Packaging Technology for SiC High Temperature Electronics
- Most Recent Progress

Liang-Yu Chen\textsuperscript{1*}, Philip G. Neudeck\textsuperscript{2}, David J. Spry\textsuperscript{2}, Roger D. Meredith\textsuperscript{2}, Leah M. Nakley\textsuperscript{2}, Glenn M. Beheim\textsuperscript{2}, and Gary W. Hunter\textsuperscript{2}

1. Ohio Aerospace Institute/NASA Glenn Research Center, Cleveland, OH 44142
2. NASA Glenn Research Center, Cleveland, OH 44135

* Liangyu.Chen-1@nasa.gov
Outline

Background
• SiC high temperature electronics/sensors in R&D for aerospace applications
• Packaging systems
  • Concepts/functions
  • Conventional electronic packaging material issues at high temperature

HTCC packaging system for high temperature application
• HTCC alumina, Pt/HTCC alumina prototype package and PCB
• Parasitic parameters of a 32-I/O package

Recent test results
• Test results with SiC ICs at 500 and 700°C
• Test results with SiC ICs in simulated Venus environment

Summary
Acknowledgements
Background: High Temperature Devices and Packaging

Background

500°C SiC electronics and MEMS sensors have been demonstrated
- JFET ICs, MEMS based pressure sensor and Schottky diode based gas chemical sensors
- Applications include aerospace engine control and long term Venus probes
- Packaging system needed for device application and long term test

Failure mechanisms of conventional packaging materials at high temperatures
- Plastic materials melt, de-polymerize, and burn at high temperatures
- Conductor and alloys (solder) melt and oxidize rapidly at high temperatures
- High thermal stress due to thermal expansion mismatch - mechanical failure at structure level
- Challenges at material and structure levels
Packaging Technology for Electronics/Sensors

- Packaging is essential to microelectronics and sensors
  - Mechanical support
  - Electrical interconnection
  - Electromagnetic, chemical environment

- Chip-level packaging
  - Substrate and metallization
  - Die-attach
  - Wire-bonding

- Printed Circuit Board (PCB)
  - Interconnecting packaged chips and passives

- PCB edge connectors
  - Subsystem level packaging

- Sensor packaging may include some of these elements but in different format
Co-fired Alumina High Temperature Packaging System

High temperature co-fired (HTCC) alumina

- Co-fired at $T > 1500^\circ C$
- A few percent of glass used in co-fired alumina systems
- Metallization for conventional co-firing process
  - Low CTE ($8.8 \times 10^{-6}/C^\circ$) high melting point metals/alloys
  - W, Mo, MoMn co-fired in noble gas
- Dielectric performance of selected HTCC alumina tested at high temperatures in 2012

Pt metallization

- Low CTE
- Chemically stable, co-fired in air
- Alloy with Au, Au is always surface rich at elevated temperatures
- Aluminum oxide as binder - thermodynamically more stable compared with glasses
Co-fired Alumina Packaging System

Test Assembly of a SiC IC with HTCC Alumina Packaging System

- Packaged SiC chip with Pt/HTCC alumina package and PCB
- PCB measures 2 inch x 2 inch, Pt traces co-fired with alumina
- 1 mil Au alloy wire thermo-sonically bonded
- High temperature die-attach

Parasitic R//C of Neighboring I/Os

R//C model
R – DC leakage and AC dielectric loss
C – Dielectric polarization

\[ \frac{1}{Z(T, \omega)} = G(T, \omega) + j\omega C(T, \omega) \]

R//C measured between I/O1 - I/O2, and I/O2 - I/O3
- I/O1 connected to all five bias pads
DC resistance measured separately

### AC Parasitic Capacitance and Conductance of Neighboring I/O1 – I/O2

| F (Hz) | T (°C) | T<sub>R</sub> | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 450 | 500 | 550 |
|-------|--------|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 120   | 10     | 1.0         | 0.7 | 0.6 | 0.4 | 0.3 | 0.5 | 0.4 | 0.6 | 0.7 | 1.4 | 1.4 |
|       | <0.001 | <0.001      | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | 0.001 | <0.001 |
| 1K    | 0.4    | 0.2         | 0.5 | 0.5 | 0.3 | 0.4 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.4 |
|       | <0.001 | <0.001      | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| 10K   | 0.5    | 0.4         | 0.5 | 0.5 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.5 | 0.4 |
|       | <0.001 | 0.0013      | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| 100K  | 0.5    | 0.3         | 0.5 | 0.4 | 0.3 | 0.4 | 0.4 | 0.5 | 0.5 | 0.5 | 0.4 |
|       | 0.01   | 0.016       | 0.014 | 0.016 | 0.016 | 0.011 | 0.014 | 0.029 | 0.035 | 0.026 | 0.045 |
| 1M    | 0.5    | 0.4         | 0.5 | 0.4 | 0.3 | 0.4 | 0.4 | 0.5 | 0.5 | 0.4 |
|       | <0.010 | <0.010      | 0.013 | 0.012 | 0.011 | 0.006 | 0.009 | 0.018 | 0.021 | 0.022 | 0.026 |

C < 1.5 pF, R > 20 MΩ

Usable for many envisioned 500°C SiC ICs

## AC Parasitic Capacitance and Conductance of Neighboring I/O2 – I/O3

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<th>T (°C)</th>
<th>T&lt;sub&gt;R&lt;/sub&gt;</th>
<th>100</th>
<th>150</th>
<th>200</th>
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</table>

C < 1.5 pF, R > 20 MΩ

Usable for packaging many envisioned 500°C SiC ICs

DC Resistance of Neighboring I/Os

- I-V curve between I/O27 and I/O28
- 500°C
- Wide DC bias range: 0 - 50V
- SMU: integration time 16.67 msec, time delay 0.1 sec
- I/O28 not connected to SiC die, I/O27 connected to isolated two-terminal test structure on SiC die
- Package mounted on PCB
- Slope of linear fits: 7.6 GΩ initially 9.7 GΩ after 69.4 hrs
- DC resistance slightly underestimate
- Noise from running oven

Extensive test with SiC high temperature ICs – Recent progress

Input (dark) and output (blue) waveforms of OPAMP in closed loop with SiC epi-resistors of ratio of 8 to 1 in 500 °C air ambient after 4000 hours (5.6 months)

NOR logic gate test waveforms measured at the start and 142 hours into 700 °C electrical testing.

G.W. Hunter, 6th International Planetary Probe Workshop, 2016

Simulated Venus atmosphere conditions

- Implemented in the NASA Glenn Extreme Environments Rig (GEER)
- GEER consists of 800 liter 304 stainless steel pressure vessel
- AC-phase controlled electric heaters
- Gases delivered by custom gas mixing system consisting of seven mass flow controllers
- Each constituent filled to achieve the molar mixing ratios of the simulated Venus surface atmospheric composition
- Simulated gas composition based on widely accepted data reported in Ref.
- The vessel heated at a rate of 7 °C/hour
- 460 °C and pressure ranging from 9.33MPa to 9.45Mpa

Test of HTCC system with SiC high temperature ICs in GEER - Recent progress

Simulated Venus Atmosphere Gas Mixture

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<th>Mixing (Mole) Ratio</th>
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<td>OCS</td>
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<tr>
<td>H\textsubscript{2}O</td>
<td>3.00 \times 10\textsuperscript{-5}</td>
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<tr>
<td>CO</td>
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<td>2.50 \times 10\textsuperscript{-9}</td>
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</table>

Test of HTCC system with SiC high temperature ICs in GEER
- Recent progress

Test of Packaging Material System in GEER

- Facilitate electrical test of SiC ICs
- Performance of packaging materials
  - Substrate materials
    - Aluminum oxides (and nitride) chemical stability in hot acidic and S contained environment
      - Bulk and surface
  - Substrate metallization
    - Precious metallization still noble in hot high pressure acidic and S environment?
  - Au alloy wire-bond
    - Is Au still noble in hot high pressure acidic environment?
    - Surface effects of impurities
    - Effects of supercritical CO₂ flow
  - Die-attach
    - Stability of metal oxides in hot high pressure acidic environment
  - If hermetic seal or encapsulation is required / feasible?
Test of HTCC system with SiC high temperature ICs in GEER
- Recent progress

Packaging and Connections

- HTCC 92% alumina substrate
- Pt metallization traces
- Glass and Pt particles die-attach
- 254 µm (10 mil) diameter Au wires bonded to Pt traces using oven-cured gold particles
- 24 µm (1 mil) diameter gold alloy wires thermo-sonically bonded connecting SiC chip to substrate
- Substrate mounted on the feed-through using alumina-based high temperature adhesive and small stainless steel screw
- 4-Nickel 201 conductors mineral insulated in Inconel 600 jacket through Swagelok
- Fiberglass sleeves for separation / insulation

Test of HTCC system with SiC high temperature ICs in GEER - Recent progress

Packaged SiC ring oscillator IC test data
- Recorded GEER vessel temperature and pressure
- Measured SiC ring oscillator IC output signal frequencies
- 3-stage SiC JFET ring oscillator IC functioned at 1.26 MHz over the entire 521 hours (21.7 days)
- 11-stage ring oscillator IC (bottom trace, green) functioned at 245 kHz for 109 hours
  - Functional following post-test disconnection from its feed-through
  - Short-circuited during Venus conditions testing
- No electrical or mechanical failure of Pt/HTCC material system observed

Summary

Pt/HTCC alumina packaging material system for SiC high temperature electronics

- Extensively tested with various SiC analogue and digital integrated circuits at 500 °C for thousands of hours
- Successfully tested together with SiC ICs at 700°C for over one hundred forty hours
- Successfully tested together with two SiC ring-oscillator ICs in simulated Venus environment for over 500 hours for the first time*
  - 460°C, 90 Bar, corrosive
  - Both Au wire-bond and die-attach tested
  - No failure observed
- Study of packaging materials in GEER continues

Acknowledgements

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