Sensata Technologies

Automotive MEMS pressure sensors

The Future of MEMS chip testing

June 6, 2019 - by Gerard Klaasse

Content:

- Sensata company introduction
- MEMS pressure sensor applications
- MEMS pressure sensor design for exhaust gas applications
- MEMS pressure sensor testing

Company introduction

About Sensata

One of the world's leading suppliers
of sensing, electrical protection, control and power management solutions

Key market player
in automotive, appliance, aircraft, industrial, military, heavy vehicle, off-road, HVAC, data, telecom, RV, and marine markets

BY THE NUMBERS

$3.5B
2018 revenues

21,600+
employees

11 countries
with Sensata sites

Sensata's Broad Global Footprint

- Manufacturing
- Business Site

Europe
Belgium, Bulgaria, France, Germany, The Netherlands, UK

Asia
China
Japan
Korea
Malaysia

Americas
Brazil, Mexico,
United States
(Arizona, California, Maryland, Massachusetts, Minnesota, Virginia, Washington)

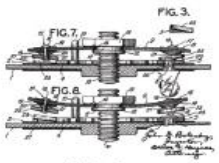
PLUS Sales & Engineering Support Offices Worldwide

What is Sensata's history?

1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020

General Plate Company founded in Attleboro, MA to provide gold plate for jewelry industry
1916

Rathbun Willard
FOUNDER



Patent our first motor protector
1937

1931
Merger with Spencer Thermostat Company

1941
Design and build our first circuit breakers for military vehicles and aircraft

1959
Merger with Texas Instruments

1960
Develop first protector for fluorescent light ballasts

Begin designing and building all panel control switches for Apollo 11 moon mission
1965

1972
Our first positive thermal coefficient (PTC) electric choke for cars

Determine how to save the corroded Statue of Liberty
1985

1999
Launched our microfused strain gauge (MSG) sensors for vehicle stability

Launched MEMS pressure sensors for diesel particulate filters
2005

Bought by Bain Capital and get our name, **Sensata Technologies**
2006

Introduce 24–volt direct switchable circuit breaker for marine uses

IPO initial public offering; ST symbol listing on NYSE
2010

2008
Lillehammer environmental award for cylinder pressure sensor (CPS)

Launch of force sensor for electromechanical braking–by–wire

2009
Hubble telescope upgraded with our switches and thermostats
Launch our first vacuum sensors for micro–hybrids

Launch of Gen 2 DPS to reduce diesel exhaust emissions
2012

Introduce UL recognized arc fault detector for solar arrays

Launch oil-filled MEMS sensor for industrial application
2013

Celebrated our 100th Anniversary #ST100

Partner with Quanergy to lead solid-state LiDAR sensors for autonomous driving
2016

2014
Launch anti-freezing urea pressure sensor

Help Society of Automotive Engineers improve global standard for Single Edge Nibble Transmission sensor signals

2017
Launch of Sensata Technologies Foundation

2018
Acquired GIGAVAC

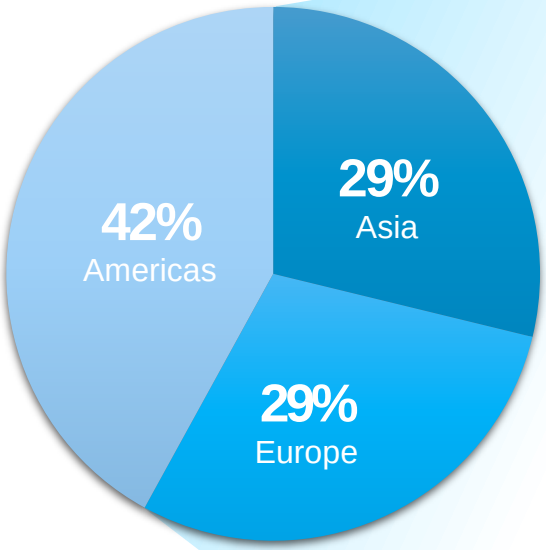
1950s
Europe & Mexico Expansion

1963–1996
Asia & Brazil Expansion

2006-16 Capabilities Expansion
Acquire First Technology, Airpax, Honeywell's Automotive On Board (AoB), Sensor–NITE, Wells–CTI, Wabash Technologies, Magnum Energy, DeltaTech Controls, Schrader, CST's Sensing Portfolio

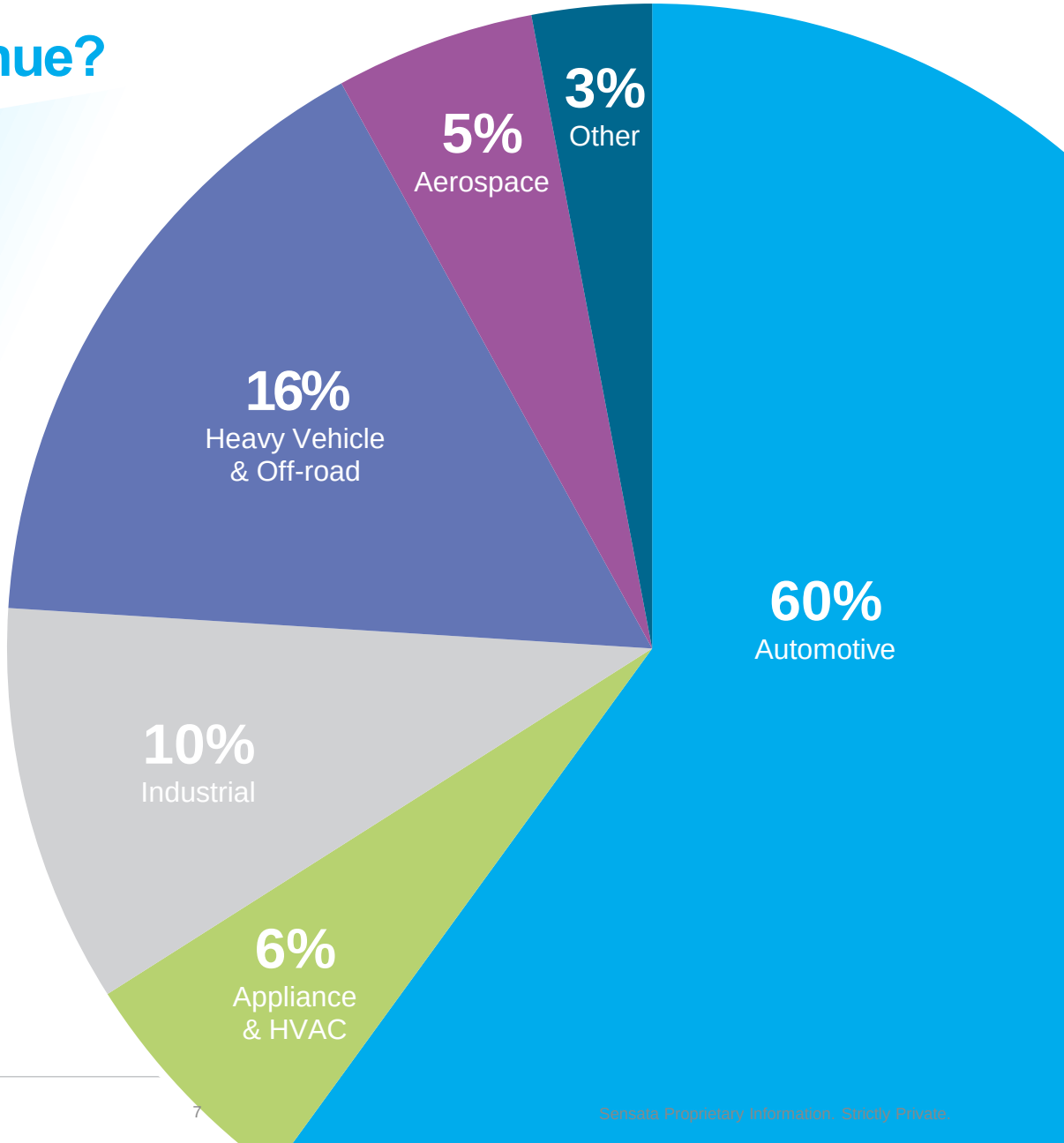
2016-NOW
Focus on Megatrend-driven Growth

What is Sensata's revenue?



$3.5B

Total 2018 Revenues



What are Sensata's products?

1.1 Billion
devices shipped each year, each highly engineered

15 Brands
we own, manufacture and sell

47,000+
Unique products

Sensata Technologies | Airpax | BEI Kimco | BEI Sensors | Crydom | DeltaTech | GIGAVAC | Kavlico
Klixon | Magnum Dimensions | Newall | Qinex | Schrader | SensorNITE | Swindon Silicon Systems

Where are Sensata systems?

1,500
in commercial jets
CIRCUIT BREAKERS, SWITCHES, POSITION & PRESSURE SENSORS

50
in automobiles
SENSORS, CONTROLS

Dozens
in large HVAC systems
SENSORS, SWITCHES

60
in RVs and Large Boats
CIRCUIT BREAKERS, SWITCHES

50
in agriculture/ construction vehicles
SENSORS, CONTROLS

30
in U.S. homes
SENSORS, SWITCHES, SAFETY SWITCHES

Sensata Technologies

AIRPAX · BEI KIMCO · BEI SENSORS · crydom · DeltaTech CONTROLS · KAVLICO · GIGAVAC · KLIXON · MAGNUM DIMENSIONS · NEWALL · Qinex · Schrader TPMS Solutions · SENSOR NITE · SWINDON SILICON SYSTEMS

A selection of our customers

MEMS pressure sensor applications

Where are Sensata systems?

Providing Sensors to Mission Critical Auto Systems

50+
DEVICES PER AUTOMOBILE

Propulsion

Engine

- ✓ Gasoline Direct Injection Pressure **MEMS**
- ✓ Common Rail Diesel Pressure **MEMS**
- ✓ Fuel Delivery Pressure and Temperature
- ✓ Crank Case Pressure **MEMS**
- ✓ Cylinder Pressure **MEMS**
- ✓ Oil Pressure and Temperature
- ✓ Air Intake Pressure and Temperature **MEMS**
- ✓ Cam / Crank Position / Speed

Exhaust

- ✓ Particulate Filter Pressure and Temperature **MEMS**
- ✓ EGR Pressure and Temperature **MEMS**
- ✓ Exhaust Back Pressure
- ✓ Turbo Protection Temperature
- ✓ SCR Temperature

Transmission

- ✓ Clutch Actuation Pressure
- ✓ Clutch Pedal Position
- ✓ Line Pressure
- ✓ Continuous Variable Pulley Pressure
- ✓ Gear Position
- ✓ Input / Output Speed

Propulsion (continued)

Electrification

- ✓ Contactors
- ✓ Active & Passive Fuses
- ✓ Electric Drive Position
- ✓ Battery Current Sensing
- ✓ Battery Aging
- ✓ Battery Management Sensing (BMS)

Safety

Active Safety/ Automated Driving

- ✓ Brake Pressure (ESC) **MEMS**
- ✓ Vacuum Boost Pressure **MEMS**
- ✓ LiDAR
- ✓ Electric Park Brake Position

Chassis

- ✓ Suspension Pressure
- ✓ Tire Pressure Monitoring Systems (TPMS) **MEMS**

User Experience

Cabin Comfort

- ✓ Air Conditioning Pressure
- ✓ Humidity
- ✓ Air Conditioning Temp

Where are Sensata systems?

In heavy duty truck and off-road applications

50+
DEVICES PER HEAVY VEHICLE

Engine

- ✓ Air Intake and Filter MEMS
- ✓ Boost, Compressor and Turbine
- ✓ Low Pressure Fuel Filter Pump
- ✓ High Pressure Fuel Rail
- ✓ Cam and Crank
- ✓ Oil Pressure
- ✓ Coolant Pressure
- ✓ Engine Temperature
- ✓ EGR MEMS
- ✓ Alternate Fuels

Transmission

- ✓ Pressure
- ✓ Speed
- ✓ Shift Position
- ✓ Electronic Transmission Control

Machine Control

- ✓ Steer by Wire
- ✓ Primary Implement Controls (electro-hydraulic joystick)
- ✓ Secondary Controls (HMI, lighting, optional functions)
- ✓ Electronic throttle, hitch, PTO controls

Chassis & Safety

- ✓ Tire Pressure MEMS
- ✓ Brake Pressure MEMS
- ✓ Electronic Stability Control MEMS
- ✓ Air Suspension MEMS
- ✓ Hydraulic Suspension
- ✓ Wheel Speed / ABS Speed
- ✓ LiDAR

Cabin Comfort

- ✓ Air Conditioning
- ✓ Cabin Air Filter

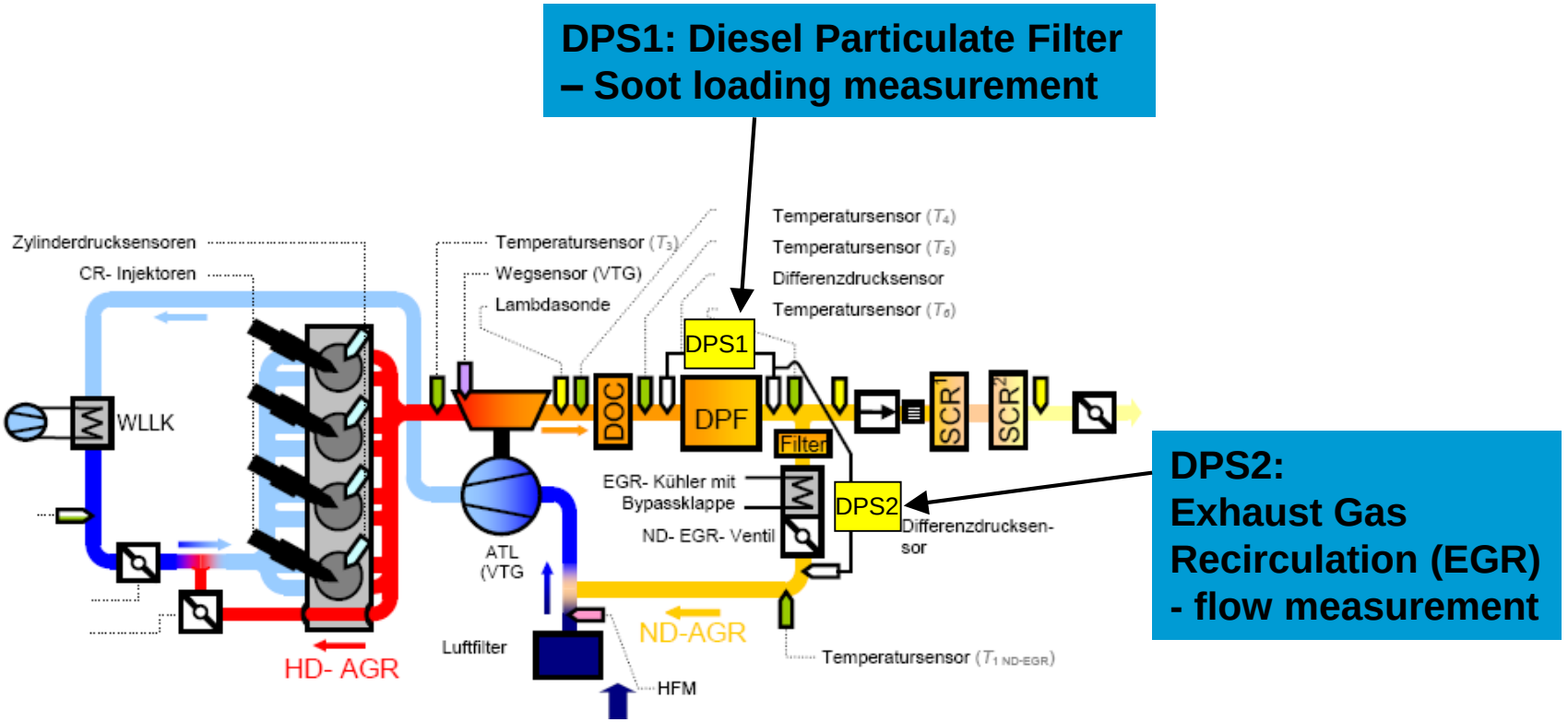
Exhaust

- ✓ Exhaust Gas Temperature
- ✓ Exhaust Gas (delta) Pressure MEMS

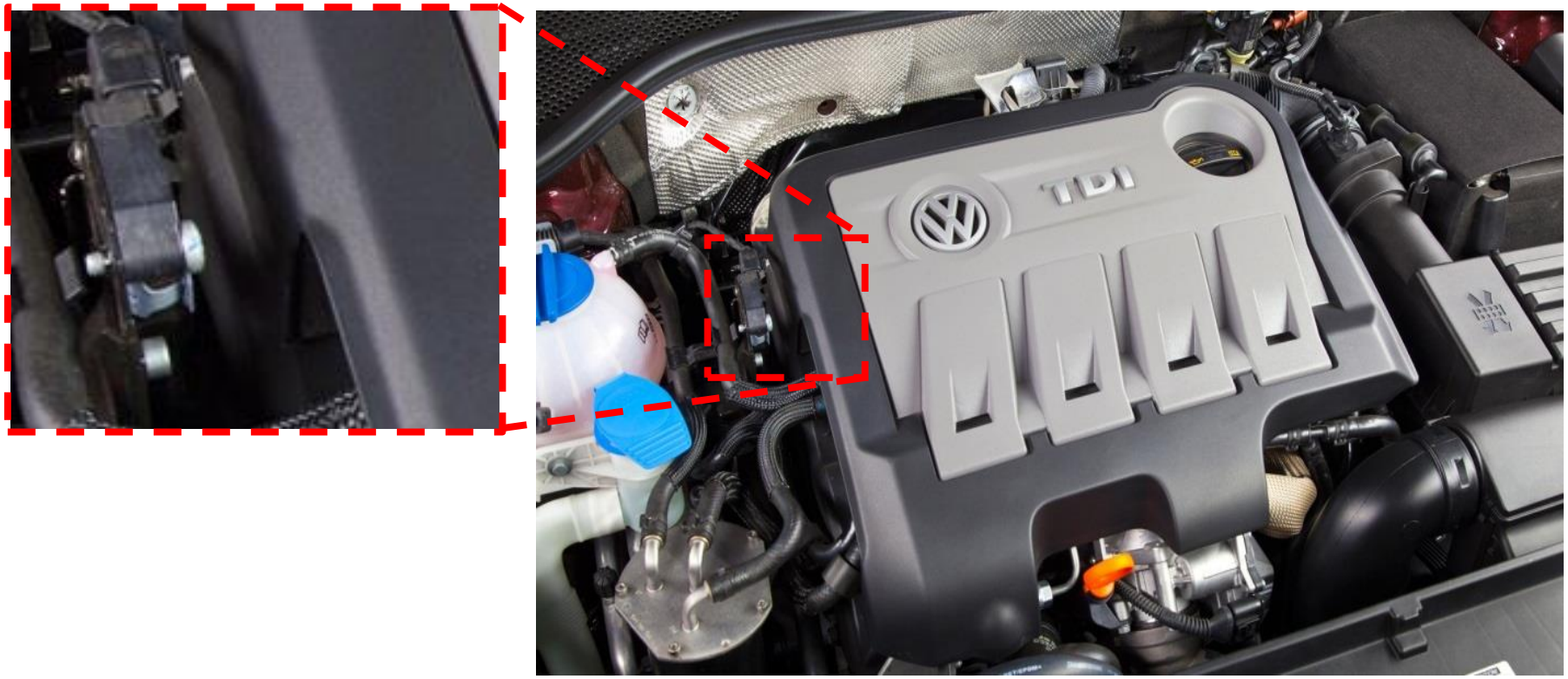
Auxiliary Systems

- ✓ Air Pressure
- ✓ Hydraulic System Pressure
- ✓ Hydraulic Filter
- ✓ Rotary Position
- ✓ Implement Position and Speed

Engine layout, including all pressure and temperature sensor positions



The Sensata Differential Pressure Sensor: mounting on a Euro5 Diesel Engine

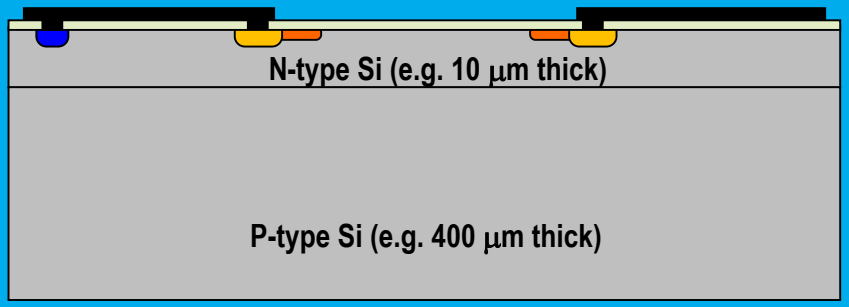


The Sensor is mounted on the engine and connected with rubber hoses to the diesel particulate filter. This ensures that the sensor will not see the high exhaust temperature. The most extreme sensor temperature is about 150°C

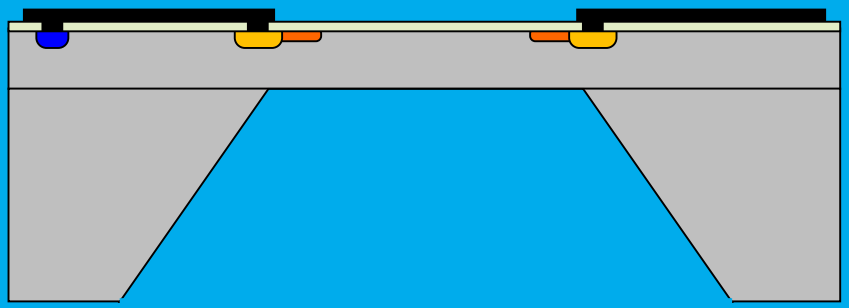
MEMS pressure sensor design for exhaust gas applications

MEMS pressure sense element:

Relative (Cavity last)



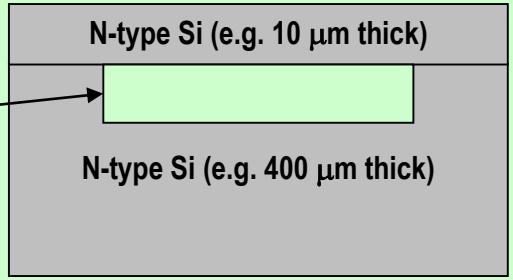
Step 1: Standard CMOS processes.



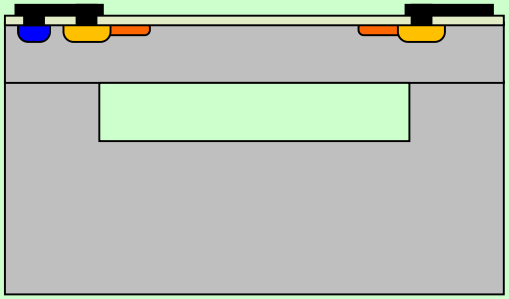
Step 2: MEMS processes.

Absolute (Cavity first)

Vacuum cavity for absolute reference pressure



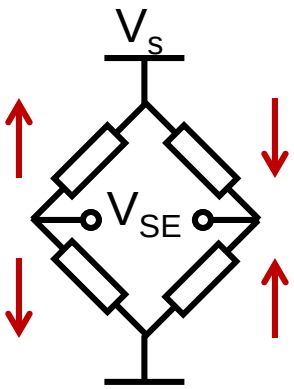
Step 1: MEMS processes.

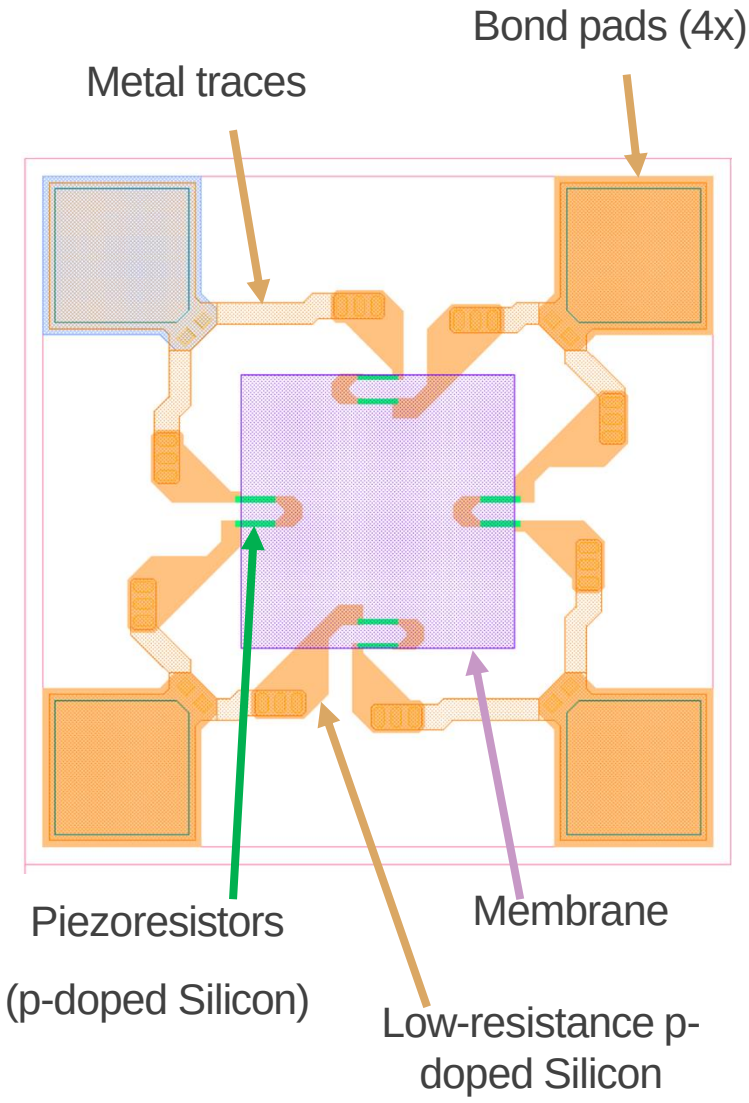


Step 2: Standard CMOS processes.

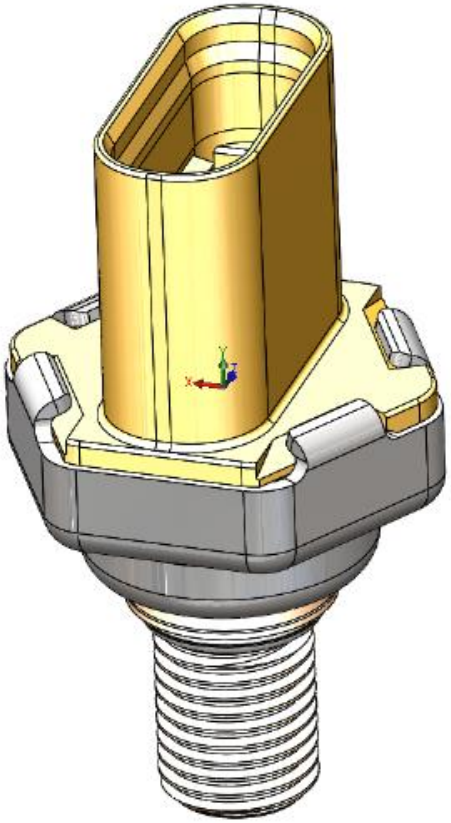
MEMS pressure sense element layout:

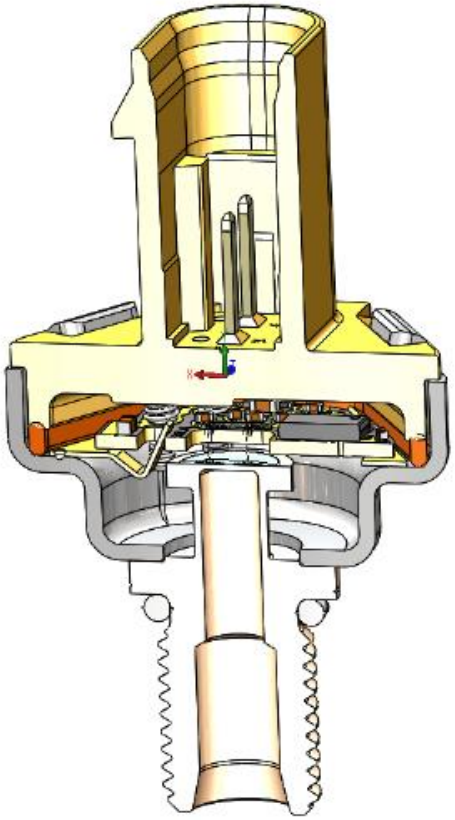
- The sense element consists of 4 resistors in a Wheatstone bridge configuration.
- When a pressure is applied to the membrane, 2 (opposite) resistors will see longitudinal strain and the other 2 resistors will see transversal strain. The voltage between the output terminals is a measure for the applied pressure.

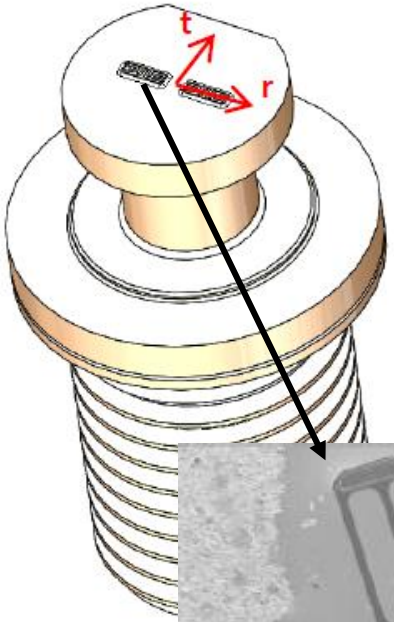


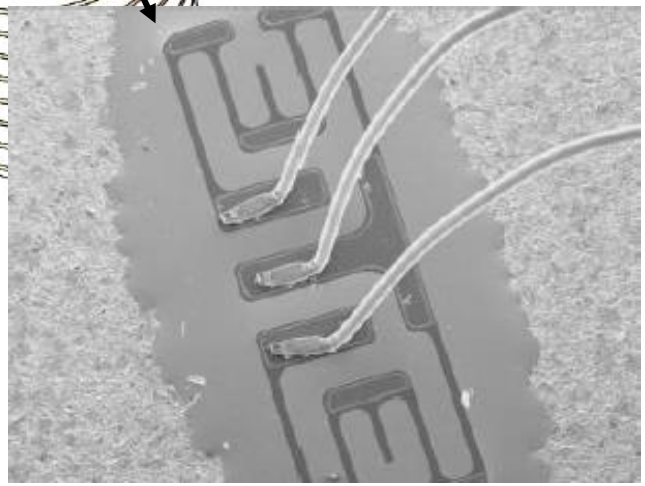


Micro-fused strain gauge sensor (also categorized as MEMS)







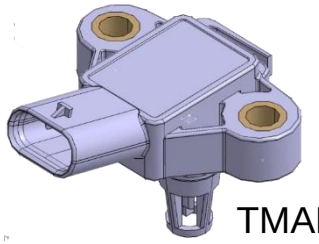


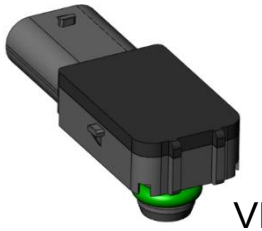
MEMS pressure sensors in a modern passenger car:

Applications that are typically served with MEMS (= Micro-Electro-Mechanical-Systems) pressure sensors:

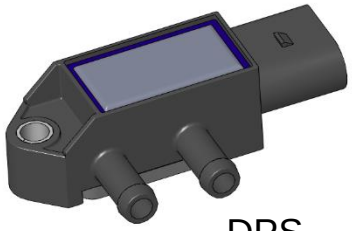
- TMAP: Temperature Manifold Air Pressure. This is a combined pressure-temperature sensor for mass-air-flow measurement. Modern engines can have up to 3 of these sensors.
- VBS: Vacuum Brake booster Sensor. Stop-start systems require monitoring of the vacuum level of the brake booster. If the level gets too low, no brake assist is present; the engine must re-start.
- TPMS: Tyre Pressure Monitoring System. All tires of a car are equipped with a battery-supplied pressure sensor that transmits the pressure information to a receiver in the car.
- DPS: Differential Pressure Sensor. Used for diesel (Gasoline) particle filter sensor monitoring and also for Exhaust Gas Recirculation flow measurements (Venturi effect).

➔ Easily 10 or more MEMS pressure sensors in a passenger car.

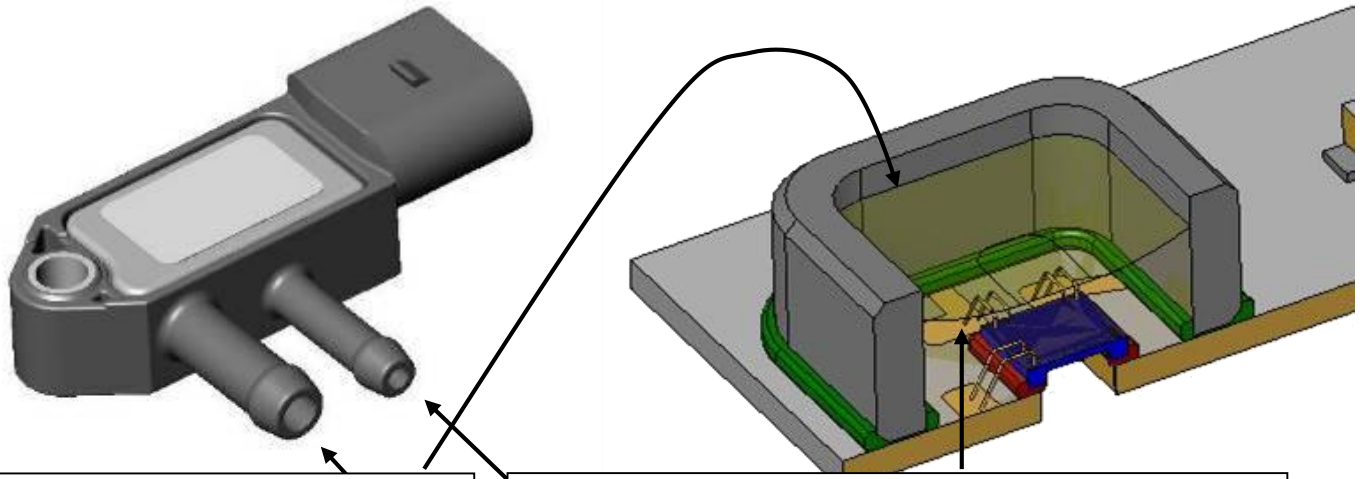

TMAP


VBS


TPMS


DPS

Single sense element differential pressure sensing



High pressure inlet, front side of SE
Dirty side of the particle filter trap

Low pressure inlet, back side of SE
Clean side of the particle filter trap

Gel protection front-side of SE provides:

- Electrical isolation against water (exhaust gas condensate) and soot.
- Mechanical isolation against deposits (soot, e.a.).
  "The gel should absorb delta's in CTE without transmitting stress to the sensing element"
- Protection of the SE and wire bonds against damaged through icing

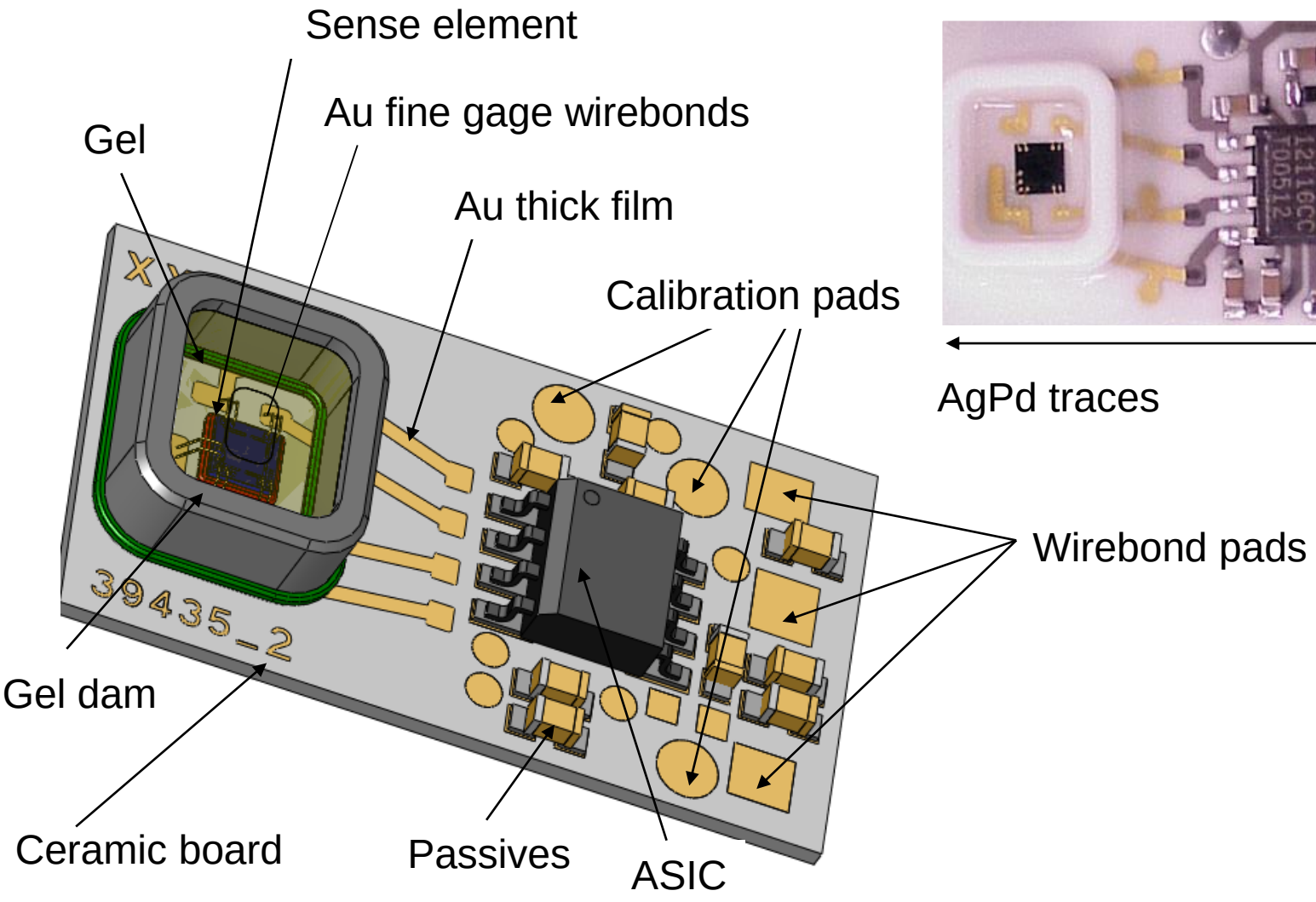
> Gel is not considered to be corrosion protection <

Protection backside of SE is not needed since the backside of the SE has:

- No open electrical contacts or connections
- An optimized shape to prevent damage through icing
- No risk for (soot) deposits since the backside is connected to the clean side of the trap.

Remark: adding a small amount of gel inside the ceramic through hole (common in industry) provides a questionable mechanical isolation which can result in output failures.

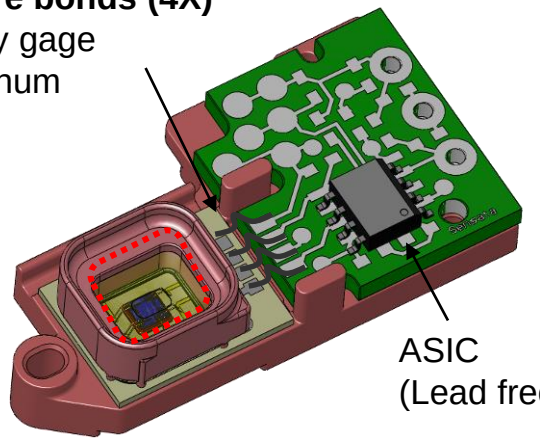
MEMS DPS EMA


Sense element
Au fine gage wirebonds
Gel
Au thick film
Calibration pads
Wirebond pads
Gel dam
Ceramic board
Passives
ASIC
39435_2

AgPd traces
25mm

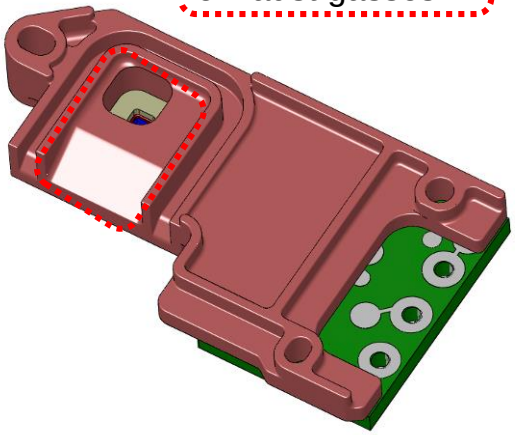
Electronic Module Assembly (EMA)

Wire bonds (4X)
Heavy gage aluminum



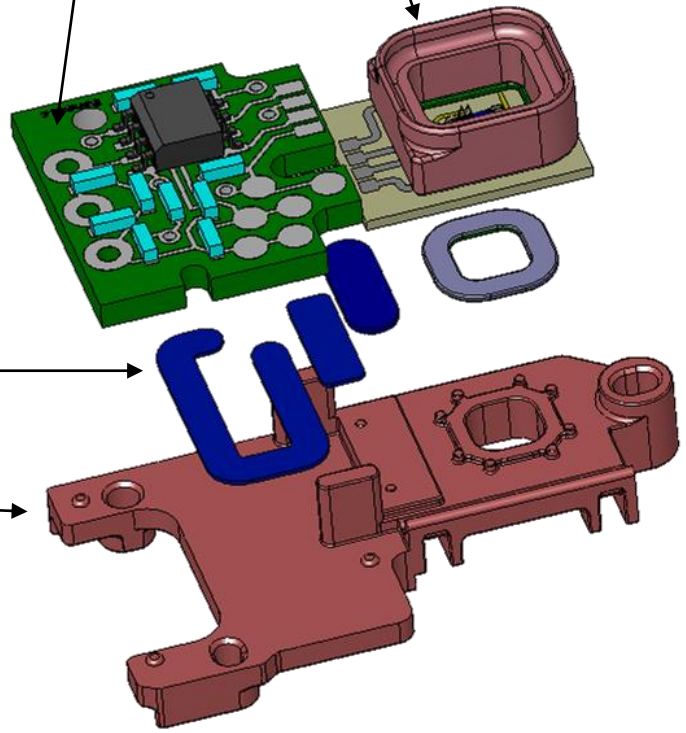
ASIC
(Lead free)

Area exposed to exhaust gasses



PCB
FR4, 1.6mm thick
Lead free solder

SEA
See next slide



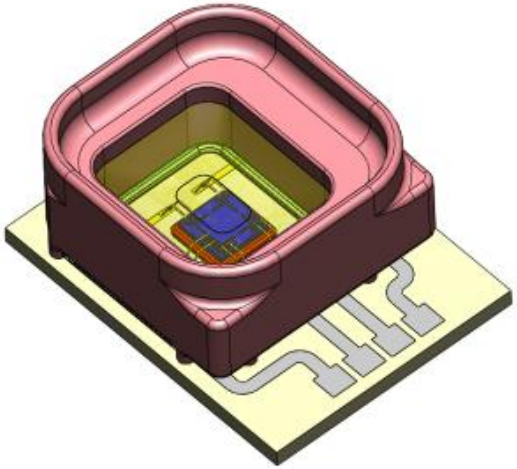
Adhesives

Carrier
PPS (40%GF)

Design features:

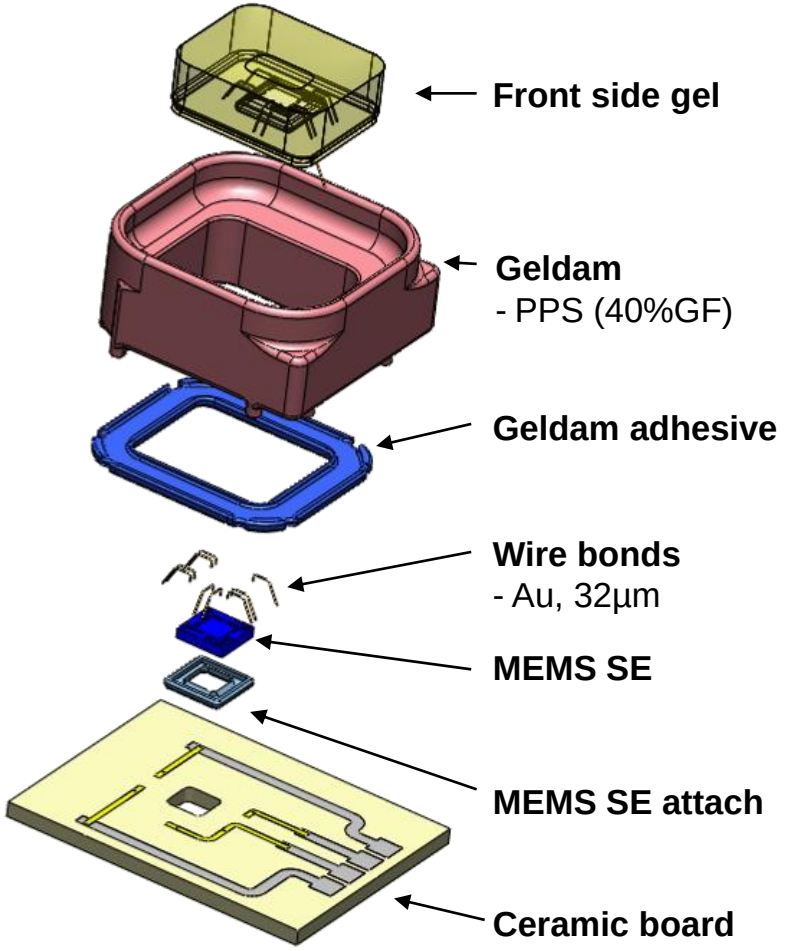
- Wire bonds from SEA (AgPd) to PCB (flash Au)
- Mechanical protection through features in carrier
- Minimal area exposed to exhaust gas
- Backside gel cavity integrated (optional)

Sense Element Assembly (SEA)

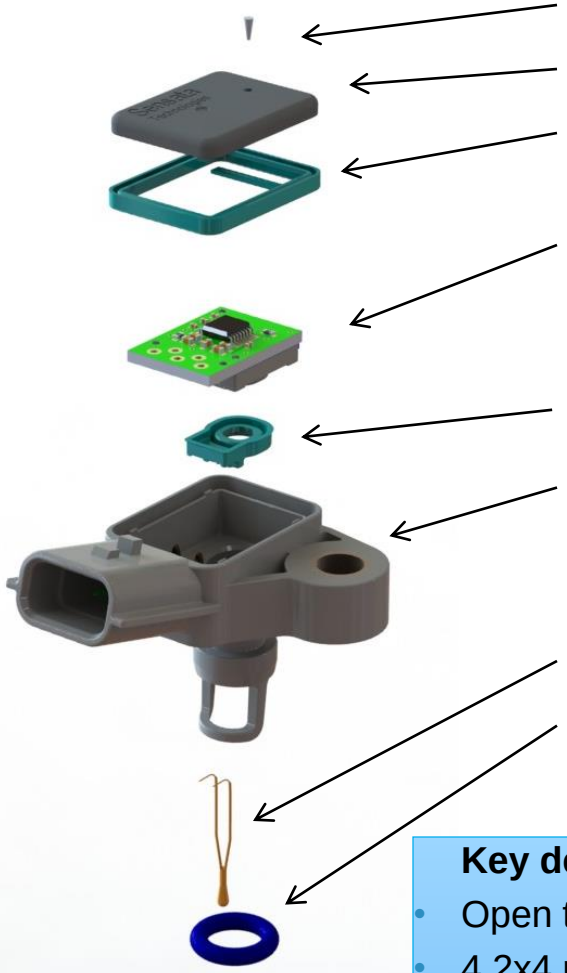


SEA (Sense Element Assembly)

- Small size: 13x10mm
- Minimized Au surface



Temperature + Manifold Air Pressure Sensor design



Cover seal: RTV

Cover: PBT

Environmental seal:
Silicone glue

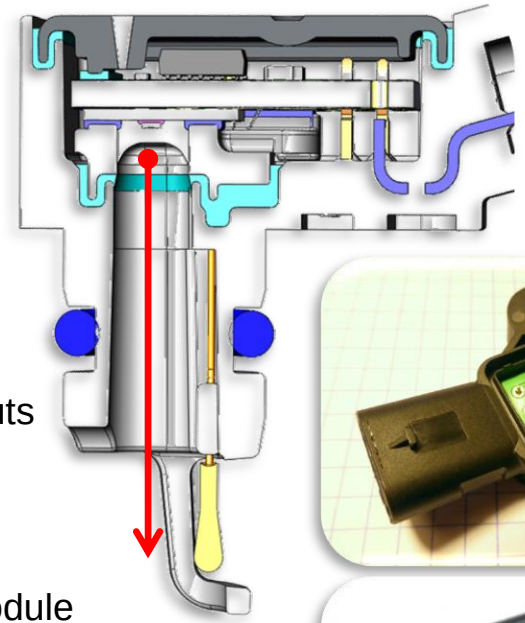
Pressure module:
Signal conditioning,
SENT & analog ratiometric outputs

Medium seal: Silicone glue

Housing: PPS-40%GF
Pressfits connect to pressure module
Custom connector / mounting

Thermistor: PTFE coated NTC

Sealing O-ring: FKM / FLSI

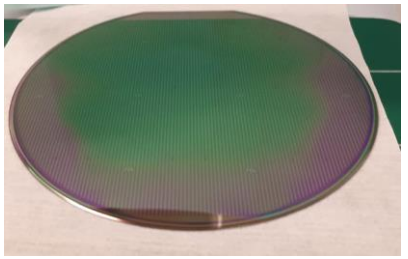


Key design features:

- Open temperature tip for fast response & small error
- 4.2x4 mm pressure opening optimized for optimal condensate drainage
- Pressure seal & electronics outside hot air flow area

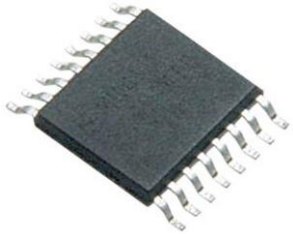
MEMS pressure sensor testing

Pressure sensor testing:



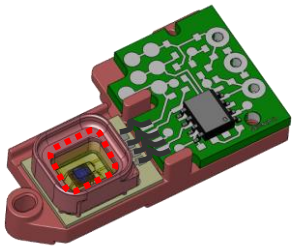
Testing occurs at different levels:

- Wafer level (both ASIC and sense element separately)
- First level package (ASIC only)
- Electronics Module level (ASIC and sense element combined). This includes pressure calibration.
- Completed sensor in final package.

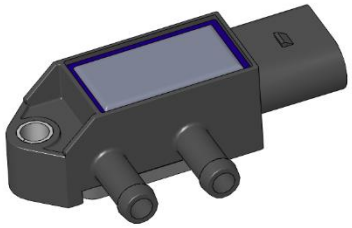


General considerations:

- The more packaging is added, the more expensive the testing. However, the accuracy of the testing is increasing as well.
  - For example: adding an ASIC that is doing the thermal compensation of the sense element makes the testing less vulnerable for temperature variations.



- The accuracy of the sense element probing is limited by the handling system, not by the electrical measurements.
- Probing a relative sense element wafer requires special wafer fixation. Commercial solutions are already available.



What can be improved to get more value out of the chip testing:

- In order to save cost on calibration at module level, it would be desired to feed-in information from the wafer probing. However, the accuracy of the probing results is not good enough to make big steps. The limitation is the mechanical handling of the wafer that is putting mechanical stress on the sense element, thereby impacting the electrical signal.

- Some failure modes are easy to capture at module level testing, but it is currently impossible to screen these out at probing. Again, the mechanical handling is probably the bottleneck.

- Probing of absolute sense elements would benefit from an integrated absolute pressure measurement during probing.

- More ideas are very welcome!

Summary:

- There is an enormous MEMS pressure sensor content in the automotive market.
- Sensata is a major player in this MEMS pressure sensor market.
- Wafer level testing of pressure sense elements imposes challenges regarding wafer handling, not regarding the electrical measurements.

Sensata
Technologies

Thank You!

sensata.com