# ESSCIRC/ESSDERC 2020
# 3D isotropic Hall sensor

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Advanced Developments & Proof-of-Concepts
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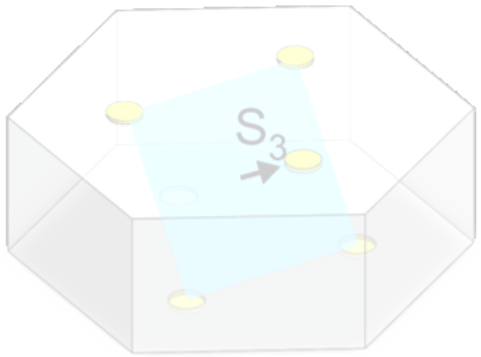


# TDK Corporation – At a glance

TDK Corporation is a leading electronics company. Our focus is on information and communication technology, automotive, industrial and consumer electronics markets. TDK's comprehensive portfolio features passive components such as ceramic, aluminum electrolytic and film capacitors, magnetics, high-frequency, and piezo & protection devices. Our product spectrum also includes sensors and sensor systems such as temperature and pressure, magnetic and MEMS sensors. In addition, TDK provides power supplies and energy devices, magnetic heads, and more. The portfolio is marketed under the product brands TDK, EPCOS, InvenSense, Micronas, Tronics and TDK-Lambda. The company has a network of design and manufacturing locations and sales offices in Asia, Europe, North and South America.

| **Key info** (fiscal year 2020, ending March 31) | |
|---|---|
| Business | • **Passive components**<br>• **Sensor application products**<br>• **Magnetic application products**<br>• **Energy application products**<br>• **Others** |
| Headquarters | **Tokyo, Japan** |
| Sales | **JPY 1,363 billion** |
| Sites | **More than 200 factories, R&D & sales offices in more than 30 countries** |
| Employees | **107,000** |

| **Major milestones** | |
|---|---|
| **1935** | TDK (*Tokyo Denki Kagaku Kogyo = Tokyo Electric & Chemical Industries*) established in Japan to manufacture and commercialize ferrites |
| **1986** | SAE Magnetics acquired |
| **2005** | Amperex Technology Limited (ATL) acquired |
| **2005** | Lambda Power Group acquired |
| **2007** | Recording Media business sold |
| **2008** | EPCOS AG acquired |
| **2016** | Micronas Semiconductor Holding AG acquired |
| **2017** | TDK-Qualcomm HF joint venture RF360 started; cooperation with Qualcomm enhanced InvenSense, Inc. acquired |
| **2018** | Chirp Microsystems, Inc. acquired |

# TDK-Micronas

**Glenrothes, Scotland**
TDK-Micronas Ltd.

- Hall ICs
- Embedded Motor Controllers

**Freiburg, Germany**
TDK-Micronas

- Hall ICs
- Embedded Motor Controllers

**MSBG HQ**

**Saku / Nagano, Japan**
**A**sama **T**echno **F**actory (ATF)

- TMR Sensors
- Sensor Modules

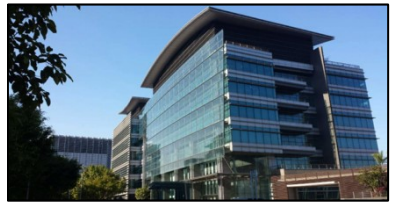
**TDK HQ**

**Tokyo, Japan**

**Leuven, Belgium**
ICsense

- Analog, Mixed Signal and High Voltage ASICs

**Dongguan, China**
SAE Magnetics LTD



- TMR Sensors
- Sensor Modules

# Product portfolio

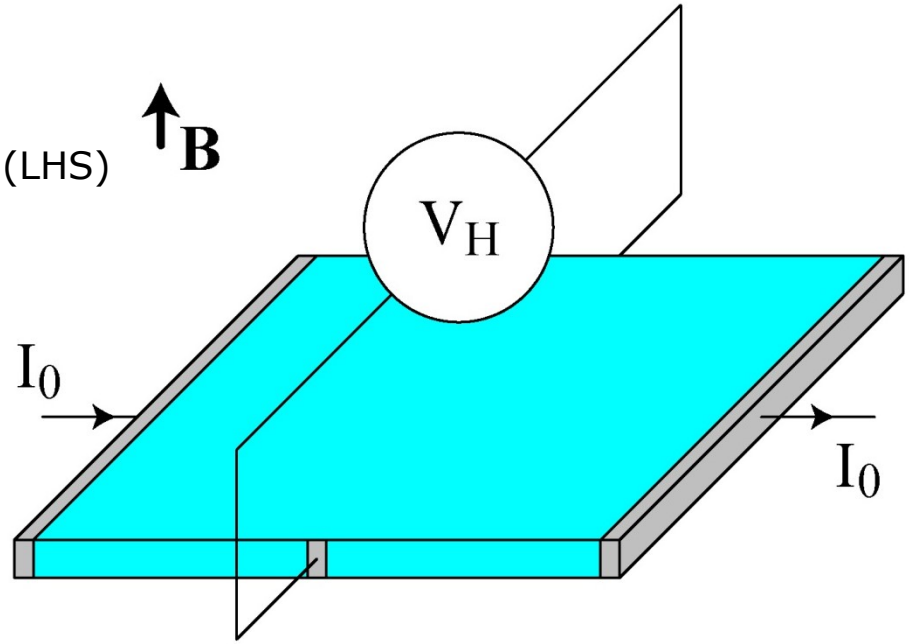
- Magnetic sensor ICs
  - Hall switches (position, RPM)
  - 1D Hall sensor (position, angle, current, torque)
  - 3D Hall sensor (position, angle)
  - TMR sensor (position, angle, linear, current)
- Sensor modules
  - Stroke sensor
  - Current sensor
  - Speed sensor
- Embedded motor controllers ICs
  - Electric motor controllers (BDC, BLDC, stepper)
- Custom ICs (ICSense)
  - Analog, mixed signal and high voltage ASICs


**MSBG Vision: "Be a World No. 1 Magnetic Sensor Supplier."**

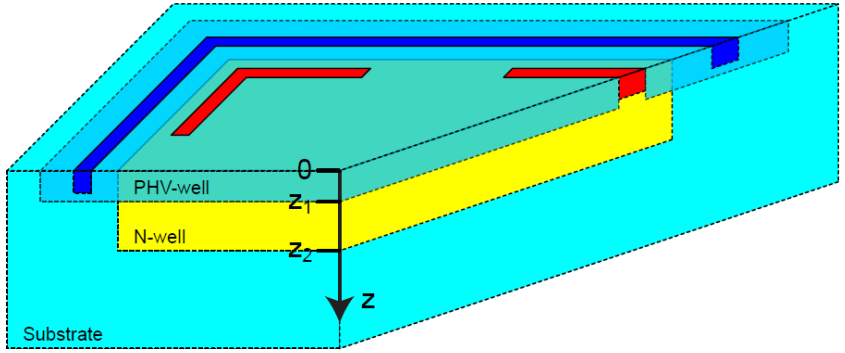
# Hall sensor basics - LHS

- Magnetic field ***B*** perpendicular to plate surface: Lateral Hall Sensor (LHS)
- Thin conductive plate with four electrical contacts
- Supply current $I_0$ between two opposite contacts
- Hall voltage $V_{Hz}$ drops between remaining contacts

$$V_{Hz} = S_z B_z = \frac{r_H}{qnt} I_0 B_z$$



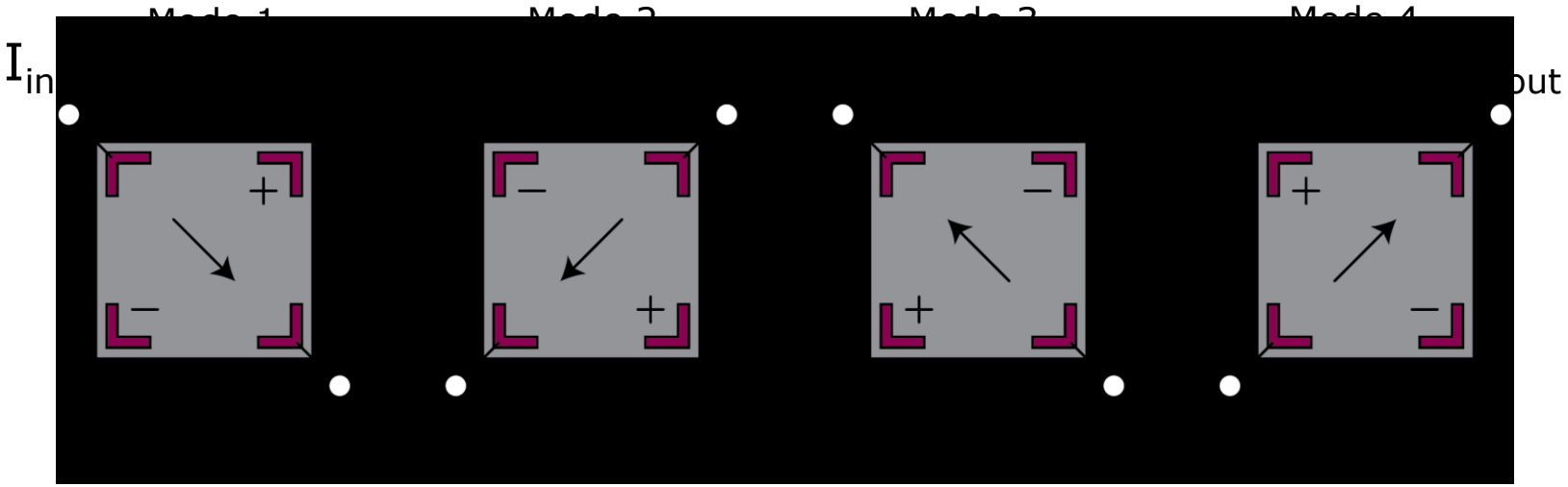

- Hall sensors in silicon based CMOS technology
  - Sensor active area realized by diffusion wells
    - Preferably low doped n-type material (→ high mobility)
    - Isolation using pn-junctions
  - Electrical ($n^+$-doped) contacts at the wafer surface
  - Realistic device: Offset



# Hall sensor basics

## Switching current

- Symmetric Hall plate design - 4 identical modes of operation

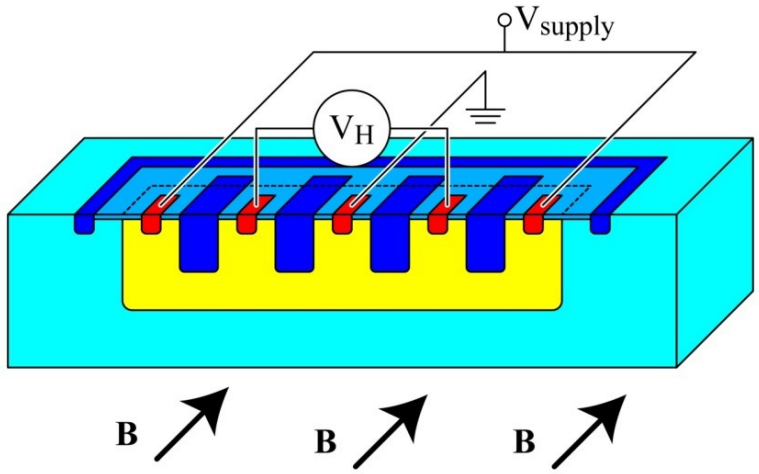



- Averaging of the Hall signal cancels out offsets due to
  - Geometry / material imperfections
  - Temperature gradients
  - Mechanical stress

- Magnetic response remains unaffected

# Hall sensor basics - VHS

- Magnetic field ***B*** in the plane of the chip: Vertical Hall sensor
  - Geometrical transformation of the LHS
  - Intrinsic lower sensitivity




- Five Contact (5C-)VHS in silicon based CMOS technology
  - Deep n-doped well (HV)
  - Five $n^+$-doped contacts

3D magnetic field sensor: combination of a LHS and two VHS

# Hall sensor basics - Pros/Cons

- Low cost / simple processing
- Small size (~10…100µm edge length)
- Robustness (rather simple and stable physical effect)
- Large magnetic field range (highly linear, non-destructive)
- Direct integration with electronics allows
  - Signal amplification
  - Application specific (digital) signal processing
  - Compensation of parasitic effects

- Limited magnetic field resolution (~earth MF)
- Current consumption (~mA)
- Expensive compensation efforts
  - Probe / final testing with magnetic fields
- Cross-sensitivity on mechanical stress
  - Causes magnetic sensitivity drifts
- 3D sensors require two different sensing structures
  - Different characteristics
  - Sensitivity mismatch

**Angular applications**

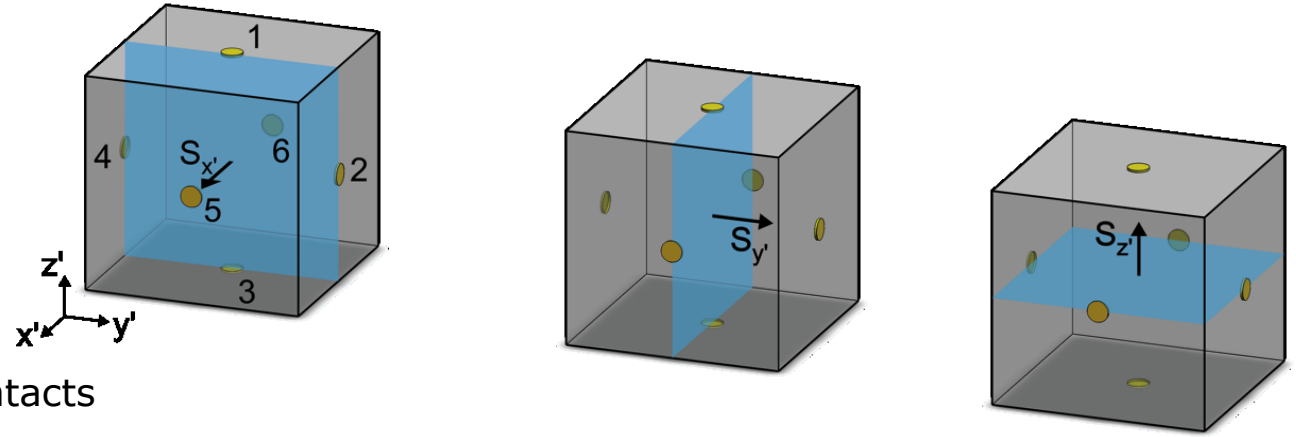
$$angle\ (\boldsymbol{B}) = \tan^{-1}\frac{B_x}{B_z} = \tan^{-1}\frac{V_{Hx}\cdot S_z}{V_{Hz}\cdot S_x} \approx \tan^{-1}\frac{V_{Hx}}{V_{Hz}}$$

**3D isotropic Hall sensor**

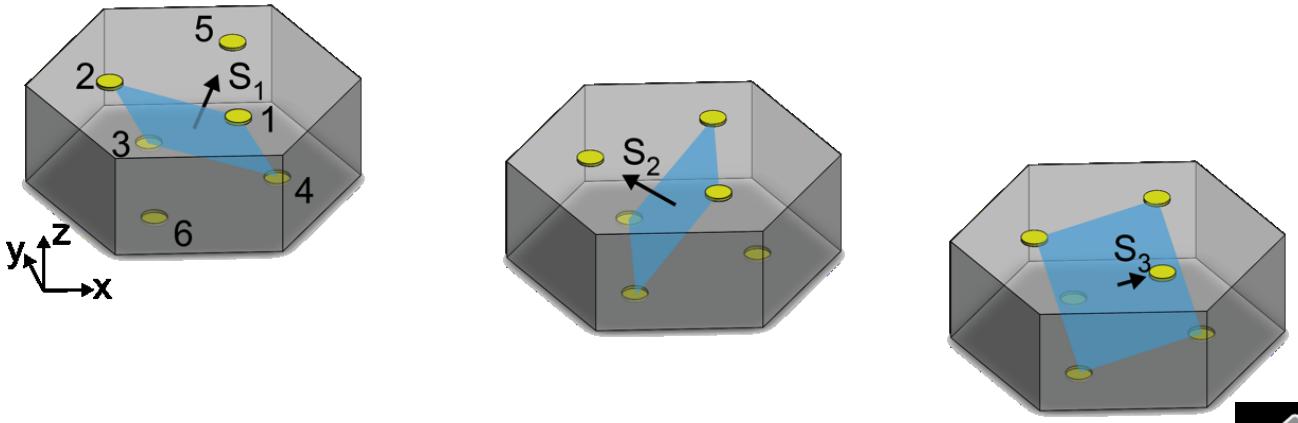
# Hall sensor basics - 3DIH

**New generation of 3D magnetic field sensors allowing to sense the three components of the magnetic field with one sensitive element**

- Cubic structure
  - 6 face-centered contacts
  - 3 virtual Hall planes (vHp)
  - Sensitivity vectors:
    - Mutually orthogonal
    - Same magnitude
  - Implementation would require sidewall contacts



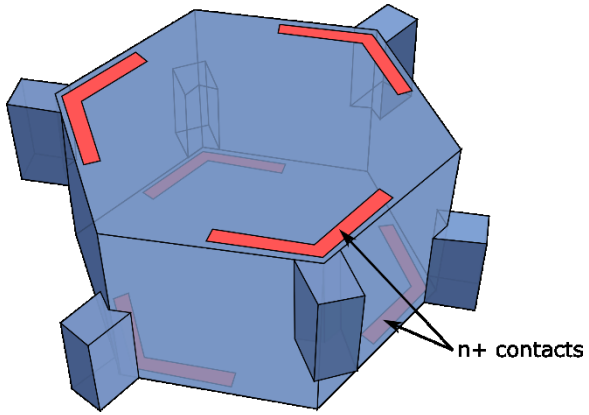

- Transformation of the cube: hexagonal prism
  - 6 contacts (front- and back-side)
  - 3 virtual Hall planes (vHp)
  - Sensitivity vectors:
    - Mutually orthogonal
    - Same magnitude

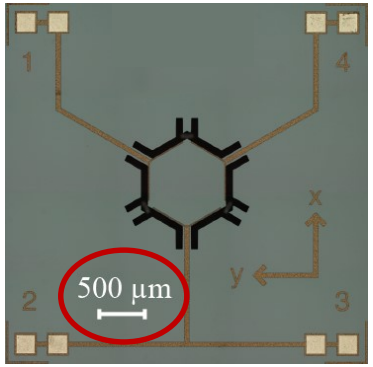


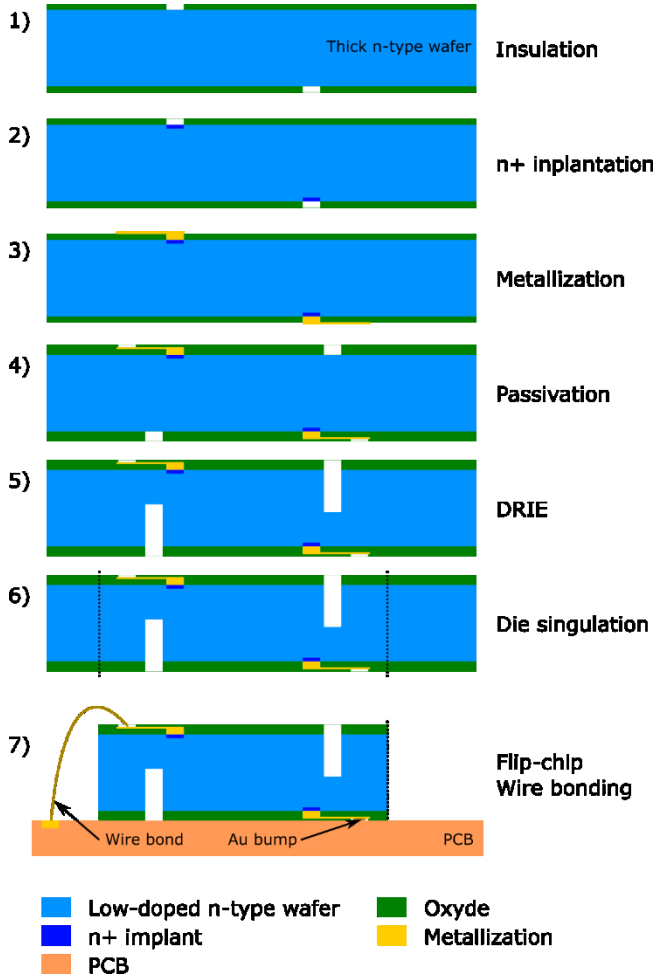
# First prototype

Main characteristics:

- Homogeneous low-doped n-type silicon wafer
- Hexagonal prism isolated by deep trenches from the substrate
- Mechanical and electrical interconnection using bridges
- n+ implantation and metallization on both sides of the wafer



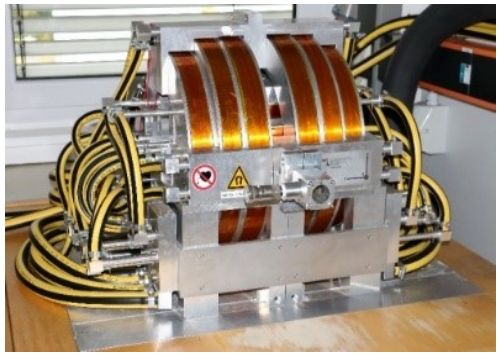



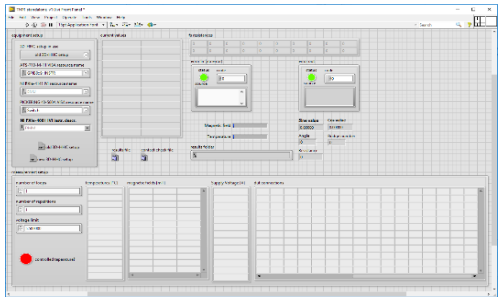



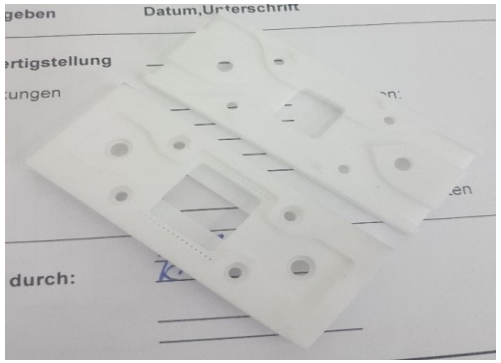

[1] Christian Sander, Carsten Leube, Taimur Aftab, Patrick Ruther, Oliver Paul, "Monolithic Isotropic 3D Silicon Hall Sensor", Sensors and Actuators A: Physical, Volume 247, 2016, Pages 587-597

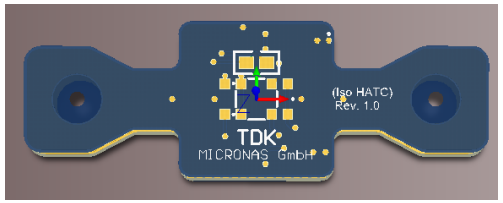
# Experimental setup

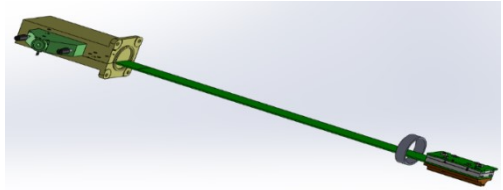
- Experimental electric/magnetic test bench integrated into existing TDK-Micronas lab environment
- 3D Helmholtz coil setup with stray field compensation
- 4-contact Kelvin measurements
- Controlled temperature





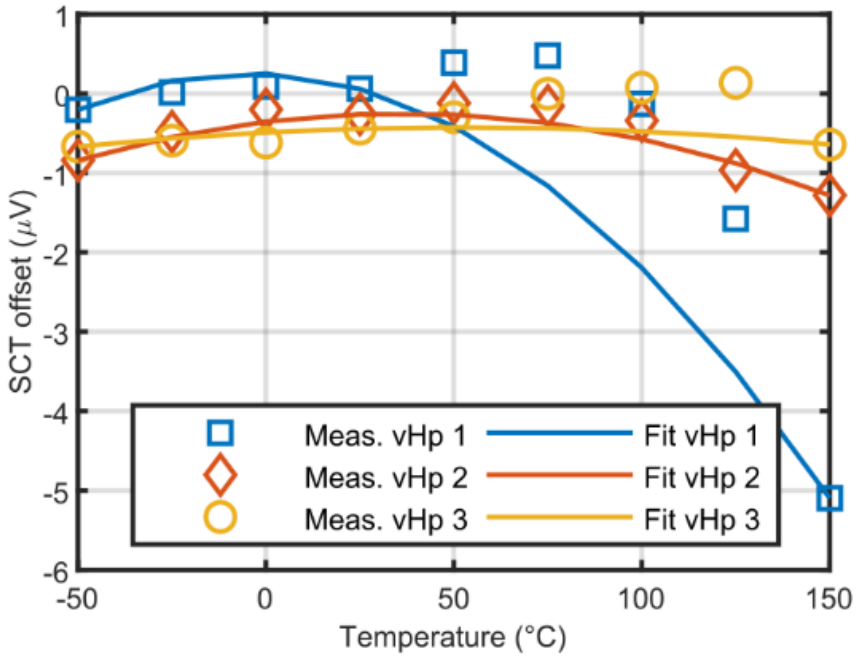


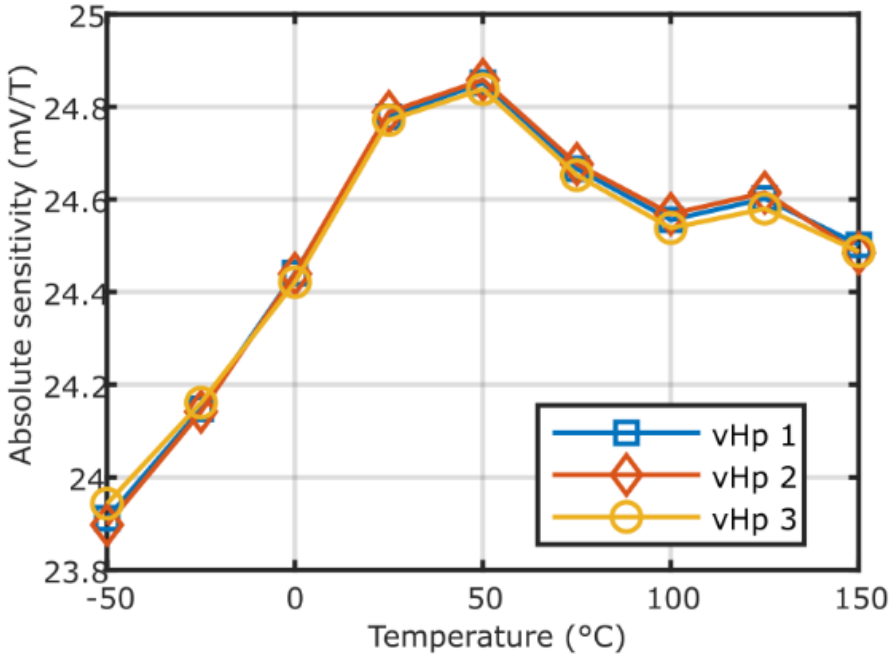



# Measurement results

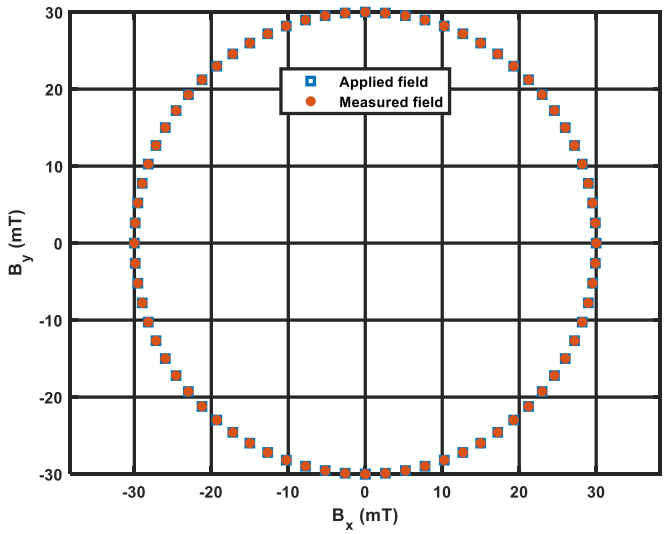
- Single mode offset in the mV range
- Residual offset after current switching in the µV range
- Sensitivity mismatch between vHps lower than 0.5% without calibration

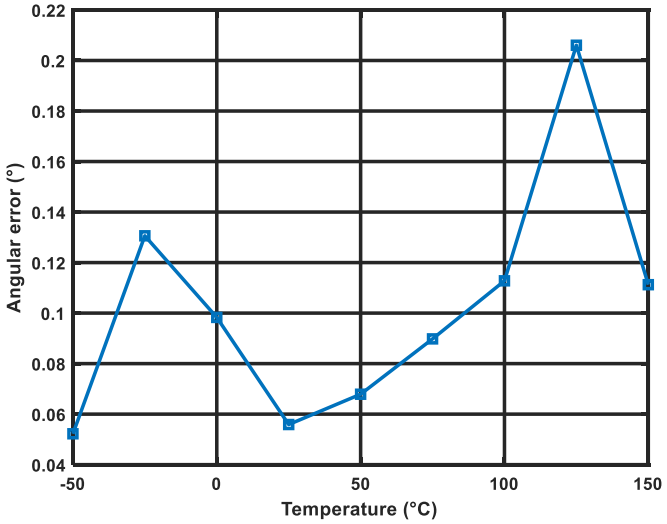


# Measurement results

- Angular sensor application
- 30 mT rotating magnetic field
- Angular error (after calibration) lower than 0.2° over extended automotive temperature range



# Conclusion

- Promising prototype
- Lab-to-fab transition
  - Industrial process development
  - Scaling down the device to reduce power consumption
  - Combination with a specific ASIC platform

# Acknowledgement

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