AEROSOL JET PRINTING PROCESS FOR SEMI-EMBEDDED POWER ASSEMBLY

S. Azzopardi, J. Lelièvre, T. Youssef, D. Labrousse, E. Pereira, P. Lasserre
Outline

1. Context & Background & Objectives

2. Aerosol Jet Printing Process
   i. Description
   ii. Strategy

3. Printed layers characterization
   i. Optical and electrical analysis of the deposit layers
   ii. Shear tests

4. Switching cell fabrication & characterization
   i. Devices selection
   ii. Switching cell design and fabrication
   iii. Electrical characterizations

5. Conclusion & Future works
Outline

1. Context & Background & Objectives

2. Aerosol Jet Printing Process
   i. Description
   ii. Strategy

3. Printed layers characterization
   i. Optical and electrical analysis of the deposit layers
   ii. Shear tests

4. Switching cell fabrication & characterization
   i. Devices selection
   ii. Switching cell design and fabrication
   iii. Electrical characterizations

5. Conclusion & Future works
Context - Background - Objectives

Progression of Aircraft Electrical Power Requirements

- **Power Optimized Aircraft**
- **More Electric Aircraft B787**
- **Current On-board Power**

**Applications**

- **Air conditioning**
- **Flight controls**
- **Fuel pumps**
- **Wing / ice protection**
- **Landing gear**
- **EGTS**
- **Engine starting**
- **ETAS**

- **Auxiliary Power Unit**

- **Environmental control system**

- **Electric Green Taxiing System**

**C2 - Restricted**

- **THSA**
- **RUDDER**
- **ELEVATOR**
- **S/G API**
- **PAC APU**

- **AILERON**
- **WIPS**
- **FLAP**
- **SPOILER**

- **THROTTLE LEVER**
- **SIDE STICK**
- **CABIN DOORS**
- **CABIN**

- **MLG BRAKING SYSTEM**
- **E/R MLG**
- **MLG DOORS**
- **CARGO DOORS**
- **EGTS**

- **NOSE STEERING**
- **NLG DOORS**
- **E/R NLG**
Context - Background - Objectives

- From 2D to 3D power assemblies

- ↑ embedded devices
- ↑ electrical perf.
- ↑ power density
- ↑ reliability
- ↑ design complexity

Source: Wolf et al., 2014

Source: Infineon

Source: GaN System

Source: Fraunhofer

Source: Bosch

Source: Ostmann et al., 2016

Source: Infineon

Source: General Electric
Context - Background - Objectives

- Evaluation of the **Aerosol Jet Printing** process
- Semi-embedded approach (less complex) : an alternative to embedded technology approach
- Low to medium power converters using Si and GaN power devices
- Several advantages
  - *Integration of power electronics on non-planar substrate*
  - *Form factor depending on the substrate and not on the assembly itself*
  - *Possibility to use various nature of materials*
Outline

1. **Context & Background & Objectives**

2. **Aerosol Jet Printing Process**
   i. **Description**
   ii. **Strategy**

3. **Printed layers characterization**
   i. Optical and electrical analysis of the deposit layers
   ii. Shear tests

4. **Switching cell fabrication & characterization**
   i. Devices selection
   ii. Switching cell design and fabrication
   iii. Electrical characterizations

5. **Conclusion & Future works**
Aerosol Jet Printing Process: description

Principle
- Direct deposition of aerosolized ink by nozzle on substrate

Materials and post-treatment
- Inks loaded with ceramic, metallic or polymer particles
- Post-process: drying, curing, UV, thermal, IR...

Advantages
- High precision
- Simple post-process
- Adapted for inks of higher viscosity
- Printing on non-planar substrates
- Multi-material

Limitations
- Rather low thickness (1µm to 10µm)
- Small size of powders (1-2 µm)

Source: CTTC
Aerosol Jet Printing Process: equipment

Virtual impactor:
- Reducing aerosol quantity
- Selecting thinner droplets

Auxiliary gas:
- Focusing the aerosol jet

Nozzle:
- Fine one to thin designs
- Wide one for surface covering

Aerosol formation:
- Pneumatic or ultra-sonic

### Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle diameter*</td>
<td>100 - 300 µm</td>
</tr>
<tr>
<td>Drop volume</td>
<td>0.001 – 0.005 µl</td>
</tr>
<tr>
<td>Line width**</td>
<td>10 – 50 µm</td>
</tr>
<tr>
<td>Ink viscosity</td>
<td>0.7 – 1000 cP</td>
</tr>
<tr>
<td>Stand-off distance</td>
<td>2-5 mm</td>
</tr>
</tbody>
</table>

* updated to 800µm for large lines
** up to 500µm width with 800µm nozzle
Aerosol Jet Printing Process: strategy (1/2)

- Multi-layer using silver ink
  - Layer thickness from 1µm to 10µm
  - > 50µm requested

- Overlap

<table>
<thead>
<tr>
<th>0%</th>
<th>25%</th>
<th>50%</th>
</tr>
</thead>
</table>

- Printing directions

(V) [ ] [ ] [ ] [ ] [ ]
(H) [ ] [ ] [ ] [ ] [ ] +

= 2 printed layers ↔ 1 Effective layer (E-layer)

- Glass substrate

(a) 50%-50% - 1 layer (V) ✖
(b) 50%-50% - 2 layers (V-H) ✔
(c) 25%-25% - 1 layer (V) ✖
(d) 25%-25% - 2 layers (V-H) ✖

- Quiet good results
- 500µm printed width
- Overlap 50%-50%
- 2 layers (V-H)
- 2-4 min to cover 1mm²
Aerosol Jet Printing Process: strategy (2/2)

- Curing conditions

<table>
<thead>
<tr>
<th>Tests</th>
<th>Curing temperature (°C)</th>
<th>Duration (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>150°C</td>
<td>60</td>
</tr>
<tr>
<td>#2</td>
<td>180°C</td>
<td>60</td>
</tr>
<tr>
<td>#3</td>
<td>165°C</td>
<td>60</td>
</tr>
<tr>
<td>#4</td>
<td>150°C</td>
<td>30</td>
</tr>
<tr>
<td>#5</td>
<td>180°C</td>
<td>30</td>
</tr>
<tr>
<td>#6</td>
<td>165°C</td>
<td>30</td>
</tr>
<tr>
<td>#7</td>
<td>150°C</td>
<td>120</td>
</tr>
<tr>
<td>#8</td>
<td>180°C</td>
<td>120</td>
</tr>
<tr>
<td>#9</td>
<td>165°C</td>
<td>120</td>
</tr>
</tbody>
</table>

Line (repeatable process)
500µm width / ~3µm thick

- Pre-heated substrate (>25°C) to start drying layers
- Overlap 50%-50%
- 2 layers (V-H)
- 8 E-layers before cleaning and curing
- Fired 120min at 180°C to evaporate the solvent and the additives
- Reference point for nozzle positioning
Outline

1. Context & Background & Objectives

2. Aerosol Jet Printing Process
   i. Description
   ii. Strategy

3. Printed layers characterization
   i. Optical and electrical analysis of the deposit layers
   ii. Shear tests

4. Switching cell fabrication & characterization
   i. Devices selection
   ii. Switching cell design and fabrication
   iii. Electrical characterizations

5. Conclusion & Future works
Printed layers characterization: analysis (1/2)

- Step Roughness

<table>
<thead>
<tr>
<th>Depth</th>
<th>Width</th>
<th>Thickness</th>
<th>Roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 E-layers + curing</td>
<td>3.01µm</td>
<td>4.157µm</td>
<td>0.497</td>
</tr>
<tr>
<td>4 E-layers + curing</td>
<td>6.18µm</td>
<td>10.288µm</td>
<td>0.773</td>
</tr>
<tr>
<td>8 E-layers + curing</td>
<td>22.8µm</td>
<td>16.864µm</td>
<td>1.168</td>
</tr>
<tr>
<td>16 E-layers + 2 curings</td>
<td>57.47µm</td>
<td>43.5µm</td>
<td>3.025</td>
</tr>
</tbody>
</table>

~120µm thick with 32 E-layers
Printed layers characterization: analysis (2/2)

- Electrical characteristics

- Number of layers
  - thickness
  - electrical resistance
  - roughness

32 E-layers to reach ~120µm
Printed layers characterization: shear stress

- Difficulty to carry out the tests (>300µm requested)
- #6 shows a shear strength of 1.4 MPa (>5MPa)
- Need of complementary tests (peel test)

8 tested pins

INSTRON Modèle 5548
Outline

1. Context & Background & Objectives

2. Aerosol Jet Printing Process
   i. Description
   ii. Strategy

3. Printed layers characterization
   i. Optical and electrical analysis of the deposit layers
   ii. Shear tests

4. Switching cell fabrication & characterization
   i. Devices selection
   ii. Switching cell design and fabrication
   iii. Electrical characterizations

5. Conclusion & Future works
Switching cell: devices selection

- Schematics
- Dice from Infineon
- AlN substrate

<table>
<thead>
<tr>
<th>Transistor</th>
<th>Diode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1GC59T120T8RL</td>
<td>IDC51D120T6M</td>
</tr>
<tr>
<td>1200V / 100A</td>
<td>1200V / 100A</td>
</tr>
</tbody>
</table>

9.5mm x 10.39mm x 113µm  
7.00mm x 7.30mm x 110µm

~270µm depth cavity
## Switching cell: design of the transistor side and diode side

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Step 4</th>
<th>Step 5</th>
<th>Step 6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transistor</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>270µm depth, 12mmx12mm surface ceramic cavity machining</td>
<td>Bottom power electrode 100µm silver ink deposit</td>
<td>50µm SnAgCu preform</td>
<td>115µm transistor die positioning and brazing</td>
<td>Epoxy resin Structalit® 5810 deposit + curing @ 160°C</td>
<td>Top power electrode 100µm silver ink deposit covering the epoxy isolator</td>
</tr>
<tr>
<td><strong>Diode</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>270µm depth, 8mmx8mm surface ceramic cavity machining</td>
<td>Bottom power electrode 100µm silver ink deposit</td>
<td>50µm SnAgCu preform</td>
<td>110µm diode die positioning and brazing</td>
<td>Epoxy resin Structalit® 5810 deposit + curing @ 160°C</td>
<td>Top power electrode 100µm silver ink deposit covering the epoxy isolator</td>
</tr>
</tbody>
</table>
Switching cell: fabrication

<table>
<thead>
<tr>
<th>TV</th>
<th>Purpose of each TV</th>
</tr>
</thead>
<tbody>
<tr>
<td>TV1</td>
<td>I-V characteristics to evaluate the bottom electrode path</td>
</tr>
<tr>
<td>TV2, TV3</td>
<td>Double pulse characteristics to evaluate bottom, top and gate electrode path</td>
</tr>
</tbody>
</table>

- TV1
- TV2
- TV3

Degradation of the resin

Purpose of each TV:
- TV1: I-V characteristics to evaluate the bottom electrode path
- TV2, TV3: Double pulse characteristics to evaluate bottom, top and gate electrode path

Degradation of the resin
Switching cell: static electrical measurements

- I-V output characteristics of IGBT (@25°C)

\[
\begin{align*}
V_{CE} & \in [0 – 10]V \\
I_C & \in [0 – 10]A \\
V_{GE} & \in [7 – 10,5]V
\end{align*}
\]
Switching cell: dynamics electrical analysis

- Double pulse switching test @ 50V / 1A & 2A

![Graphs showing voltage and current dynamics](image)

- Current ramp up to 1A
- Current ramp up to 2A

![Circuit diagram](image)

- $V_{dc}$
- $V_{ge}$
- $V_{ce}$
- $L = 0.7 \text{ mH}$
- $r = 10 \text{ mΩ}$

- K A
- C G
- E

- Bottom electrode path
- Gate electrode path
- Top electrode path

- TV2, TV3

- Failure analysis on-going
Outline

1. Context & Background & Objectives

2. Aerosol Jet Printing Process
   i. Description
   ii. Strategy

3. Printed layers characterization
   i. Optical and electrical analysis of the deposit layers
   ii. Shear tests

4. Switching cell fabrication & characterization
   i. Devices selection
   ii. Switching cell design and fabrication
   iii. Electrical characterizations

5. Conclusion & Future works
Conclusion

- Aerosol Jet Printing process has been evaluated and shows promising results as semi-embedded approach for power devices (low to medium power)

- Possibility to use non planar substrate

Future works

- Failure analysis of the 1st run

- Improvement: resin choice and deposit + process optimization for thickness

- Reliability: behavior of the silver layers on epoxy resin and evolution of the stacking layers microstructure under ageing

- Design a full low power converter
Thank you for your attention