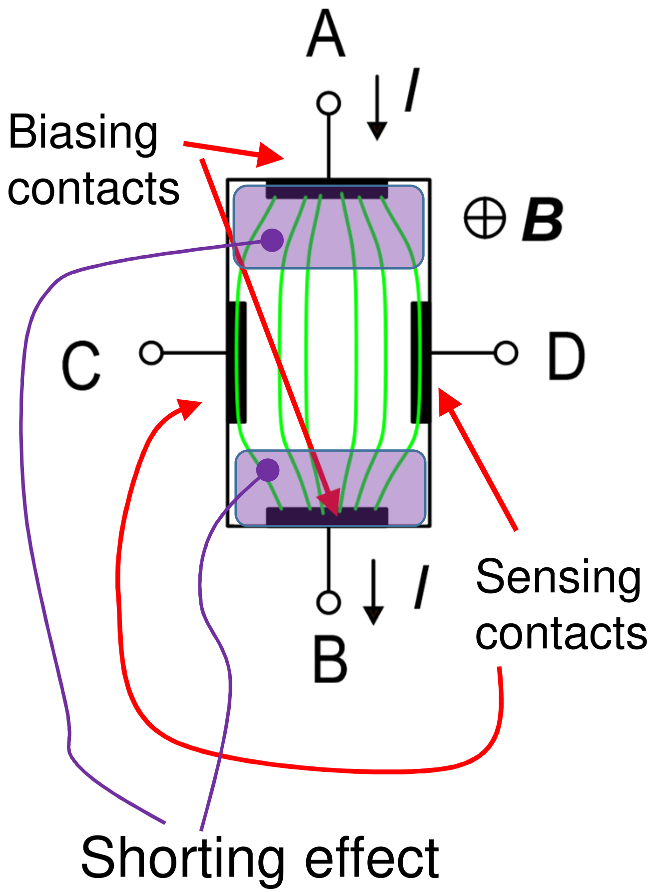
Hall sensors: a more accurate expression



$$V_H = G \cdot r_h \cdot \frac{1}{qnd} I \cdot B$$

Geometrical effects:

- The sensing contacts "short" the Hall voltage in their proximity (shorting effect). The full V_H develops only far from the sensing contacts

- Current lines are not straight and parallel, due to the effect of both the sensing and biasing contacts

***G*<1**

- Scattering factor: it takes into account the real complexity of the charge carrier scattering (random thermal velocity and drift velocity, etc)

$$r_h = \frac{\mu_H}{\mu}$$

μ_H="Hall mobility"

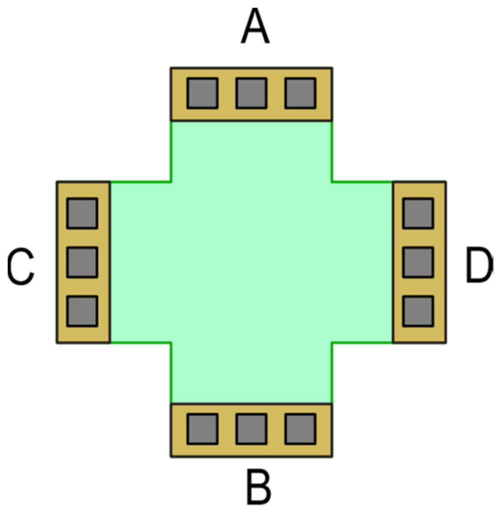
Absolute sensitivity

$$V_H = G \cdot r_h \cdot \frac{1}{qnd} I \cdot B$$

Absolute sensitivity:

$$S_A = \frac{V_H}{B} = G \cdot r_h \cdot \frac{1}{qnd} I$$

Example of layout: symmetric cross



$G \cong 0.9$ (0.85-0.95)
r_H (Si) ~ 1.15

Possible implementation in a CMOS process

Advantages:

1) Symmetry (bias and sensing contact can be swapped)
2) Minimum perturbation caused by sensing contacts

More on sensitivity:

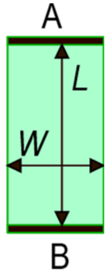
$$S_A = G \cdot r_h \cdot \frac{1}{qnd} I$$

The larger the bias current I, the larger the sensitivity. However, increasing the current causes V_{AB} and the dissipated power P_D to increase as well.

$$V_{AB} = R_{AB} I \qquad P_D = R_{AB} I^2$$

$$R_{AB} = \frac{\rho}{d} F_S \qquad \rho = \frac{1}{\sigma} = \frac{1}{qn\mu}$$

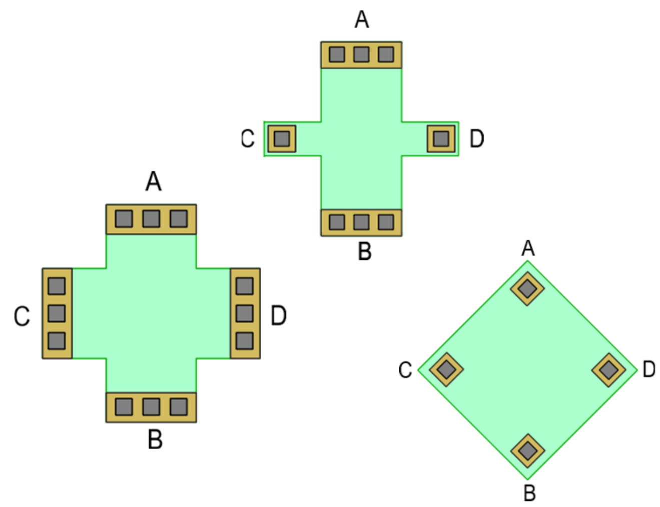
For a rectangular conductor: $F_S = L/W$



Dissipated power: $$P_D = \frac{1}{qn\mu d} F_S I^2$$

G and F_S are dimensionless factors depending on the shape

Example of shapes



Power vs sensitivity efficiency

$$S_A = G \cdot r_h \cdot \frac{1}{qnd} I \qquad P_D = R_{AB} I^2 = \frac{1}{qn\mu d} F_S I^2 \Rightarrow I = \sqrt{\frac{qn\mu d}{F_S}} \cdot \sqrt{P_D}$$

$$S_A = G \cdot r_h \cdot \frac{1}{qnd} \underbrace{\sqrt{\frac{qn\mu d}{F_S}} \cdot \sqrt{P_D}}_{I} = G \cdot r_h \cdot \sqrt{\frac{\mu}{qnd} \frac{1}{F_S}} \cdot \sqrt{P_D}$$

For the same power dissipation, the sensitivity is higher for materials with:

- Highest mobility (μ)
- Lowest charge carrier density (***n***)

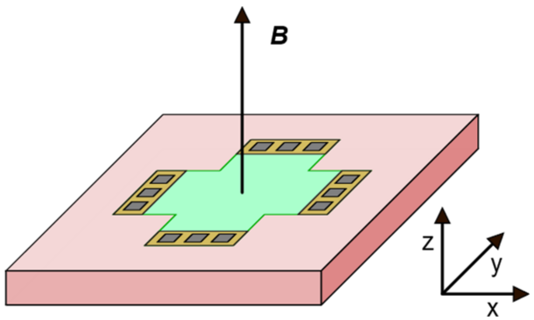
Materials used for Hall sensors

Material	**E_g (eV)**	**μ_n cm^{-2}V^{-1}s^{-1}**
Si	1.12	~ 1000
GaAs	1.42	~ 8000
InAs	0.36	~ 33000
InSb	0.17	~ 80000

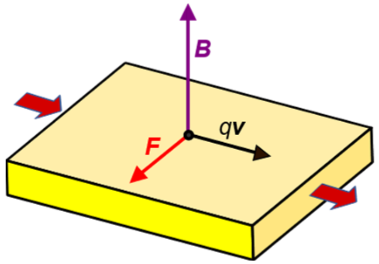
Despite having the smallest sensitivity, Silicon is by far the preferred material for fabrication of Hall Sensors, for the following reasons:

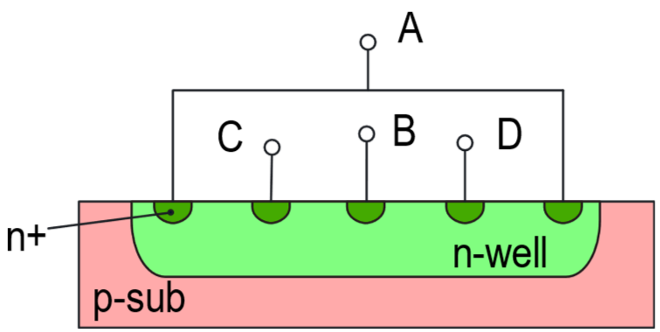
1) Cost (sensors can be fabricated with standard CMOS processes)
2) Allows integration with complex readout interfaces on the same chip (miniaturization, cost, robustness, electromagnetic immunity)

Integrated 3-axis Hall magnetometers.

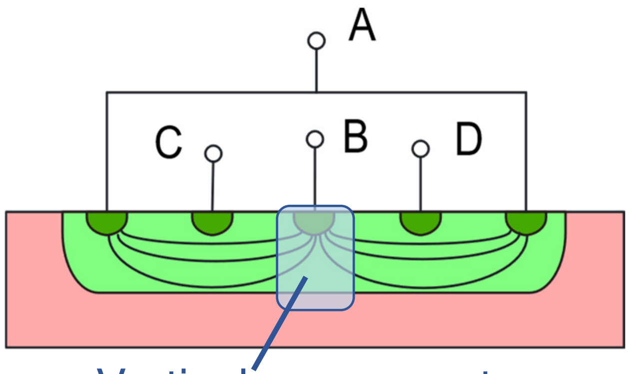


Horizontal (planar) Hall plates are sensitive only to the component of ***B*** orthogonal to the substrate surface (B_z)



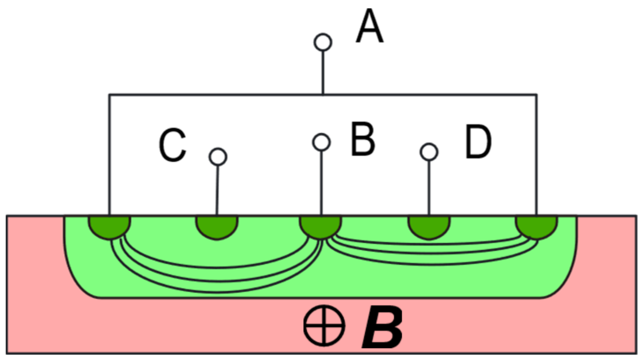


Vertical Hall Sensor (VHS)



$B_y=0$

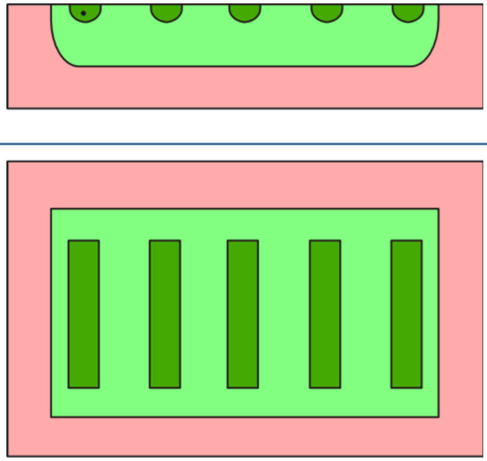
(symmetry, $V_H=V_{CD}=0$)



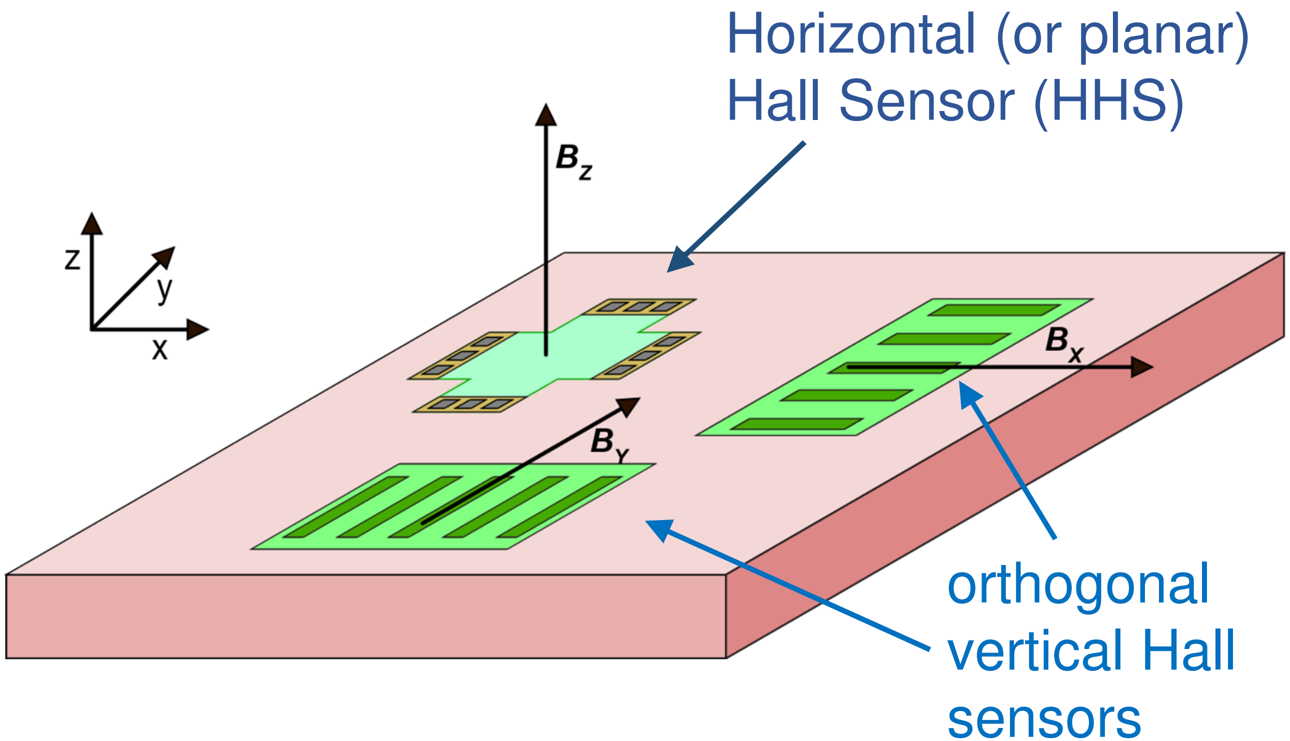
$B_y \neq 0$

(asymmetry, $V_H=V_{CD} \neq 0$)

Single-chip, 3-D magnetometer



Top view of a VHS



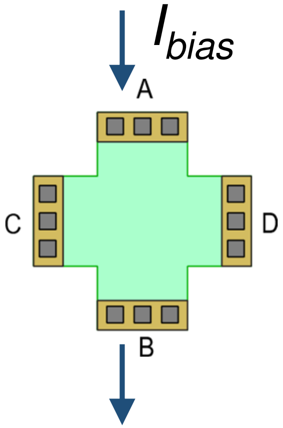
A single-chip, CMOS compatible 3-D magnetometer can be obtained by combining an HHS and two orthogonal VHS

Main non-idealities of Hall Sensors

- Offset voltage
- Temperature dependence of the sensitivity
- Non-linearity
- Noise

- The offset is by far the problem that limit the performances of the Hall sensors. We will focus mainly on this aspect.
- Temperature dependence is reduced by driving the sensor with a constant current and applying temperature compensation in the estimation process.
- Non-linearity occurs at very large fields and can be compensated in the digital domain by a proper non-linear estimator.
- Thermal noise is generally not an issue, due to the small output resistance of the sensor (typically of the order of 1 kΩ in integrated sensor). Flicker noise can be more important.

Just a mention to current vs voltage biasing



$$S_A = G \cdot r_h \cdot \frac{1}{qnd} I_{bias}$$

$$S_A = G \cdot r_h \cdot \frac{1}{qnd} \frac{V_{AB}}{R_{AB}} \quad I_{bias}$$

$$R_{AB} = \frac{1}{\sigma d} F_S \qquad \sigma = qn\mu \qquad S_A = G \cdot r_h \cdot \frac{1}{qnd} \frac{qn\mu d}{F_S} V_{AB}$$

$$S_A = G \cdot r_h \cdot \frac{\mu}{F_S} V_{bias}$$

$(V_{bias} = V_{AB})$

$$\begin{cases} S_A = S_I I \\ S_A = S_V V_{bias} \end{cases}$$

$$S_I = G \cdot r_h \cdot \frac{1}{qnd}$$ Current-related sensitivity

$$S_V = G \cdot r_h \cdot \frac{\mu}{F_S}$$ Voltage-related sensitivity

Just a mention to current vs voltage biasing

$$
\begin{cases}
S_A = S_I I \\
S_A = S_V V_{bias}
\end{cases}
$$

$$S_I = G \cdot r_h \cdot \frac{1}{qnd}$$

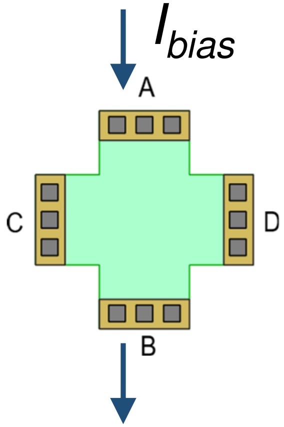
Temperature affects only the carrier concentration n, which, in a doped semiconductor is practically constant

$$S_V = G \cdot r_h \cdot \frac{\mu}{F_S}$$

Temperature affects only mobility, which has a strong temperature dependence

Constant current biasing is generally the preferred choice

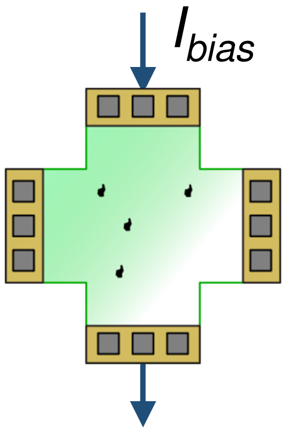
Offset voltage and equivalent magnetic field offset



$$V_H = V_{CD} = S_A B_Z + V_{offset} \qquad V_H = S_A \left(B_Z - B_{Zio} \right)$$

$$B_{Zio} = -\frac{V_{offset}}{S_A}$$ Equivalent offset magnetic field

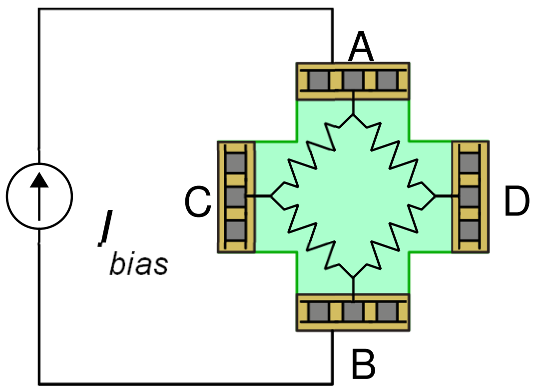
Origin of the offset voltage V_{offset}:



Non uniform resistivity due to:

- Parameter gradients
- Local non homogeneity (defects, etc)
- Mechanical stress associated with material piezoresistivity

Simple offset model

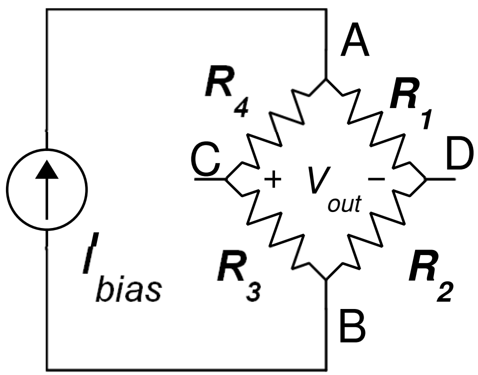


$$V_{offset} = V_C - V_D$$

$$V_{offset} = I_{bias}\frac{(R_1+R_2)R_3}{R_1+R_2+R_3+R_4} - I_{bias}\frac{(R_3+R_4)R_2}{R_1+R_2+R_3+R_4}$$

$$V_{offset} = I_{bias}\frac{R_1R_3 + R_2R_3 - R_4R_2 - R_3R_2}{R_1+R_2+R_3+R_4}$$

$$R_1+R_2+R_3+R_4 = R_T$$



$$V_{offset} = I_{bias}\frac{R_1R_3 - R_4R_2}{R_T}$$

$$V_{offset} = 0 \Rightarrow R_1R_3 = R_4R_2 \quad \Leftrightarrow \quad \frac{R_3}{R_4} = \frac{R_2}{R_1}$$

Balanced bridge

Due to unavoidable asymmetries the bridge is unbalanced, and a significant offset appears

Offset magnetic field

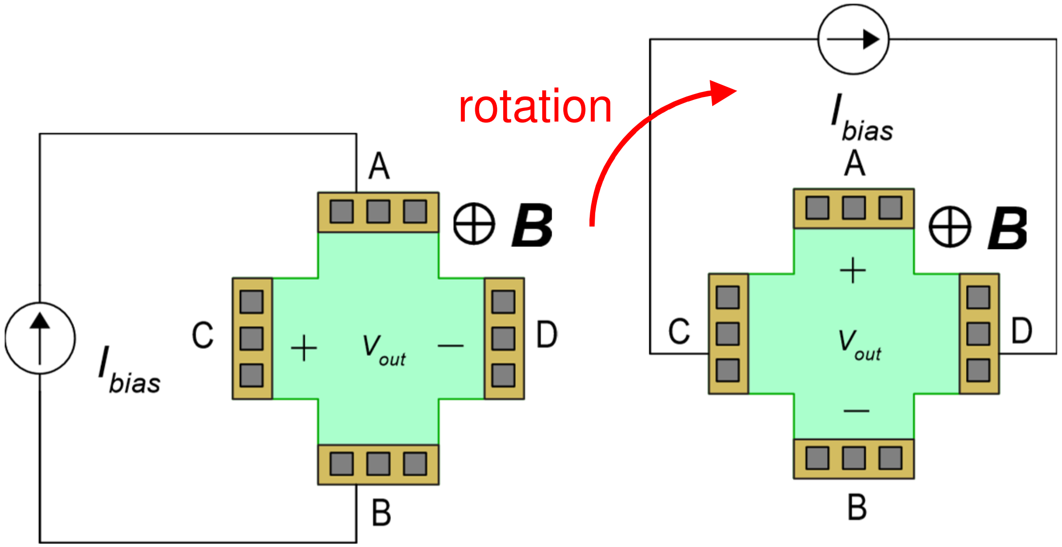
- Typical offset voltage that are observed in silicon integrated planar Hall sensors are of the order of 10 mV
- Current related sensitivities, S_I, are of the order of 400 V/A/T
- With bias currents of the order of 1 mA , the absolute sensitivity, S_A, is of the order of 0.4 V /T.

$$\left|B_{Zio}\right| = \frac{\left|V_{offset}\right|}{S_A} = \frac{10\times10^{-3}}{0.4} = 25 \text{ mT}$$

This offset value is often larger than the field to be measured!

The offset of Hall sensors is also marked by important temperature drift, so that standard offset cancellation techniques (e.g. zero calibration) generally leave a large residual offset.

Principle of current spinning approach to offset cancellation

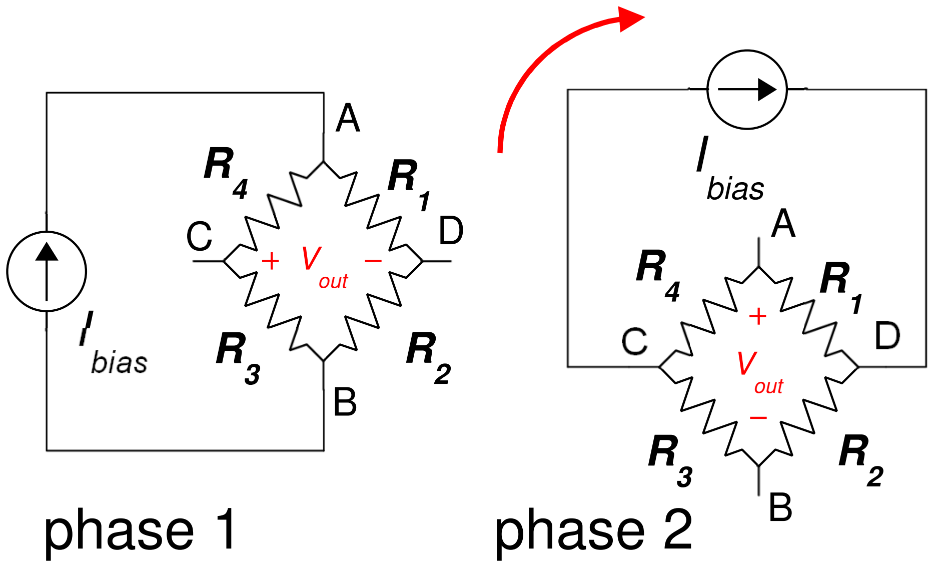


phase 1

phase 2: 90° rotation of both the bias and sensing axis.

Thanks to the symmetry of the layout, the voltage induced by the field B does not change after the rotation.

Effect of the terminal rotation on the offset voltage



phase 1

$$V_{offset}^{(1)} = I_{bias} \frac{R_1 R_3 - R_4 R_2}{R_T}$$

The rotation simply changes the terminals in such a way:

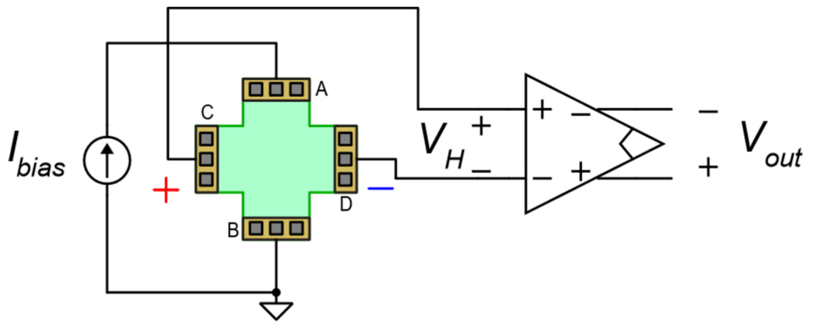
$$R_1 \to R_2, \quad R_2 \to R_3, \quad R_3 \to R_4, \quad R_4 \to R_1$$

Making all resistor transformations:

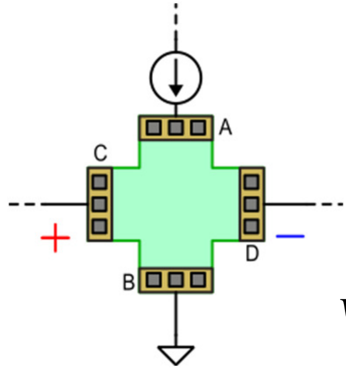
$$V_{offset}^{(2)} = I_{bias} \frac{R_2 R_4 - R_1 R_3}{R_T} = -V_{offset}^{(1)}$$

The useful signal, $S_A B_Z$, remain the same, the offset undergoes sign reversal

Current spinning

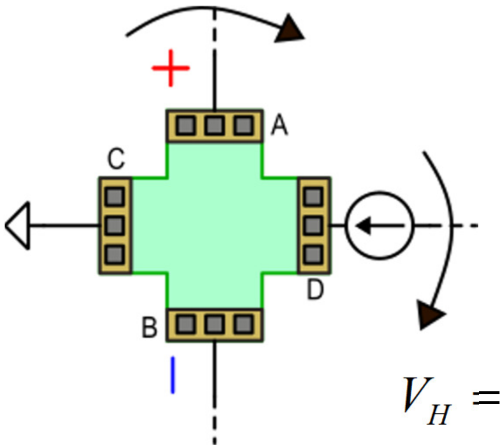


Let us start from this connection



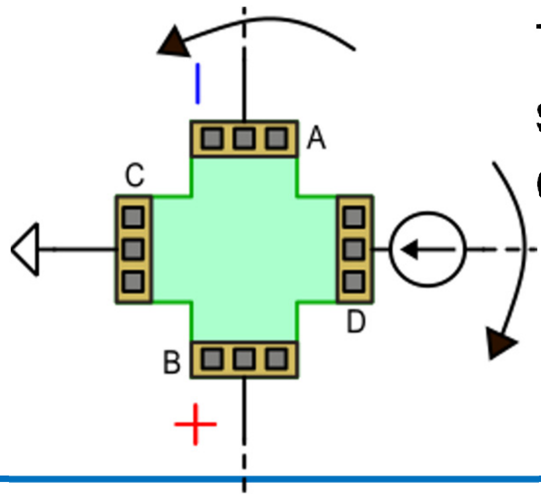
$$V_H = V_{CD} = S_A B_Z + V_{offset}$$

... that can be represented in this way



Turning the bias and sensing terminals in the same direction:

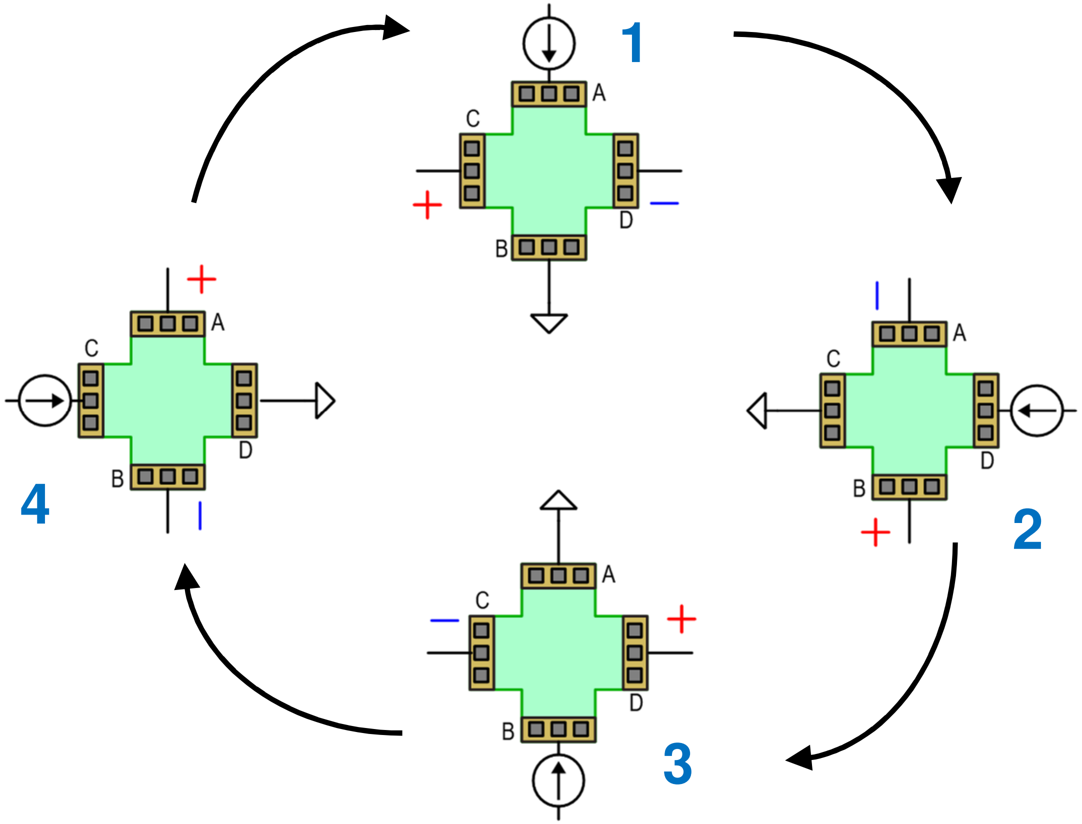
$$V_H = V_{CD} = S_A B_Z - V_{offset}$$

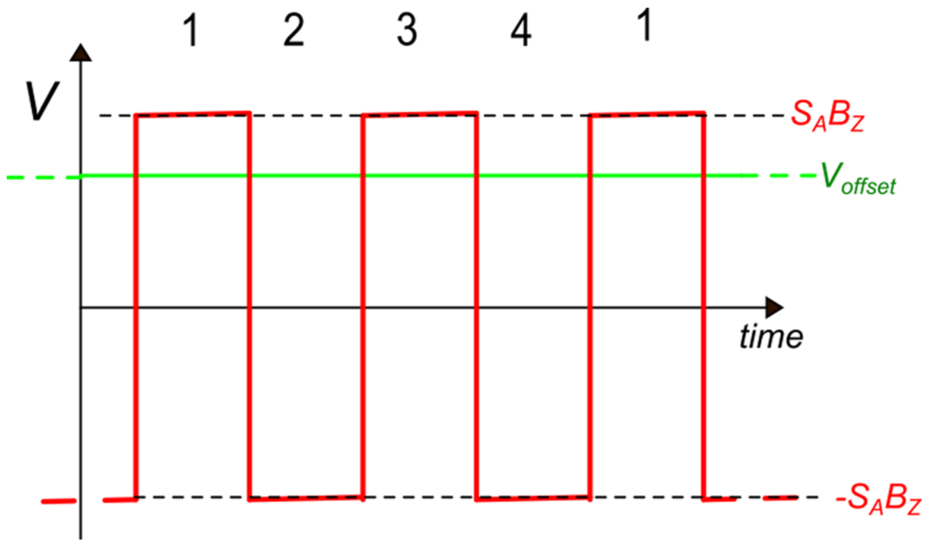


Turning the bias and sensing terminals in opposite directions:

$$V_H = -S_A B_Z + V_{offset}$$

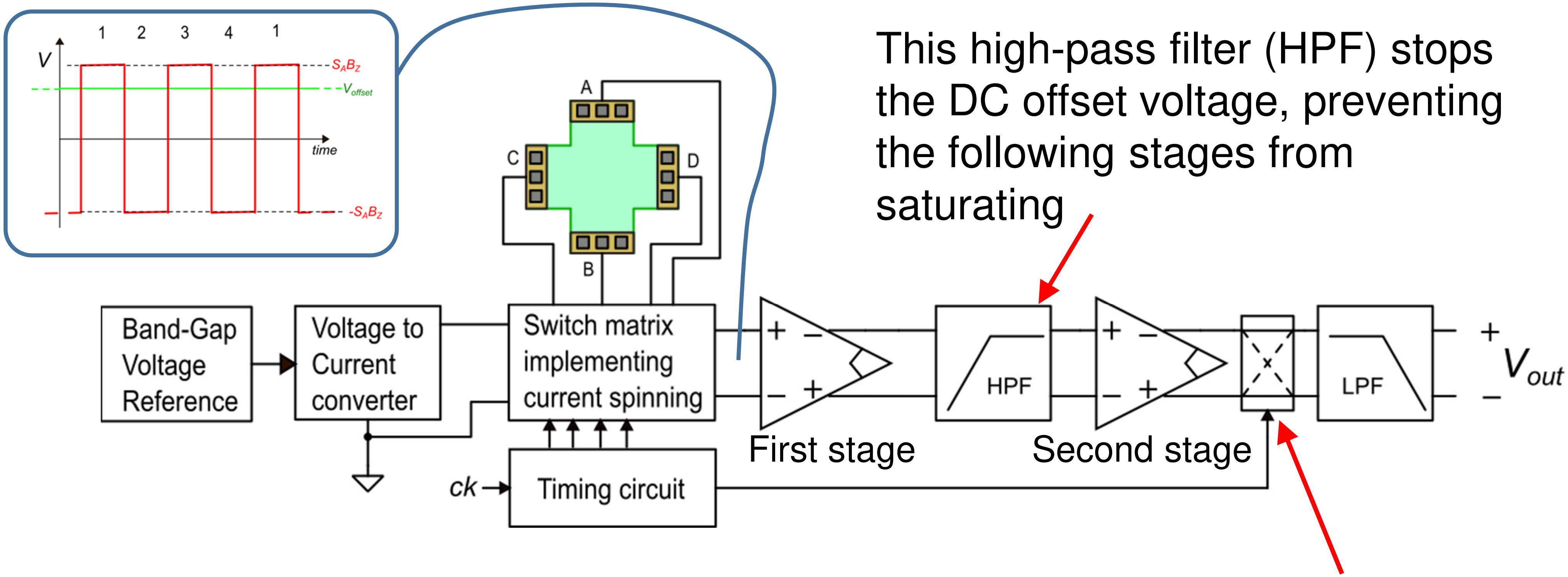
Current spinning





Current spinning applied by rotating the biasing and sensing axis in opposite directions leaves the offset in DC, while modulates the useful signal ($S_A B_Z$)

Possible interface circuit for Hall sensors



This high-pass filter (HPF) stops the DC offset voltage, preventing the following stages from saturating

The demodulator brings the useful signal back to baseband and shifts the DC offset and flicker noise of the second stage to high frequencies, where it is rejected by the low-pass filter (LPF)

Magnetometer based on Hall sensors: open problems

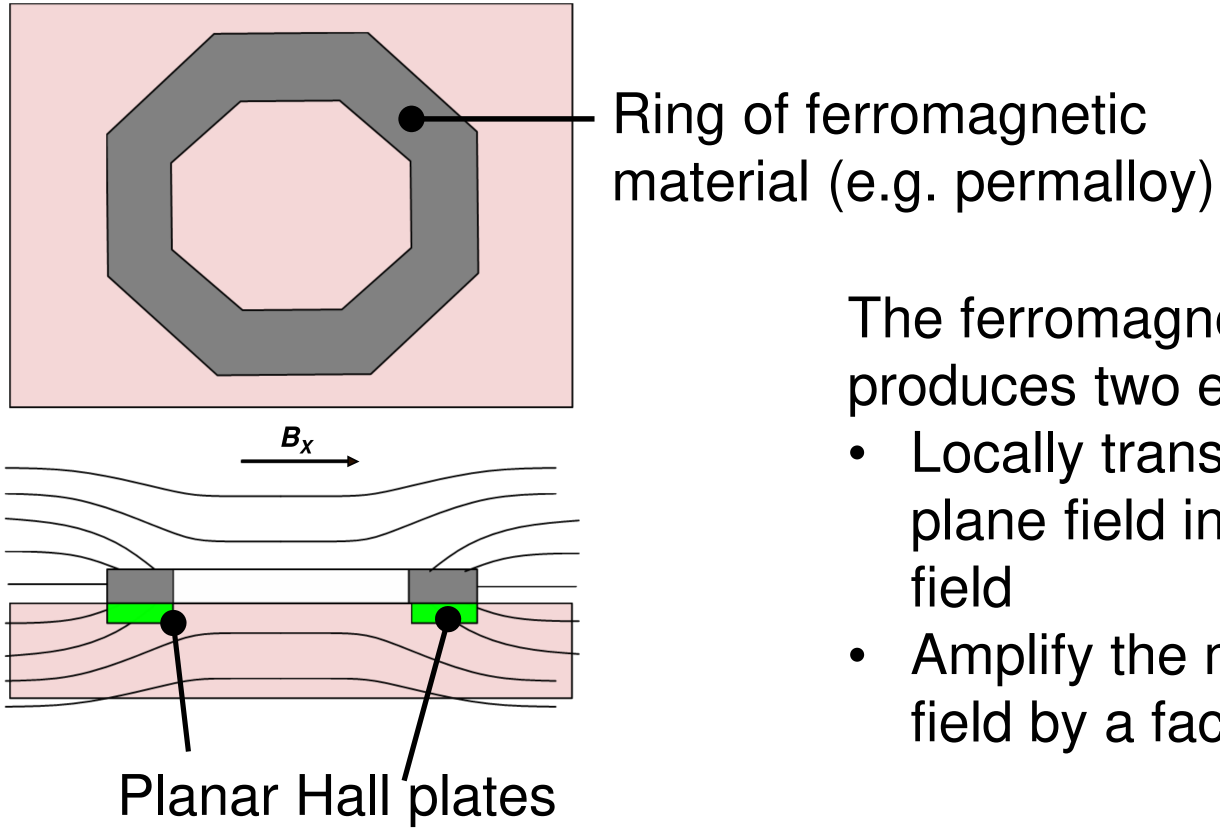
- Performance with small fields

  The spinning approach can reduce the offset field (B_{io}) by more than a factor of 100, but a residual offset in the order of 10-100 mT typically remains. This is comparable with the Earth's magnetic field and is not compatible with fabrication of an accurate magnetic compass.

- Reduced performance of vertical Hall Sensors: These sensors have typically a smaller sensitivity than planar hall sensors: Furthermore, they do not present symmetry between biasing and sensing contacts, and this makes the spinning approach less effective.

Classical Silicon-based Hall sensors are not suitable for fabrication of e-compasses

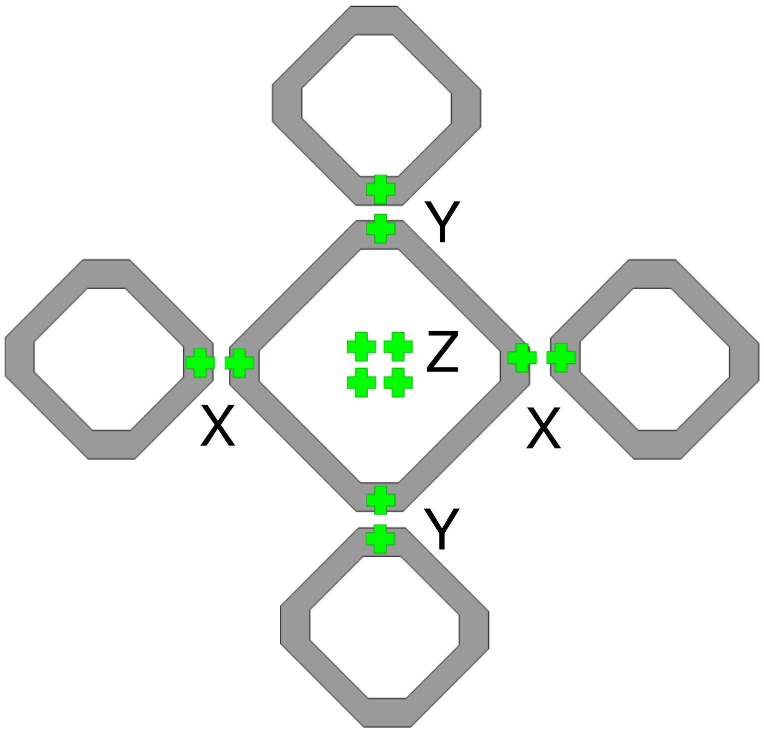
Possible solution for 3D sensors: application of magnetic concentrators



The ferromagnetic ring produces two effects:

- Locally transform an in-plane field into a vertical field
- Amplify the magnetic field by a factor 3-8

Commercial product: a single-chip, three axis e-compass



Melexis MLX90333

The magnetic field amplification is maximum at the gaps between the ferromagnetic rings

Each axis is read by four hall plates whose output signals are summed at the amplifier input: this boost the sensitivity and reduce the offset.
The Z axis does not benefit from the magnetic field amplification caused by the concentrators.

Requires deposition of a thick (20 μm) ferromagnetic layer.
The ferromagnetic layer can acquire permanent magnetization