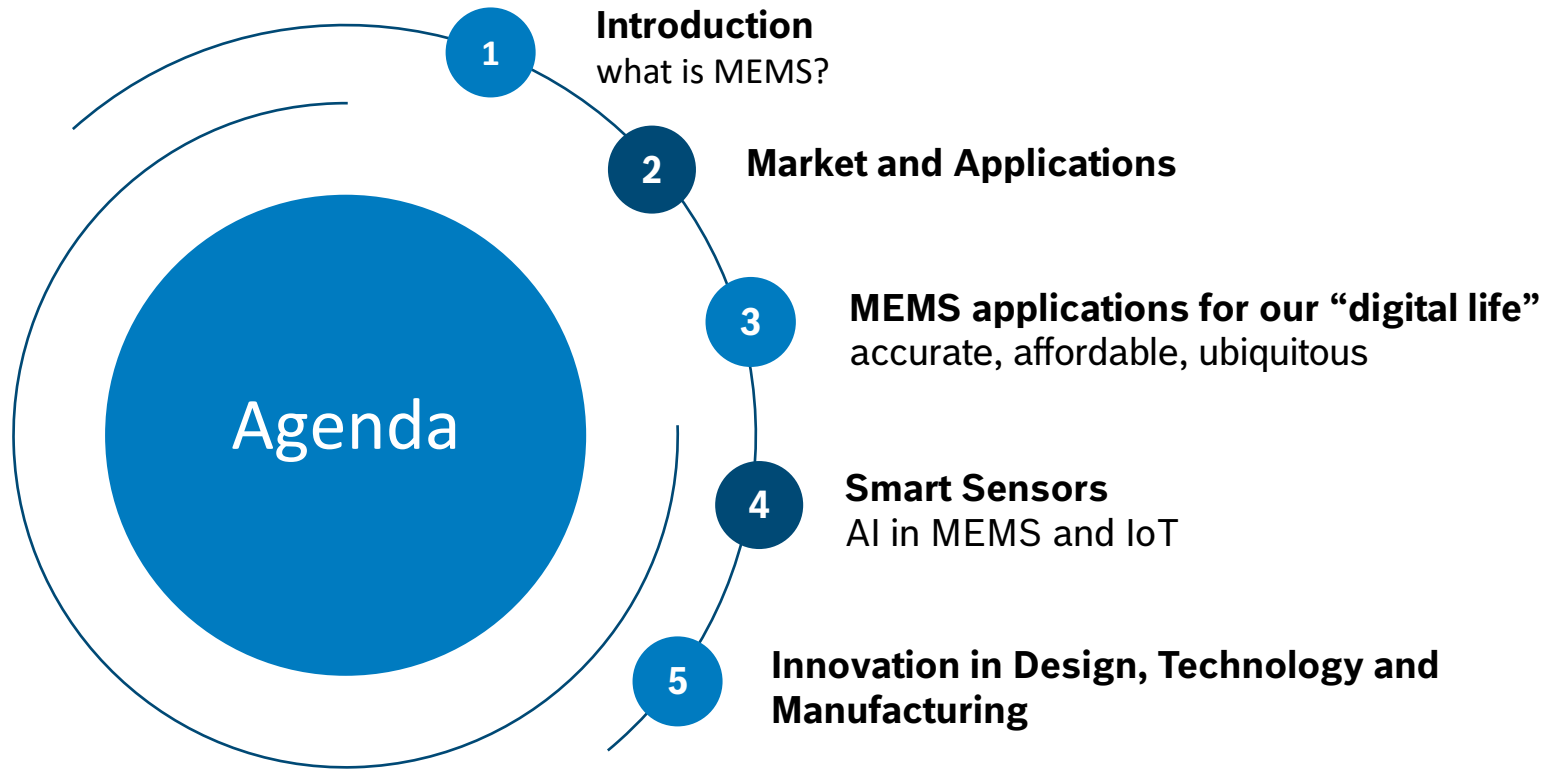# Innovation in MEMS for the IoT and our digital lifestyle
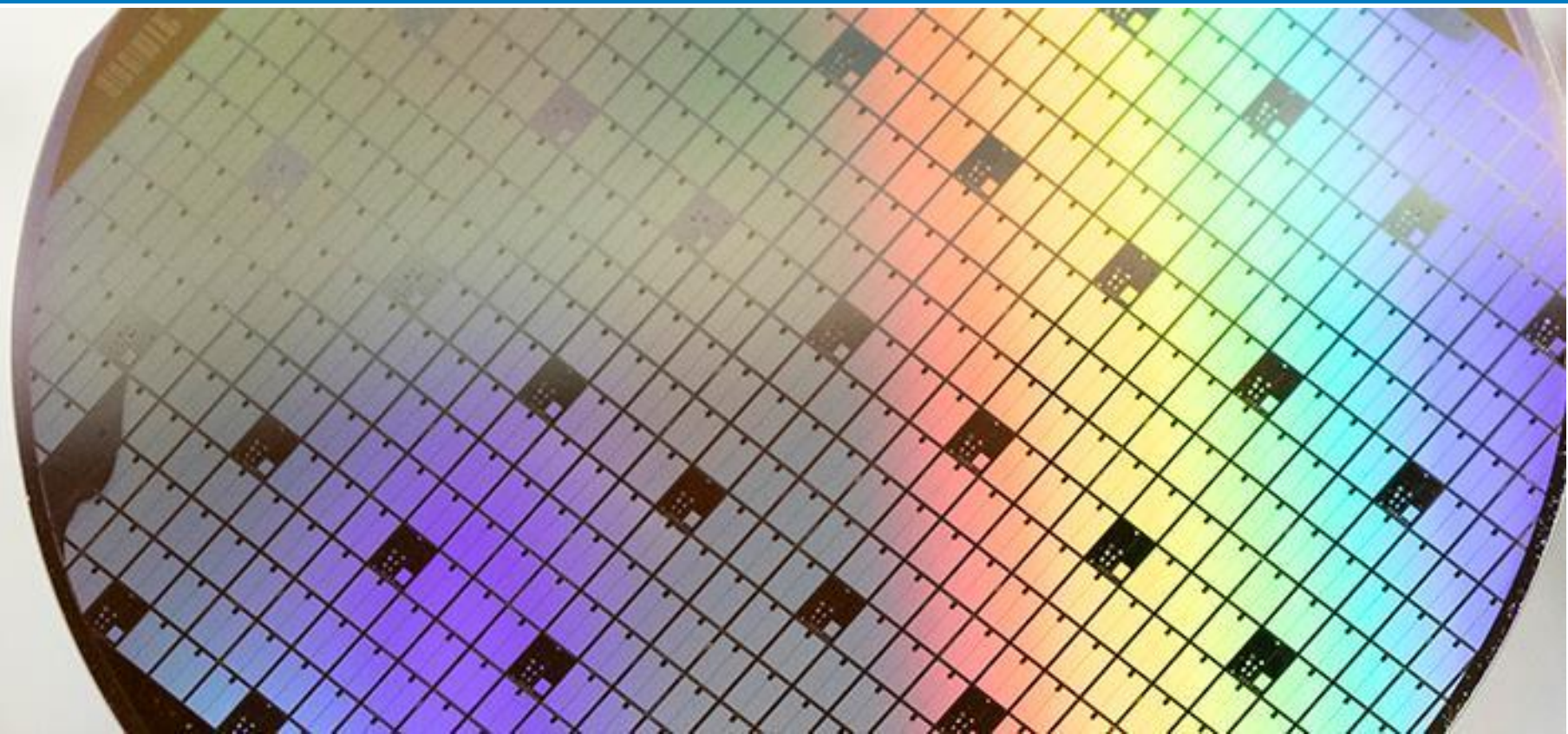
Dr. Matthias Illing,
Program coordinator cooperative R&D

Robert Bosch GmbH

Overview

Agenda

1. **Introduction**
what is MEMS?

2. **Market and Applications**

3. **MEMS applications for our "digital life"**
accurate, affordable, ubiquitous

4. **Smart Sensors**
AI in MEMS and IoT

5. **Innovation in Design, Technology and Manufacturing**

01

Introduction

Bosch semiconductors
Frontend sites

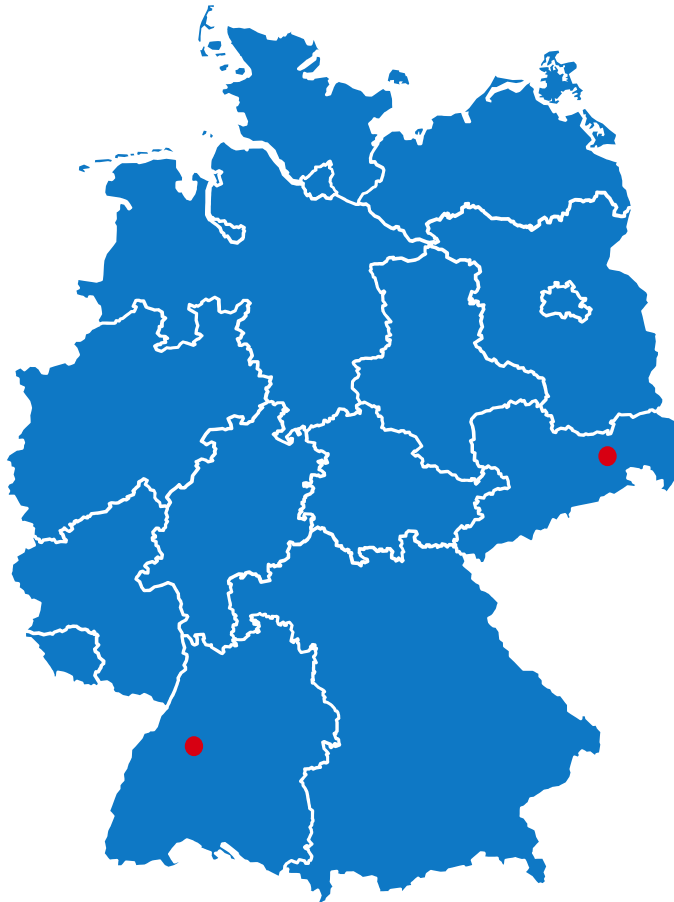
REUTLINGEN (1970, 1995, 2010)

Wafer size 150mm, **200 mm**
Floor space 12 000 m²
Nodes 1 µm ... 180 nm
Technologies: Mixed signal, Power
MOS, SiC, **MEMS**

DRESDEN (since 2020)

Wafer size **300 mm**
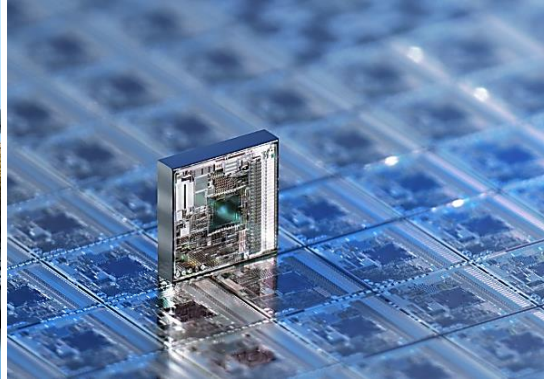Floor space 10 000 m²
Node capability 180 ... 65 nm
Start technology: **Mixed signal,
Power MOS**

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Bosch semiconductors
## A MEMS pioneer

- Start of MEMS production in 1995

- More than 15 billion MEMS sensors produced

- More than 1000 MEMS patents

- 100% in-house – from MEMS design to MEMS manufacturing

Bosch - Decades of expertise in MEMS development and MEMS mass production

Automotive Electronics | MEMS Team | 2023-02-01

BOSCH

Innovation in MEMS for IoT and digital life
Semiconductors come in many ‚colors' and functions ...
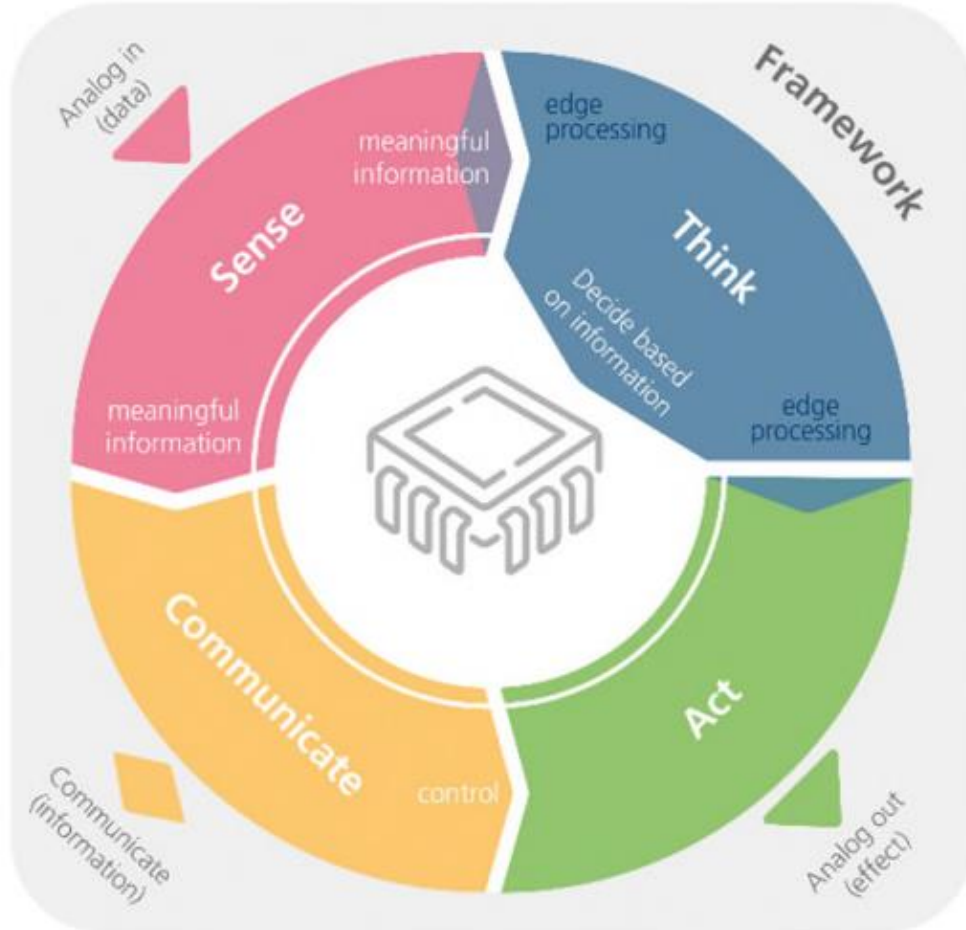
... and the digital life needs all of them

Today's focus: **Sense.**
And a bit of **Think** and **Act...**

Automotive Electronics

BOSCH

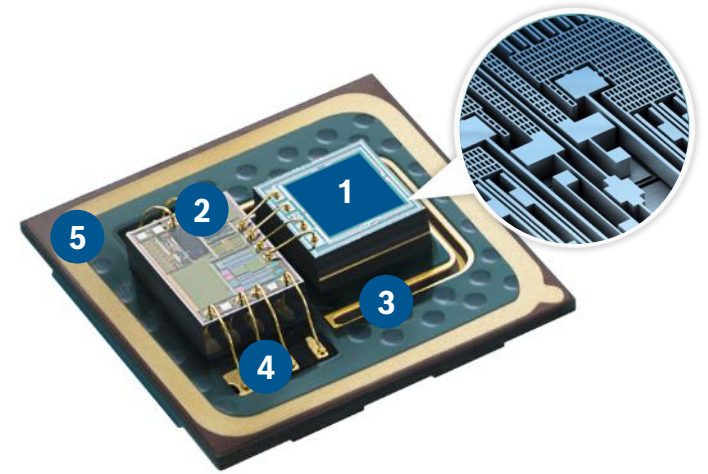# Innovation in MEMS for IoT and digital life
What are MEMS and ASICs?

Micro-Electro-Mechanical Systems

- MEMS is a chip-based technology where sensors are composed of miniaturized mechanical and electro-mechanical elements. Typical individual structures have a size of a few μm.

Application-Specific Integrated Circuit

- ASICs are custom integrated circuits designed for individual MEMS sensors and consist of, for example, amplifiers, ADCs and communication interfaces.

1 MEMS

2 ASIC

3 Decoupling unit

4 Bonding wires

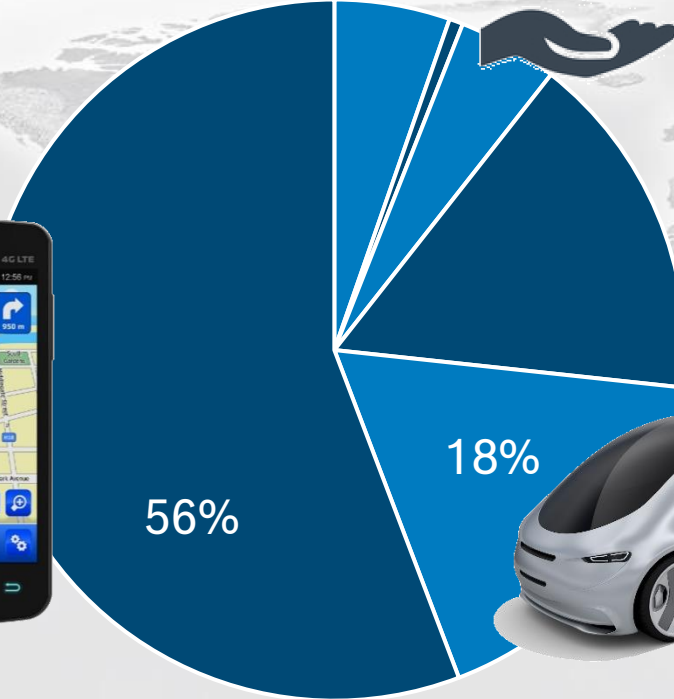5 Printed Circuit Board (PCB)

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02 Market and Application fields

Innovation in MEMS for IoT and digital life
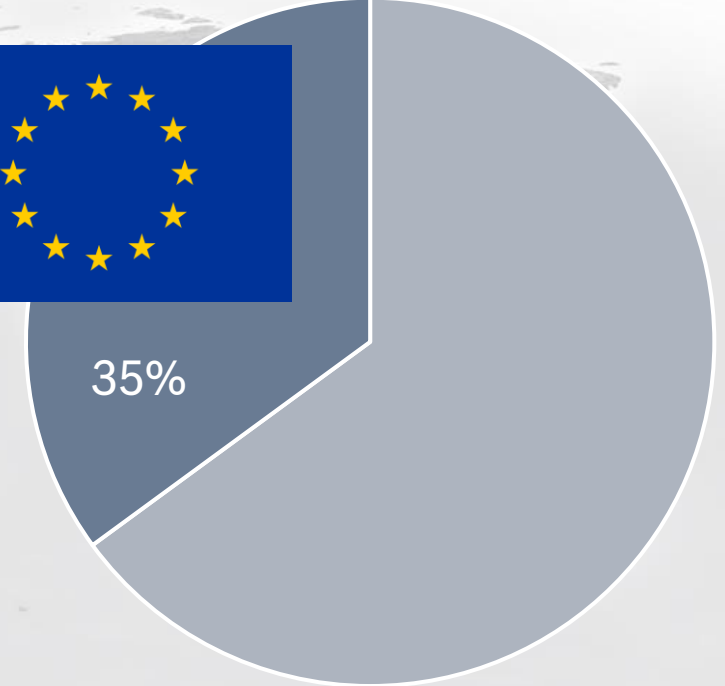## Global MEMS market 2022*
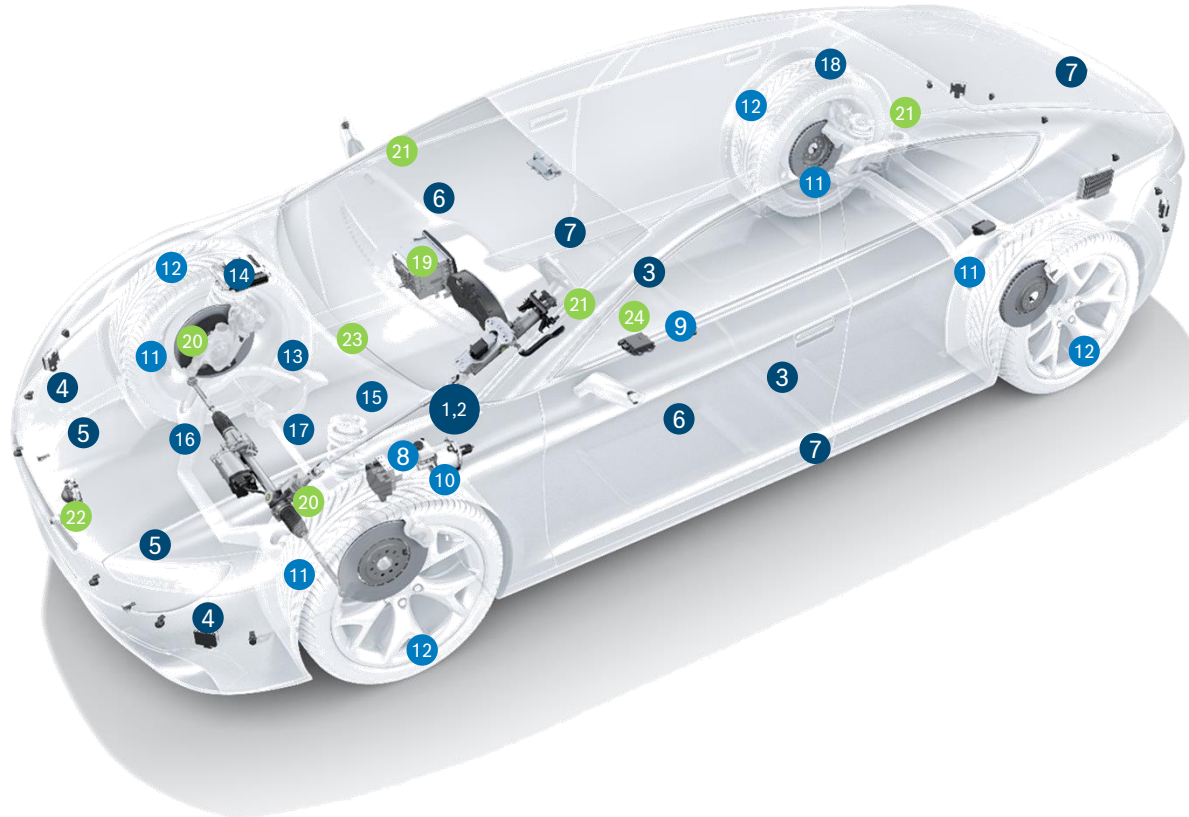
by application

by region of manufacturer

56%

18%

35%

EUR 14bn+, 30+ bn sensors yearly – The heart of multiple applications world-wide!

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Innovation in MEMS for IoT and digital life
Automotive Applications

More than 50 MEMS sensors per car

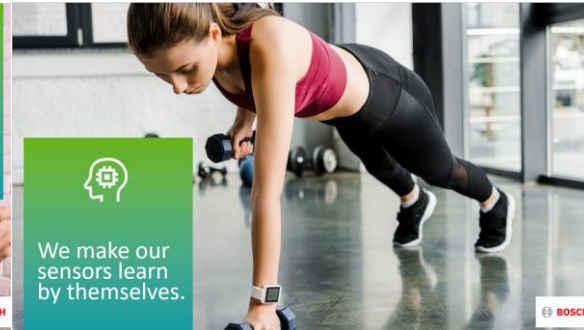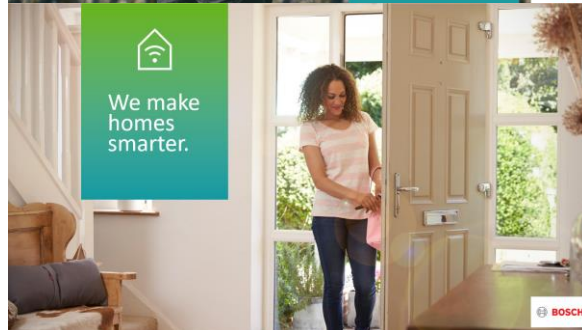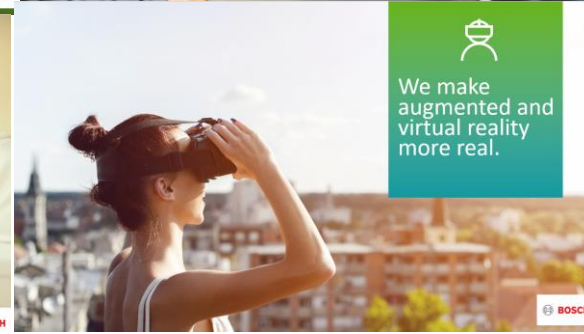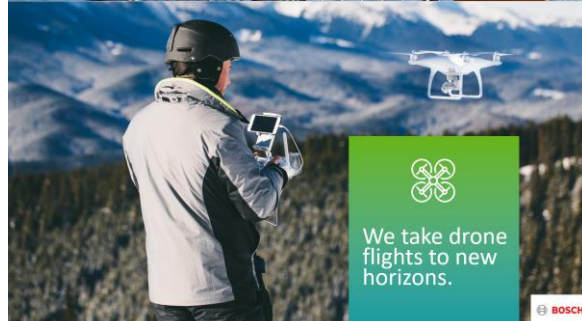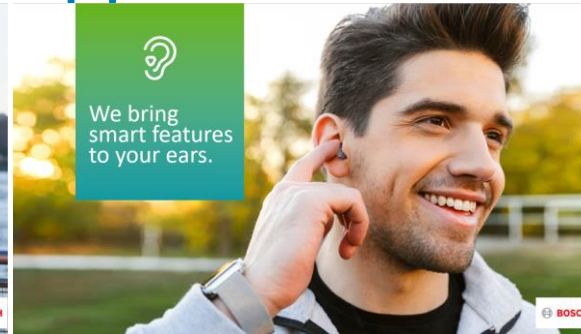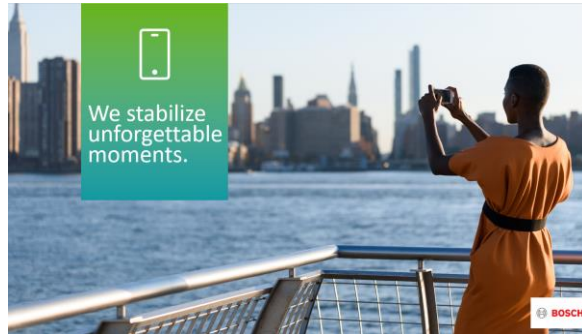|	Passive Safety
1	High G acceleration sensors for AB-ECU and eCall
2	Rollover sensor for Airbag ECU
3	Occupant weight sensors or pressure sensors
4	PTS – Pedestrian tube sensors
5	UFS - Upfront sensors
6	PPS - Peripheral pressure sensors
7	PAS - Peripheral acceleration sensors
	Active Safety
8	Inertial sensors für ESP, RSC, RoSe
9	MM – Sensor cluster for ESP (accel + gyro)
10	High pressure sensor for ESP
11	Low G acceleration sensors for active suspension
12	TPMS- Tire pressure monitoring system
	Power Train
13	MAP – Manifold air pressure
14	BAP – Barometric air pressure
15	Medium Pressure for transmission
16	Mass flow sensor
17	High pressure sensor for fuel injection
18	Tank pressure sensor
	Comfort Functions
19	Inertial sensor for navigation
20	Motor damping / noise cancellation
21	Microphones
22	Night vision
23	Gas / air quality and humidity
24	Car alarm

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
Innovation in MEMS for IoT and digital life
Consumer Electronics Applications

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Innovation in MEMS for IoT and digital life
MEMS products − Innovative and smart sensors for consumer

Motion sensors	Environmental sensors	Smart sensor systems	Optical microsystems
Absolute orientation sensor (BMX)*	Gas sensor (BME)	AI sensor systems (BHI260AP)	Smartglasses Light Drive (BML)
Inertial measurement unit (BMI)	Humidity sensor (BME)	Programmable sensor systems (BHI, BHA)	
Accelerometer (BMA) Magnetometer (BMM)	Barometric pressure sensor (BMP)	Sensor nodes (BNO)	

Software & tools, embedded algorithms and AI solutions

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Innovation in MEMS for IoT and digital life
Market drivers

Smaller
- ► Size causes cost
- ► Size limits design

Ultra low power
- ► Always-on applications
- ► Power management

Performance
- ► Higher accuracy
- ► Lower noise

Smarter
- ► Integrated data processing
- ► Embedded software / algorithms
- ► Functionality for use cases
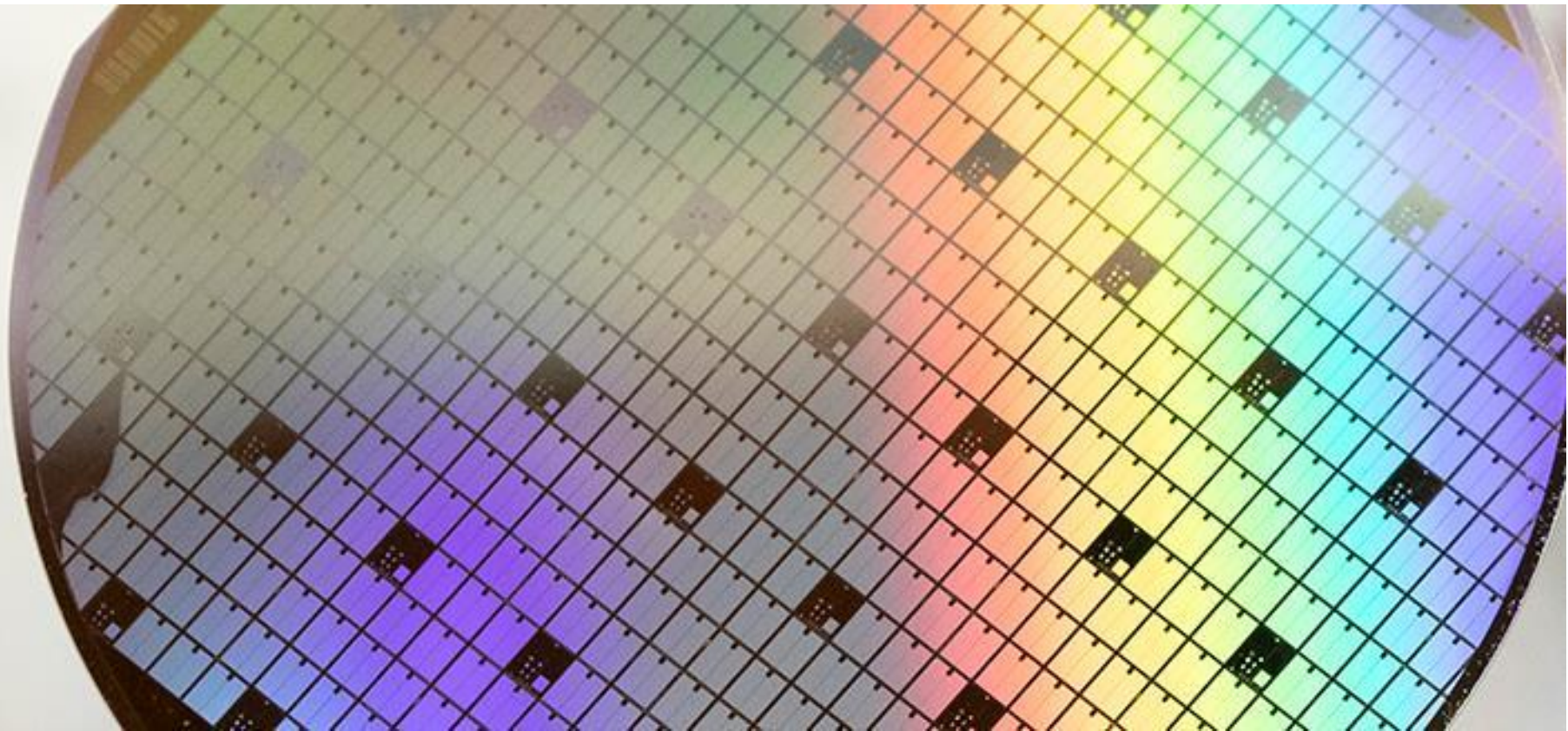
New measurants
- ► Environmental data
- ► Imaging

Connectivity
- ► SPI, I²C, MIPI I3C, GPIO
- ► BTLE, WiFi, LoRa for IoT, I4.0, ...
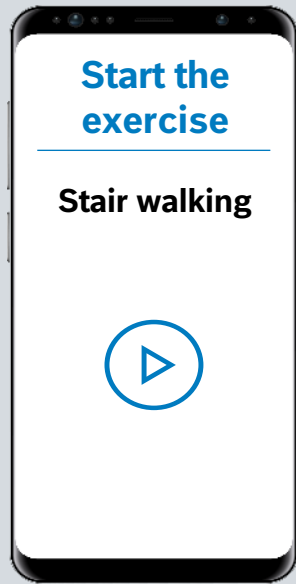
Simply.
Connected.

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03 Applications for MEMS
accurate, tiny, ubiquitous

Innovation in MEMS for IoT and digital life
Example: Measuring smallest height changes during stair walking

Switch on the app connected to your earbuds:

Start the exercise

Stair walking

▶

Start with the stair walking exercise:

earbuds •

~15cm

height changes

90cm

~15cm

earbuds

0cm

time
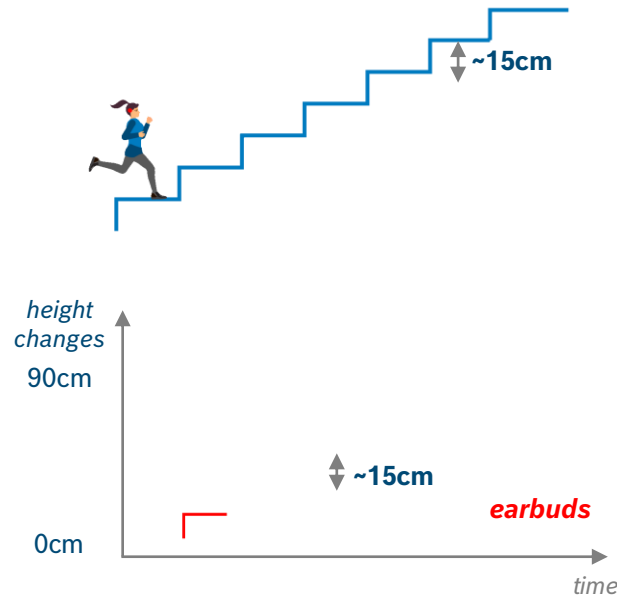
Look at your fitness tracking app.
The sensor accurately measures the height changes and recognizes the exercise:

Exercise tracking

Stair walking

1
stairs

ongoing exercise
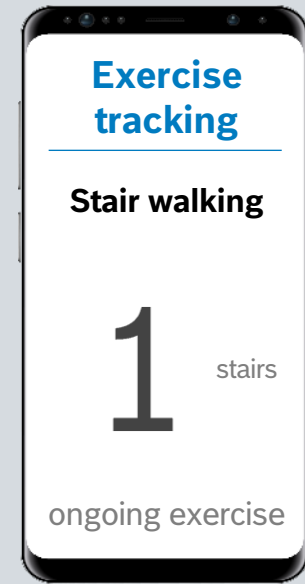
Measuring smallest height changes during stair walking with the barometric pressure sensor BMP581

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Innovation in MEMS for IoT and digital life
Example step height: What does accuracy of 17.5cm mean?

Walking the stairs or measurement to the extreme

Walking stair steps

ca. 32 Pa

Single stair
step resolution

— piezoresistive pressure sensor
— capacitive pressure sensor

Equivalent of

	/ 11	~17.5 cm step height air coloumn **13km vs. 13km + 17.5cm**
		2,1 Pa = ~0,002% pressure difference **101300 Pa vs. 101302 Pa**
	/ 1.000	**~7.6 µg** **weight change of air**
	/ 1.000.000	**~12.6 aF** **capacitance change**

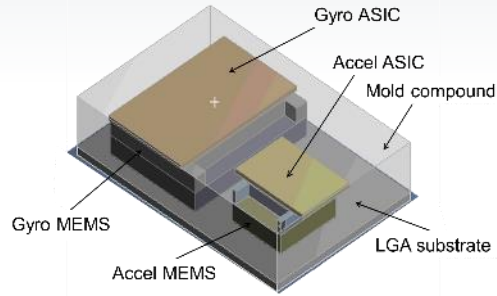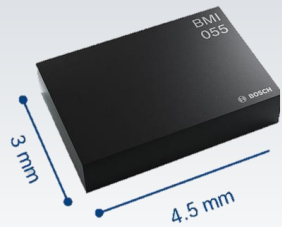**Resolving 17.5cm with a pressure sensor means measuring the charge difference of 60 electrons!**

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Innovation in MEMS for IoT and digital life
IMUs − New design approaches for miniaturization

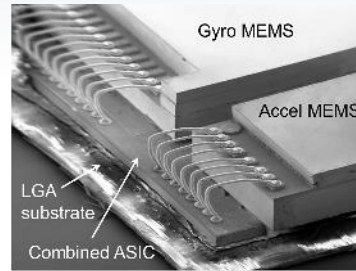**Example: Overview integration concepts Bosch Sensortec IMUs for CE**

BMI055 (2012)

3 mm · 4.5 mm

2 ASICs + 2 MEMS
I = 5 mA

−44%

BMI160 (2014)

2.5 mm · 3 mm
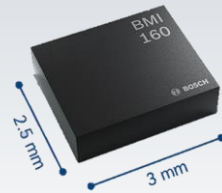
1 ASIC + 2 MEMS
I = 0.95 mA

same size
pin-to-pin compatibility

BMI260 (2018)

2.5 mm · 3 mm

1 ASIC + 1 MEMS
I = 0.68 mA

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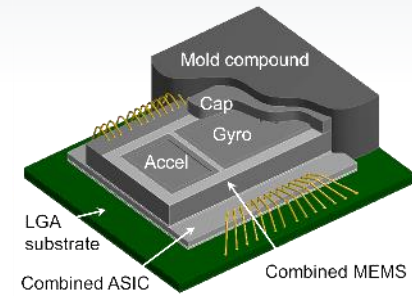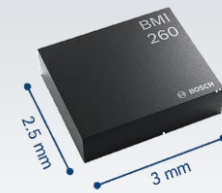
Innovation in MEMS for IoT and digital life
IMUs – Evolution of gyroscope sizes

BMI055 (2012)

BMI160 (2014)

BMI260 (2018)

1 / 3.3

Shrink by factor 3.3 achieved within two gyro generations

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Innovation in MEMS for IoT and digital life
Example Localization − Why is inertial sensor bias important?
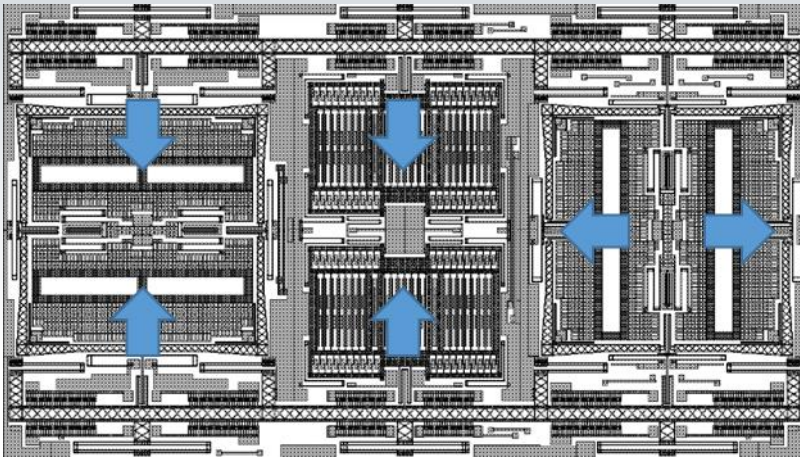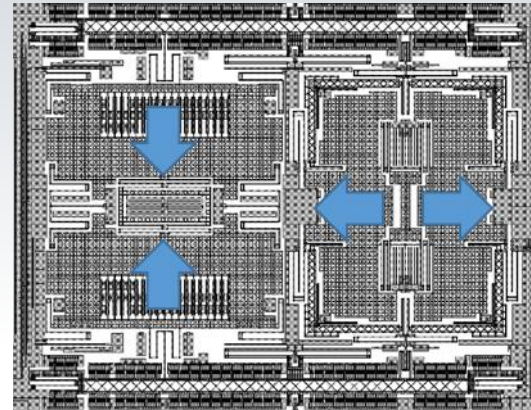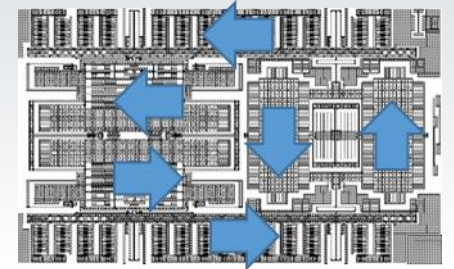
- **Role of Bias instability BIS**
  - Bias instability is a measure of slow signal fluctuations without external stimulus
  - During navigation fluctuations are integrated and lead to orientation errors
  - BIS is quantified by **Allan variance**

Typ. Allan variance and std. angle error of integrated rate signal
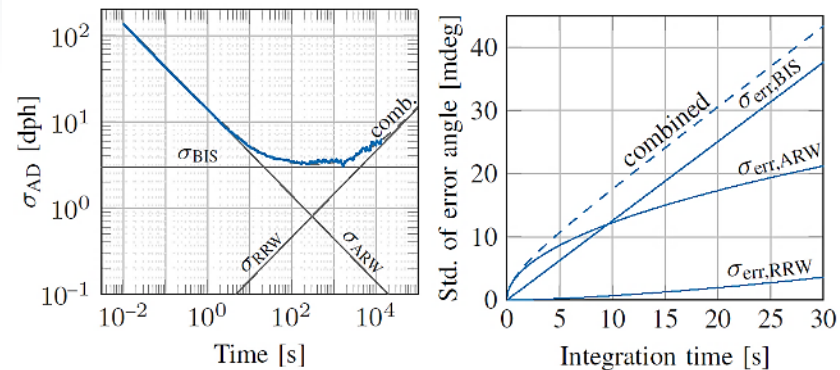
- **Normal vs. high performance IMU**

Bias instability is critical for localization applications and a strong market driver for performance!

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NASA MISSION

Bosch MEMS sensors stabilize
NASA'S INGENUITY MARS HELICOPTER

Source: www.nasa.gov

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04 Smart sensors
Artificial intelligence in MEMS
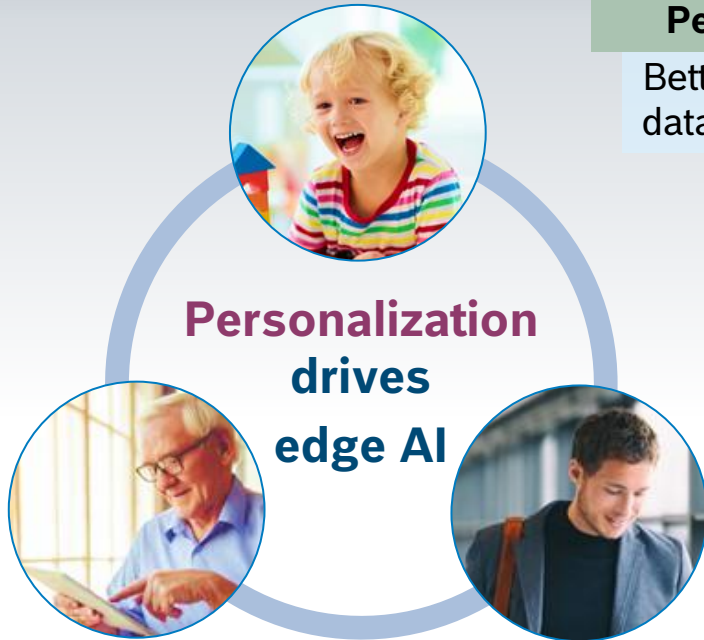
Innovation in MEMS for IoT and digital life
Examples: Self-learning AI sensor

Edge AI market drivers and user benefits

Personalization drives edge AI

Personalization
Better user adaptation, as only data of the user are collected

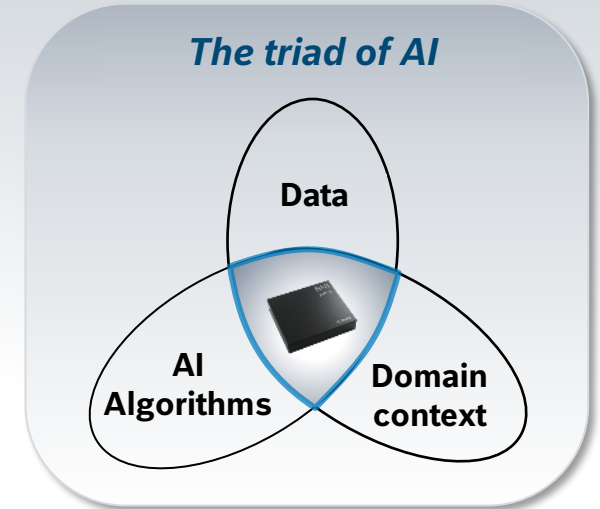**Privacy of user data**
Low latency due to avoidance of data transfer

Real time feedback
Edge data processing without cloud involvement

Improved battery life
Demand-optimized data transmission and connectivity

Critical success factors

The triad of AI

Data

AI Algorithms

Domain context

Source: Santhanam P et. al. 'Engineering Reliable Deep Learning Systems', AAAI Fall Symp. Series on AI in Government & Public Sector, Nov. 7-9, 2019, p. 2

AI creates value for the user, if one combine data, application knowledge, and algorithms intelligently!
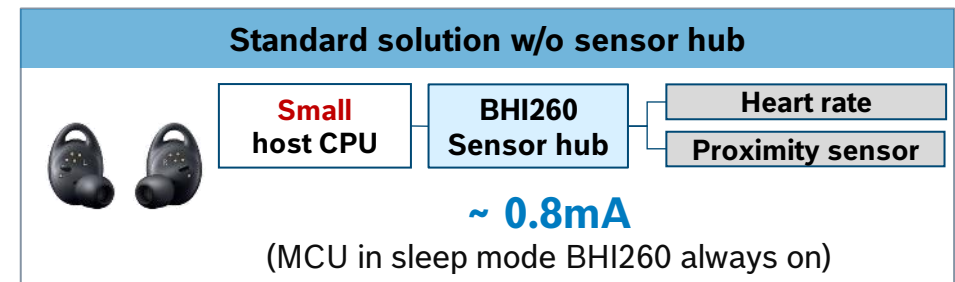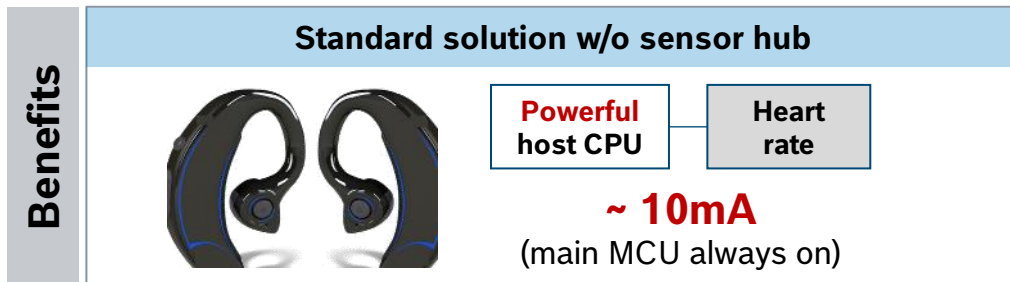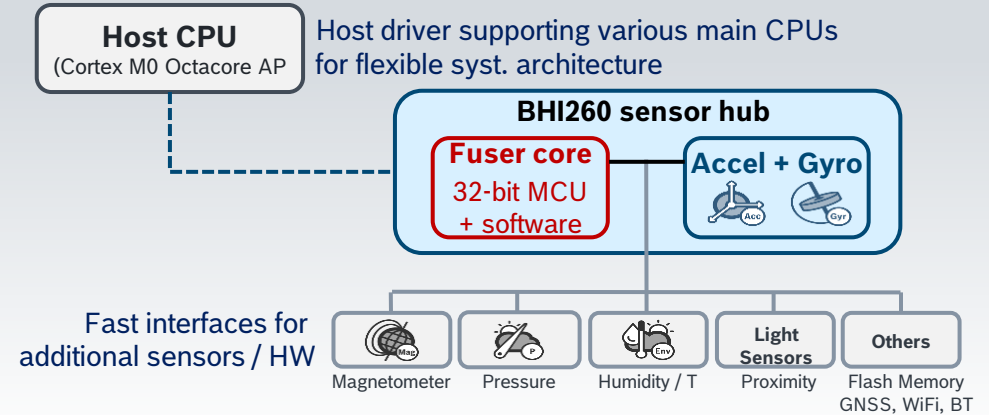
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Innovation in MEMS for IoT and digital life
Examples: Integration, data fusion and sensor hub

- Complex use-cases with different sensors need smart sensor data fusion

- **Solution: Smart sensor hub with integrated µC**

- **Example:**
  - 6-axis motion sensor (gyro + accel)
  - 32-bit Fuser2 Core (ARC EM4 CPU)
  - Memory for software and data batching
  - Bosch Sensor Fusion BSX4 with 800Hz

Sensor hub concept

Host CPU (Cortex M0 Octacore AP)

Host driver supporting various main CPUs for flexible syst. architecture

BHI260 sensor hub

Fuser core 32-bit MCU + software

Accel + Gyro

Fast interfaces for additional sensors / HW

Magnetometer | Pressure | Humidity / T | **Light Sensors** Proximity | **Others** Flash Memory GNSS, WiFi, BT

Benefits

Standard solution w/o sensor hub

Powerful host CPU — **Heart rate**

~ 10mA
(main MCU always on)

Standard solution w/o sensor hub

Small host CPU — **BHI260 Sensor hub** — **Heart rate** / **Proximity sensor**

~ 0.8mA
(MCU in sleep mode BHI260 always on)

Enables smart sensing far beyond commodity at ultra-low power consumption

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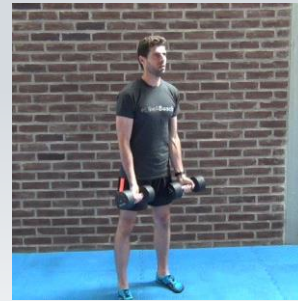# Innovation in MEMS for IoT and digital life
Glimpse of automatically tracked activities via sensor with AI

Tricep extension

Bicep curl
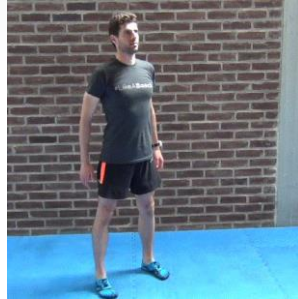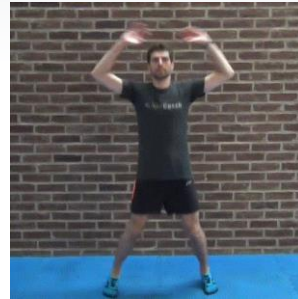

Palm face

Bench press

Chest fly

Pull over

Side lateral raise

Squats
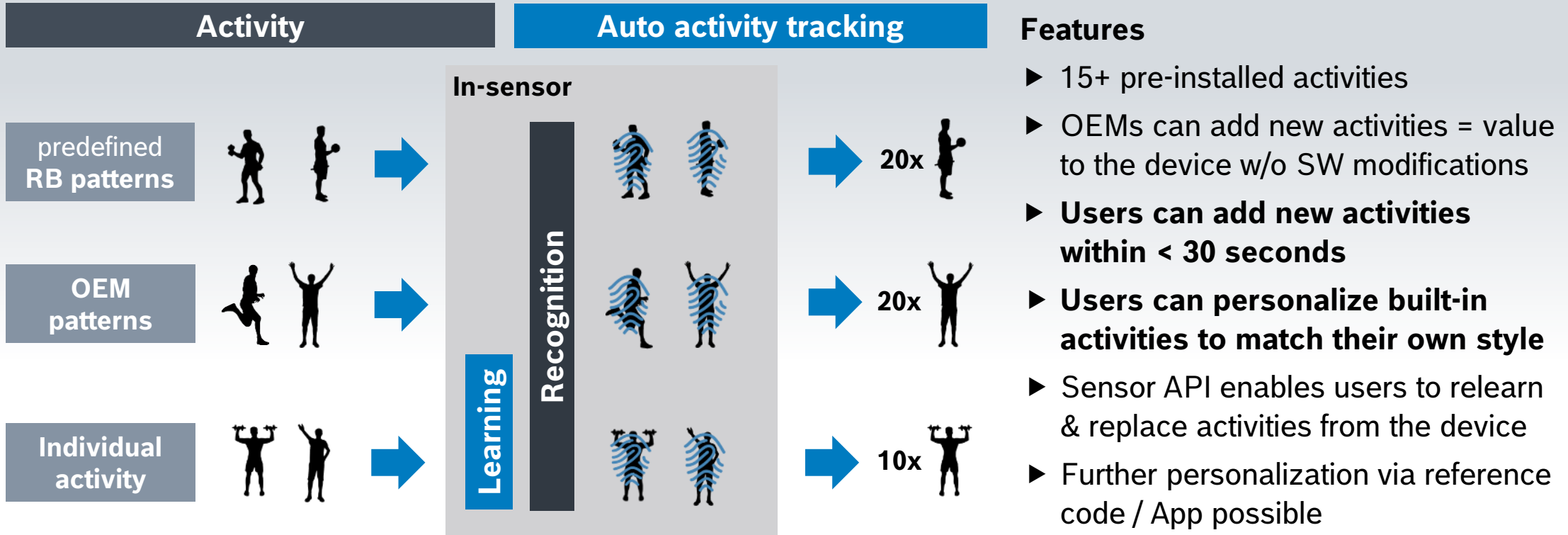

Jumping jacks

Russian twist

Kettle bell swing

Row machine

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Innovation in MEMS for IoT and digital life
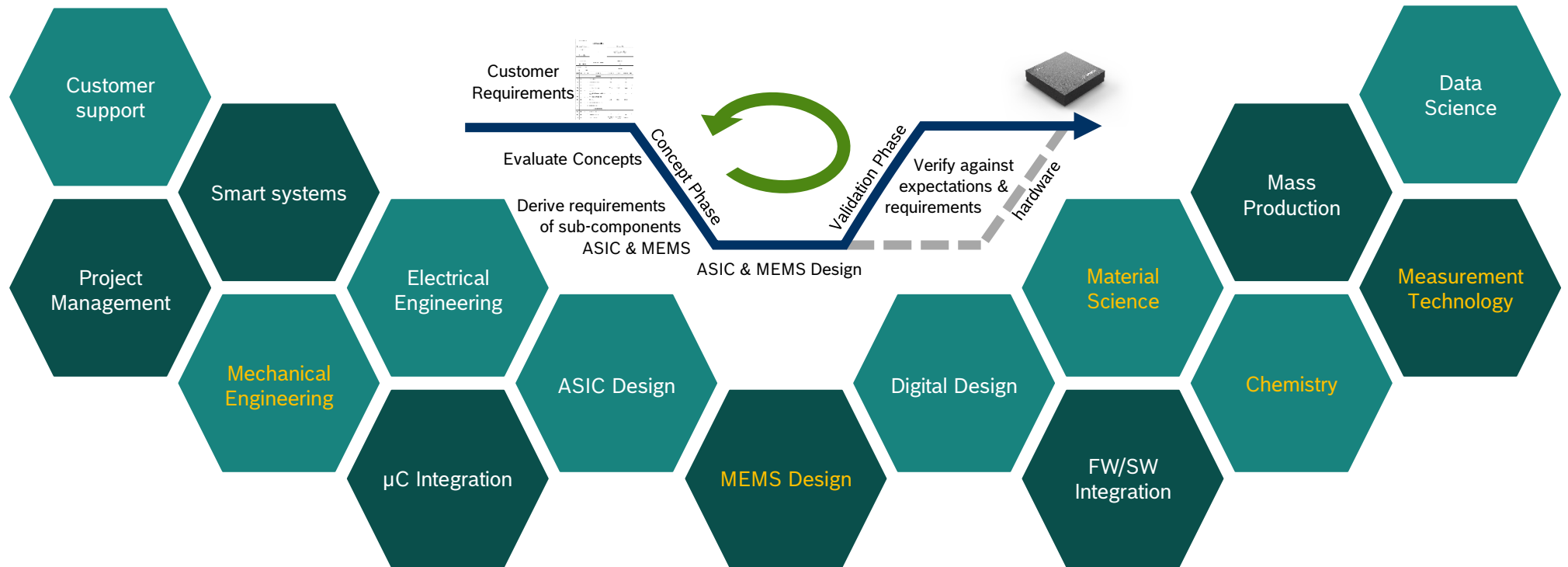## Example: Fitness tracking – Learn new activities from user

Activity	Auto activity tracking
predefined RB patterns	
OEM patterns	
Individual activity	

In-sensor

Recognition

Learning

20x

20x

10x

Features

▶ 15+ pre-installed activities

▶ OEMs can add new activities = value to the device w/o SW modifications

▶ **Users can add new activities within < 30 seconds**

▶ **Users can personalize built-in activities to match their own style**

▶ Sensor API enables users to relearn & replace activities from the device

▶ Further personalization via reference code / App possible

Self-learning sensors with AI open completely new personalization functions for the user

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05 Design, Technology and Manufacturing
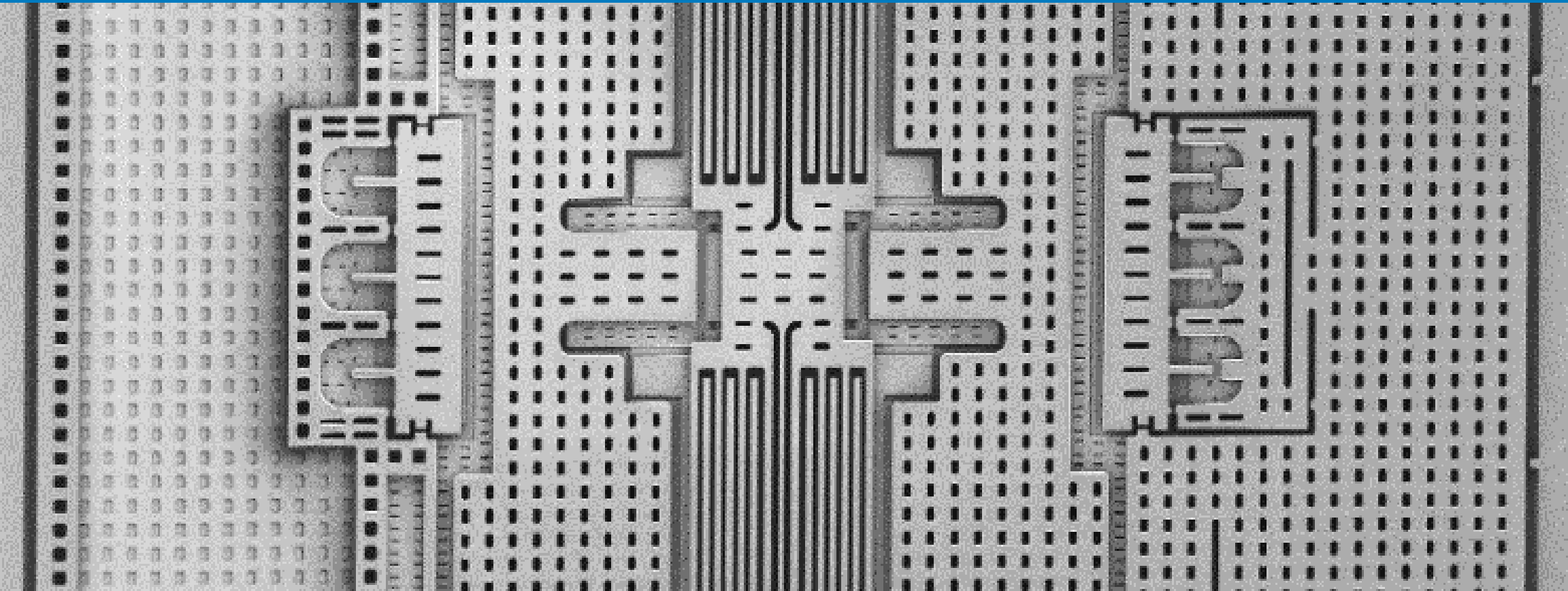
Innovation in MEMS for IoT and digital life
## Broad spectrum of competences in interdisciplinary teams

Customer support

Smart systems

Project Management

Mechanical Engineering

Electrical Engineering

ASIC Design

µC Integration

MEMS Design

Digital Design

FW/SW Integration

Material Science

Mass Production

Chemistry

Data Science

Measurement Technology

Customer Requirements

Evaluate Concepts

Concept Phase

Derive requirements of sub-components ASIC & MEMS

ASIC & MEMS Design

Validation Phase

Verify against expectations & requirements

hardware

A huge variety of different domains are needed in the MEMS development process

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Innovation in MEMS for IoT and digital life
Modelling, design, simulation and software development
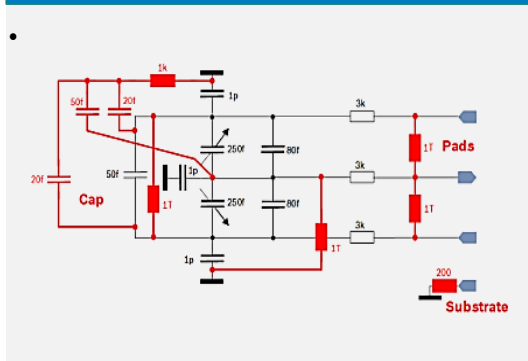

Model based system engineering
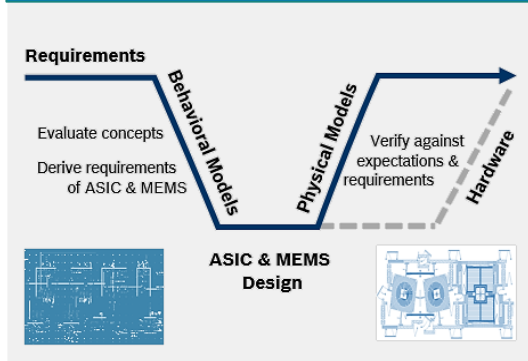
MEMS design
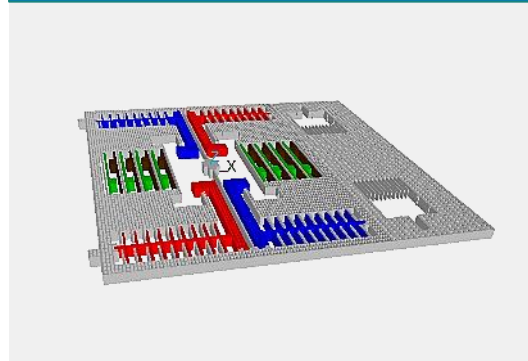
MEMS and package simulation
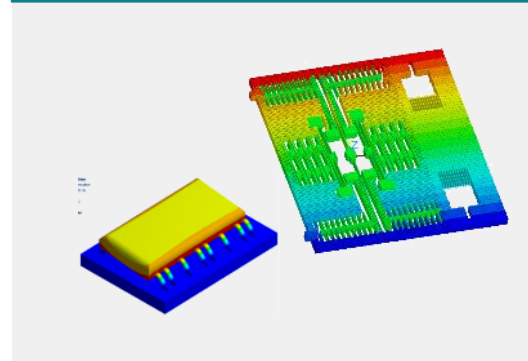
MEMS layout

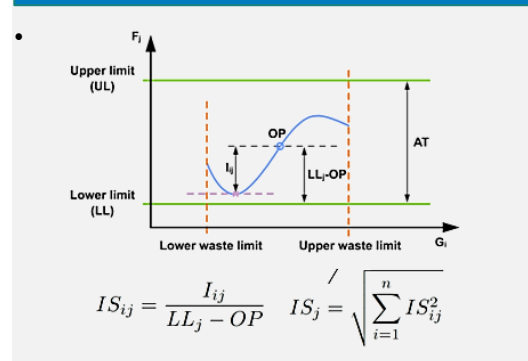Verification MEMS-ASIC-IF

Simulation tools / methods

Sensitivity analysis / IFS

Software / Algorithms / ML

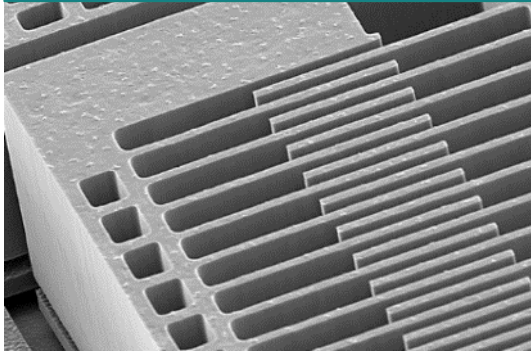$$IS_{ij} = \frac{I_{ij}}{LL_j - OP} \qquad IS_j = \sqrt{\sum_{i=1}^{n} IS_{ij}^2}$$
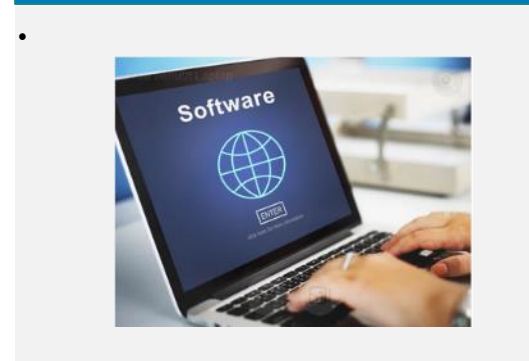
Complex multidomain simulation/design with specialized tools

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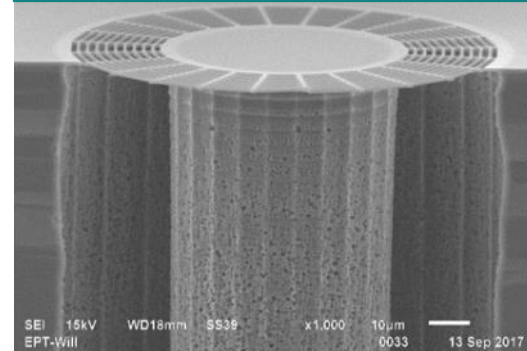# Innovation in MEMS for IoT and digital life
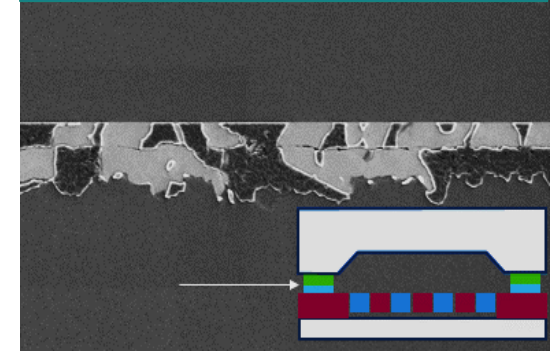## MEMS process technology
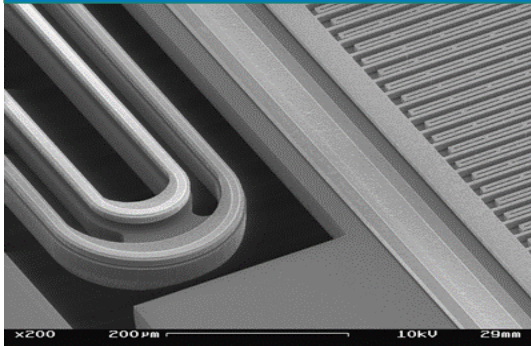

Surface Micromechanics
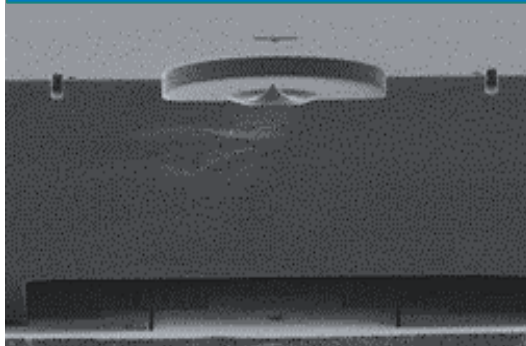

APSM – Porous Silicon
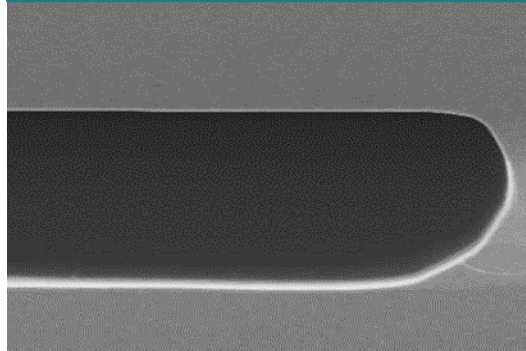
Trough Silicon Vias

Eutectic wafer bonding

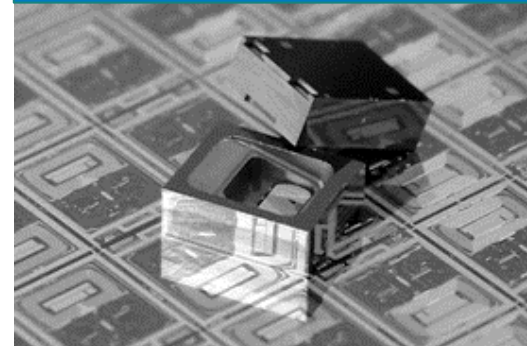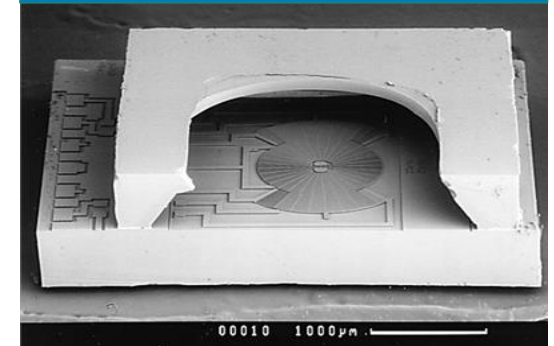Bulk Micromechanics

Laser Reseal
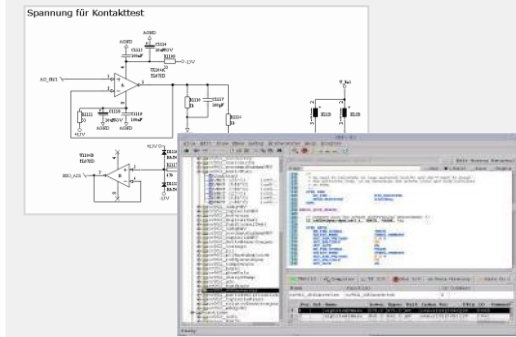

MEMS actors

Anodic and glass frit bonding

Silicon process innovation generates new functionality for the user

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Innovation in MEMS for IoT and digital life
Testing, characterization and qualification
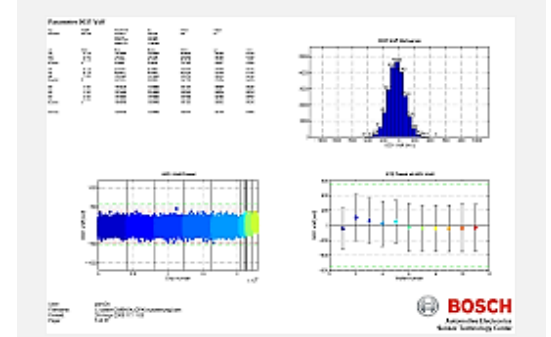

Testing Hard- and Software

Wafer Level Testing

Multi-axis/ multi stimuli final test

In depth data analysis

Series Testing

Lifetime Testing

Vibrational Testing (Shaker)

Physical and chemical analysis

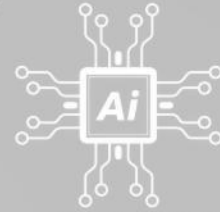**MEMS require very specific test and manufacturing equipment**

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06 Summary

Innovation in MEMS for IoT and digital life
Summary and conclusion

- **MEMS sensors make a difference** in our daily life ... and even on Mars.

- Progressing **strong innovation** scales size down and increases integration, accuracy and functionality

- The development of MEMS is a unique **cross domain challenge** requiring the best available engineering skills.

- **Europe has the ecosystem, the application and the experience** to continue a success-story in innovation and commercial success.

[1] Bosch presents: Sensor tech #LikeABosch - YouTube

NASA MISSION

Bosch MEMS sensors stabilize
NASA'S INGENUITY MARS HELICOPTER

BMI160 inside

Source: www.nasa.gov

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THANK YOU

WORKSHOP - Sustainable Electronics & International Cooperation On Semiconductors

www.icos-semiconductors.eu