ROLE OF MATERIALS IN PERFORMANCE OF PRINTED TEMPERATURE SENSORS

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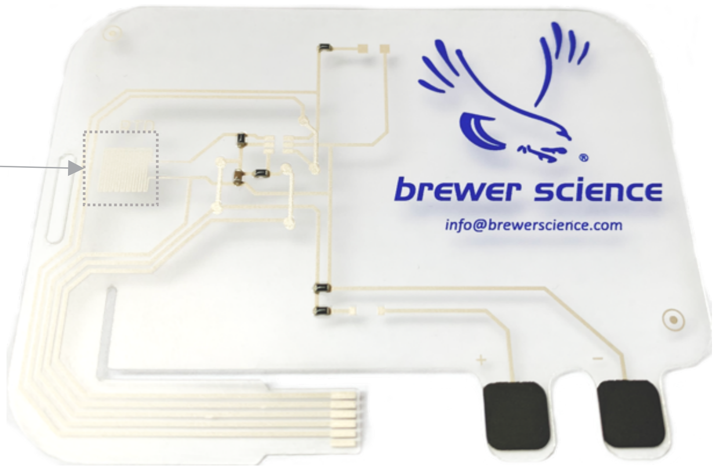
brewer science

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

Brewer Science's printed temperature sensor



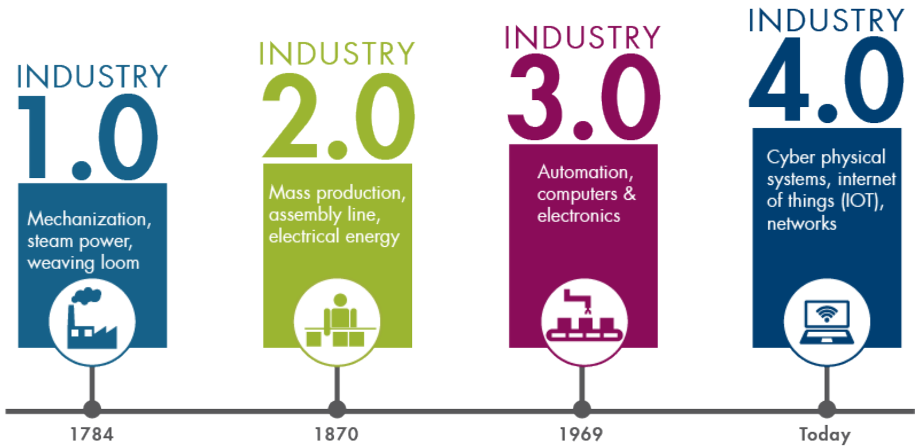
Industry 4.0 Warehousing

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

Warehouses adopted automated warehouse equipment

>10%

Westernacher

Expected 2021 shipment of warehouse automation technologies worldwide

620,000 units

Tractica

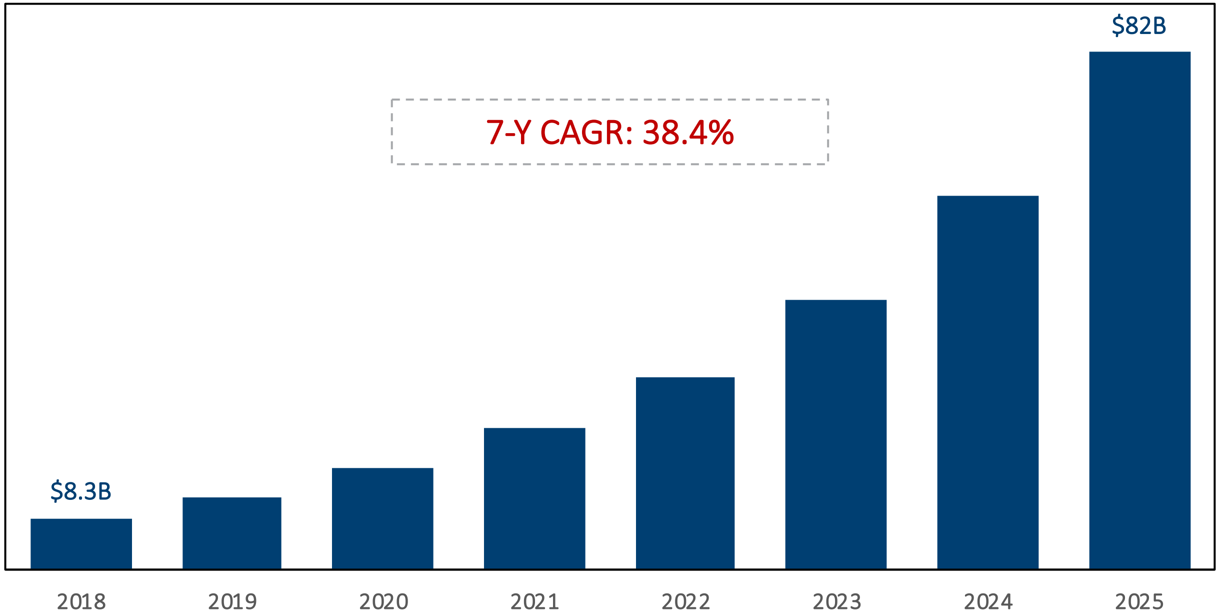
Companies plan to have more automated processes

70%

Realstevierichards

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

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

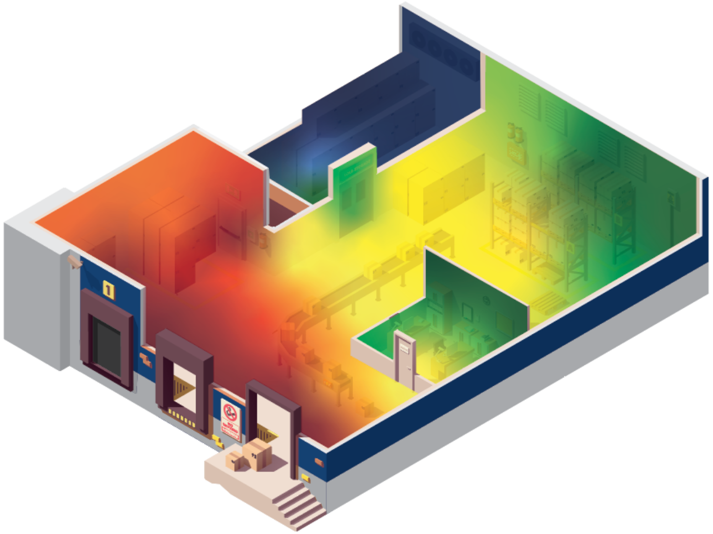


Source: 1. Service Level Agreement/ Realstevierichards.com; 2. Tractica

Thermal Mapping of Industry 4.0 Warehouses

- Configure sensors into arrays through defined areas of your warehouse
- Monitor temperature condition of different zones of your warehouse

Industry 4.0 Warehouses



Temperature mapping

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

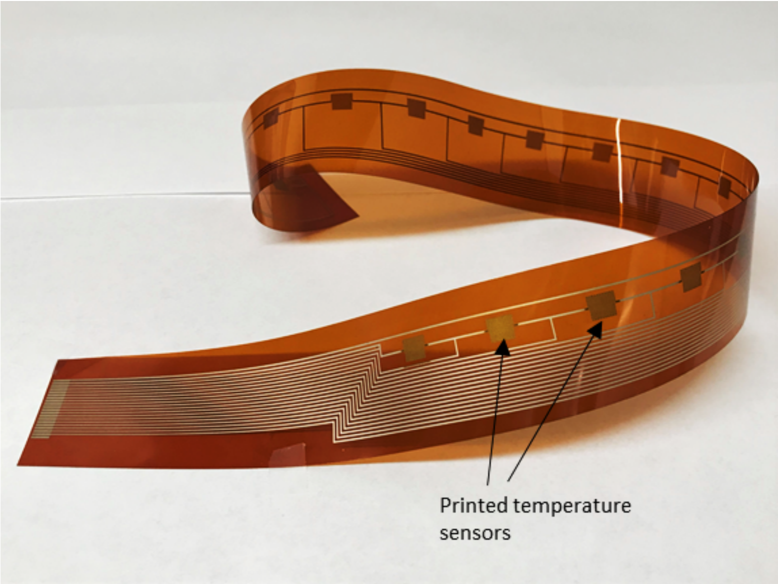


Figure: Temperature sensor array with 16 printed temperature sensors

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

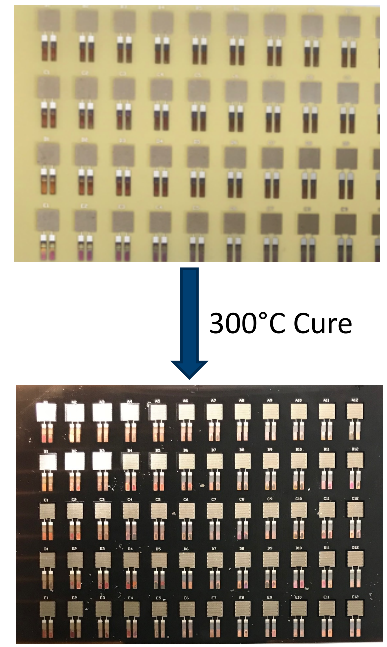


Figure: Substrate degradation with sensor processing

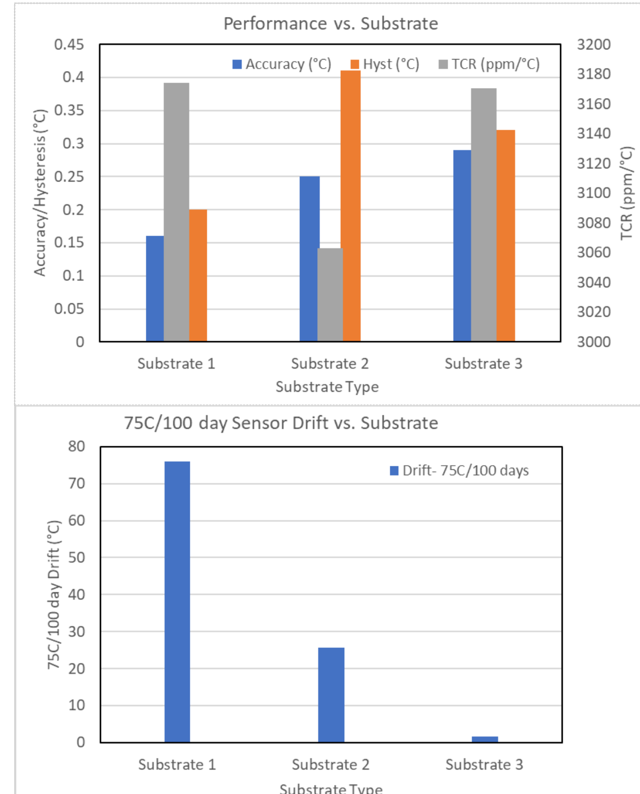


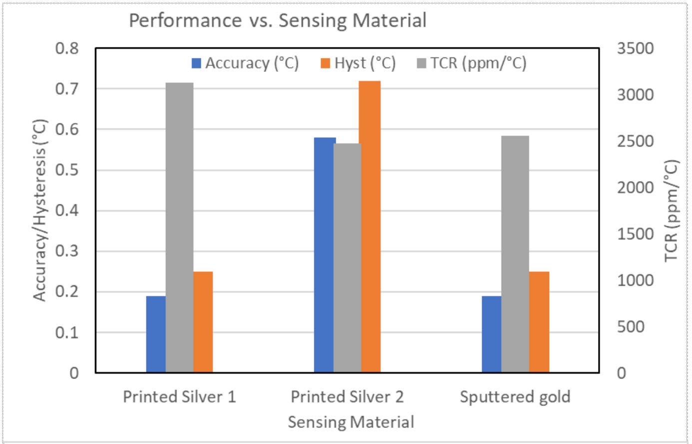
Figure: Performance comparison between sensors, prepared on different substrates

Sensing Material

Desired Properties

- Larger response to temperature change (temperature co-efficient 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



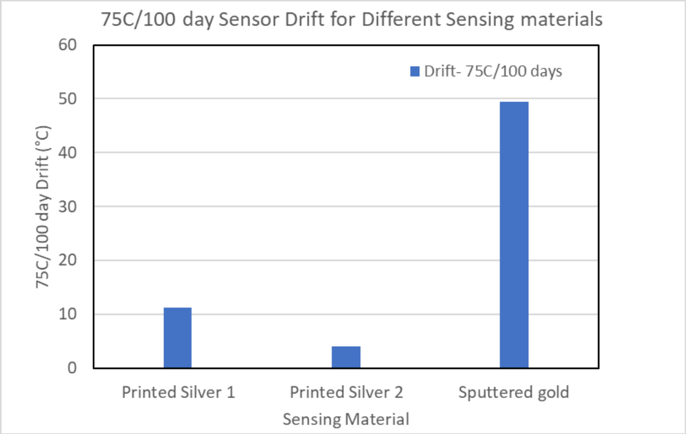


Figure: Performance comparison of 3 different materials

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

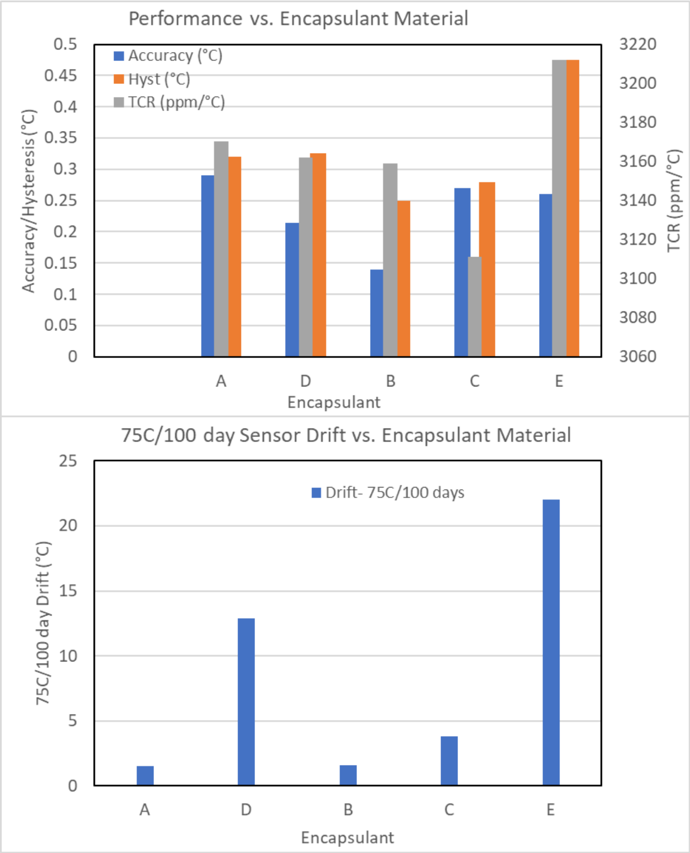


Figure: Performance comparison of 5 different encapsulants

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

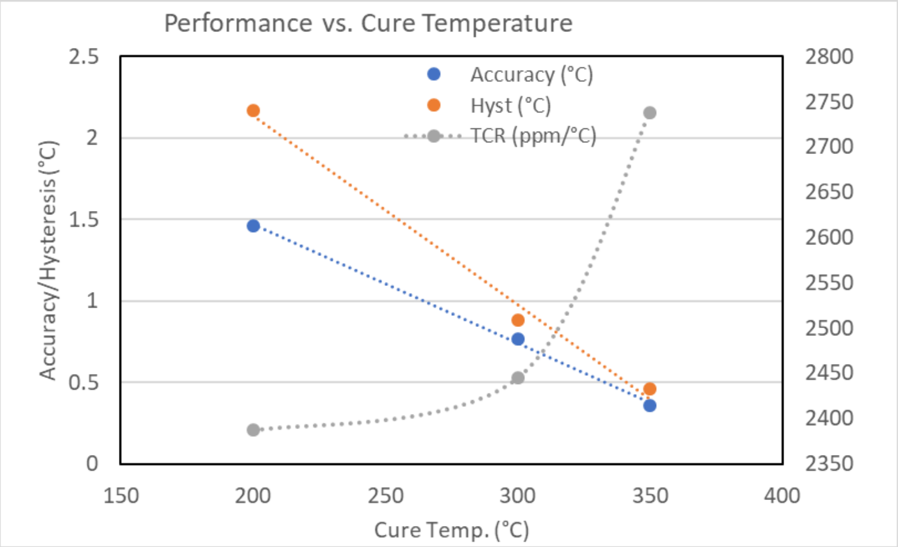


Figure: Performance comparison of same type of sensors cured at different temperatures

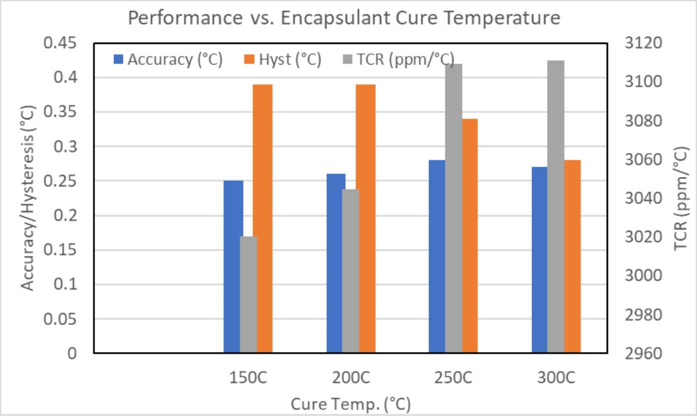
Curing of Encapsulant

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



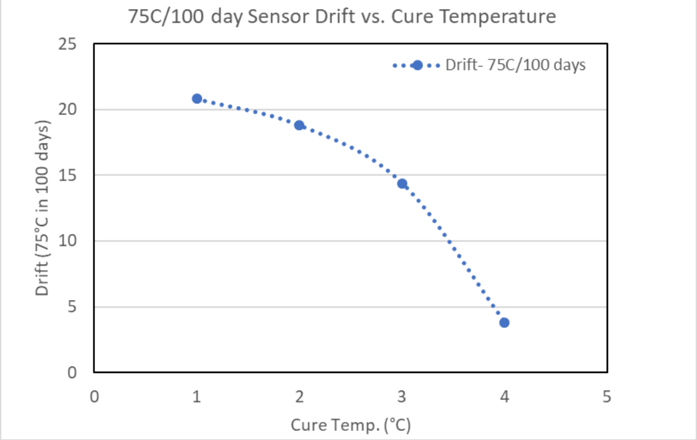


Figure: Sensor drift at 75C vs. encapsulant cure temperature

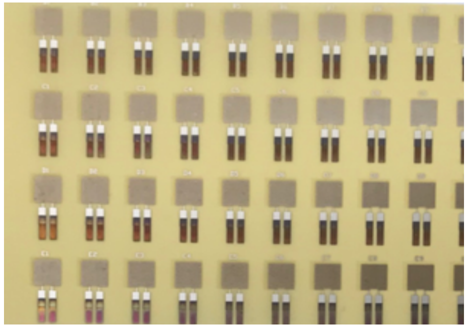
Processing Atmosphere

Cure atmosphere conditions

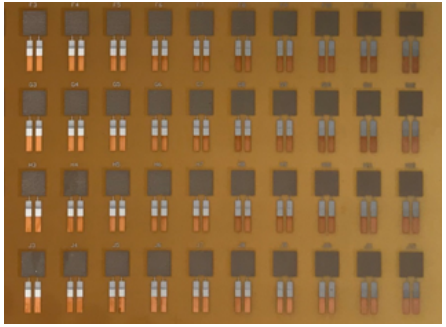
- Air, vacuum, inert conditions (N_2)

Why Difference

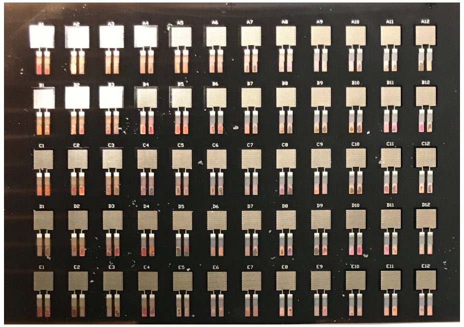
- Air cure: Possible chemical change and material degradation through material oxidation
- Vacuum cure: Different heat transfer process (radiation only)
- Inert atmosphere cure: Efficient heat transfer (convection + radiation) without material oxidation



No cure



290°C vacuum cure



290°C air cure

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

350°C Break in	75°C/100 day Drift (°C)
1X	10.5
2X	7.5
5X	3.0

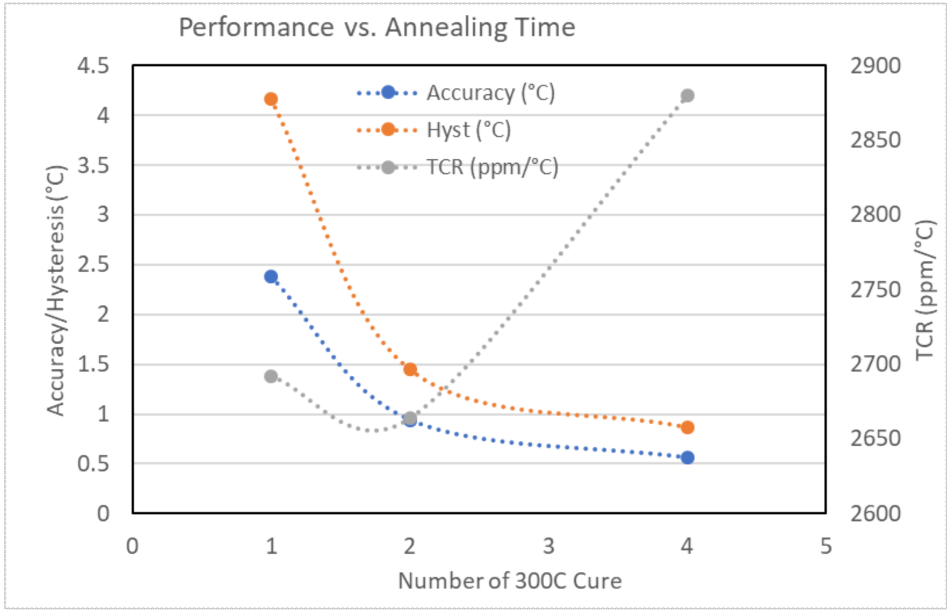


Figure: Sensor break-in duration vs. performance

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.

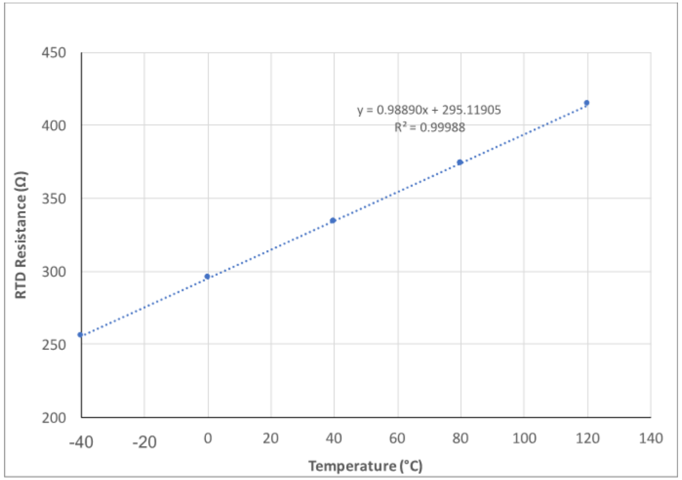


Figure: Sensor response to temperature

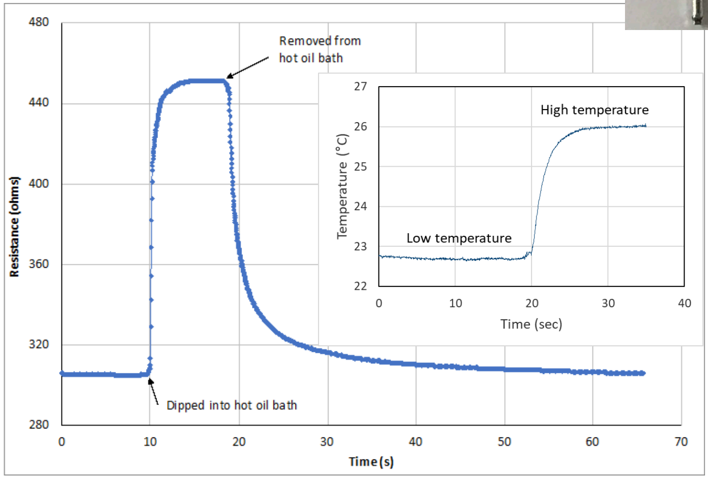


Figure: Sensor response to hot oil

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

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

Conclusion

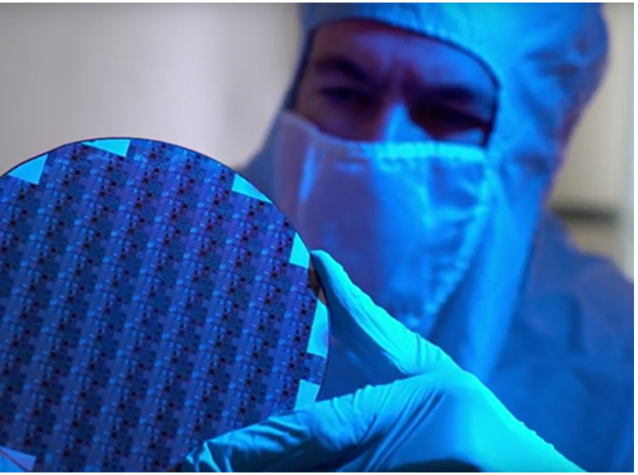
- Monitoring temperature in Industry 4.0 warehousing protects unnecessary loss of inventory and equipment damage, and also protects warehouses from potential unauthorized access.

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

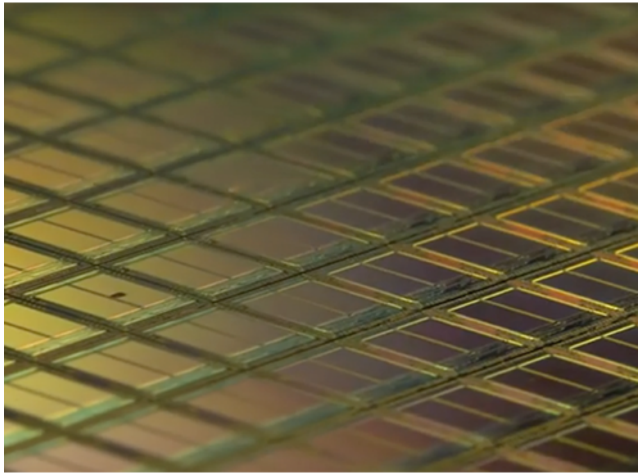
- Choice of right materials and right set of properties is a key to printed sensor performance

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

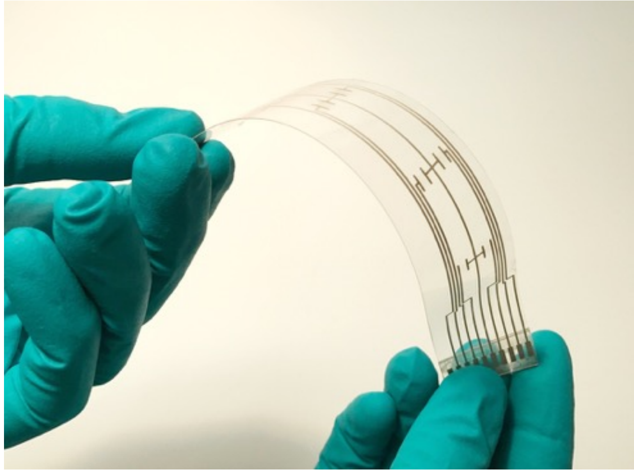
What We Do



Advanced Lithography



Wafer-Level Packaging



Printed Electronics

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

Invent → Develop → Manufacture → Process Improvement