PASSIVE COMPONENT EMBEDDING IN PRINTED CIRCUIT BOARDS FOR SPACE APPLICATIONS

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3. QinetiQ Space, Kruibeke, Belgium
4. ESA (TEC-QTC), ESTEC, Noordwijk, The Netherlands
PROJECT GOAL

Investigate the suitability of embedding passive components in printed circuit boards for space applications

- Overview of available technologies for component embedding
- Assessment of the AT&S ECP® technology
- Evaluation of reliability of passive component embedding
- Realization of a functional demonstrator
- Procedures for procurement and qualification of PCBs with embedded components for space applications
EMBEDDED COMPONENT PACKAGING TECHNOLOGY

ECP® Technology
Embedded Component Packaging

Component are embedded inside an organic substrate / PCB core by combination of
- Component Assembly
- Component Packaging
- PCB Manufacturing

▸ Embedding of both active and passive components
▸ Component thickness and pad metallization compatibility
» Embedded core can be integrated in various PCB build-ups
Available components for embedding

- **Resistors**

<table>
<thead>
<tr>
<th>Size</th>
<th>Voltage (V)</th>
<th>Power (W)</th>
<th>Tolerance</th>
<th>Operating temperature</th>
<th>TCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>01005</td>
<td>??</td>
<td>0.03</td>
<td>1%, 5%</td>
<td>-55 °C to 125 °C</td>
<td>200-300 ppm/°C</td>
</tr>
<tr>
<td>0201</td>
<td>25</td>
<td>0.05</td>
<td>1%, 5%</td>
<td>-55 °C to 125 °C</td>
<td>200-300 ppm/°C</td>
</tr>
<tr>
<td>0402</td>
<td>50</td>
<td>0.06 – 0.1</td>
<td>1%, 5%</td>
<td>-55 °C to 125 °C</td>
<td>100-200 ppm/°C</td>
</tr>
</tbody>
</table>

- **Capacitors**

<table>
<thead>
<tr>
<th>Type</th>
<th>Size</th>
<th>Range</th>
<th>Voltage (V)</th>
<th>Tolerance</th>
<th>Thickness (µm)</th>
<th>TCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0G</td>
<td>0201</td>
<td>1 – 100 pF</td>
<td>10 – 50</td>
<td>5%</td>
<td>150 – 330</td>
<td>30 ppm/°C</td>
</tr>
<tr>
<td>X5R</td>
<td>0201</td>
<td>0.1 – 100 nF</td>
<td>2.5 – 50</td>
<td>10 – 20%</td>
<td>110 – 330</td>
<td>±15 %</td>
</tr>
<tr>
<td>X5R</td>
<td>0402</td>
<td>1 – 4700 nF</td>
<td>2.5 – 50</td>
<td>10 – 20%</td>
<td>110 – 330</td>
<td>±15 %</td>
</tr>
<tr>
<td>X7R</td>
<td>0201</td>
<td>0.1 – 22 nF</td>
<td>2.5 – 50</td>
<td>10%</td>
<td>150 – 330</td>
<td>±15 %</td>
</tr>
<tr>
<td>X7R</td>
<td>0402</td>
<td>1 – 10 nF</td>
<td>6.3 – 25</td>
<td>10%</td>
<td>150 – 330</td>
<td>±15 %</td>
</tr>
</tbody>
</table>
TEST BOARDS

Board Type I

- Board level reliability and component characterization
- Components selection based on availability and BTII
  - 33 Ω, 0402 / 10 kΩ, 0402 / 10 kΩ, 0201 / 1 MΩ, 0201 from Panasonic
  - Murata 10 pF & 100 pF (0201, 150 µm), AVX 10 nF (0402, 300 µm, 16 V to 50 V and 150 µm, 6.3 V) and Murata 100 nF (150 µm, 6.3 V)
- Test structures
  - Probe pad test structure for electrical measurement of components
  - Disk, comb and tree test pattern for interlayer and intralayer insulation
  - Daisy chains (0-ohm resistors) for continuity and interconnect resistance
  - Interconnect stress test (IST) patterns on separate coupon
Board Type II

- Spacecraft Interface Module (SIM) board from QinetiQ Space
  - Redesigned for the use of embedded passives by AT&S
- Twelve layer rigid-flex construction with two embedded cores
- Initial electrical tests, FPGA tests and functional tests passed
- Performance is on par with the standard SIM-FUMO board
EVALUATION TEST PLAN

Chart I: INCOMING INSPECTION

- Visual inspection
  - Capacitor
    - El. meas. at room temperature
      - El. meas. at low and high temp.
    - BTI-18
  - Resistor
    - Overload
      - El. meas. at room temperature
        - BTI-16
  - Dimensional check
    - Microsectioning
  - BTI-19-20

- ECCS-Q-ST-70-10C
- ESCC 3009 & 4001

- BTI-1
- BTI-17-18
- BTI-3
- BTI-14
- BTI-15
- BTI-18

ESCC 3009
ESCC 4001

ECCS-Q-ST-70-10C
EVALUATION TEST PLAN

Chart II: STRESS TESTING

INTERCONNECT LEVEL
- BTI1-2: Vibration
  - Continuity
  - Interconnection resistance
  - EL meas. at room temperature
- BTI3-4: Mechanical shock
  - Continuity
  - Interconnection resistance
  - EL meas. at room temperature
- BTI5-6: Bending
  - Continuity
  - Interconnection resistance
  - EL meas. at room temperature
- BTI7-8: Thermal cycling
  - Continuity
  - Interconnection resistance
  - EL meas. at room temperature

COMPONENT LEVEL
- BTI9-11: Resistor
  - Continuity
  - Interconnection resistance
  - EL meas. at room temperature
- BTI12-14: Capacitor
  - Continuity
  - Interconnection resistance
  - EL meas. at room temperature

To Chart III

BOARD LEVEL
- BTI15-16: Thermal stress
  - Insulation resistance
  - Dielectric withstand voltage
  - Continuity
  - Interconnection resistance
- BTI17-18: Damp heat
  - Insulation resistance
  - Dielectric withstand voltage
  - Continuity
  - Interconnection resistance
- COUPON: IST
  - Continuity
  - Interconnection resistance

ESCC 3009
ESCC 4001

ECCS-Q-ST-70-38C
AEC-Q200-005

ECCS-Q-ST-70-10C
EVALUATION TEST PLAN

Chart III: COMPONENT LEVEL

Resistor

- BTI9
  - Power step-stress testing

- BTI10-11
  - Operational life (1000 h)
    - El. meas. at room temperature
    - Operational life (1000 h)
    - El. meas. at room temperature

Capacitor

- BTI12
  - Voltage step-stress testing

- BTI13-14
  - Operational life (1000 h)
    - El. meas. at room temperature
    - Operational life (1000 h)
    - El. meas. at room temperature
# TEST RESULTS

<table>
<thead>
<tr>
<th>Test</th>
<th>Type</th>
<th>Resistor</th>
<th>Capacitor</th>
<th>0-ohm resistor</th>
<th>Board</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component values</td>
<td>Embedded</td>
<td></td>
<td></td>
<td></td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>Surface-mount</td>
<td></td>
<td></td>
<td></td>
<td>n.a.</td>
</tr>
<tr>
<td>Overload</td>
<td>Embedded</td>
<td></td>
<td></td>
<td></td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>Surface-mount</td>
<td></td>
<td></td>
<td></td>
<td>n.a.</td>
</tr>
<tr>
<td>Board insulation resistance</td>
<td>Embedded</td>
<td></td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
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<tr>
<td>Board dielectric withstanding voltage</td>
<td>Embedded</td>
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<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
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<tr>
<td>Vibration</td>
<td>Embedded</td>
<td></td>
<td></td>
<td></td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>Surface-mount</td>
<td></td>
<td></td>
<td></td>
<td>n.a.</td>
</tr>
<tr>
<td>Mechanical shock</td>
<td>Embedded</td>
<td></td>
<td></td>
<td></td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>Surface-mount</td>
<td></td>
<td></td>
<td></td>
<td>n.a.</td>
</tr>
<tr>
<td>Bending (AEC-Q200)</td>
<td>Embedded</td>
<td></td>
<td></td>
<td></td>
<td>n.a.</td>
</tr>
<tr>
<td>Thermal cycling</td>
<td>Embedded</td>
<td></td>
<td></td>
<td></td>
<td>n.a.</td>
</tr>
<tr>
<td>Thermal stress</td>
<td>Embedded</td>
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<td></td>
<td></td>
<td>n.a.</td>
</tr>
<tr>
<td>Damp heat</td>
<td>Embedded</td>
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<td>n.a.</td>
<td></td>
<td>n.a.</td>
</tr>
<tr>
<td>IST</td>
<td>Embedded</td>
<td></td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>Operating life</td>
<td>Embedded</td>
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<td></td>
<td></td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>Surface-mount</td>
<td></td>
<td></td>
<td></td>
<td>n.a.</td>
</tr>
</tbody>
</table>
TEST RESULTS

Component performance

▸ Resistors are within spec for 5% tolerance, outside spec for 1% tolerance

▸ Capacitors are within spec for capacitance, loss factor, insulation resistance and voltage proof testing
  - Multiple outliers below 1 GΩ on C0G capacitors

▸ Resistor operating life time
  - 0402 embedded resistors perform slightly worse than SMT resistors
  - 0201 embedded resistors started failing after 512 hours

▸ Capacitor operating life time
  - Decrease in capacitance is larger for the embedded components compared to their surface-mount equivalents
  - X5R capacitors out of spec after 1000 hours of testing
TEST RESULTS

Board-level insulation

- Insulation resistance ($3x < 1 \, \text{G}\Omega$) and dielectric withstanding voltage failure ($4x < 1.5 \, \text{kV/mm}$) between component and PTH
  - Two additional failures after thermal stress testing
- Micro sections show glass fibers extending to component

- Failure mechanism: carbonized epoxy at fiber cut results in conductive path between PTH and component
TEST RESULTS

Mechanical testing

- No failures in interconnection or components after vibration, mechanical shock and three-point bending
  - Capacitor insulation resistance in spec after testing
- No differences observed between embedded components and surface-mount components
- Four-point bending down to a bending radius of 56.2 mm revealed slight advantage of embedded components
  - 0402 and 0201 sized components small compared to bending radius
TEST RESULTS

Interconnection stress testing

- 10 coupons with SuperHeat only and three sense circuits including embedded 0-ohm resistors
  - PTH daisy chain (S1)
  - Daisy chain with 0201 resistors (S2)
  - Daisy chain with 0402 resistors (S3)
- 180 connections per coupon (PTH chain: 268 vias)
  - microvia is ±15 % of chain resistance
- Performed at PWB interconnect solution in Canada
TEST RESULTS

Interconnection stress testing (IST)

▸ Test protocol (ESA IST draft test procedure QT/2014/030/SHv2)
  - 6 times preconditioning to 230 ºC
  - 1000 cycles at 150 ºC (sense PTH, 0402)
  - 100 cycles at 190 ºC (sense 0402, 0201)

▸ No failures after 1000 cycles at 150 ºC

▸ Two chains with 0201 resistors failed during cycling to 190 ºC
  - Failure mechanism: CTEz of adhesive ($T_{\text{max}} \gg T_g$) causes microvia to lift
SUMMARY

Status of passive component embedding

▸ Performance of embedding technology is at high level
  - Board Type II performed on par with its SMT counterpart
  - No failure observed in interconnection to component (except for IST)

▸ Embedding has minor impact on components
  - Component performance is adequate, except for 0201 resistors
  - Operating life time does not match space requirements

▸ Available components are limitation for space applications
  - Range of available values is limited, no European supply chain, voltage and temperature ratings not sufficient for derating
  - Qualification testing and lot screening need to be upgraded to ESCC requirements and better matched with embedded technology

▸ General considerations
  - Testing of PCBs with embedded component is challenging
  - No automated design flow for space PCBs with design rule checks
  - No repair possible
WHAT’S NEXT?

Passive component embedding is in volume production for commercial applications
  ▶ Automotive qualification is ongoing

PCESA project demonstrated potential for space applications and identified remaining challenges
  ▶ Component availability
  ▶ Design rules for embedding
  ▶ Qualification and procurement
PRODUCTION FLOW PROPOSAL

Components for embedding

- ESCC guidelines
- Lot acceptance testing

Embedded core

- Design rules
- Test plan
- Inspection criteria

Qualified PCB

- ECSS-Q-ST-70-10/11/12C
- Manufacturing flow and logistics
OUTLOOK

Next steps

▸ Establish a European supply chain with an extension of the possible voltage, power and temperature ratings

▸ Implement qualification flow
  - Cooperation between AT&S and ESA qualified PCB supplier
  - Test methodology for PCBs with embedded components

▸ Define technology demonstrator with embedded passive components (GSTP IOD)
  - Verify design and procurement flow
  - Validate product reliability and performance

▸ Embedding active components
  - Diodes, MOSFETs
  - Small modules (PM, RF)
  - Power components (GAN)
  - More complex SIP modules
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