Abstract

NASA space and aeronautical missions for probing the inner solar planets as well as for in situ monitoring and control of next-generation aeronautical engines require high-temperature environment operable sensors and electronics. A 96% aluminum oxide and Au thick-film metallization based packaging system including chip-level packages, printed circuit board, and edge-connector is in development for high temperature SiC electronics. An electronic packaging system based on this material system was successfully tested and demonstrated with SiC electronics at 500°C for over 10,000 hours in laboratory conditions previously. In addition to the tests in laboratory environments, this packaging system has more recently been tested with a SiC junction field effect transistor (JFET) on low earth orbit through the NASA Materials on the International Space Station Experiment 7 (MISSE7). A SiC JFET with a packaging system composed of a 96% alumina chip-level package and an alumina printed circuit board mounted on a data acquisition circuit board was launched as a part of the MISSE7 suite to International Space Station via a Shuttle mission and tested on the orbit for eighteen months. A summary of results of tests in both laboratory and space environments will be presented. The future development of alumina based high temperature packaging using co-fired material systems for improved performance at high temperature and more feasible mass production will also be discussed.
Alumina Based 500°C Electronic Packaging Systems and Future Development

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Outline

Background
- 500°C SiC electronics and sensors
- 96% alumina and thick-film metallization based packaging system for 500°C applications

Review of laboratory test results of 96% alumina packaging system for 500°C SiC electronics and sensors

Space and flight test of 96% alumina based high temperature packaging system

Future development of alumina based high temperature packaging system using co-fired alumina systems

Summary
Background

500°C SiC electronics and MEMS sensors have been demonstrated

- JFETs and JFETs based circuits demonstrated at NASA GRC
- MEMS based pressure sensors and Schottky diode based gas chemical sensors developed at NASA GRC
- Applications include aerospace engine control and long term Venus probes

96% alumina and thick-film metallization based prototype packaging system in development for 500°C SiC electronics and sensors

- 96% alumina provides acceptable electric/dielectric properties at high temperatures up to 550°C
- The system composed of chip-level package, printed circuit board (PCB), and edge-connector (in development)
96% alumina packaging system

Ceramic Chip-level Packages and PCBs

- Three types of ceramics and Au thick-film metallization based chip-level packages and printed circuit boards (PCBs)
- Chip-level packages characterized between room temperature and 500°C
- An edge connector in development for PCB – PCB (subsystem-level) interconnection
- 96% alumina provides best electrical performance at high temperatures

Chen and Hunter, 2005 HiTEN
Performance of 96% Alumina Substrate

Required dielectric properties of substrate materials at high temperature
- Stable and low dielectric constant at elevated temperatures
- Low dielectric loss at elevated temperatures

Dielectric Constant of 96% Al₂O₃

AC Conductivity of 96% Al₂O₃

• The challenge for 500°C packaging technologies is at the materials level
• Compared with other alumina substrate materials tested, 96% alumina has better dielectric performance at high temperatures

Chen, 2007 icept
### 96% Alumina Chip-level Packages

**Parasitic Capacitance and Conductance of Neighboring I/Os**

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- **Usable for packaging many envisioned low power 500°C devices/circuits**
- **> 50°C margin above 500°C**

**Notes:**
- **Usable for** packaging many envisioned low power 500°C devices/circuits
- **> 50°C margin** above 500°C
96% alumina packaging system - Laboratory test

Static Thermal Test

- 96% alumina packaging system – chip-level packages and PCB
- less than 7% change in the JFET characteristics in first 6000 hours
- Tested at 500°C for over 10,000 hrs
- Demonstrated for long term operation at 500°C for the first time
Dynamic Thermal Test

- 96% Alumina substrate and Au thick film metallization based chip-level packages and PCB
- Four SiC chips on the circuit board
- $T_R \leq T \leq 500^\circ C$
- 40$^\circ C$/min up ramp and cooling in air

- SiC JFETs based NAND logic gate
- 1744 accumulated hours at 500 $^\circ C$
- Before and after 100 cycles
- No packaging degradation/failure observed

96% alumina packaging system - Laboratory test

PCB Edge Connector for 500°C Low Power Electronics
- Subsystem Level Interconnection

- PCB level interconnection
- For 500°C operation
- 96% alumina structure
- High temperature thick-film metallization
- 15 mil Au wires with fiber insulation sleeves
- High temperature alloy springs for electrical contacts
- In development and test
96% alumina chip-level packaging, PCB, and joining materials

- First flight and space test of 96% alumina high temperature harsh environment packaging system
- Monitor packaged SiC JFET DC parameter and compare with a SiC JFET in a conventional package

Prokop et al, 2010 National Space & Missile Materials Symposium
Space and Flight Test of 96% Alumina Packaging System

- MISSE7 suite exposed to Shuttle launch, atomic oxygen, space radiation, thermal cycling, and reentry
- In an aluminum box
- Eighteen months on ISS orbit

Prokop et al, 2010 National Space & Missile Materials Symposium
On-orbit I-V Data of Packaged SiC JFETs

- I-V data acquired every hour with temperature measurement
- Eighteen months on orbit
- Latest Set of $V_{DS}$ vs. $I_D$ curves shows no degradation
- No packaging degradation/failure detected after space and flight tests

Prokop et al, 2010 National Space & Missile Materials Symposium
Future development of alumina high temperature packaging systems

LTCC and HTCC Alumina

- 96% alumina substrate based packaging system
  - Dielectric properties of 96% alumina measured at temperatures up to 550°C
  - Excellent electrical and dielectric properties as substrate for conventional electronics
  - Thin-film and thick-film metallization available
  - 96% alumina packaging system long term tested with SiC electronics at 500°C
  - Chip-level packages not fabricated with co-fired process

- Low temperature and high temperature co-fired (LTCC and HTCC) alumina substrates?
  - A few percent of glass used in co-fired alumina systems
  - Suitable for large scale commercialization
  - Dielectric performance at high temperatures?
  - Metallization scheme?
Future development of alumina high temperature packaging systems

Dielectric constant of LTCC alumina stable below 300°C, increases rapidly with T above 300°C

At 120 Hz and 1kHz, it increases by a factor of ~300 and 68, respectively at 550°C

Dielectric constant of HTCC alumina is lower and increases less at 120Hz and 1kHz, compared with 96% alumina

Chen, 2012 HiTEC
Future development of alumina high temperature packaging systems

- Dielectric constant of LTCC alumina increases rapidly with T above 300°C
  - At 10 kHz, 100kHz, and 1MHz, it increases by a factor of 13, 3.6, and 2, respectively at 550°C
- Dielectric constant of HTCC alumina is always lower and increases less with T

Chen, 2012 HiTEC
Future development of alumina high temperature packaging systems

Conductivity of LTCC alumina is higher than 96% alumina and it increases rapidly ~ 300°C at both 120Hz and 1 kHz.

At 120 Hz and 1kHz, it is four-three orders of magnitude higher compared with 96% alumina at 550°C.

Conductivity of HTCC alumina is ~ an order of magnitude lower compared with 96% alumina at 120Hz and 1kHz at temperatures above 300°C.

Chen, 2012 HiTEC
Future development of alumina high temperature packaging systems

- Conductivity of LTCC alumina is higher than 96% alumina and it increases rapidly above ~ 300°C at 10kHz, 100kHz, and 1 MHz
  - At 10 kHz, 100kHz, and 1MHz, it is about two orders of magnitude higher compared with 96% alumina at 550°C
- Conductivity of HTCC alumina is always lower and increases less with T at 10kHz, 100kHz, and 1 MHz

Chen, 2012 HiTEC
Future development of alumina high temperature packaging systems

Compared with 96% alumina

- Dielectric constant and AC conductivity of LTCC alumina increase with T rapidly above 300°C, so this material is more suitable for the temperature range below 350°C
- Dielectric constant of HTCC alumina is slightly lower and it increases less with temperature. AC conductivity of this material is also lower than that of 96% alumina at temperatures above 200°C
- Dissipation factor of LTCC alumina is always higher at temperatures above 100°C
- Dissipation factor of HTCC alumina is always lower compared with that of 96% alumina at temperatures above 250°C
- HTCC alumina is also better for hermetic sealing
- Alumina based binders used for HTCC thick-film materials are expected to be thermal dynamically stable in a wide temperature range
Summary

96% alumina substrate and thick-film metallization based packaging systems demonstrated at 500°C
- Alumina and aluminum nitride chip-level packages and PCBs
- Edge-connector in development and test
- Static thermal test of packaged SiC JFET circuits successfully over 10,000 hours at 500°C
- Thermal dynamic test between room temperature and 500°C
- Tested in Shuttle flight, and ISS low earth orbit for eighteen months
- Chip-level packages not fully commercially fabricated

HTCC alumina system
- Selected material characterized and tested at temperatures up to 550°
- Lower parasitic effects
- More suitable for large scale commercialization
- Alumina binder for HTCC alumina systems are expected to be stable at high temperatures
- Further development needed
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