



MAGNETIC SENSOR SYSTEMS FOR MOTION CONTROL

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In this presentation, I am addressing a brief history of sensor systems for motion control and my role in it.





Outline

- The electromechanical system with a resolver
- Encoders
- Optical systems
- Integrated magnetic sensors
- Hall element



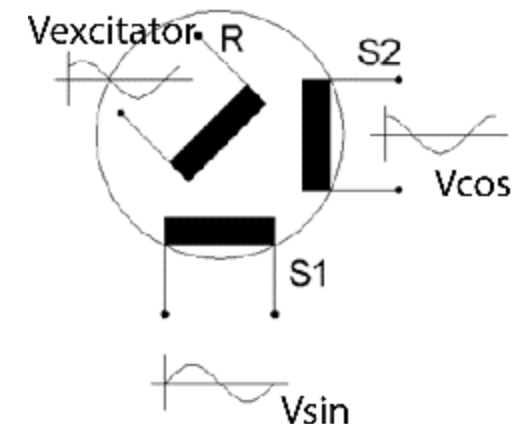
Outline

- AMR (Anisotropic Magneto Resistor) sensors
- TMR (Tunnel Magneto Resistor) sensors
- Integrated Hall elements
- Integrated micro-coil
- Example of magnetic microsystems based on Hall element arrays
 - State of the art of magnetic microsystems
 - conclusions



Resolver

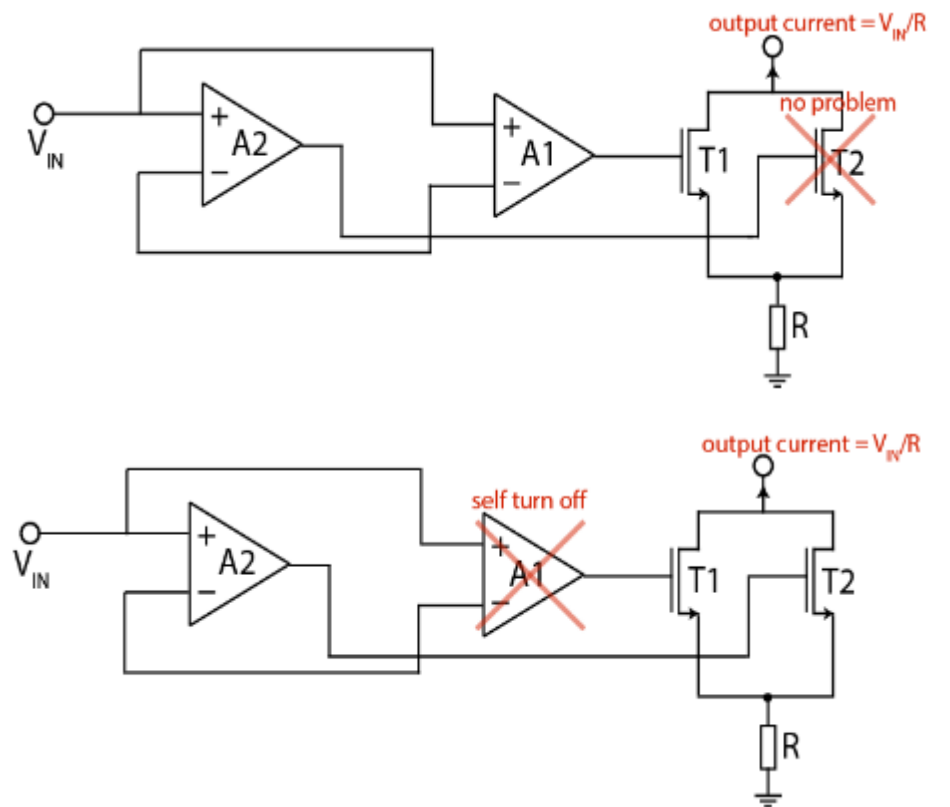
- In the second part of the last decade of the previous century, I was asked to design an ASIC for motion control for satellite applications. The real challenge was a requirement of the ASIC to be radiation hardened to operate after up to 100kRad radiation dose.
- Resolver principle
- The resolver is a transformer looking similar to electromotor, where the two starter winding perpendicular to each other and the rotor turning for 360 degrees. The stator outputs are sine and cosine shaped functions. The rotary position angle is the arctan of the ratio V_{\sin}/V_{\cos} .
- The device is completely radiation-proof, but the associated electronic is vulnerable to cosmic radiation.





Resolver

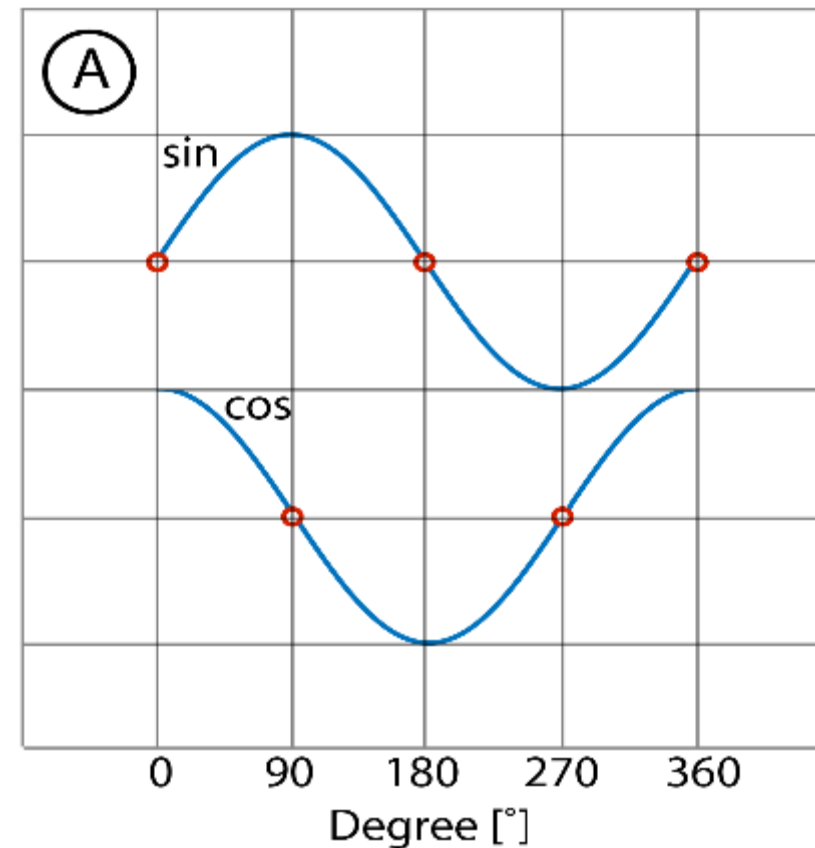
- The designed ASIC successfully survived 120 krad dose. The design methodology to achieve this was based on the redundancy of transistors used both in analog and digital parts, on the robustness of the design, and on selecting the CMOS technology.
- The figure presents an example of redundancy in an analog subcircuit. If the gate of transistor T1 or of T2 is shortened, no action is needed as the function operates normally using just an undamaged part of the circuit.
- If the damage occurs in amplifier 1 or in amplifier 2, the input voltage is internally compared to input, and this amplifier automatically shuts off, but the functionality remains unchanged.





Encoders

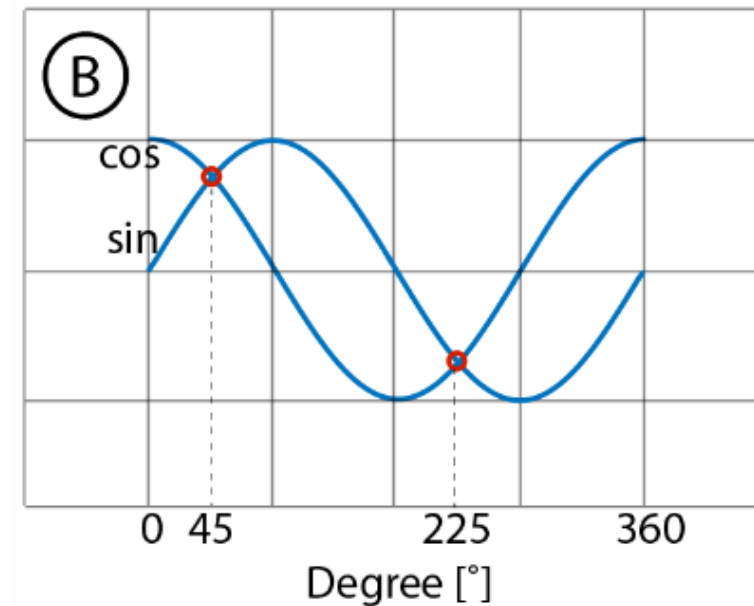
- The most position sensors output is two signals, one with a sine function shape and the other with a cos function shape. There are many ways to calculate the position from these signals, although the angle is simple to obtain from the arctan calculation of the ratio V_{\sin}/V_{\cos} . Initially, this was performed with analog signal processing, as shown in fig. A.





Encoders

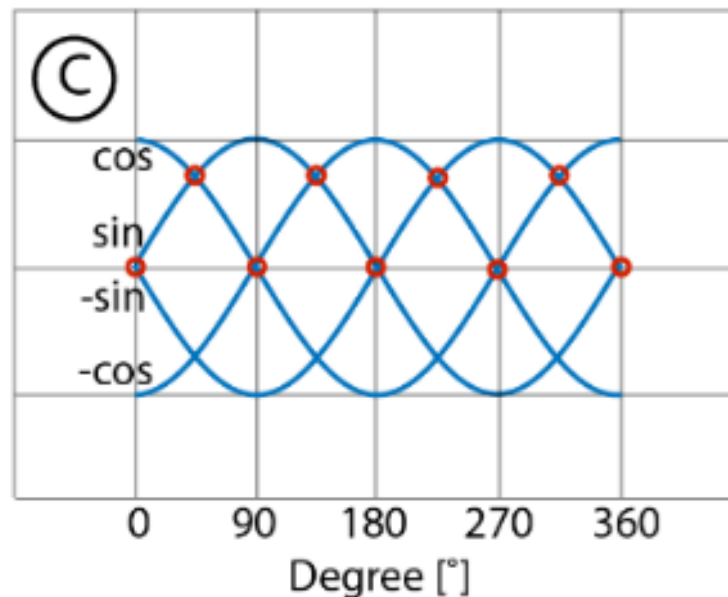
- From a simple zero-crossing detector, the angles 0 degree, 90 degrees, 180 degrees, 270 degrees, and 360 degrees are obtained, as shown in fig. B, the comparison between sin and cos provides additional angles of 45 degrees and 225 degrees.





Encoders

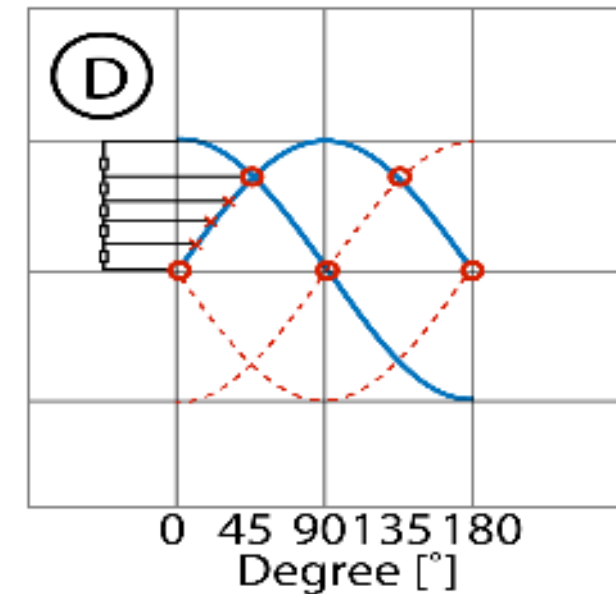
- A simple additional signal processing using inverted signals $-\sin$ and $-\cos$ the resulting signal is shown in fig. C. We see the eight segment with 45 degrees apart, and we require eight comparators and two inverters if the sensor does not provide inverted values for \sin and \cos .
- From fig. C, we see that the situation repeats every 90 degrees.





Encoders

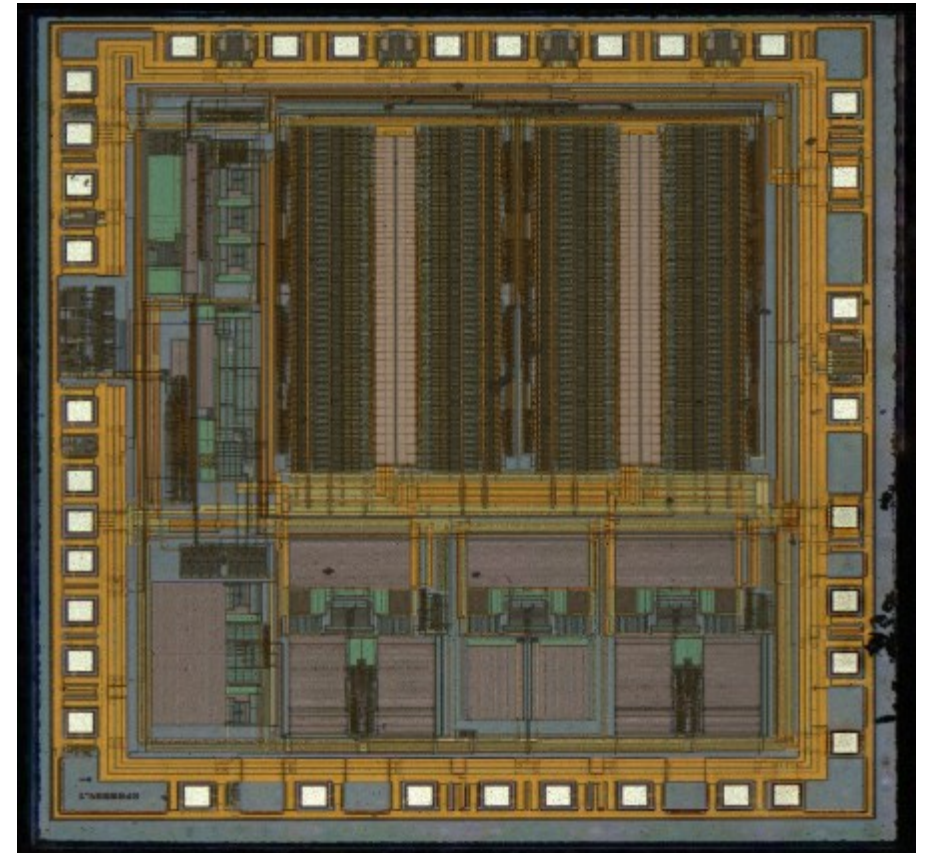
- This detail is shown in fig. D. The segment 0-45 degrees requires an additional comparator to compare sin to the fraction cos. A resistor divider connected between cos and sin provides as many angles as is the number of resistors and comparators.
- From angle 45 degrees to angle 90 degrees, we can use the same resistor divider but new connectors between sin and cos. The resistor string and comparator array is used for segment 90 degrees to 135 degrees but now connected to sin and $-\cos$.





Optical Systems

- The described encoder principle accuracy depends on the accuracy of resistor divider and of comparator offset. It has been realized for encoders with up to (9+3)-bit resolution. Also, the comparator speed limits the accuracy of fast-moving object position.
- With the new ultrafast and accurate A/D converters and microprocessors, the calculation of the position is performed with digital processing. Faster and better resolution needs additional future work.





Optical Systems

- Optical systems consists of the photodiodes usually reverse polarized. When exposed to light, a photocurrent is generated. The light is modulated by the pattern on the transparent material, usually glass. The pattern has either binary code or preferably Gray code, as shown in the table. The photodiodes are arranged to read the light modulation according to the pattern on the mask.
- Table shows the Gray code, which has the advantage that only one bit changes its value when proceeding to the next state.

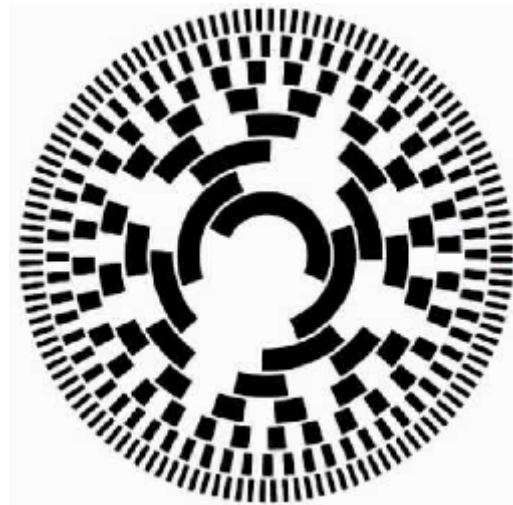
Gray code table

	0	0	0	0	0
	1	0	0	0	1
	1	1	0	0	2
	0	1	0	0	3
	0	1	1	0	4
	1	1	1	0	5
	1	0	1	0	6
	0	0	1	0	7
	0	0	1	1	8
	1	0	1	1	9
	1	1	1	1	10
	0	1	1	1	11
	0	1	0	1	12



Optical Systems

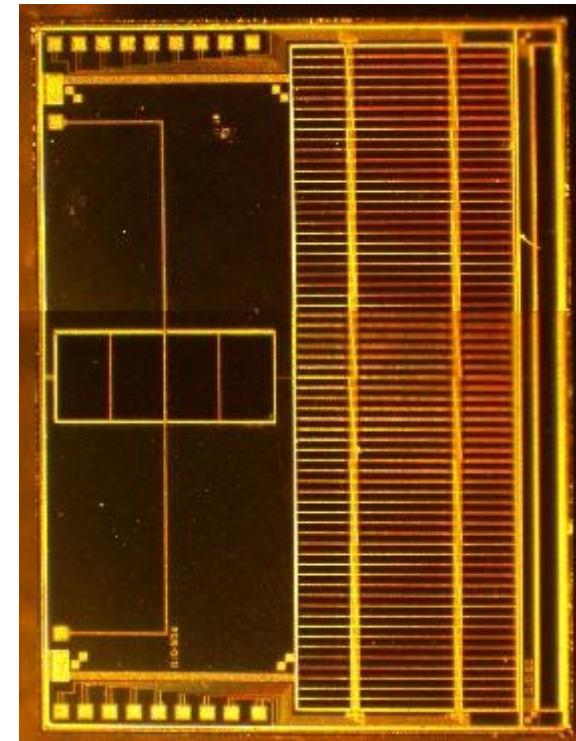
- Optical disk with the printed Gray code is shown in the figure. It consists of eight tracks providing a 256 absolute angle position in the full circle.





Optical Systems

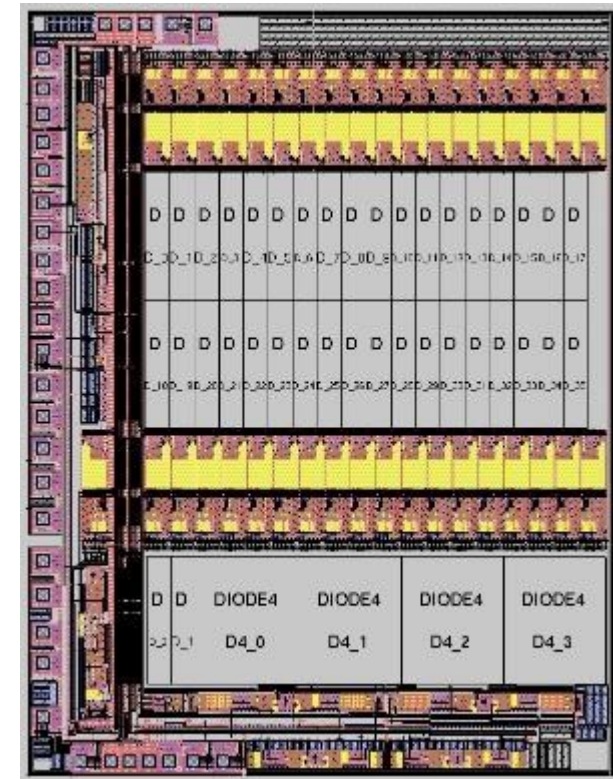
- The ASIC capable of reading the optical mask has to include integrated photodiodes. In a standard CMOS process, any p/n or n/p junction operates as a photodiode. Some silicon foundries have developed the special process for optical ASIC, where the resulting diode offers better sensitivity, lower dark current, and consequently lower noise. The figure shows an example of such ASIC.





Optical Systems

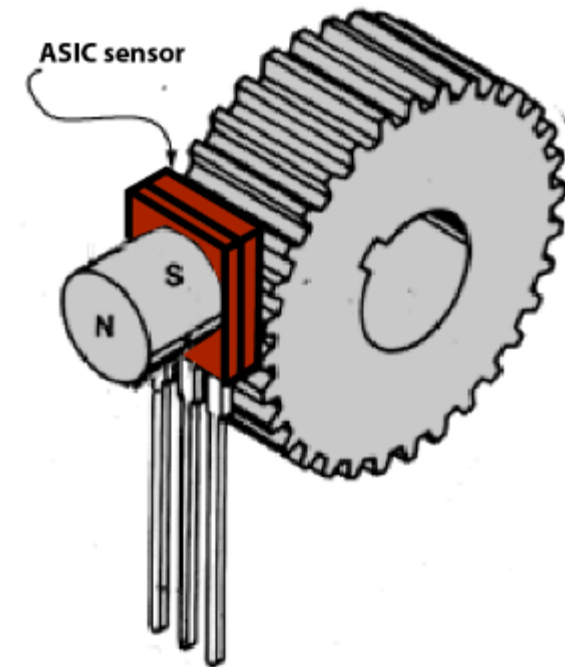
- The development of photodiodes signal processing has been advanced to optimize the problems associated with distortion minimization where we used our patented methods.
- A very complex and sophisticated state of the art Opto ASIC is shown in fig. having a 36 diode array plus 4 layer diodes and 2 small index diodes. It also includes all analog and digital processing.





Integrated Magnetic Sensors

- **Hall element**
- Optical systems were considered very accurate but not very reliable as the sensitive optical setup was sensitive to external conditions like dust, vibration, etc. So the researchers spent a lot of effort to design a more robust sensor system. The use of discrete Hall elements as magnetic sensors increased the Hall element sensor popularity. The automotive market used the Hall element to monitor wheel rotation velocity. Such devices were soon replaced with integrated circuits with integrated Hall elements.. Such an arrangement is shown in the figure.

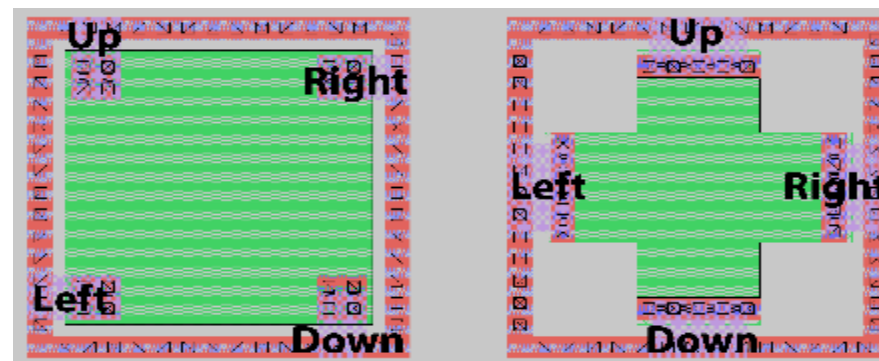




Integrated Magnetic Sensors

Hall element

- Hall element in a CMOS process is a thin layer of light doped silicon providing a device, as shown in fig.
- The Hall element bias current is connected between contacts Up and Down, and the Hall voltage appears at the contacts Left and Right. The Hall voltage is linearly dependent on the magnetic field strength and Hall element bias current.





Integrated Magnetic Sensors

- **Hall element**
- The critical parameters of the Hall element are:
 - Sensitivity
 - The offset voltage; caused by the irregularity of the fabrication process and is a function of the Hall element size and the physical stress caused by package and processing. It can be reduced by layout.
 - The noise voltage; dominantly thermal noise and $1/f$ noise.
 - Temperature coefficient of the sensitivity.



Integrated Magnetic Sensors

Hall element

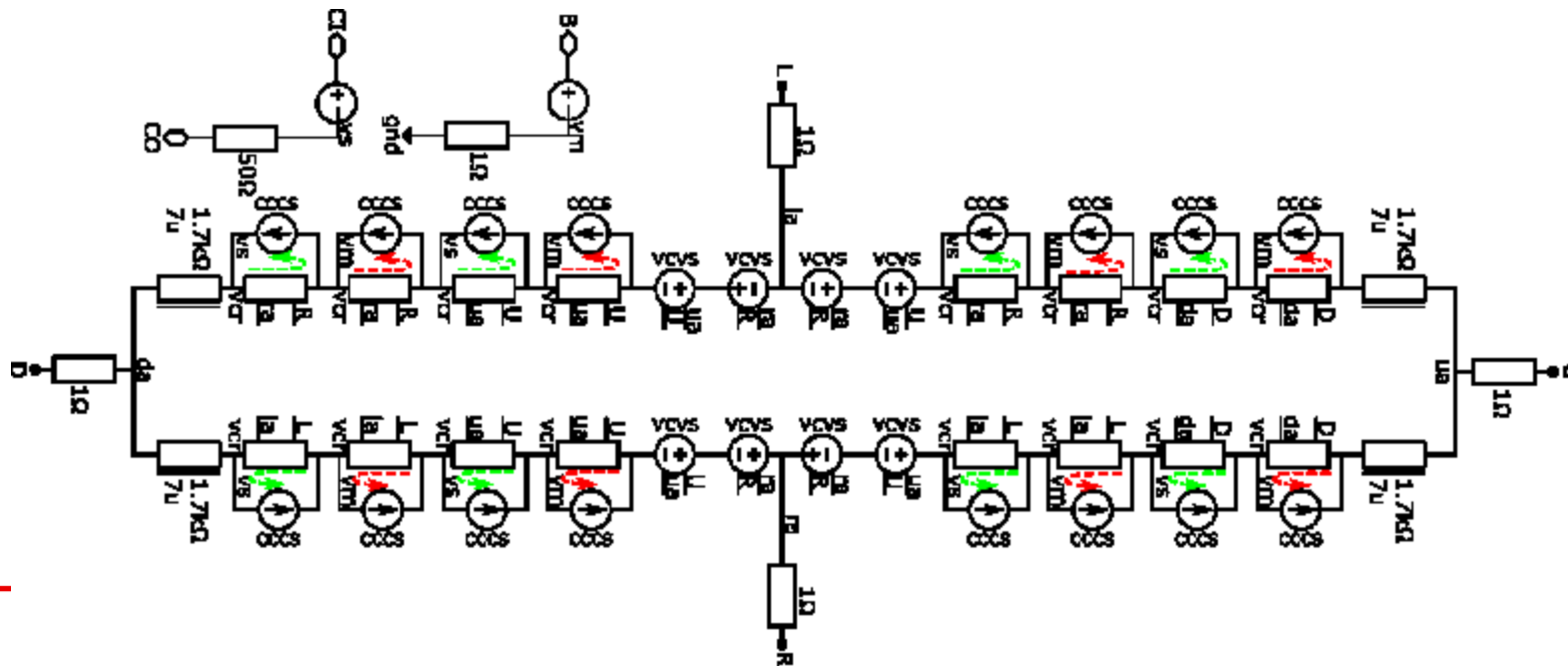
- Hall element is now a key player in the sensor systems and is projected to keep this position for many more years.
- Therefore the design community requires a reliable design tool, a simulation model covering most of the integrated Hall element characteristics.
- A sophisticated model of the Hall element shown in the figure has been developed covering most of the features of these sensors.



Integrated Magnetic Sensors

Hall element

Simplified schematic of hall element model.



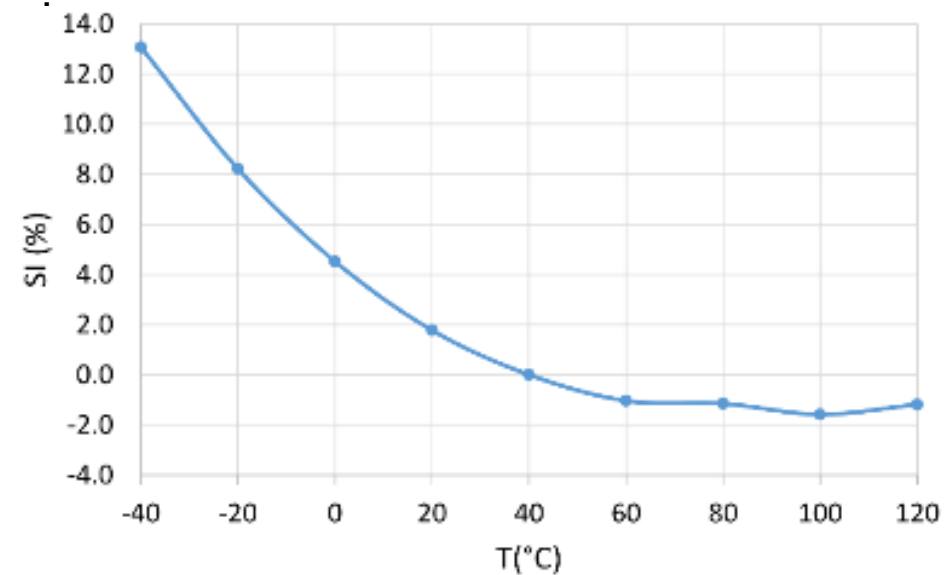


Integrated Magnetic Sensors

Hall element

Summary of the Hall element parameters for 180nm CMOS process

- Sensitivity (50 V/AT)
- Offset (11.5 μV) at 1 mA
- Noise (0.41 $\mu\text{T}/\sqrt{\text{Hz}}$)
- Temperature coefficient of the Sensitivity – SI (%)





Integrated Magnetic Sensors

Anisotropic Magneto Resistor sensors (AMR)

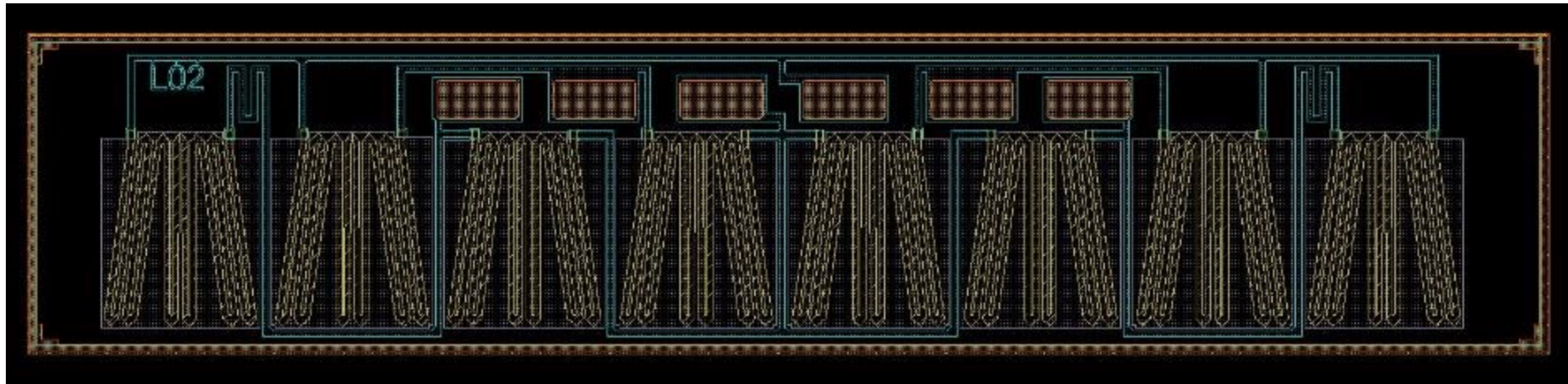
- These types of sensors have a potential to take over a small portion motion control market. They are more sensitive than Hall element, but are not compatible with CMOS technology. They can be fabricated on top of the CMOS chip using a thin layer deposition technique. They are sensitive to magnetic field parallel to the surface. Beside this phenomena they do not detect the direction of the magnetic field.
- Figure presents the dual bridge type position sensor.



Integrated Magnetic Sensors

Anisotropic Magneto Resistor sensors (AMR)

- Figure presents the dual bridge type linear position sensor.

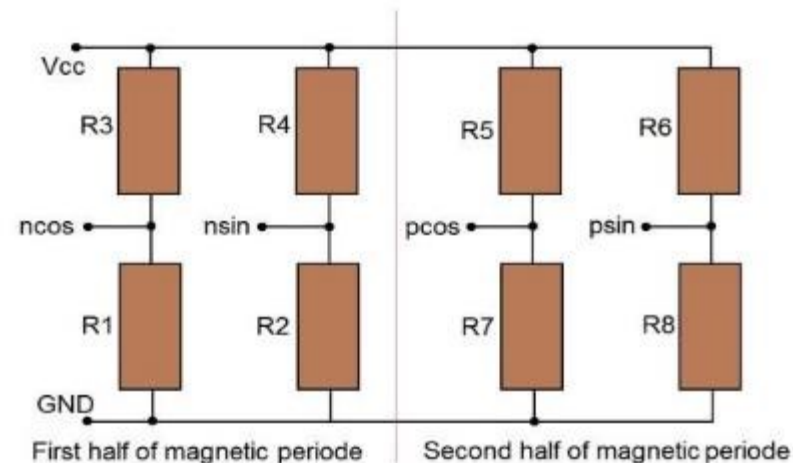




Integrated Magnetic Sensors

Anisotropic Magneto Resistor sensors (AMR)

- Figure presents the equivalent circuit.

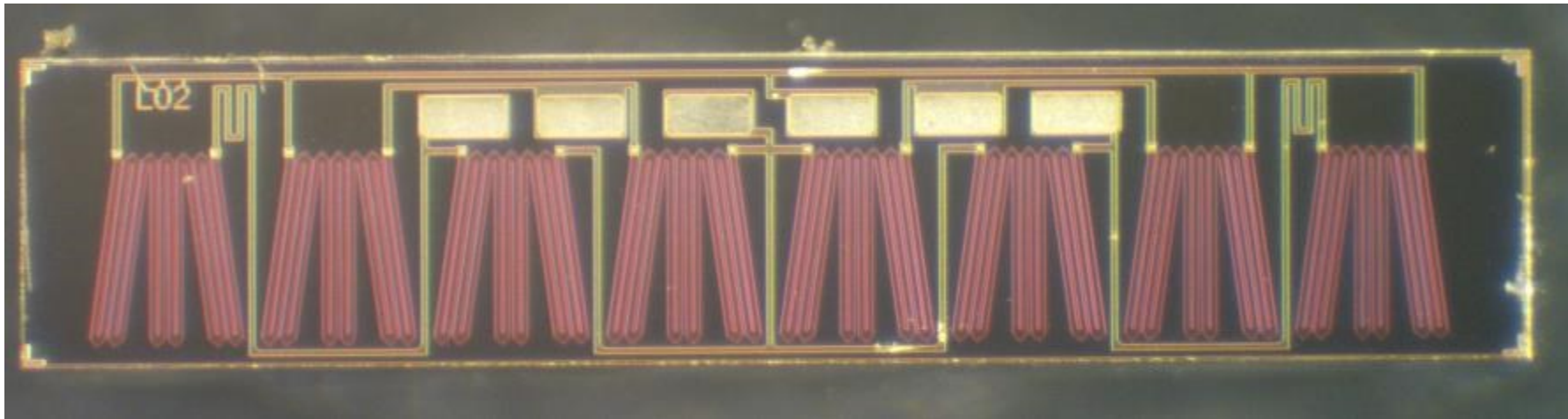




Integrated Magnetic Sensors

Anisotropic Magneto Resistor sensors (AMR)

- Microphotograph of the fabricated sensor.

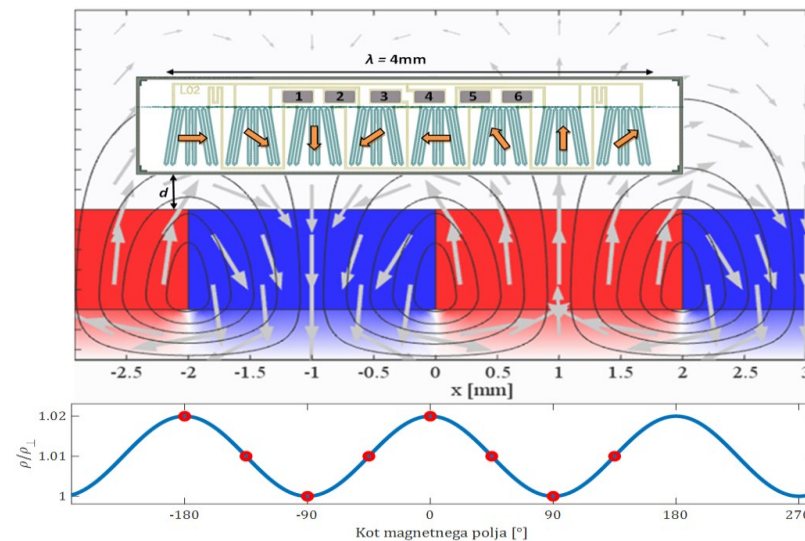




Integrated Magnetic Sensors

Anisotropic Magneto Resistor sensors (AMR)

- Application principle of the operation of the fabricated sensor.

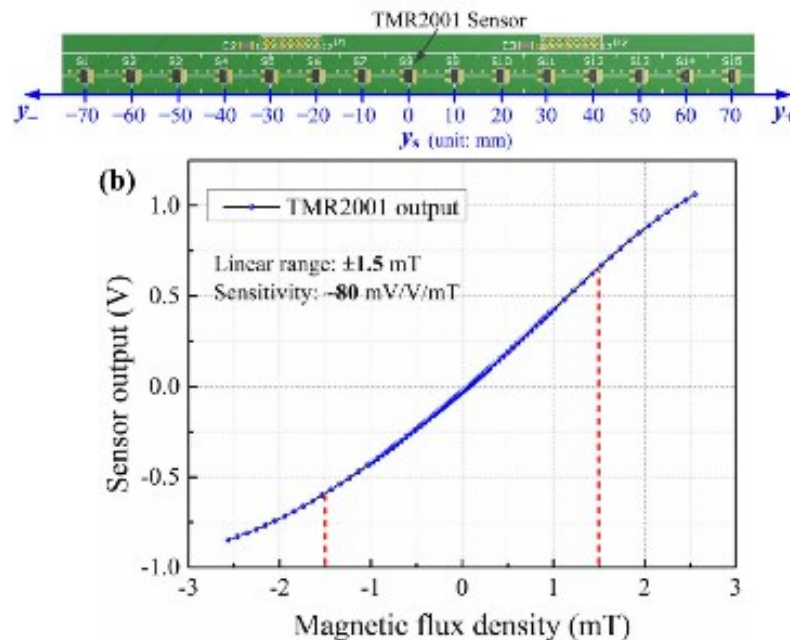




Integrated Magnetic Sensors

Tunnel Magneto Resistor sensor (TMR)

- The figure presents an application for linear positioning sensor. Unfortunately there is disadvantage of limited linear region from -1.5 mT to +1.5 mT.



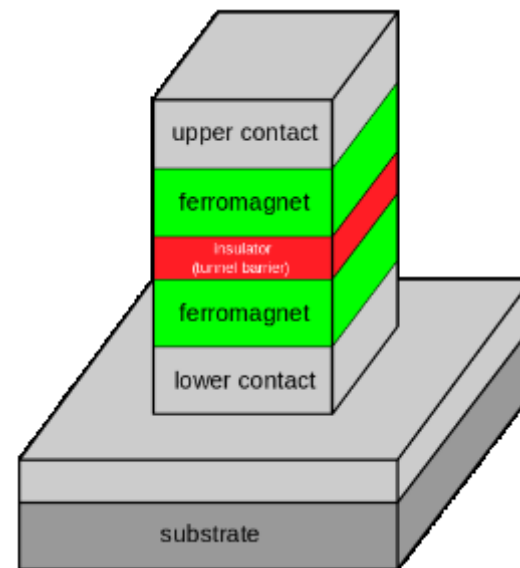
Xuyang, Liu & Han, Wei & Chunhua, Liu & Pong, Philip. (2018). Marker-Free Coil-Misalignment Detection Approach Using TMR Sensor Array for Dynamic Wireless Charging of Electric Vehicles. IEEE Transactions on Magnetics. PP. 1-5



Integrated Magnetic Sensors

Tunnel Magneto Resistor sensor (TMR)

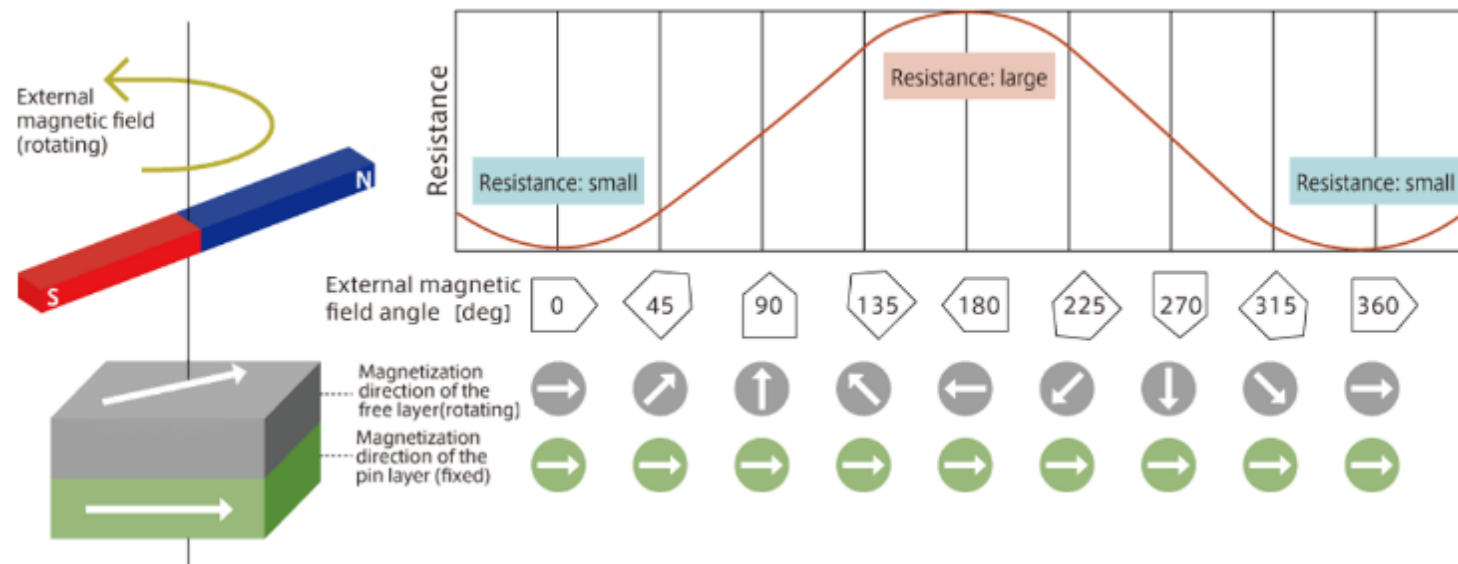
- The figure presents the layers of the TMR simplified structure.





Integrated Magnetic Sensors

Tunnel Magneto Resistor sensor (TMR)





Integrated Magnetic Sensors

Tunnel Magneto Resistor sensor (TMR)

- There is a huge disadvantage. As seen in figure it has an extremely low saturation threshold, which is hard to shield in the application.



Integrated Magnetic Sensors

Integrated Hall elements

Key parameters: FAVORABLE

- Low cost of fabrication due to integration without any fabrication process modification
- ease of creating smart sensors with a possibility to integrate the Hall element biasing circuit and signal processing and the same die, i.e. System on Chip (SoC)
- Robustness: Hall element is very robust as it operates over a large range of the input magnetic field.



Integrated Magnetic Sensors

Integrated Hall elements

Key parameters of Hall element: less favorable

- High power consumption due to large bias current
- Modest sensitivity
- High offset field when no spinning used
- High noise compared to competitive sensors
- Limited bandwidth due to signal settling time during spinning.



Integrated Magnetic Sensors

Integrated Hall elements

Most important innovations of integrated Hall element

- Spinning technique
- Vertical Hall element sensor
- Combination of Hall element and microcoil magnetic sensor
- Hall element array

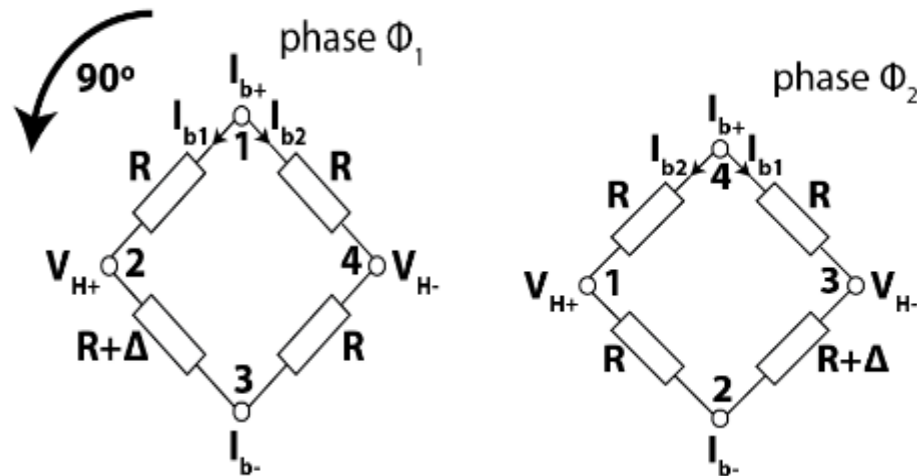


Integrated Magnetic Sensors

Integrated Hall elements

Most important innovations of integrated Hall element

- Simplified spinning technique



$$I_b = I_{b1} + I_{b2},$$

$$I_{b1} \approx I_{b2}$$

$$V_{off1} \approx \frac{I_b}{2} \cdot \Delta \approx V_{off}$$

$$V_{off2} \approx -\frac{I_b}{2} \cdot \Delta \approx -V_{off}$$

$$\Phi_1 = V_H + V_{off}$$

$$\Phi_2 = V_H - V_{off}$$

$$\Phi_1 + \Phi_2 = 2 \cdot V_H$$

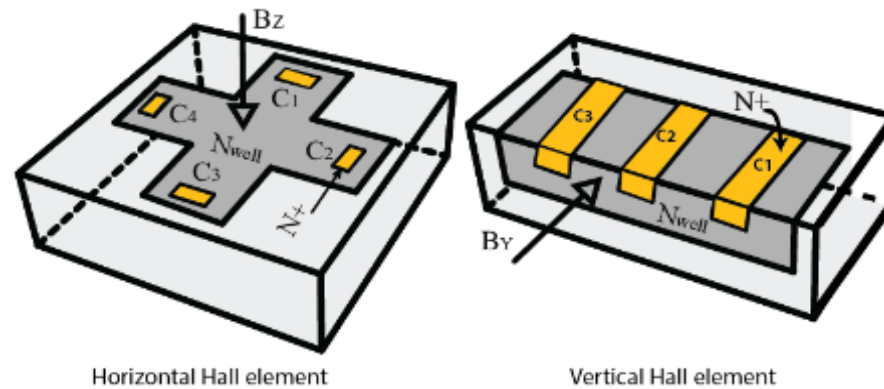
Integrated Magnetic Sensors



Integrated Hall elements

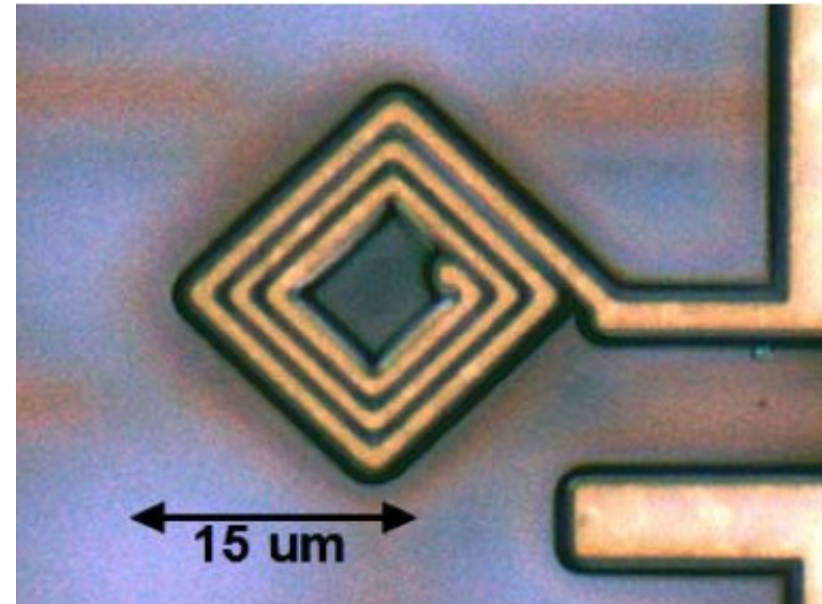
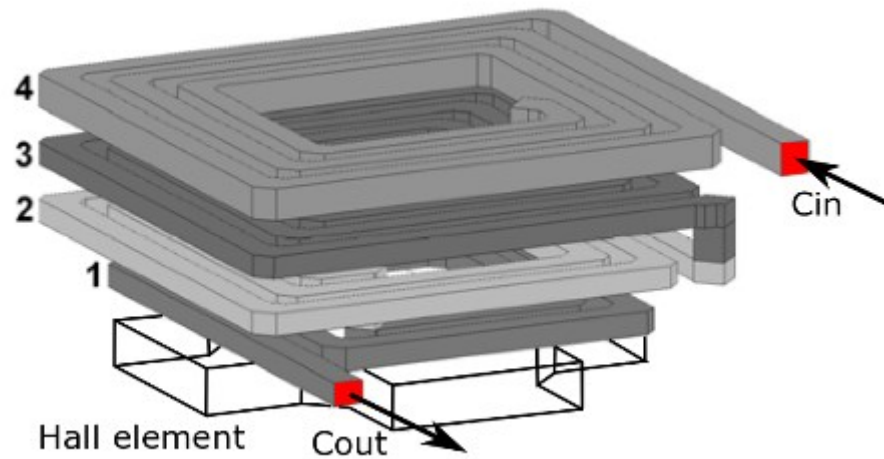
Most important innovations of integrated Hall element

vertical Hall element





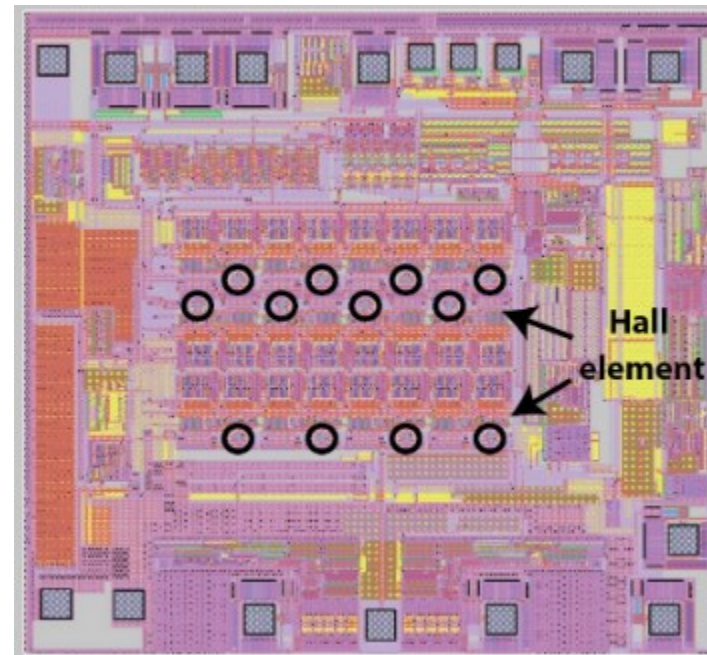
Integrated Microcoil





Integrated Magnetic Sensors

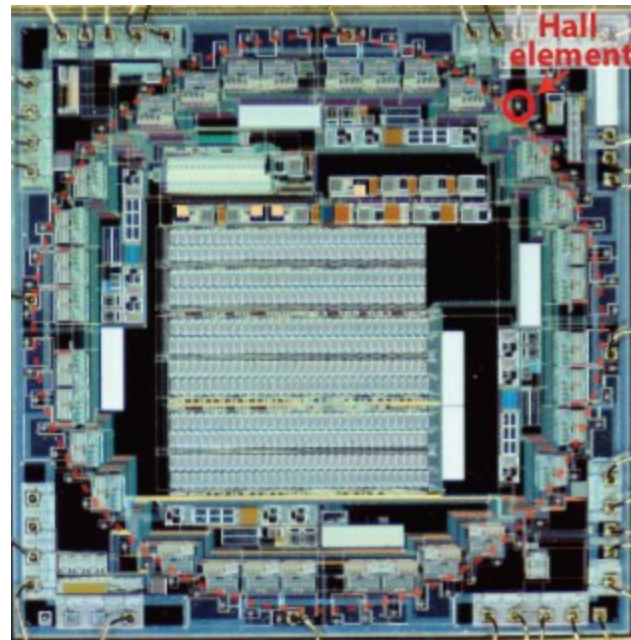
Examples of magnetic microsystems based on integrated Hall element array of 12 Hall elements





Integrated Magnetic Sensors

Examples of magnetic microsystems based on integrated Hall element array of 64 Hall elements





State of the Art of Magnetic Microsystems

- Motion control is a fast developing activity. The market projection predicts that in five years from now the total market will grow up to one and a half billion US dollars. For magnetic sensors, a half of it would be Hall elements.
- The developments which we achieved were in the area of sensitivity boosting, signal to noise improvements and current consumption reduction.



State of the Art of Magnetic Microsystems

- The results look promising. In the realistic industrial project we can achieve sensitivity boosting about 10 times, signal to noise improvement about four times and current consumption also reduction up to 10 times, without seriously increasing the production cost.
- The low production cost is the driving force for Hall elements systems winning over the competitors. With the mature production technology and with improved design, the gap between Hall element system versus TMR or AMR in terms of performance is narrowing but the production cost and reliability remains the big advantage.



Conclusions

- It is our experience that Hall elements sensor system for motion control is on a good track to keep the first place on the market according to the projection prediction with more than 50% of market share. This is the reason to continue with the research and development work in the future.



MAGNETIC SENSOR SYSTEM FOR MOTION CONTROL

Thank you!

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