ROLE OF MATERIALS IN PERFORMANCE OF PRINTED TEMPERATURE SENSORS

Dr. Vijaya Kayastha

June 26, 2019
Presentation Outline

• Application Background
• Why Printed Temperature Sensors
• Sensor Components and Material Properties
• Role of Sensor Materials
• Importance of Manufacturing Processing
• Brewer Science’s Printed Temperature Sensors
• Conclusion
Modern warehousing requires more and better environmental control

- Temperature is a key environmental factor to monitor and control

Why is this?

- Monitors temperature and activates an alarm in response to an undesired condition
- Protects unnecessary damage or loss of inventory and equipment
- Protects warehouses from potential unauthorized access.

Brewer Science Industry 4.0 solutions will support modern warehousing
Warehousing Automation Is Rising

Warehouse Automation Expected To Growth At ~ 40% CAGR Until 2025

- Warehouses adopted automated warehouse equipment: >10%
  - Westernacher

- Expected 2021 shipment of warehouse automation technologies worldwide: 620,000 units
  - Tractica

- Companies plan to have more automated processes: 70%
  - Realstevierichards

- 2018 Shipment of Warehousing Robots: 194,000 Units
- 2022 Shipment of Warehousing Robots: 938,000 Units

7-Y CAGR: 38.4%

Source: 1. Service Level Agreement/Realstevierichards.com; 2. Tractica
An accurate and reliable temperature sensor is a key.
What’s Needed to Accomplish This

• Sensors
• Power
• Design & Hardware
• Software
• Data Transmission
• Data Acquisition and Computing
• Execute

Brewer Science offers the complete industry 4.0 solution
Why Printed Temperature Sensors?

• Low-cost, scalable manufacturing
• Unlimited customization
• Flexibility and printability on conformal surfaces
• Configurable into sensor array
• High speed (< 200 ms)
• Direct integration with other sensors for multi-pixel sensing

Current Issues

• Less accurate than existing, commercial temperature sensors
• Some drift over time
• Poor manufacturing yield with current manufacturing practices
• Less matured technology
Printed Temperature Sensor/Array

Sensor components
• Substrate
• Sensing material
• Encapsulant

Key Material Properties
• Thermal robustness (against degradation, expansion)
• Sensor material inertness to other environmental parameters (e.g. humidity, VOCs, gases, etc.)
• Good thermal conductivity
• Matched thermal expansion between different components

Figure: Temperature sensor array with 16 printed temperature sensors
Role of Substrates

Substrate is the largest component of a sensor!

Desired Properties

• Thermally robust and stable
• Low MVTR
• Inertness to other conditions (e.g. humidity, VOCs, gases, etc.)
• Excellent thermal conductivity
• No outgassing

Cause for Different Performance??

• Different glass temperature
• Difference in thermal stability, degradation
• Different in inertness at higher temperature

Figure: Substrate degradation with sensor processing

Figure: Performance comparison between sensors, prepared on different substrates
Sensing Material

Desired Properties

- Larger response to temperature change (temperature coefficient of resistance - TCR)
- Temperature response linearity
- Thermally robust (against degradation)
- Repeatability in a wide temperature range
- Inertness to other conditions (e.g. humidity, VOCs, gases, bend, etc.)
- Excellent thermal conductivity

- Cause for different performance
  - Different TCR for different materials
  - Residual solvent in printed film
  - Response to other conditions
  - Contact resistance

Figure: Performance comparison of 3 different materials
Role of Encapsulant

Desired Properties

• Thermally robust (against degradation and expansion)
• Stable in a wide temperature range
• Good adhesion to substrate and active layer
• Good barrier against undesired environmental conditions (e.g. humidity, VOCs, gases, etc.)
• Excellent thermal conductivity

• Cause for different performance
  • Difference in material thermal properties (Tg, thermal expansion, stability)
  • Different solvents and incomplete curing
  • Mismatched thermal expansion with substrate and active layer

Figure: Performance comparison of 5 different encapsulants
Sensor Curing/Processing

• Curing of different components (printed layers)
  • Sensing material
  • Encapsulant

• Thermal break-in of sensors (annealing at higher temperature)

• Processing variables: temperature, time, atmosphere

• **Why optimized cure processing and break-in??**
  • To eliminate issues with incomplete removal of all solvents
  
  • To get best out of each material components
  
  • Thermal break-in at higher temperature eliminates thermal-related stress and drift on sensors during use
Curing of Sensing Layer

- Improved accuracy and TCR with higher cure temperature
- But avoid material degradation and decomposition with extra-high temperature!

Causes for Difference Performance

- Difference in solvent removal from printed film
- Higher TCR comes from solvent-free conductive film
- Thermal break-in at higher temperature cure releases thermal-related stress from the film

Figure: Performance comparison of same type of sensors cured at different temperatures
Curing of Encapsulant

Results

• Higher encapsulant cure temperature: Improved TCR and long-term stability

• However, avoid temperature that can cause material degradation!

Why Difference

• Residual solvent in printed films
• Completion of thermal-related changes
• Thermal break-in at higher temperature

Figure: Sensor drift at 75C vs. encapsulant cure temperature
**Processing Atmosphere**

**Cure atmosphere conditions**
- Air, vacuum, inert conditions (N₂)

**Why Difference**
- Air cure: Possible chemical change and material degradation through material oxidation
- Vacuum cure: Different heat transfer process (radiation only)
- Inert atmosphere cure: Efficient heat transfer (convection + radiation) without material oxidation

![No cure](image1)

![290°C vacuum cure](image2)

![290°C air cure](image3)

Figure: Same sensor/substrate cured at different conditions
Thermal break-in

- Variable: temperature, time, atmosphere
- Improved accuracy and TCR with longer break-in
- Eliminates thermal-related stress from each component of the sensors, and reduces drift during use

<table>
<thead>
<tr>
<th>350°C Break in</th>
<th>75°C/100 day Drift (°C)</th>
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</thead>
<tbody>
<tr>
<td>1X</td>
<td>10.5</td>
</tr>
<tr>
<td>2X</td>
<td>7.5</td>
</tr>
<tr>
<td>5X</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Figure: Sensor break-in duration vs. performance
Brewer Science’s Printed Temperature Sensor

- Resistive-type, printed metal-based
- Accurate; < 0.3°C accuracy for (0°C to 75°C), and ~ 0.6°C for (-20°C to +100°C) range
- Minimal drift over time
- Very fast (175 ms response time measured)
- Hermetically sealed; environmentally stable
- Flexible form factor.

![Sensor response to temperature](image1)

![Sensor response to hot oil](image2)

**Figure: Sensor response to temperature**

**Figure: Sensor response to hot oil**
# Sensor Specifications

## Limitations

- Bigger drift at >100°C (about 10°C at 100°C in 100 days). <2°C drift with improved sensing material.

## Improvements

- Use of more thermally stable sensing material and encapsulant
- Prolonged thermal break-in
- 4-point design to eliminate contact resistance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Performance</th>
<th>Unitt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance Value (At 25°C)</td>
<td>200 ± 10%</td>
<td>Ω</td>
</tr>
<tr>
<td>Accuracy (0°C to +750°C)</td>
<td>0.3</td>
<td>°C</td>
</tr>
<tr>
<td>Accuracy (-20°C to +100°C)</td>
<td>0.6</td>
<td>°C</td>
</tr>
<tr>
<td>Accuracy (-40°C to +120°C)</td>
<td>0.8</td>
<td>°C</td>
</tr>
<tr>
<td>Hysteresis (0°C to +75°C)</td>
<td>0.4</td>
<td>°C</td>
</tr>
<tr>
<td>Hysteresis (-20°C to +100°C)</td>
<td>0.8</td>
<td>°C</td>
</tr>
<tr>
<td>Hysteresis (-40°C to +120°C)</td>
<td>1.1</td>
<td>°C</td>
</tr>
<tr>
<td>Linearity (-40°C to +120°C)</td>
<td>&gt; 99.99</td>
<td>%</td>
</tr>
<tr>
<td>Temperature Coefficient of Resistance</td>
<td>~ 3200</td>
<td>ppm/°C</td>
</tr>
<tr>
<td>Temperature Sensitivity</td>
<td>&lt; 0.1</td>
<td>°C</td>
</tr>
<tr>
<td>Thermal Time Constant (1/e in slow moving air)</td>
<td>175</td>
<td>ms</td>
</tr>
<tr>
<td>Recovery time (1/e) *</td>
<td>~1</td>
<td>s</td>
</tr>
<tr>
<td>Device Drift</td>
<td></td>
<td></td>
</tr>
<tr>
<td>At 75°C in 100 days</td>
<td>&lt; 2</td>
<td>°C</td>
</tr>
<tr>
<td>At 100°C in 100 days</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>
Conclusion

• Monitoring temperature in Industry 4.0 warehousing protects unnecessary loss of inventory and equipment damage, and also protects warehouses from potential unauthorized access.

• Printed temperature sensor offers low-cost, scalable manufacturing, with unlimited customization and flexibility

• Choice of right materials and right set of properties is a key to printed sensor performance

• Optimized cure/processing of each printed material and thermal break-in gives best sensor performance
What We Do

As a leading technology innovator and manufacturer, Brewer Science is here to help with the world’s semiconductor and micro- and nanoelectronics needs.