# BOSCH MEMS SENSORS: ENABLER FOR THE IOT

DR. UDO-MARTIN GÓMEZ, CTO
BOSCH SENSORTEC GMBH

BOSCH

# OUTLINE

01 **INTRODUCTION** | MEMS OVERVIEW & MEMS@BOSCH

02 **AUTOMOTIVE MEMS** | TECHNOLOGY & APPLICATIONS

03 **CE MEMS** | DRIVING TECHNOLOGY INNOVATION

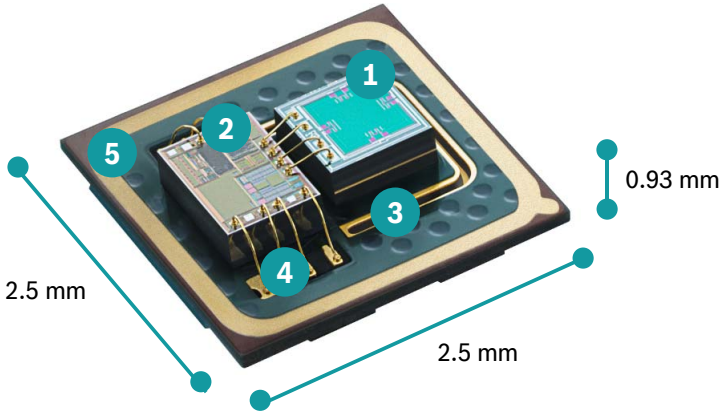
04 **MEMS FOR IOT** | ENABLING NEW APPLICATIONS

# 01 INTRODUCTION

# MEMS OVERVIEW & MEMS @ BOSCH

# What are MEMS?
## Micro-Electro-Mechanical Systems

- MEMS are miniature systems that combine tiny mechanical structures with electronic circuits. Typical individual structures have a size of a few µm.
- The MEMS sensor element is usually packaged together with an ASIC and made into one unit, e.g. into a LGA package.




1. MEMS
2. ASIC
3. Decoupling unit
4. Bonding wires
5. Printed circuit board (PCB)

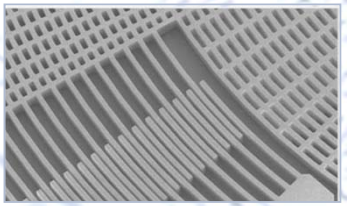
# Technology
## Why MEMS technology?

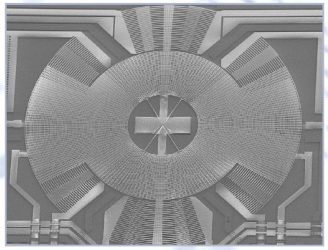
**Cost Reduction**
Fewer components
Batch production

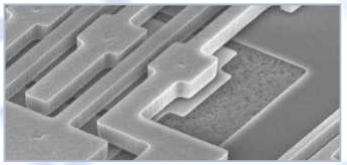
**Size & Weight**
Compact
Highly integrable

**Reliabilty**
Fewer plugs and cables
Fewer components

**More Functionalities**
Self-test
Accuracy check



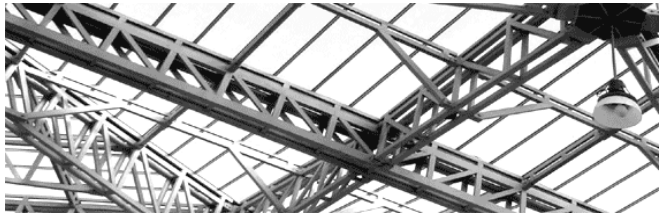


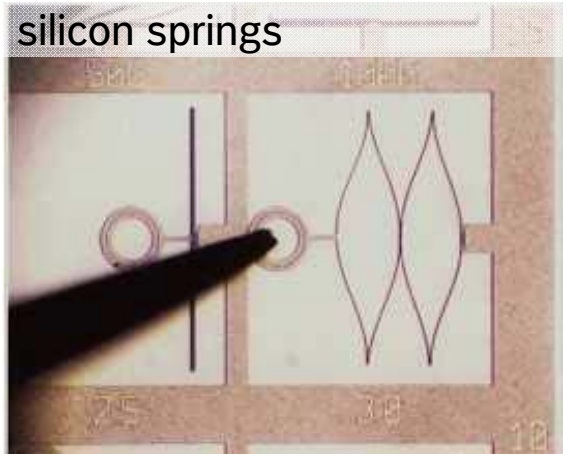


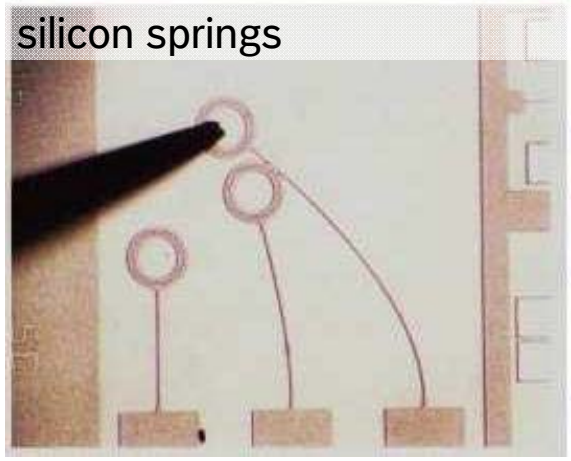
# Technology
## Mechanical properties of silicon

**Silicon compared to steel**

- Over 3 times lower density
- 4 times higher yielding strength
- 3 times lower thermal expansion
- Brittle material, no plastic deformation



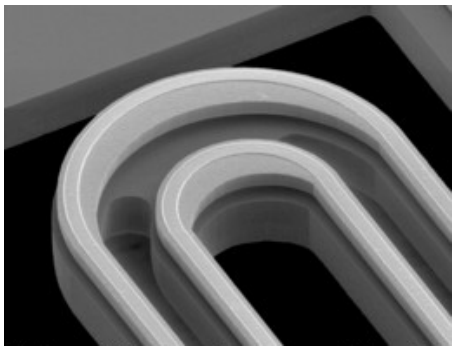


# Technology
## MEMS technology

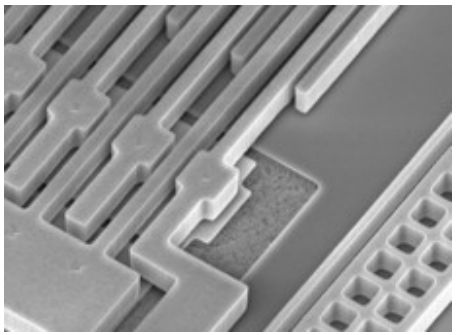
### Bulk Micromachining

- Structure definition by selective etching
- of bulk wafer
- Structures are monocrystalline
- Contamination risks (potassium, natrium, ...)



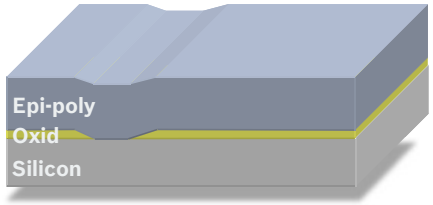
### Surface Micromachining

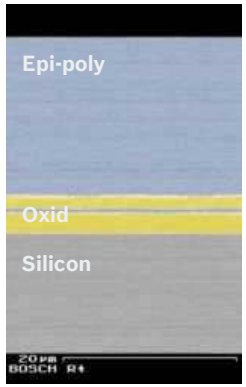
- Structures are made on top of wafer by deposition
- and selective etching
- Structures are of poly silicon and silicon dioxide
- Few contamination risks



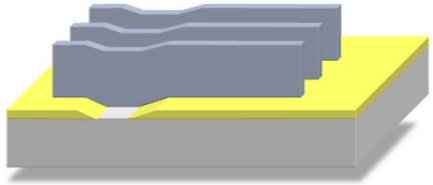
# Automotive sensors – Angular rate sensors
## MEMS technology: surface micromachining

Thick epitaxy
("epi-poly")

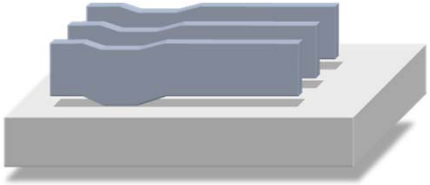



DRIE
("Bosch-process")



Sacrificial etching
of oxide



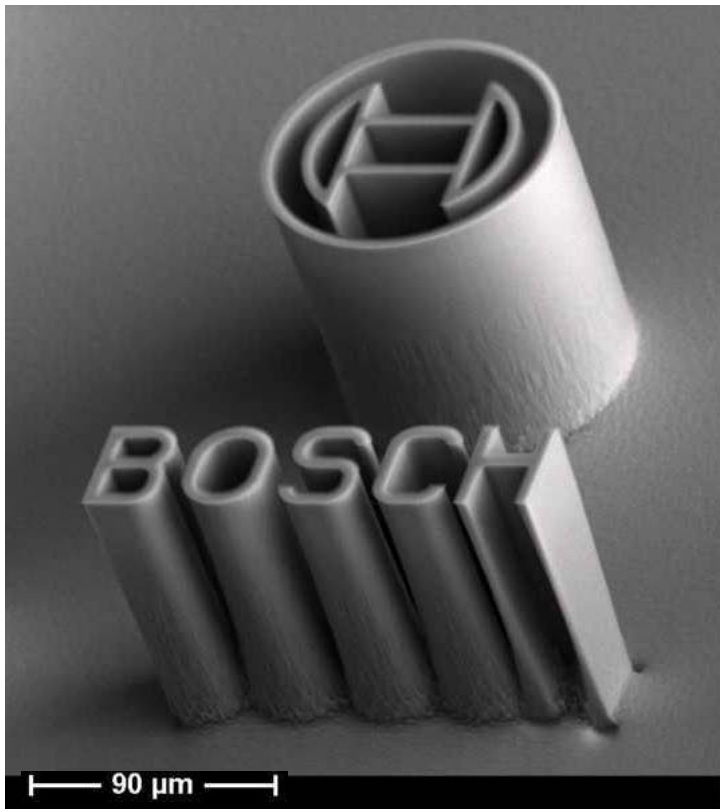
# Technology
## MEMS technology: surface micromachining

**...comparison to a human hair**

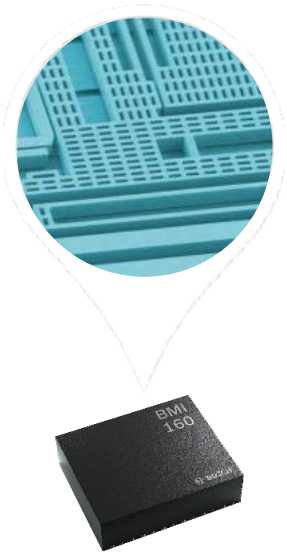
# Technology
## DRIE – the Bosch process

- Deep RIE of silicon trenches
- Alternating etch- (SF6) and  passivation cycles (C4F8)
- High aspect ratio ( >>10:1 )
- High anisotropy (underetch <<2 % of etch depth)
- High etch rate

"European Inventor of the Year 2007"
Andrea Urban and Dr. Franz Lärmer

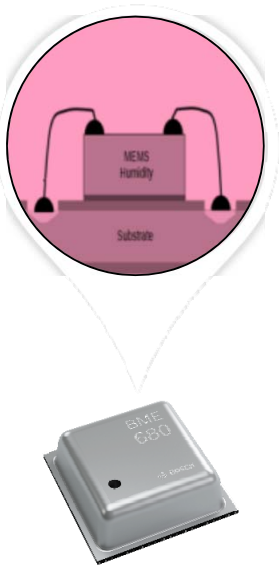


# MEMS challenge:
## One product / one technology




**Inertial**


**Pressure**

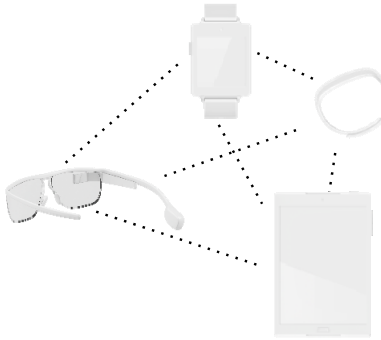



**Environmental**


**Geomagnetic**

Each product segment requires specific technology (not fully CMOS compatible)
Challenge for integration, need for advanced packaging technologies (SiP)

# Waves of MEMS
## sensor proliferation



3rd wave

**Internet of Things (IoT)**

2nd wave

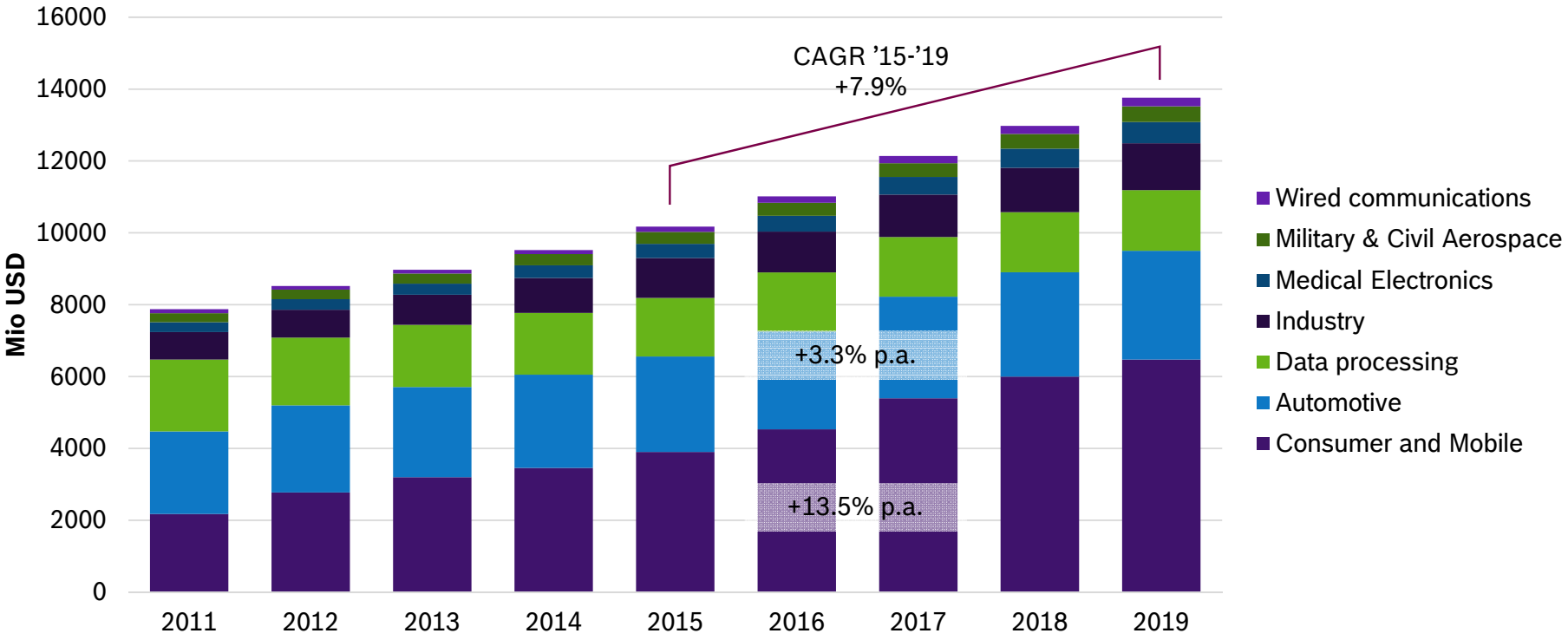
**Consumer Electronics**

1st wave

**Automotive**

1990 2000 2010 2020

# MEMS market overview
## MEMS market by application




Source: IHS – MEMS Market Tracker – Q3 2015

# MEMS @ Bosch
## Bosch – the MEMS pioneer

### MEMS Pioneer

- Start of MEMS production in 1995
- **Over 8 billion MEMS sensors produced**
- More than 1,000 MEMS patents
- 100 % in-house from MEMS design to manufacturing

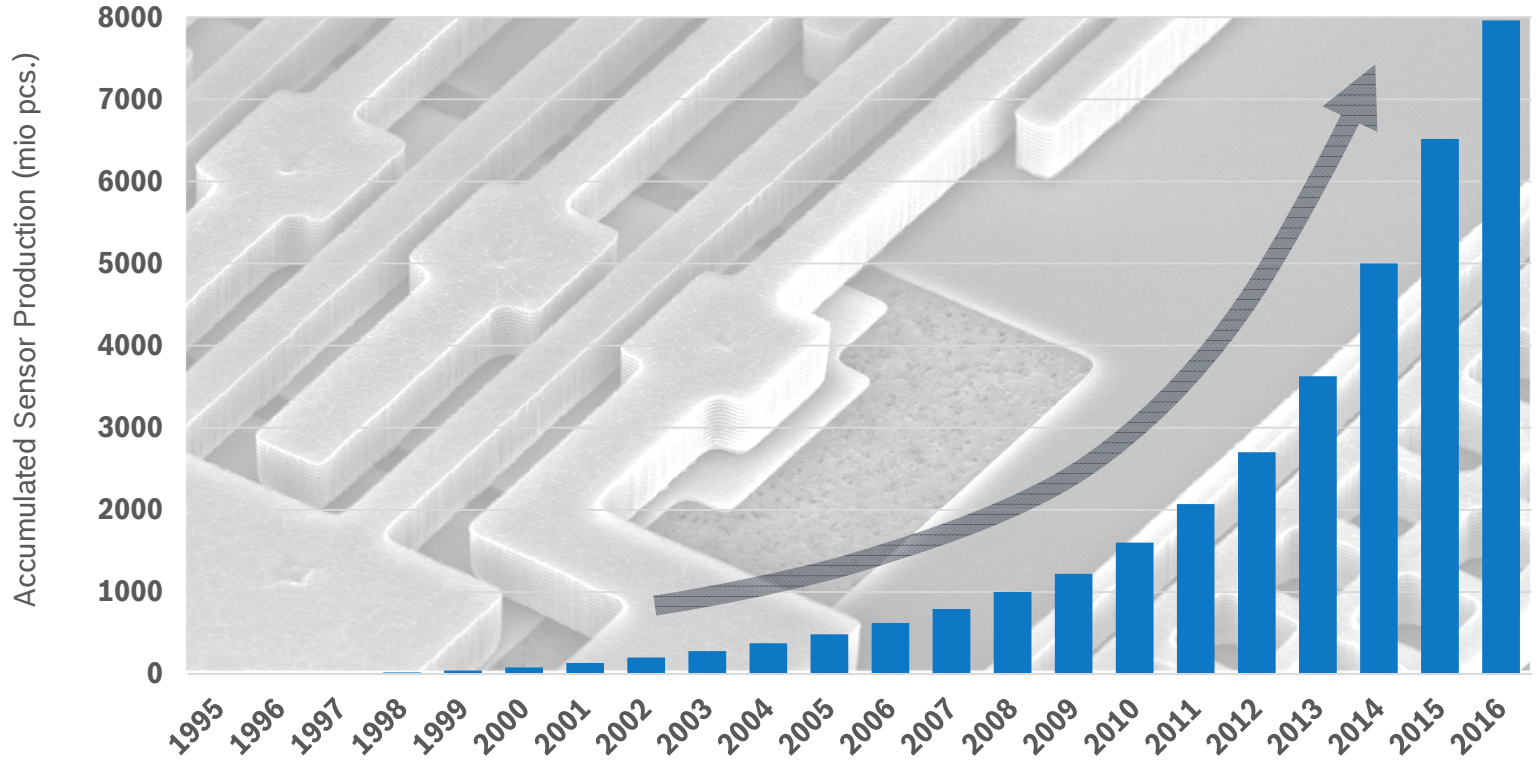
### Value Proposition

- Technology leadership for MEMS solutions:  Driving technology roadmaps with in-house technologies
- Global support & systems capabilities:  Support beyond component supply (in hardware & software)
- Supply capability & reliability:  Capacity, volumes of scale, proven processes,  industry's best reliability

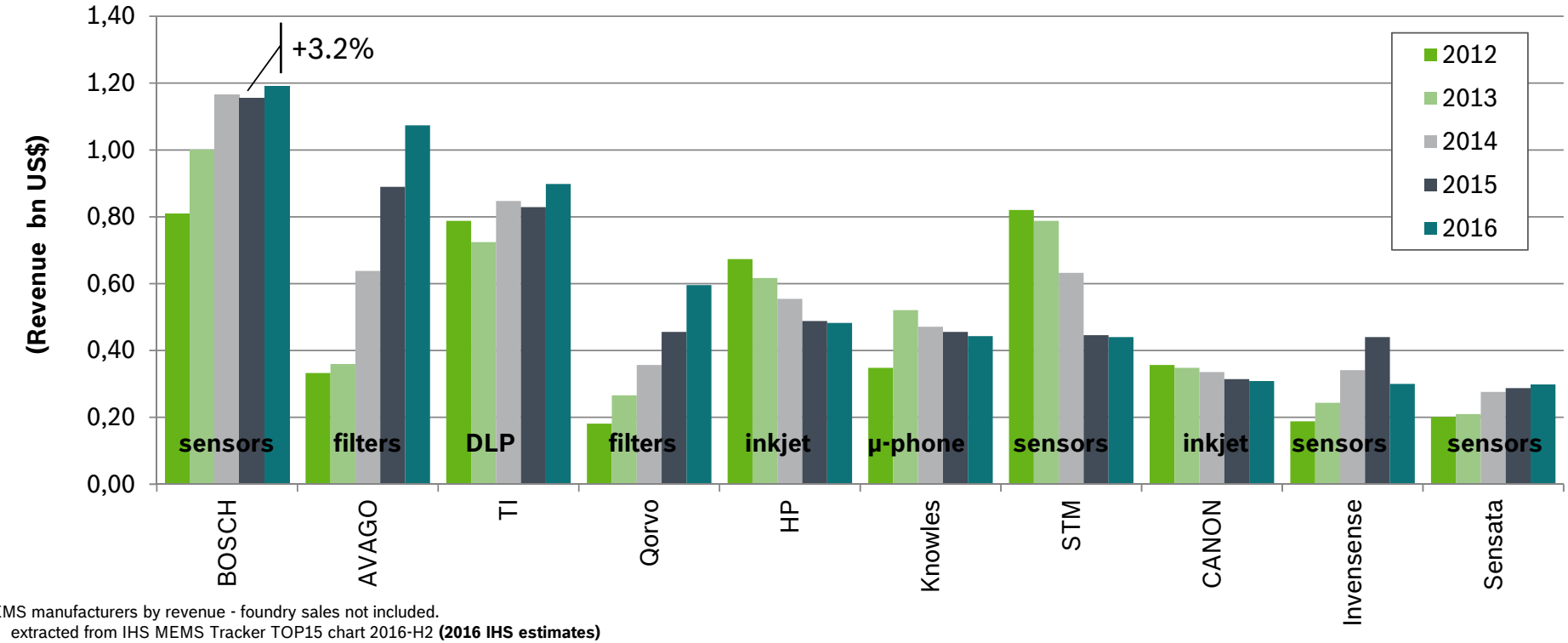
Bosch is the #1 MEMS sensor supplier worldwide

# MEMS @ Bosch

## Volume MEMS production at Bosch (accumulated)



# MEMS market overview
## TOP 10 MEMS suppliers (2016)




Top MEMS manufacturers by revenue - foundry sales not included.
Source: extracted from IHS MEMS Tracker TOP15 chart 2016-H2 **(2016 IHS estimates)**

**Bosch by far world's largest MEMS supplier**

# MEMS market overview
## MEMS sensors – a multitude of markets

**Automotive**

Safety Systems

Motor Management

**Consumer Electronics**

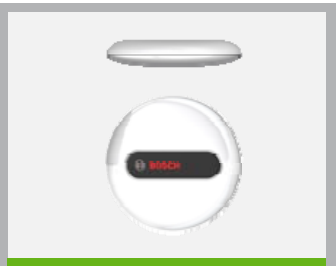
Mobile

Imaging

Health & Fitness

Home Appliances

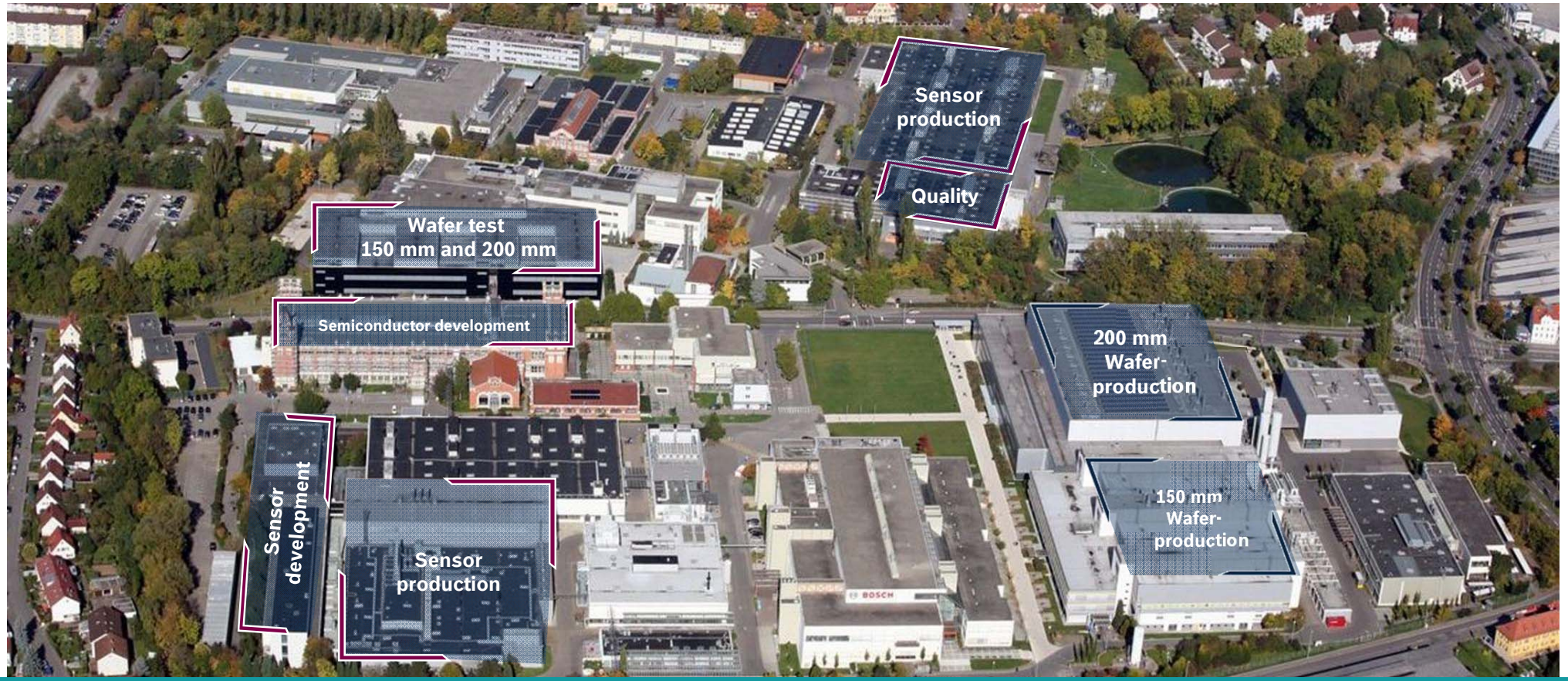
Industrial & Logistics



Smart Systems

**Internet of Things**

# MEMS @ Bosch




**Technology site in Reutlingen, Germany**

# MEMS @ Bosch
## Wafer fab in Reutlingen

| | |
|---|---|
| **Employees** | 2 758 |
| **Production area** | 34 300 sqm |
| **Minifactories** | Wafer fab, sensor frontend, sensor backend, test center |
| **Products** | IC, power S/C (chip and packaged), sensors (packaged, customer specific mold package) |


**150 mm module**

- 4 100 sqm
- 1 500 wafer starts/day
- Technologies:
  - BCD1, 2, 3, 3s, 4, 4s
  - CMOS, Bipolar, PSC bipolar, MOS
  - Pressure sensors
  - Inertial sensors
  - Process: ≥ 0.5 µm

**200 mm module**

- 4 600 sqm
- 1000 wafer starts/day
- Technologies:
  - BCD4, 4s, 6, 6sCu
  - Advanced CMOS, HVCMOS
  - Pressure sensors
  - Inertial sensors
  - Process ≥ 0.18 µm

# 02 AUTOMOTIVE MEMS

# TECHNOLOGY & APPLICATIONS

# Technology
## Requirements for automotive MEMS



- High functional requirements:
  - high accuracy, self test, advanced safety concepts
- High reliability / quality: 15 years, < 1 ppm
  - extreme environmental conditions (-40 .. +120°C)
- Additional 15 years of aftermarket supply
- Product life cycle up to 10 years, product development 3 years

**High volume, reliability and quality are main success factors**

# Automotive sensors
## More than 50 MEMS sensors in 1 car

### Engine Management *e.g. Diesel*

10 Sensors

1 Mass flow sensor
1 Pressure sensor [Barometric air pressure]
2 Pressure sensors [Manifold air pressure, oil]
1 High pressure sensor [Common Rail]
1 Pressure sensor [Tank pressure]
1 Pressure sensor [Start/stop function]
2 Acceleration sensors [Active engine mounting]
1 Pressure sensor [Diesel particulate filter]

### Safety

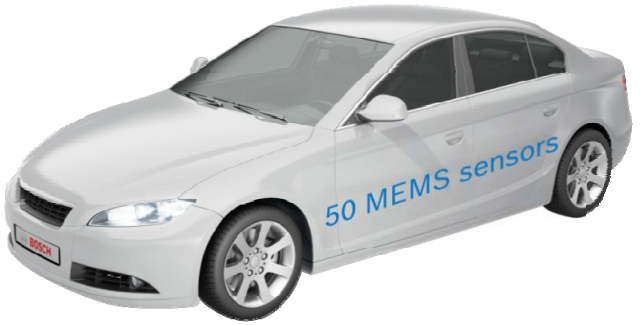
27 Sensors

2 High-g acceleration sensors [Airbag]
1 Angular rate sensor, 1 Low-g acceleration sensor [Roll-over sensing],
1 Acceleration sensor (Structure-borne sound sensor) [Airbag]
4 Acceleration sensors, 2 Pressure sensors [Peripheral airbag sensors]
2 Pressure sensors [Pedestrian safety]
1 Angular rate sensor, 1 Low-g acceleration sensor, 1 High pressure sensor [ESP (incl. ACC)]
1 Angular rate sensor [Active steering]
1 Acceleration sensor [eCall]
4 Pressure sensors, 4 acceleration sensors [TPMS]
1 Pressure sensor [Occupant detection]

### Comfort

17 Sensors

2 Pressure sensors [Automatic transmission]
5 Acceleration sensors [Active suspension]
1 Pressure sensor, 1 Humidity sensor,
2 Gas sensors [Air conditioning, air quality]
1 Angular rate sensor, 1 Acceleration sensor [Navigation]
3 Microphones [telephone]
1 Bolometer Array [Night vision]
1 Acceleration sensor [Car alarm]
(Seldom: 16 Pressure sensors (up to 8 pressure sensors per seat)



# Automotive sensors
## Product portfolio

### Acceleration sensors

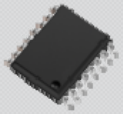
**Central/peripheral acceleration sensor**
for occupant protection

**Low-g acceleration sensors**
for VDC, RoSe and active suspension

**Low-g acceleration sensor (3-axis)**
for navigation and non-safety applications

### Angular rate sensors

**Rollover sensor**
for occupant protection

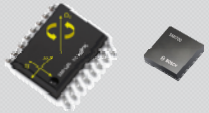


**Yaw rate sensor**
for VDC

**Angular rate sensor (3-axis)**
for navigation and non-safety applications

### Inertial sensors

**Combined inertial sensor (3-axis)**
(yaw rate and acceleration sensor)
for VDC and RoSe



**Combined inertial sensor (6-axis)**
(yaw rate and acceleration sensor)
for navigation and non-safety applications

### Pressure sensors

**Low pressure sensor**
for engine control

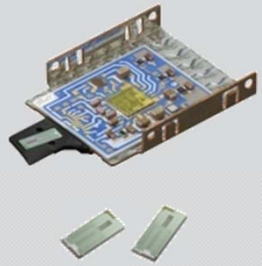
**Mid-pressure sensor**
for transmission control

**Pressure sensor**
for occupant protection

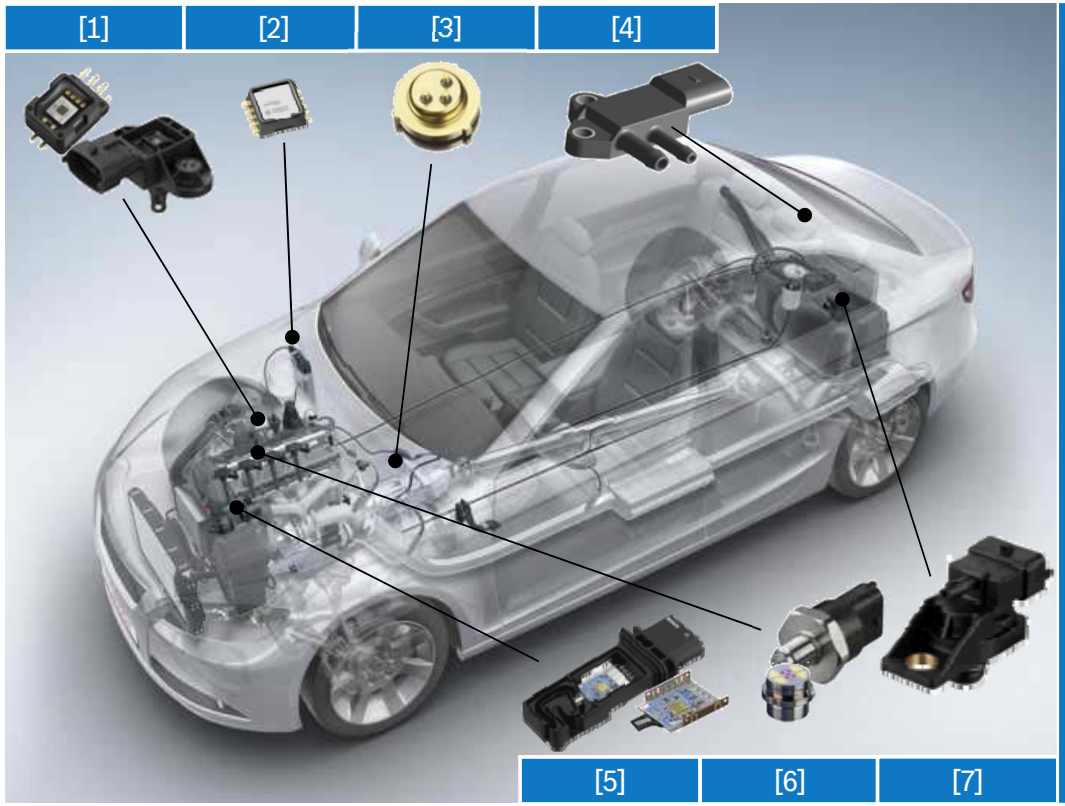
**High pressure sensor**
for engine and brake systems

### Mass flow sensors

**Mass flow sensor**
for engine management



# Automotive sensors
## More MEMS sensors for engine management



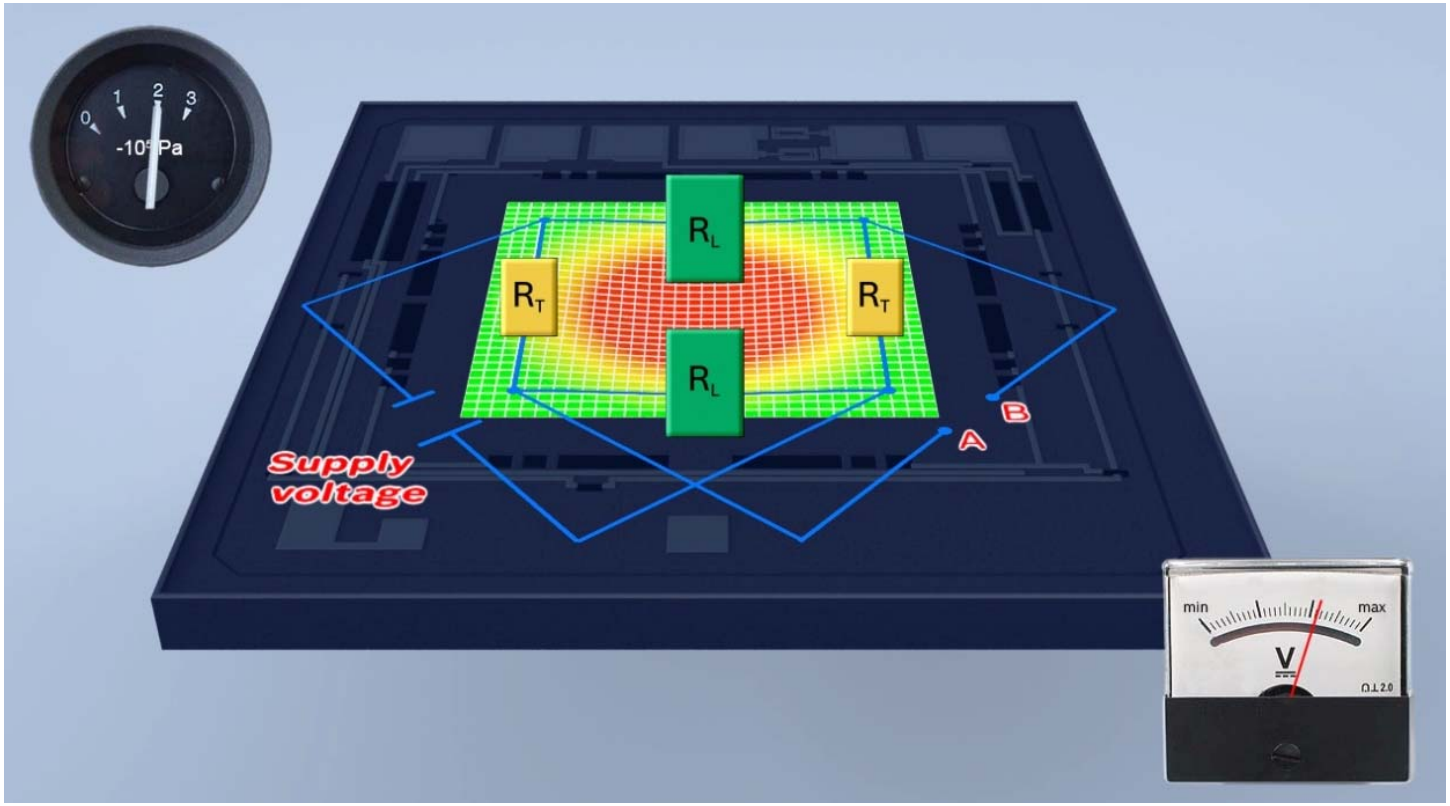

**MEMS Sensor products for engine management**

[1] Manifold Air Pressure MAP
[2] Barometric Air Pressure BAP

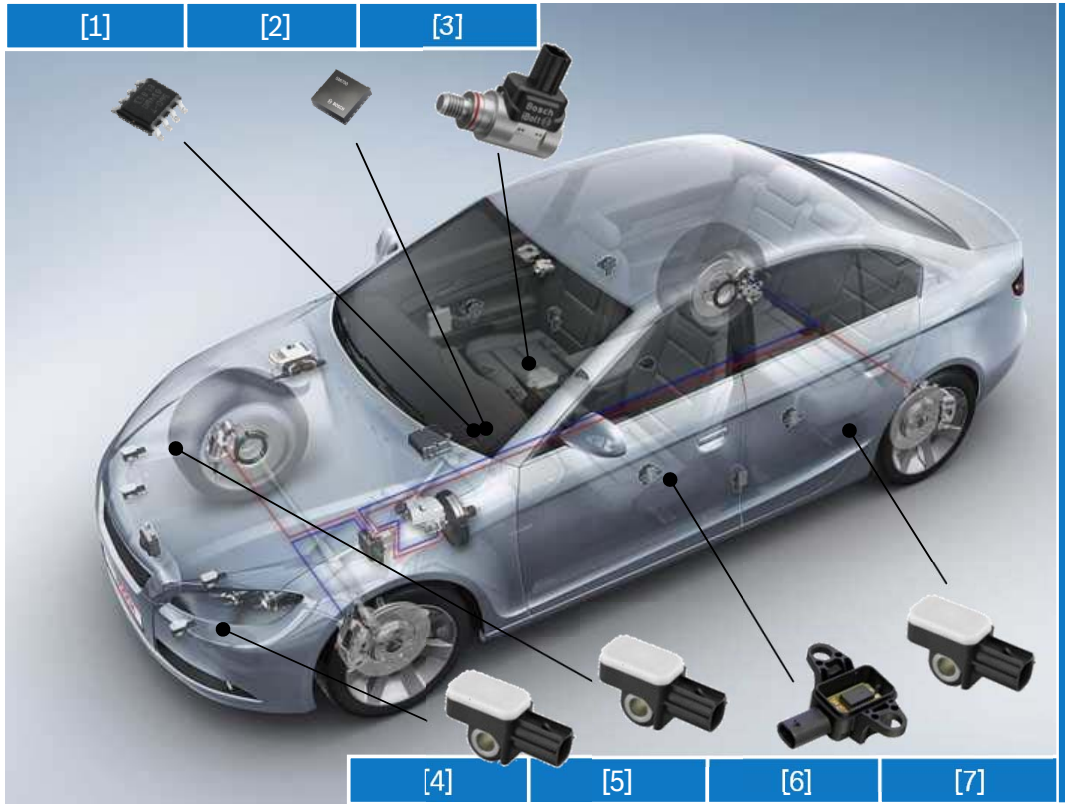
[3] Medium pressure sensor
[4] Diesel particulate filter
[5] Mass flow sensor
[6] High pressure sensor
[7] Tank pressure sensor

# Automotive sensors – Pressure sensors

## Barometric pressure sensors: working principle



# Header of section
## MEMS sensors for safety systems




- **MEMS sensors forsafety systems**

[1] Acceleration sensor (central)

[2] Rollover sensor (central)

[3] Occupant weight sensor iBolt

[4] Pedestrian Contact Sensor PCS

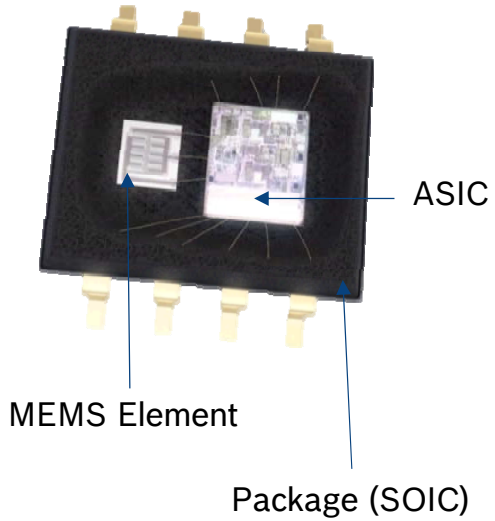
[5] Upfront Sensor UFS

[6] Peripheral Pressure Sensor PPS (side)

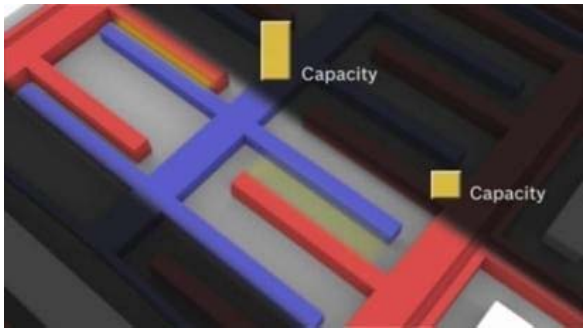
[7] Peripheral Acceleration Sensor PAS

# Automotive sensors – Acceleration sensors
## Working principle

### Construction of an acceleration sensor



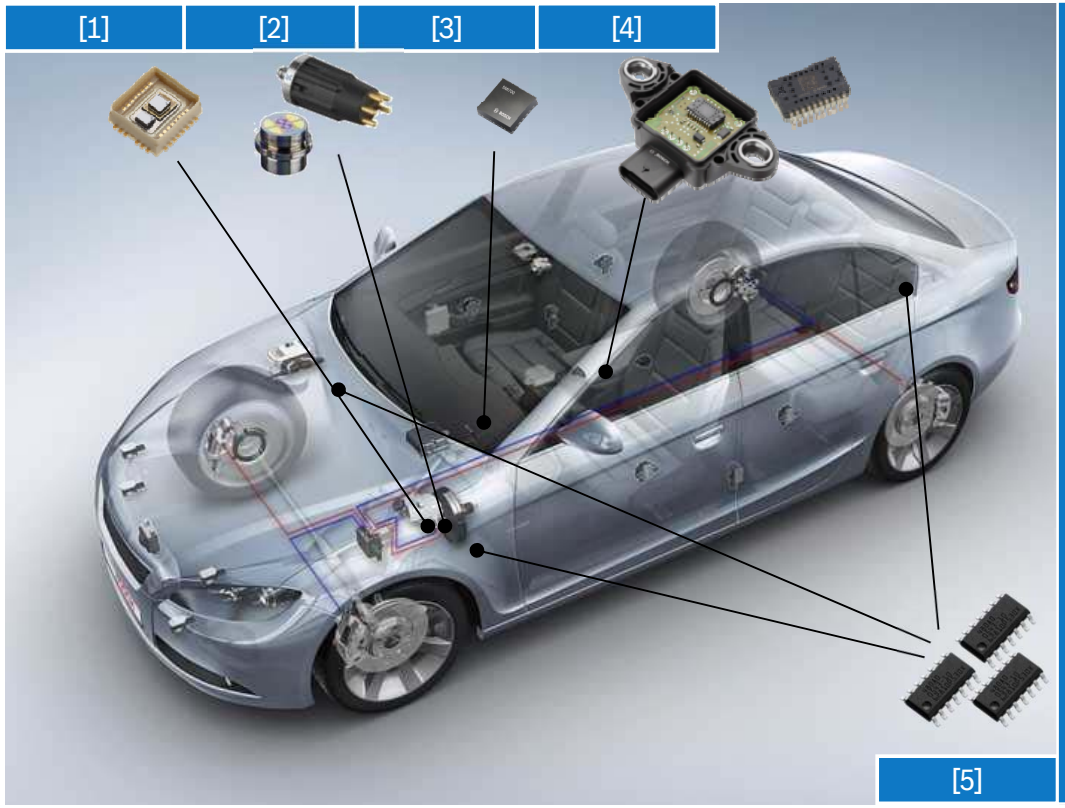

### Functionality of an acceleration sensor




- Seismic mass moves due to external acceleration
  (crash, car movements, vibration, ...)
- Capacitance between MEMS fingers and seismic mass changes with acceleration

# Automotive sensors

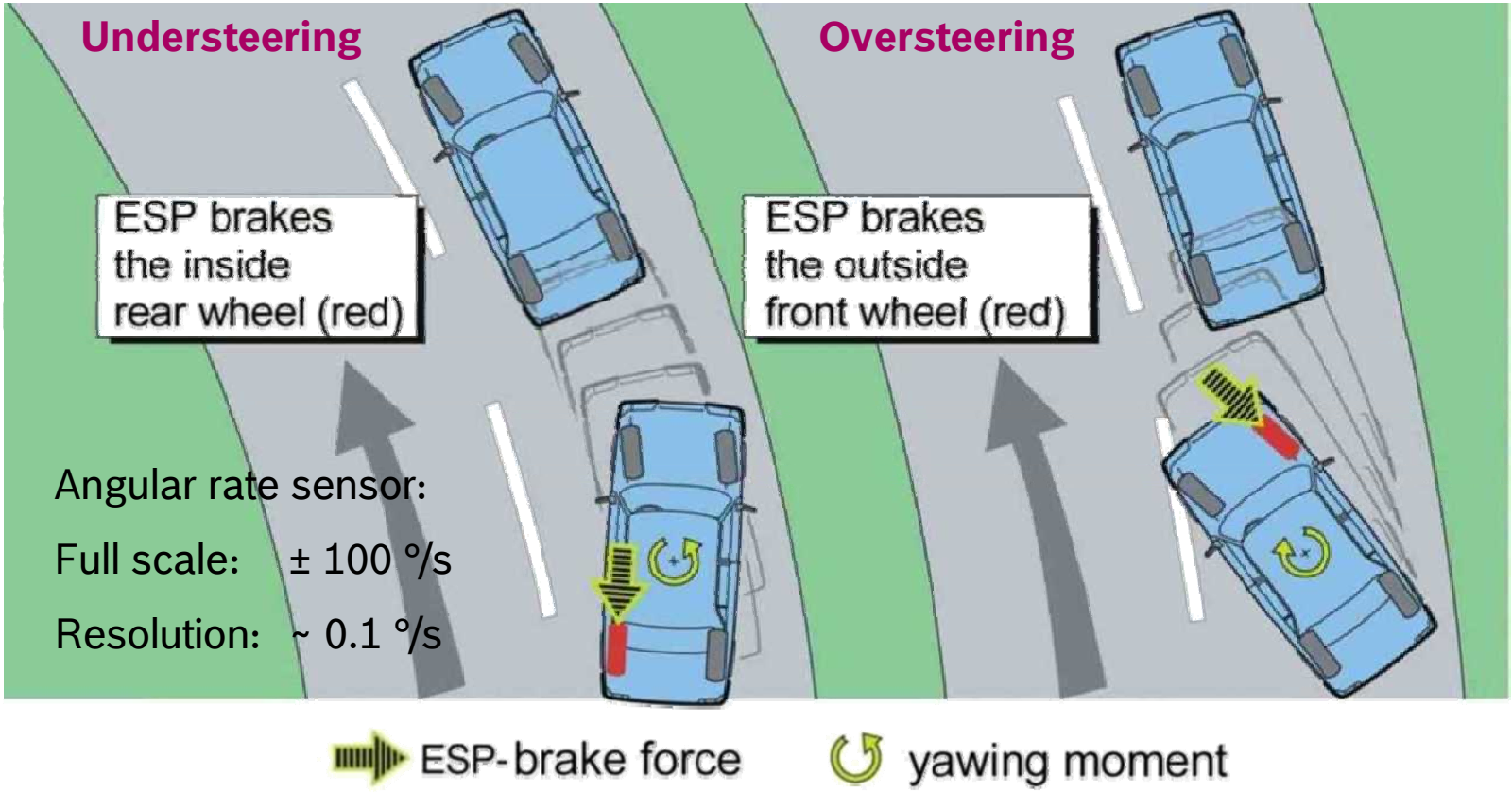
## MEMS sensors for vehicle dynamics control VDC




**MEMS sensors for vehicle dynamics control VDC**

[1] Inertial sensor
[2] High pressure sensor
[3] Inertial sensor
[4] Sensor cluster with yaw rate and acceleration sensor
[5] Low-g acceleration sensor for active suspension

# Automotive sensors – VDC applications
## ESP® system – working principle



# Automotive sensors – Angular rate sensors
## Measurement principle

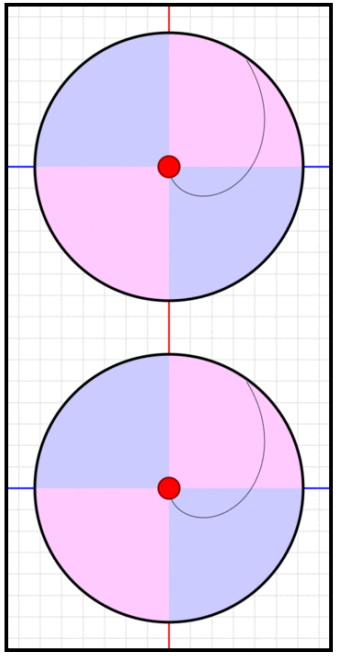
Natural example

**Coriolis effect (pseudo force)**

$$\vec{a}_C = 2\vec{v} \times \vec{\Omega}$$

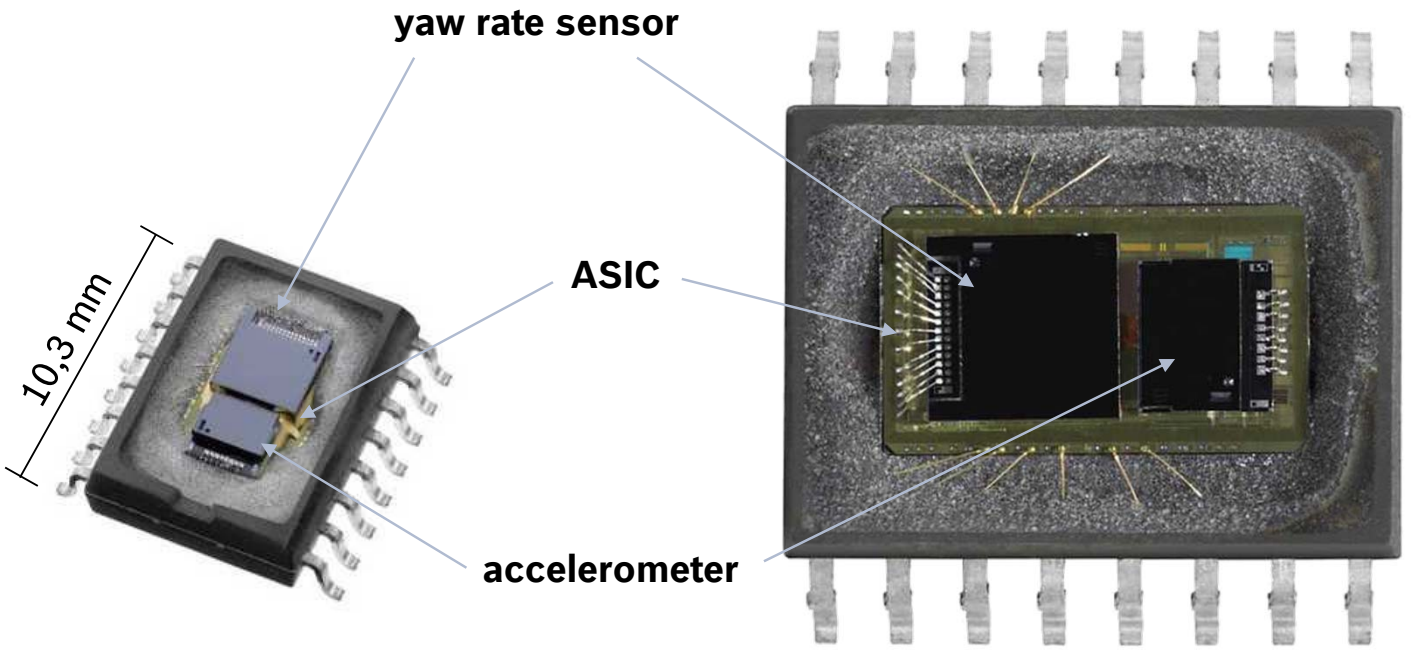
**Idle observer**
sees
(i) a rotating plate and
(ii) a straight downward moving sphere

**Observer on rotating plate**
sees a sphere moving on a curved trajectory:
Coriolis effect



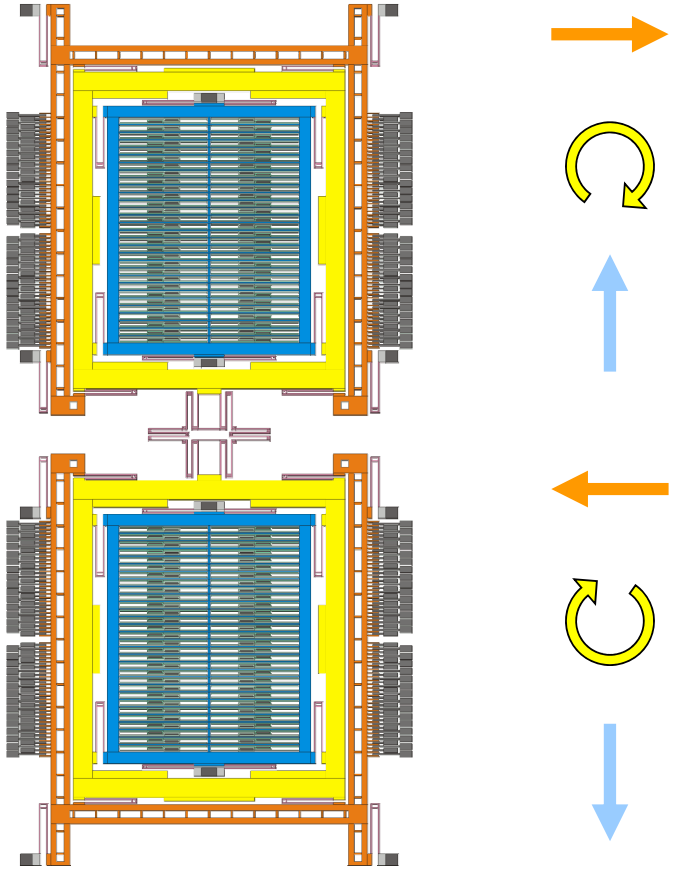
# Automotive sensors – Combined inertial sensors
## SMI540

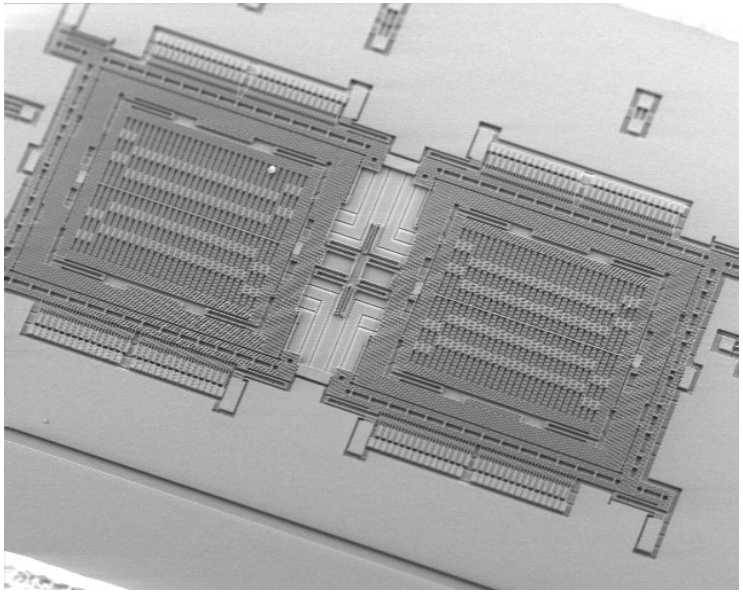
**World's first ESP combi-inertial sensor (yaw rate and acceleration) in mold-package.**



# Automotive sensors – Angular rate sensors

## Micromechanical sensing element



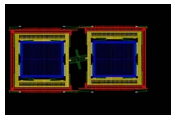


drive frame

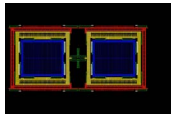
coriolis frame

detection frame

drive



detection



# Automotive sensors – Angular rate sensors
## Noise and resolution limit – comparison

**Device Sensitivity**

- mechanical sensitivity Sm ~ 5.2 pm / (°/s)
- electrical sensitivity Se ~ 2.3 aF / (°/s)

**Resolution Limit**

**~3 °/h (0.005 Hz)**

- amplitude change in micromechanical structure

**~4 fm**
(compares to ~0.00001 x Si-Si distance or
~radius of atomic nucleus)

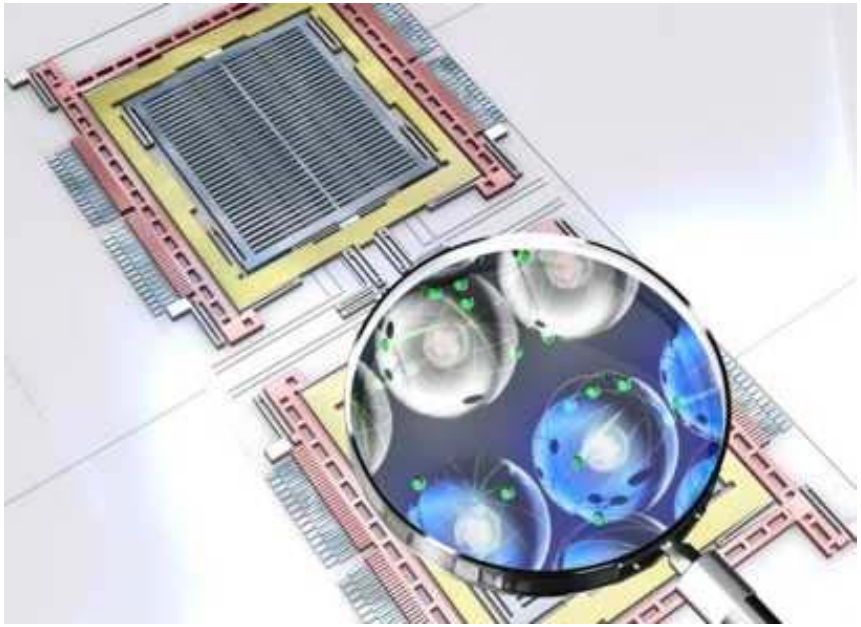
- capacitance change

**~2 zF**

(μ - n - p - f - a - z)

$10^{-6}$ $10^{-21}$

(compares to charge variation of
~0.06 electrons (at 5V))



# 03 CE MEMS

# DRIVING TECHNOLOGY INNOVATION

# CE MEMS sensors in mobile devices

**Inertial Measurement Unit**
Integrates accelerometer and gyroscope

**Accelerometer**
Detects acceleration and orientation

**eCompass**
Combines accelerometer and geomagnetic sensor

**Gyroscope**
Measures yaw rates

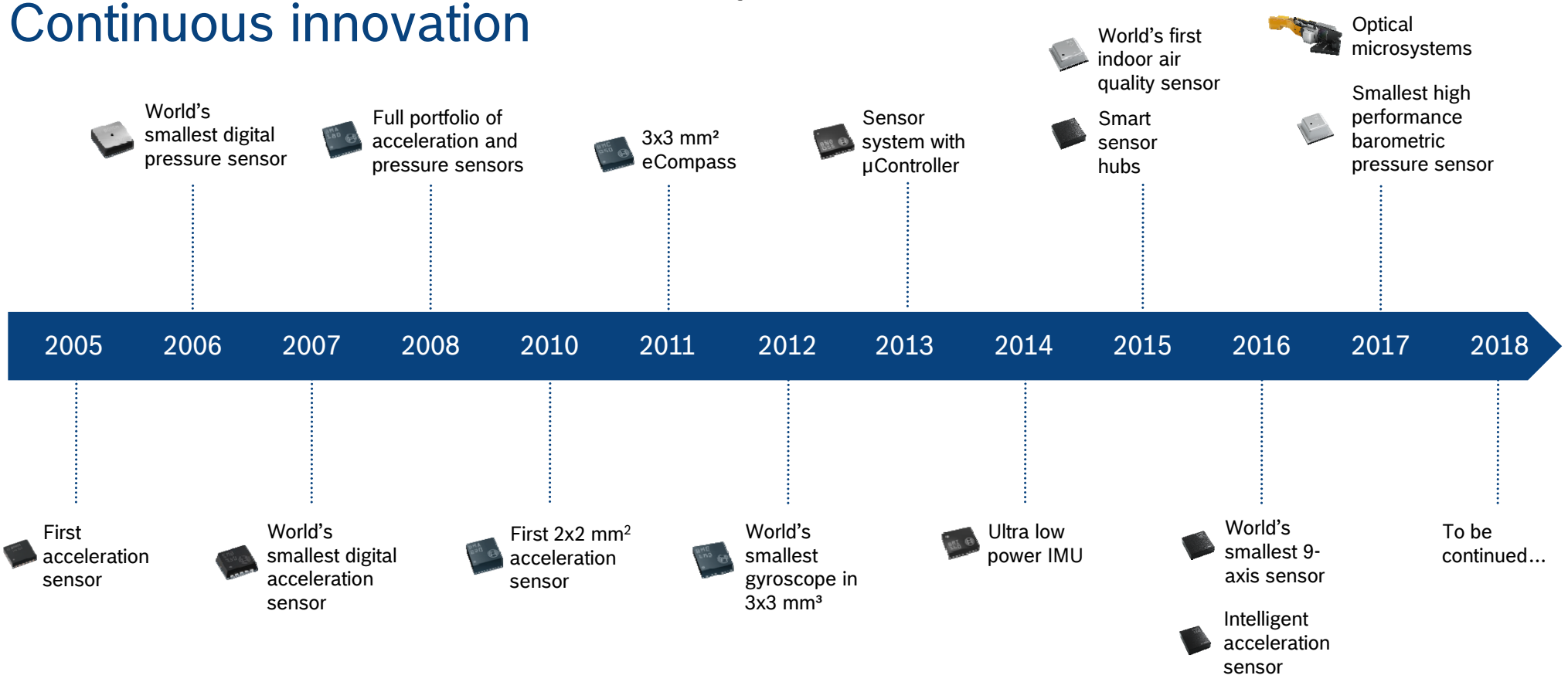
**Software**
Intelligently fuses raw data from multiple sensors

**Microphone**
Highly integrated MEMS-based microphone solution

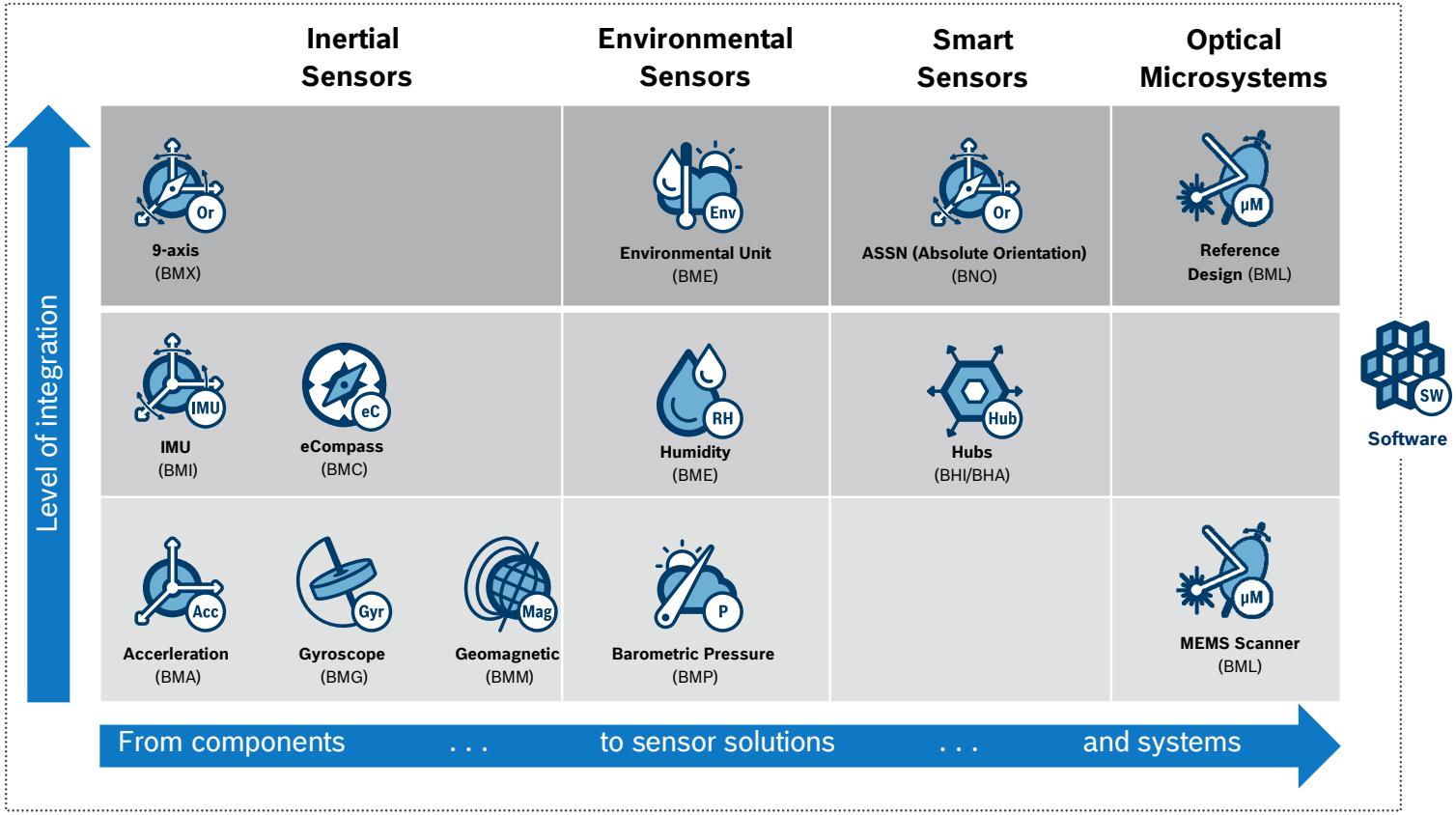
**Environmental Unit**
Measures pressure, humidity and temperature

**Absolute Orientation**
Integrates accelerometer, gyroscope and magnetometer

# Consumer MEMS success story
## Continuous innovation



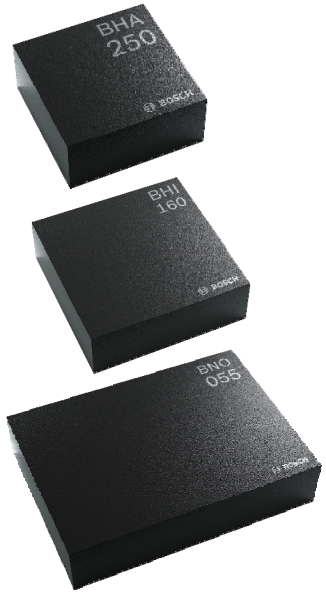
# Bosch Sensortec is a full-portfolio provider



# Today’s state-of-the-art portfolio


**Inertial Sensors**

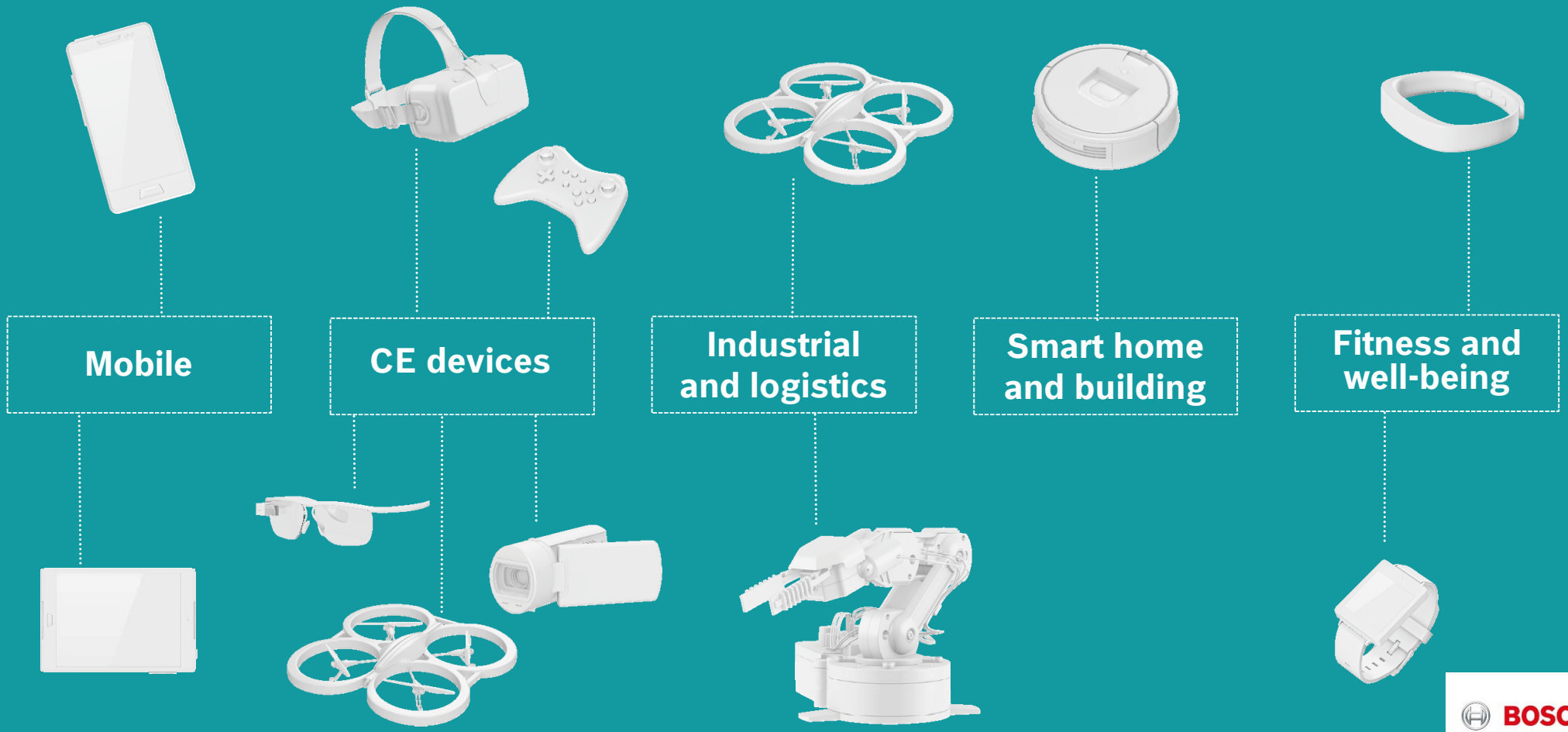

**Environmental Sensors**




**Smart Sensors**

**Optical Microsystems**

# MEMS sensors – a multitude of devices

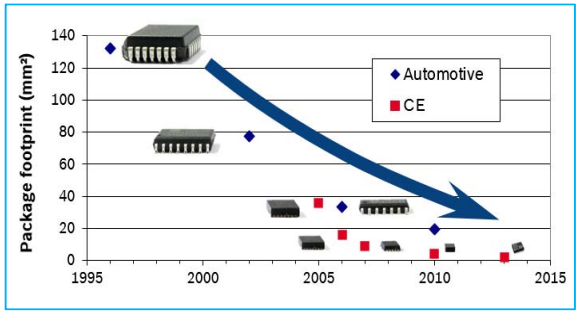


# Technical challenges and solutions

# Enabler for IoT – MEMS technology innovation
## Technology is ready for IoT

**Size / power**

Continuing shrinking of sensor footprint / size and power consumption (e.g. accelerometer)

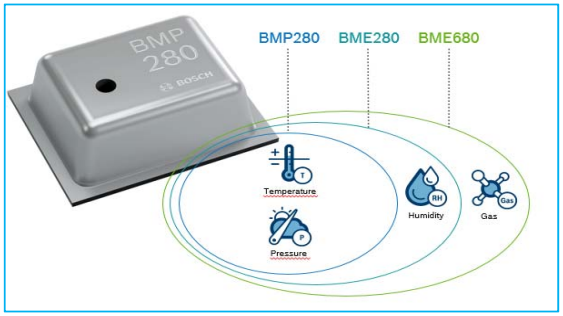



**Integration / µC + software**

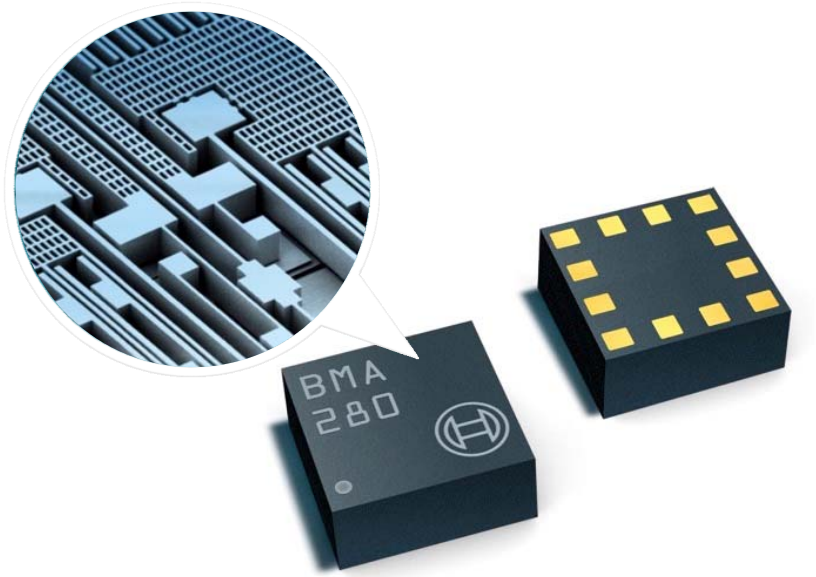
Integration of multi-axis sensors + µC + SW in combo package (e.g. motion / orientation)


**New measurants**

Rise / emergence of novel sensor clusters (e.g. environmental cluster → T, p, H, ...)



# Old challenge
## Shrinking the size / power consumption of components

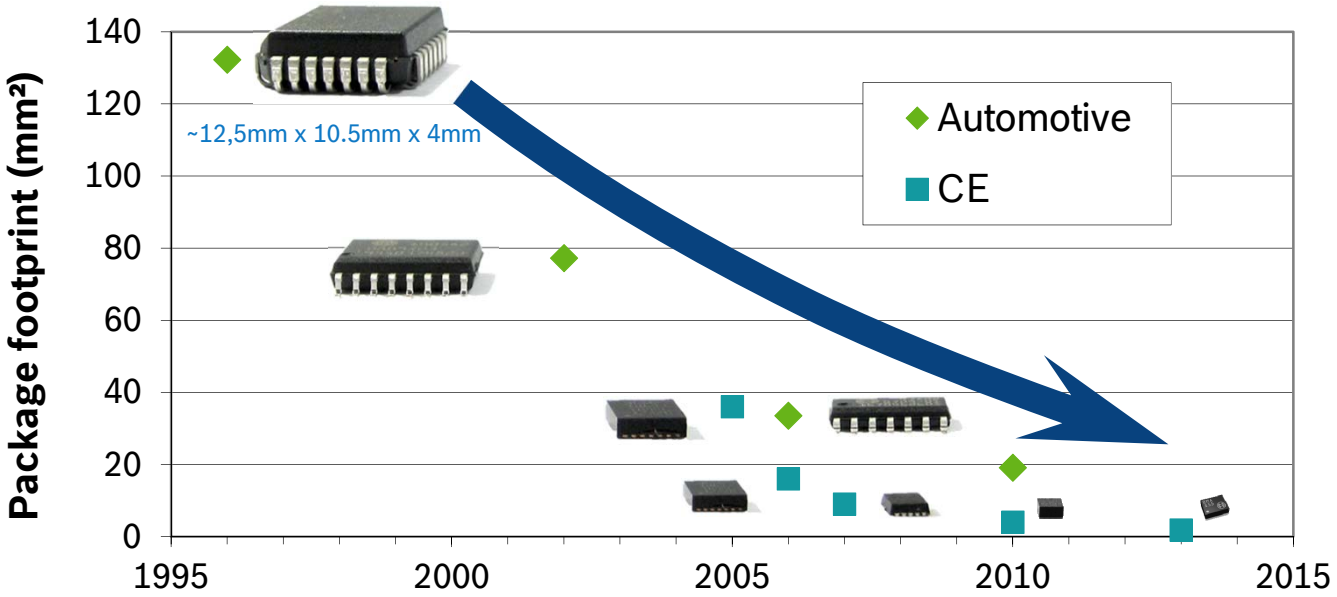


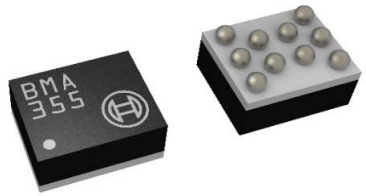

### Size / power

Continue shrinking of sensor footprint / size and power consumption (e.g. accelerometer)

**Size alone is not an enabler anymore… but functional density increases**

# Old challenge
## Continuous shrinking of sensor footprint / size of accelerometers



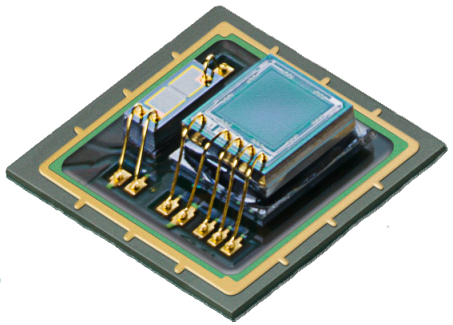




3-axis accel: only
1.2mm x 1.5mm x 0.8mm

| PLCC28 (Automotive) 1996 | SOIC16w (Automotive) 2002 | SOIC14n (Automotive) 2006 | SOIC8 (Automotive) 2010 | 4x4 QFN (CE) 2006 | 3x3 QFN (CE) 2007 | 2x2 LGA (CE) 2010 | 1.2x1.5 LGA (CE) 2013 |
|---|---|---|---|---|---|---|---|

....

# New challenge
## Environmental sensing solutions



### New drivers for new applications

- Pressure
- Temperature
- Humidity
- VOC (gas)

### Size

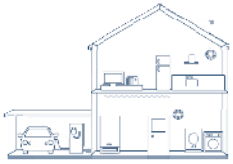
- Sensor footprint <= 3 x 3 mm²

### Power

- Low power << 1 mA (avg)

### Accuracy

- High accuracy and fast setting time

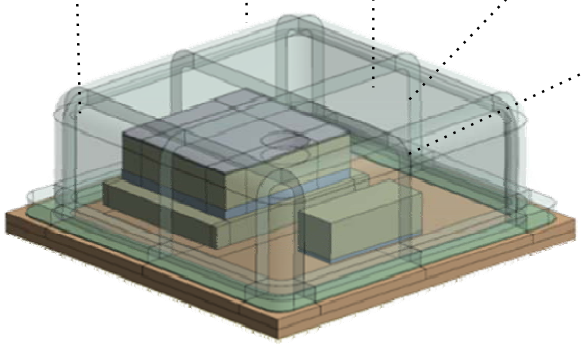


# New challenge
## BME680 environmental sensor

**Dimension: 3.0 x 3.0 x 0.95 mm³**
package with LGA metal lid

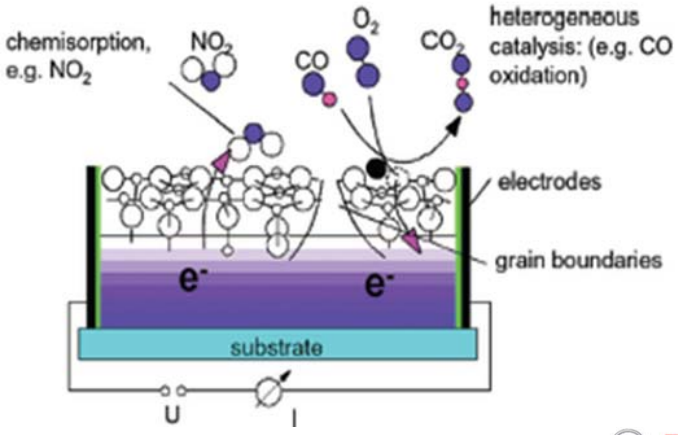
**Minimized current consumption between 0.2mW to 2mW with maximum 20mW peak**
depending on working mode (low, medium or high power)

**Supply voltage: 1.8V**
**max. peak current: 20 mA**



**Integrated MEMS gas Technology**

- Integration of gas sensor chip into BME module enables better gas sensor performance by compensation of P/T/H
- High sensitivity for VOC (10 ppb-1000 ppm)
- High stability of > 5 years with proven automotive-known reliability tests

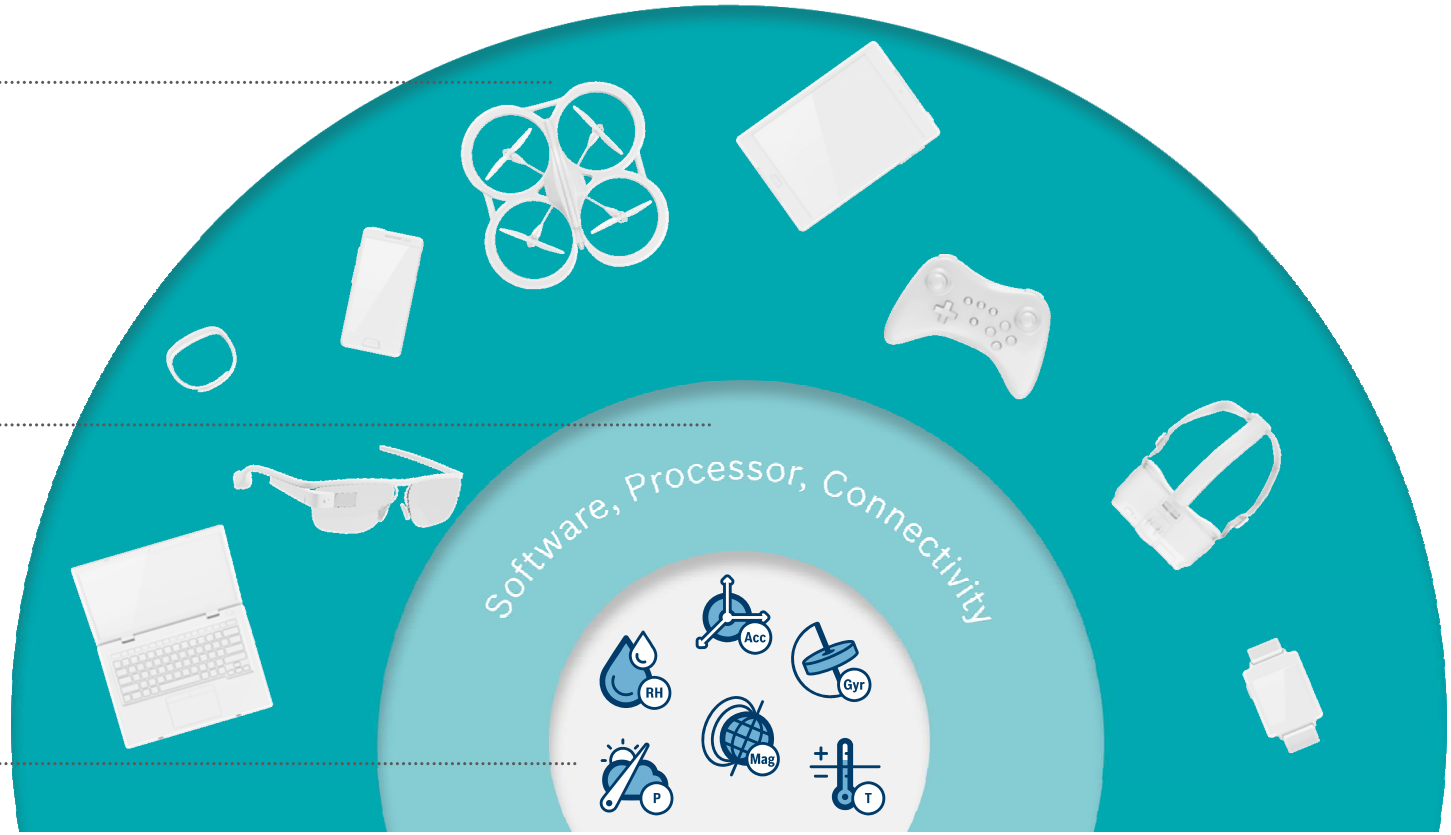


# New challenge
## Total sensor solutions

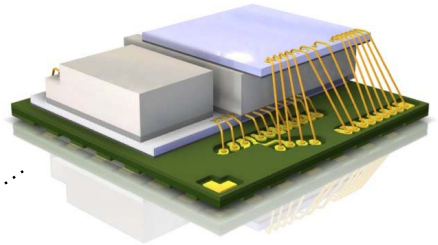
Application specific solutions

Intelligent processing

Multitude of technologies



# New challenge
## Data fusion at lowest power

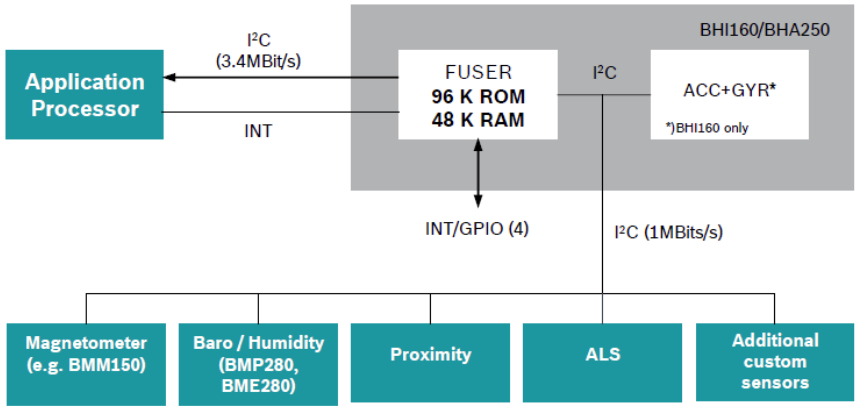


### Performance output ready to use

- Quaternion
- Linear acceleration
- Rotation
- Gravity
- Robust heading
- eCompass fast calibration
- Step counter
- Activity monitoring & interrupt
- Significant motion detection


### Smart Sensor Hub BHI160

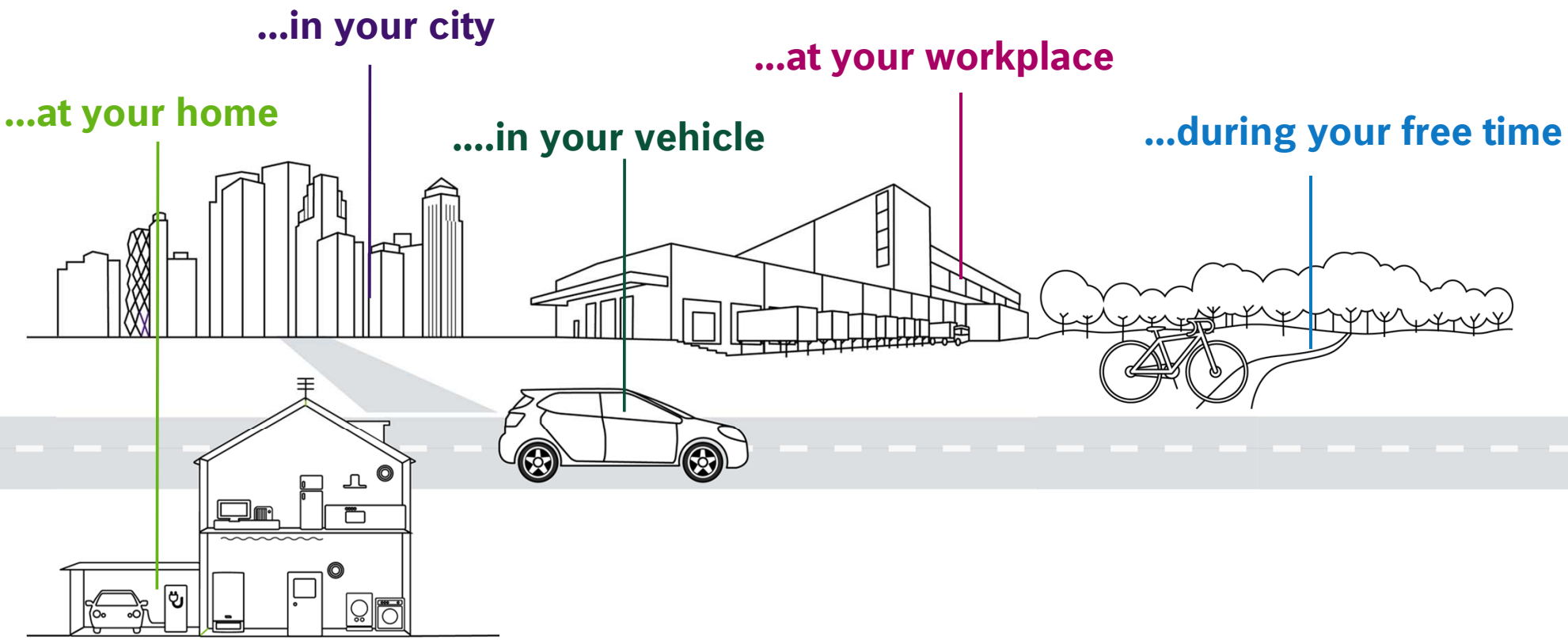
- 3 x 3 x 0.95 mm³
- 32-bit floating-point microcontroller (optimized for sensor fusion)
- 96 kByte ROM, 48 kByte RAM
- 30 µA step detector / 1.59 mA full 9DoF Fusion @100Hz



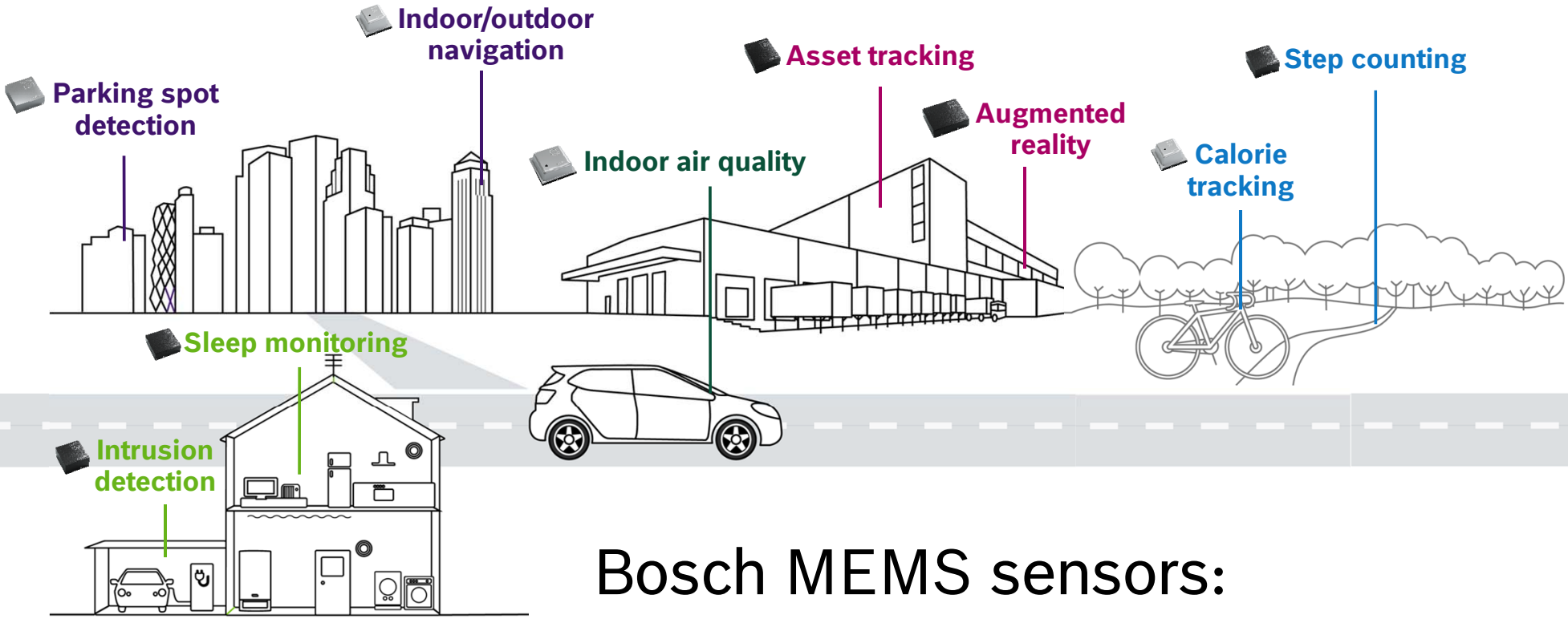
# 04 MEMS FOR IOT

# CHALLENGES & SOLUTIONS

# Bosch MEMS sensors – The hidden champions of your everyday life



# Bosch MEMS sensors – The hidden champions of your everyday life

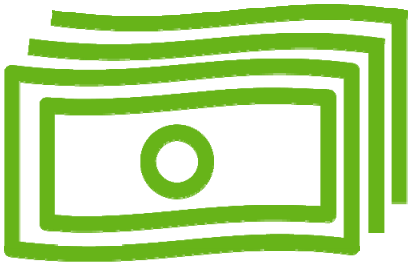



## Bosch MEMS sensors: Enablers for the Internet of Things

# Role of smart sensors in the IoT
## Everything will be connected

Today, about **6bn*** devices are connected worldwide.

By 2020, about **21bn*** devices will be connected.



By 2020, the global market for IoT solutions is expected to be worth some **250bn** USD.

Source: *Gartner

IoT is about making life simpler and more exciting.

**Everything should be “Simply. Connected“ for the user.**


But sensing everything in **multiple and complex environments** bears a lot of **challenges**…

# Role of smart sensors in the IoT
## Challenges and barriers

**IoT is...**

**... technologically demanding**

**CE sensor technology**

- Many technologies available…
- …but not always adapted for IoT
- Power (always-on applications), size, scalability, cost

# Role of smart sensors in the IoT
## Challenges and barriers

**IoT is...**

**...fragmented**

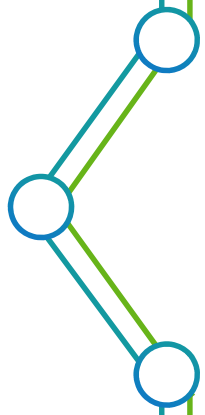
**System/application customization**

- Different applications: home, vehicle, city, industry, entertainment
- Deep application know-how needed
- Small volume customers
- Lack of synergies & standardization

# Role of smart sensors in the IoT
## Challenges and barriers

### Cooperation and collaboration

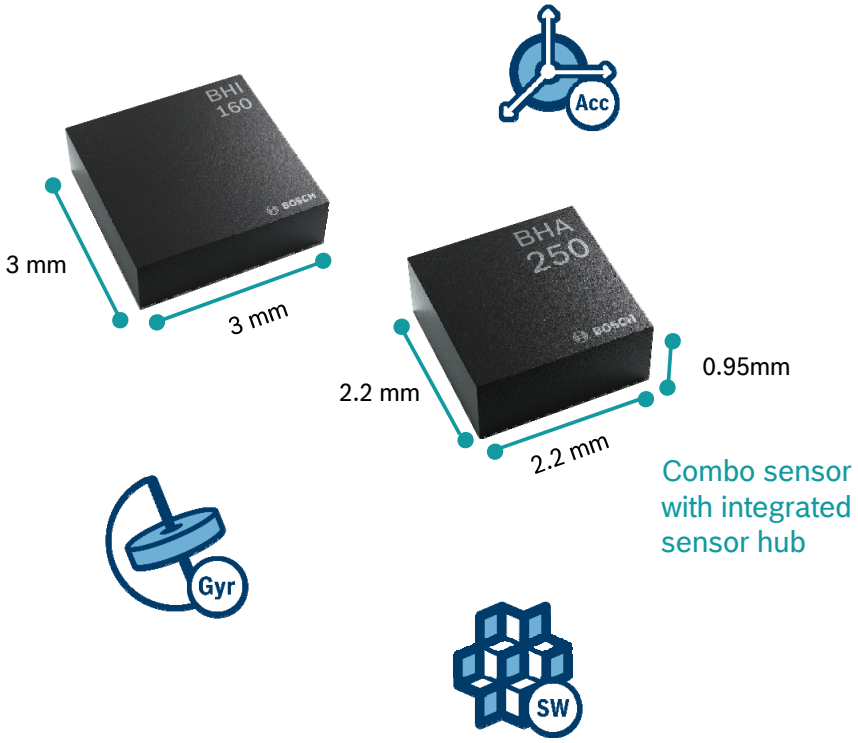
- Value is in end-to-end solution
- Large and diverse eco-system
- Business models not yet established
- Fast time to market (fast prototyping)



### IoT is...

### ... complex

# Role of smart sensors in the IoT
## Smart sensor hubs




Combo sensor with integrated sensor hub

**Integrated sensor hubs BHI160 and BHA250**

SmartHub solutions combine Bosch Sensortec's…

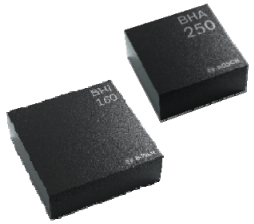
- lowest power sensors (IMU < 1mA)
- best-in-class sensor data fusion software
- optimized microcontroller, "FUSER Core"
- … to provide the lowest power solution without compromising features or performance.

# Role of smart sensors in the IoT

## Driving innovation and cooperation: Smart sensor hubs

**Innovation:** Development of smart sensor solutions

- **Overcoming the challenge of TECHNOLOGY**
  - Leverage CORE MEMS- and system know-how
  - Size, power, performance, embedded intelligence
- **Overcoming the challenge of FRAGMENTATION**
  - Platform solution with hardware and software
  - APPLICATION know-how in the Bosch Group
  - Application-specific software, e.g. AR/VR/PDR
- **Overcoming the challenge of COMPLEXITY**
  - From components to systems and solutions
  - Simple design and TURN-KEY solution
  - COOPERATION with third parties, reference designs

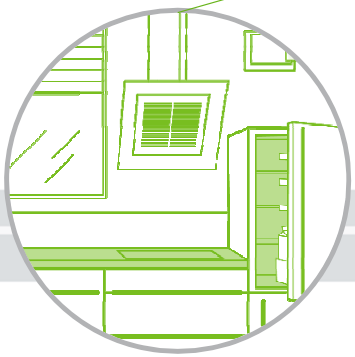



### Role of smart sensors

Smart sensors are sensing our world in multiple and complex environments, allow things to be “Simply.Connected” and act as the enablers of the IoT.

BOSCH

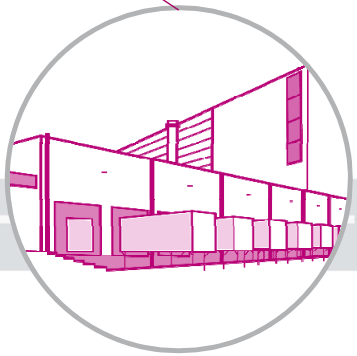
Invented for life



...at your home

....in your vehicle

...in your city



...at your workplace

...during your free time


# SMART SENSOR technology is the foundation of the IoT




BOSCH

# Summary

- MEMS sensors are well established in **automotive applications** and **mobile devices**
- **Additional requirements** for the IoT:
  - Size
  - Power
  - New measurands: e.g. Environmental cluster
  - Connectivity
  - Intelligence
- IoT - **“Next Big Wave”** for MEMS sensors.
- We believe that **intelligent & distributed** sensor and actuator solutions will be an important building block for all IoT implementations.
- Bosch is leading user and leading supplier (Dual Strategy) of MEMS sensors for IoT systems.
- We provide our unique **cross industrial** and **vertical integration** capabilities to enable our customers for **IOT applications and services.**


THANK YOU!
BOSCH