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

**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)

Manufacturing
Business Site

PLUS Sales & Engineering Support Offices Worldwide
What is Sensata’s history?

- 1910: General Plate Company founded in Attleboro, MA to provide gold plate for jewelry industry.
- 1920: Begin designing and building all panel control switches for Apollo 11 moon mission.
- 1931: Merge with Spencer Thermostat Company.
- 1937: Design and build our first circuit breakers for military vehicles and aircraft.
- 1940: Develop first protectors for fluorescent light ballasts.
- 1941: Our first positive thermal coefficient (PTC) electric choke for cars.
- 1950s: Europe & Mexico Expansion.
- 1959: Merge with Texas Instruments.
- 1960: Determine how to save the corroded Statue of Liberty.
- 1965: IPO initial public offering; ST Symbol listing on NYSE.
- 1968: Bought by Bain Capital and got our name, Sensata Technologies.
- 1972: Launch our microfiltered strain gauge (MSG) sensors for vehicle stability.
- 1985: Introduce 24-volt direct switchable circuit breaker for marine use.
- 1990: Launch our first vacuum sensors for micro-hybrids.
- 1999: Lillehammer environmental award for cylinder pressure sensor (CPS).
- 2005: Introduced UL recognized arc fault detector for solar arrays.
- 2008: Launched MEMS pressure sensors for diesel particulate filters.
- 2010: Celebrated our 100th Anniversary.
- 2010: Partner with Quanergy to load solid-state LiDAR sensors for autonomous driving.
- 2012: Launch of Gen 2 DPS to reduce diesel exhaust emissions.
- 2013: Acquired GIGAVAC.
- 2018: Focus on Mega-trend driven Growth.
- 2018: Hubble telescope upgraded with our switches and thermostats.
- 2016: Launch anti-freezing ural pressure sensor.
- 2016: Capabilities Expansion.
What is Sensata’s revenue?

$3.5B
Total 2018 Revenues

60%
Automotive

16%
Heavy Vehicle & Off-road

10%
Industrial

6%
Appliance & HVAC

5%
Aerospace

3%
Other

42%
Americas

29%
Asia

29%
Europe

42%
Asia

29%
Europe

$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
A selection of our customers
MEMS pressure sensor applications
Where are Sensata systems?
Providing Sensors to Mission Critical Auto Systems

Propulsion

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

Exhaust
- Particulate Filter Pressure and Temperature
- EGR Pressure and Temperature
- 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)
- Vacuum Boost Pressure
- LiDAR
- Electric Park Brake Position

Chassis
- Suspension Pressure
- Tire Pressure Monitoring

User Experience

Cabin Comfort
- Air Conditioning Pressure
- Humidity
- Air Conditioning Temp

MEMS pressure sensor applications
Where are Sensata systems?
In heavy duty truck and off-road applications

- **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

**50+ DEVICES PER HEAVY VEHICLE**
Engine layout, including all pressure and temperature sensor positions

**DPS1:** Diesel Particulate Filter – Soot loading measurement

**DPS2:** Exhaust Gas Recirculation (EGR) - flow measurement

- **Zylinderdrucksensoren** (cylinder pressure sensors)
- **CR-Injektoren** (common rail injectors)
- **WLLK** (water liquid line)
- **HD-AGR** (high pressure fuel return line)
- **DPS1** (Diesel Particulate Filter)
- **DPS2** (Exhaust Gas Recirculation)
- **DOC** (Diesel Oxidation Catalyst)
- **DPF** (Diesel Particulate Filter)
- **EGR-Kühler mit Bypassklappe** (Exhaust Gas Recirculation cooler with bypass valve)
- **ND-EGR Ventil** (Nozzles for EGR Gas Recirculation)
- **ATL (VTG)** (Air Temperature and Volume Flow Sensor)
- **Temperatursensor (T1)** (Temperature sensor)
- **Temperatursensor (T2)** (Temperature sensor)
- **Temperatursensor (T3)** (Temperature sensor)
- **Temperatursensor (T4)** (Temperature sensor)
- **Wegsensor (VTG)** (Distance sensor)
- **Lambda sensor** (Oxygen sensor)
- **HFM** (Hot Film Sensor)
- **Differenzdrucksensor** (Differential pressure sensor)

MEMS pressure sensor applications
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)

- N-type Si (e.g. 10 μm thick)
- P-type Si (e.g. 400 μm thick)

Step 1: Standard CMOS processes.
Step 2: MEMS processes.

Absolute (Cavity first)

- N-type Si (e.g. 10 μm thick)
- N-type Si (e.g. 400 μm thick)

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.
Single sense element differential pressure sensing

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

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.

> Gel is not considered to be corrosion protection <
MEMS DPS EMA

- Sense element
- Gel dam
- Ceramic board
- Au fine gage wirebonds
- AgPd traces
- Calibration pads
- Wirebond pads
- Au thick film
- Passives
- ASIC
Electronic Module Assembly (EMA)

**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)

**Materials:**
- **ASIC** (Lead free)
- **Carrier** PPS (40%GF)
- **PCB** FR4, 1.6mm thick, Lead free solder
- **SEA** See next slide

**Notes:**
- Wire bonds (4X) Heavy gage aluminum
- Area exposed to exhaust gasses
Sense Element Assembly (SEA)

SEA (Sense Element Assembly)
- Small size: 13x10mm
- Minimized Au surface

Front side gel
Geldam adhesive
Wire bonds
- Au, 32μm
MEMS SE attach
Ceramic board
- Thick film printed (Au, AgPd & sometimes glass)

Geldam
- PPS (40%GF)
Temperature + Manifold Air Pressure Sensor design

**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

**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
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.
Thank You!

sensata.com