Switching Performance

- Switching energy
- Switching time
- Gate charge
- Reverse recovery
High Temperature Reverse Bias Test

HTGB Test (25V)  HTGB Test (-10 V)  HTRB Test (960 V)
The Ideal Device

- **Ideal Switch**
  - Zero leakage in off-state
  - Zero voltage in on-state
  - Zero switching loss

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**Breakdown Voltage**

- **Silicon**
- **WBG (SiC, GaN)**
- **UWBG (AlN, Diamond)**

**Specific On-resistance (Ron * Area)**

- **Lower Ron * Area, closer to ideal switch**

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**Switch On**

**Switch Off**

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Voltage vs. Current Graph
Littelfuse SiC Strategy

- Industry-leading customer support
- Global manufacturing and supply chain excellence
- Diverse technology portfolio to enrich systems-level engagements
- Extensive industrial and automotive experience

- Deep power semiconductor and applications expertise
- High performance and quality SiC MOSFET and diode technology
UIL Testing Environment

Avalanche Test Circuit

Short-circuit Test Circuit
Dynamic Characterization Testing Environment

- Temperature Control
- Auxiliary Power Supply
- Function Generator
- DC Voltage Monitor
- Oscilloscope
- Energy Storage Capacitors
- Temp. Measure
- Testing Board
Dynamic Characterization

- Switching energy
  - External gate resistance
  - Current
  - Temperature
- Switching times
- Gate charge

Robust at dV/dt >70V/ns
Global Footprint – R&D, Manufacturing & Support
Global Footprint – R&D, Manufacturing & Support

Americas
- Chicago, Illinois, USA (S)
- Aliso Viejo, California, USA (RD, M)
- Fremont, California, USA (RD, M)
- Long Beach, California, USA (RD, M)
- Milpitas, California, USA (RD, M)
- Orange, California, USA (M)
- Santa Clara, California, USA (M)
- Fort Collins, Colorado, USA (RD, M)
- Champaign, Illinois, USA (RD)
- Mount Prospect, Illinois, USA (RD)
- Beverly, Massachusetts, USA (RD, M)
- Boston, Massachusetts, USA (S, RD)
- Troy, Michigan, USA (S)
- Rapid City, South Dakota, USA (S, RD, M)
- Lake Mills, Wisconsin, USA (S, RD)
- Manaus, Brazil (S)
- São Paulo, Brazil (S)
- Burlington, Canada (S)
- Saskatoon, Canada (S, RD, M)
- Matamoros, Mexico (M)
- Muzquiz, Mexico (M)
- Piedras Negras, Mexico (RD, M)

Europe
- Bremen, Germany (S, RD)
- Essen, Germany (S)
- Lampertheim, Germany (RD, M)
- Lauf, Germany (S)
- Legnago, Italy (RD, M)
- Ozegna, Italy (RD, M)
- Kaunas, Lithuania (RD, M)
- Amsterdam, Netherlands (S)
- Deventer, Netherlands (S)
- Leiden, Netherlands (S)
- Charneca de Caparica, Portugal (M)
- San Sebastian, Spain (RD)
- Chippenham, United Kingdom (RD, M)

Asia
- Beijing, China (S)
- Chu-Pei, Taiwan, China (RD)
- Dongguan, China (RD, M)
- Hong Kong, China (S)
- Kunshan, China (RD, M)
- Shanghai, China (S, RD, M)
- Suzhou, China (S, RD, M)
- Taipei, Taiwan, China (S)
- Wuxi, China (RD, M)
- Tokyo, Japan (S)
- Tsukuba, Japan (RD, M)
- Seongnam, South Korea (S, RD)
- Seoul, South Korea (S)
- Lipa City, Philippines (RD, M)
- Taguig City, Philippines (M)
- Singapore (S)

S – International Sales
RD – Research & Development
M – Manufacturing