HALL MAGNETIC SENSOR DEVICES

Radivoje S. Popovic

EPFL, Swiss Federal Institute of Technology
Lausanne, Switzerland,

and

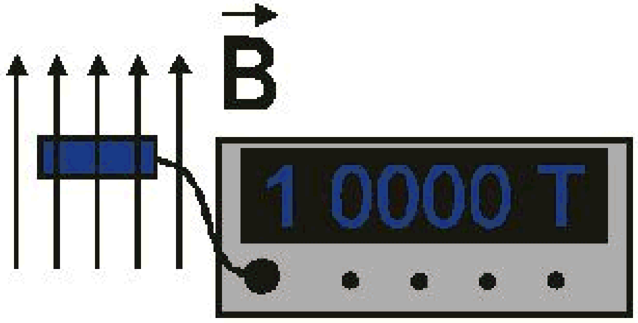
SENIS AG, Zug, Switzerland

Why HALL MAGNETIC SENSORS?

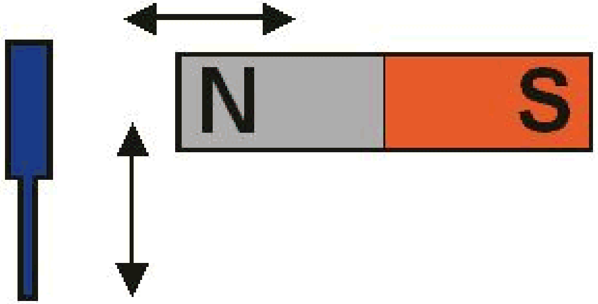
- High measurement range: from <10µT to >20T
- High spatial resolution: <1µm
- Broad bandwidth: DC to >1MHz
- Vector sensitivity
- Compatible with IC technologies
- Good performance – cost ratio

Typical Applications of Hall Devices

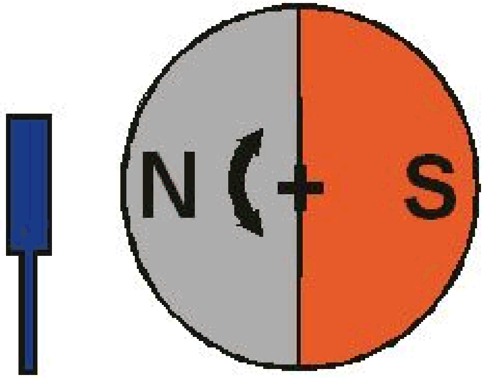
Magnetometry



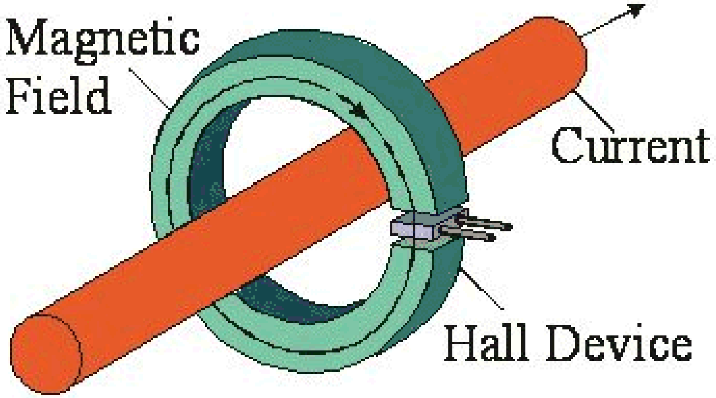
Translation Displacement



Rotary Displacement



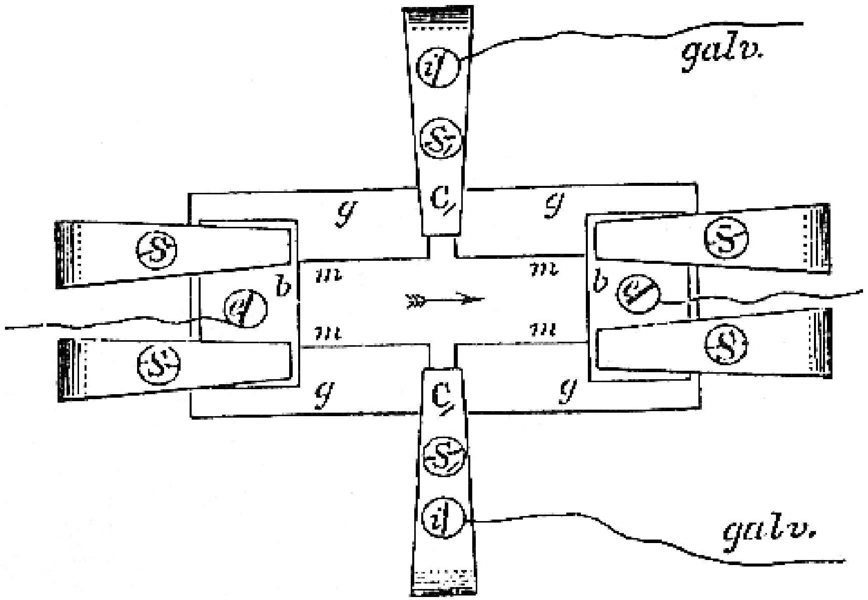
Current Measurement

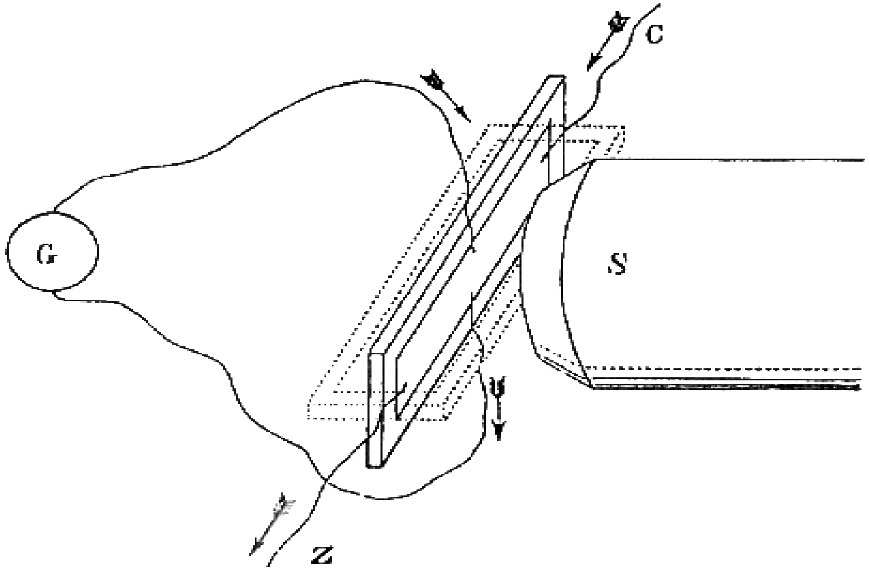


Outline

- The Hall Effect
- Magnetic Sensitivity
- Technology and Geometry
- Horizontal and Vertical Hall Devices
- 3-Axis Hall Magnetic Sensor
- Parasitic Effects

The Hall Effect



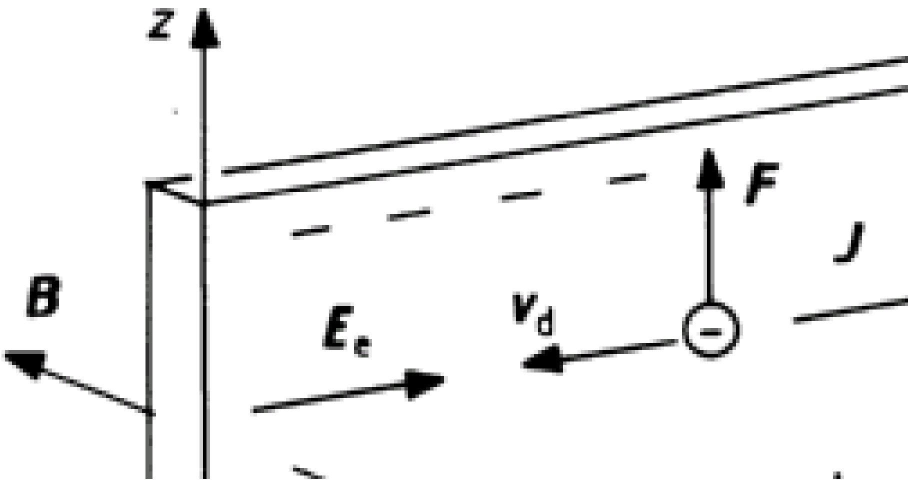


Edwin Hall:

“On a new action of the magnet on electric current” Am.J.Math. **2** (1879) pp.287–92

$$V_H \propto I \cdot B$$

The Hall Electric Field



Lorentz Force: $\boldsymbol{F} = e\boldsymbol{E} + e[\boldsymbol{v} \times \boldsymbol{B}]$

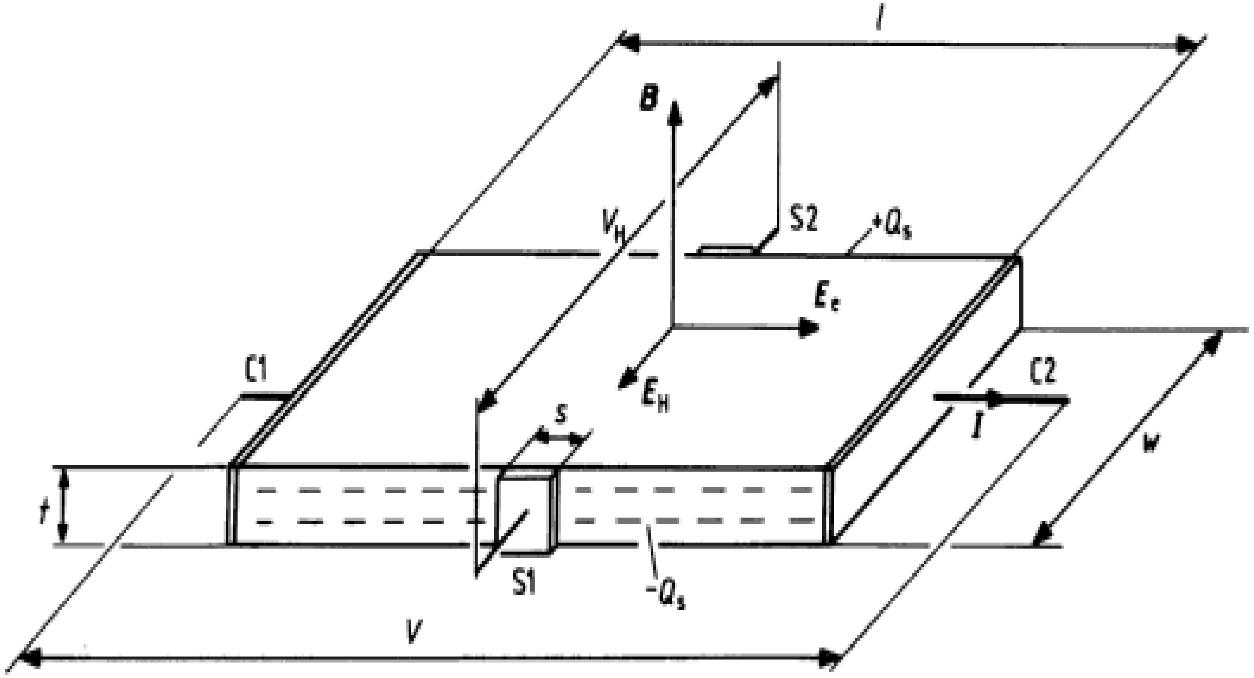
Electron Drift: $\boldsymbol{v}_{dn} = \mu_n \boldsymbol{E}_e$ $\boldsymbol{J}_n = q\mu_n n\boldsymbol{E}_e$

Force || z = 0: $e[\boldsymbol{v}_d \times \boldsymbol{B}] + e\boldsymbol{E}_H = 0$

Hall Electric Field: $\boldsymbol{E}_{Hn} = \mu_n[\boldsymbol{E} \times \boldsymbol{B}]$ $\boldsymbol{E}_{Hn} = \frac{1}{qn}[\boldsymbol{J} \times \boldsymbol{B}]$

Hall Coefficient: $R_{Hn} = -\frac{1}{qn}$ $\boldsymbol{E}_H = -R_H[\boldsymbol{J} \times \boldsymbol{B}]$

Hall Voltage & Magnetic Sensitivity



Hall Voltage: $$V_H = \int_{S1}^{S2} \boldsymbol{E}_H \, \mathrm{d}\boldsymbol{w}$$

$$V_H = E_H w$$

$$\boldsymbol{E}_{Hn} = \mu_n [\boldsymbol{E} \times \boldsymbol{B}]$$ ⇨ $$V_H = \mu_n \frac{V}{l} w B_\perp$$ ⇨ $$V = RI = \frac{1}{q\mu_n n} \frac{l}{wt} I$$

$$V_H = S_V \, \mathrm{V} \, B_\perp$$

$$V_H = S_I \, I \, B_\perp$$

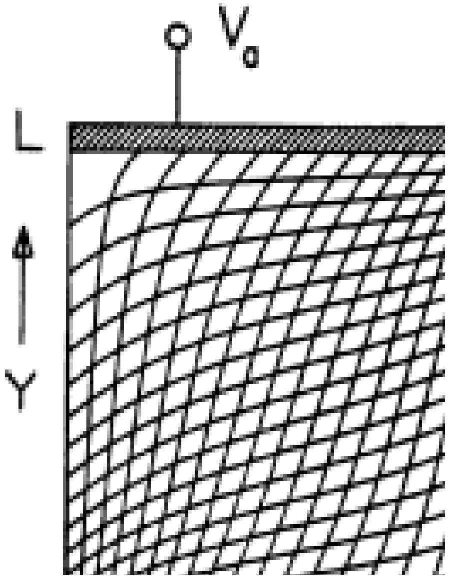
Voltage-Related Sensitivity:

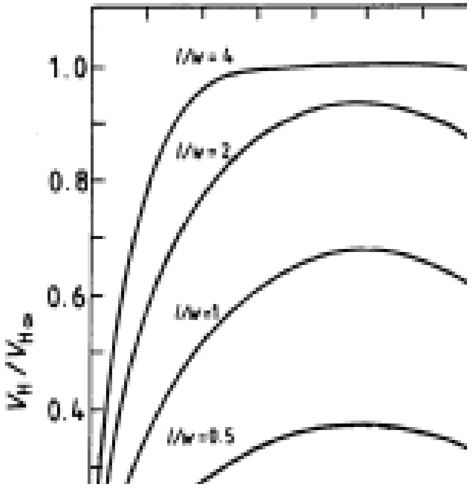
$$S_V \approx \mu_n \frac{w}{l}$$

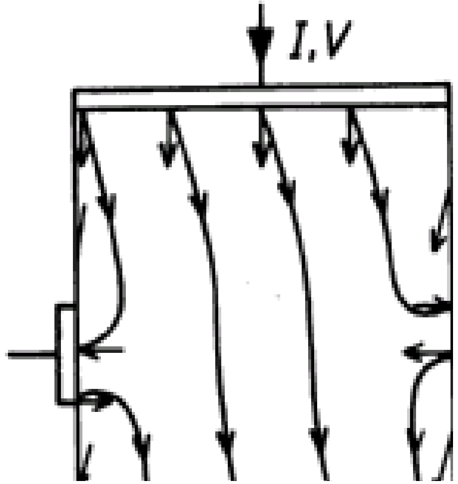
Current-Related Sensitivity:

$$S_I \approx \frac{1}{q\,n\,t} \approx \frac{R_H}{t}$$

Geometrical Factor of Hall Voltage







Short – circuiting effects by the electrodes!

$\boldsymbol{G_H = V_H / V_{H\infty}}$ $\rightarrow$ $V_H = G_H \dfrac{R_H}{t} I B_\perp$

Typically, $G_H \approx 0.3 \ldots. 0.7$

Magnetic Sensitivity

- Absolut Sensitivity: $S_A = \left| \frac{V_H}{B_\perp} \right|_c$
- Relative Sensitivity

Current-related:

Voltage-related:

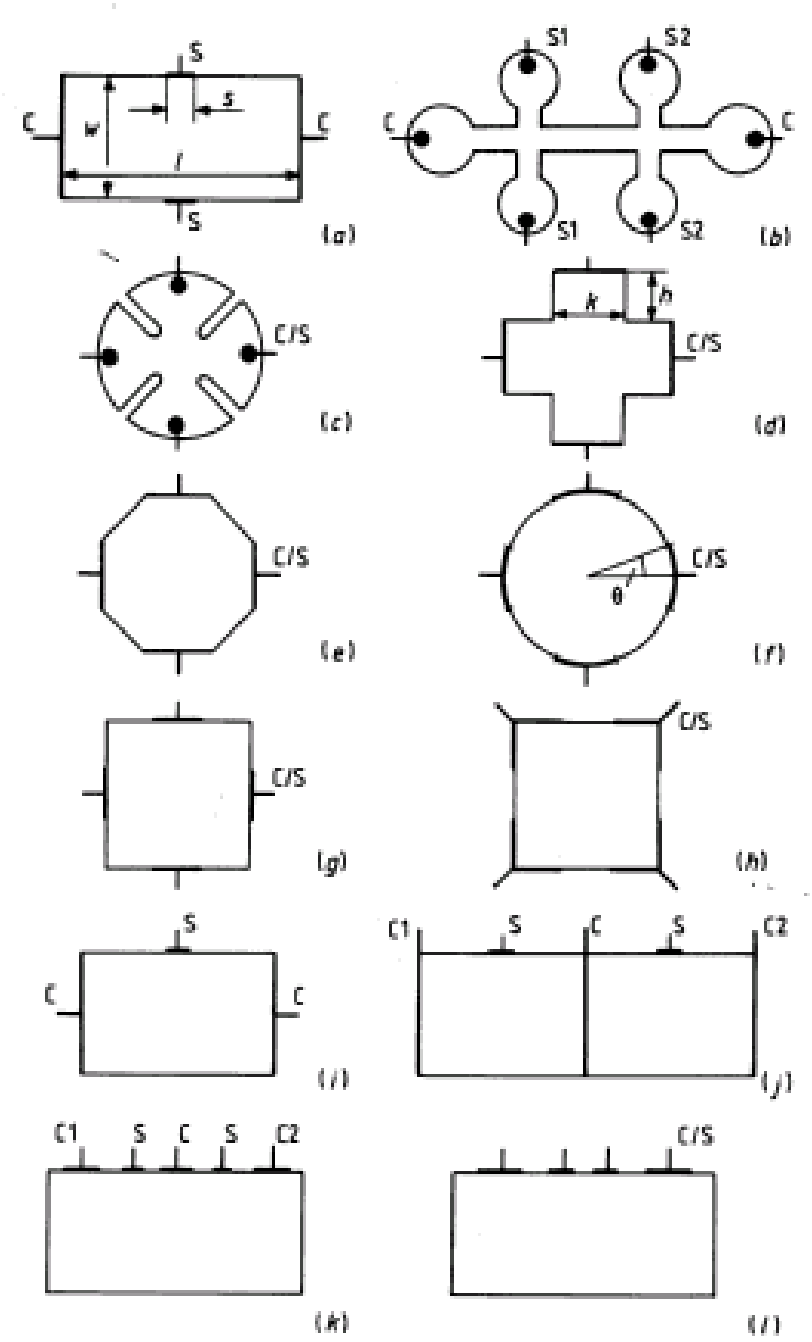
$$S_I = \frac{S_A}{I} = \left| \frac{1}{I} \frac{V_H}{B_\perp} \right| \qquad S_V = \frac{S_A}{V} = \left| \frac{1}{V} \frac{V_H}{B_\perp} \right| = \frac{S_I}{R_{in}}$$

$$S_I = G_H \frac{|R_H|}{t} \qquad S_V = \mu_H \frac{w}{l} G_H$$

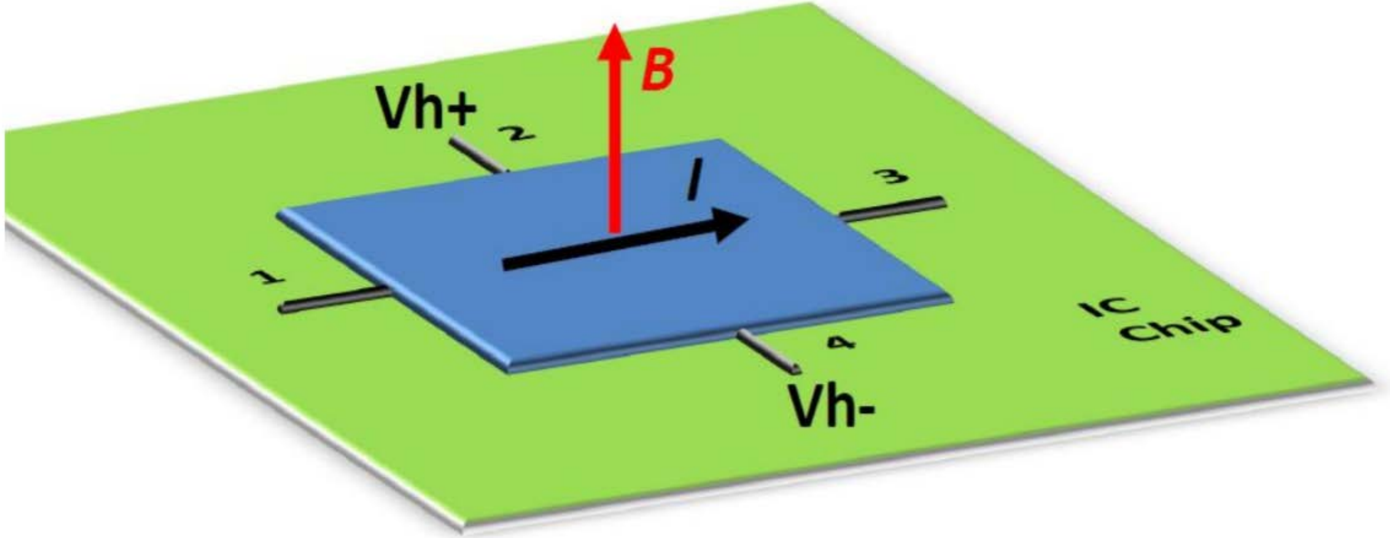
S_I [V/AT]: 10 … 1000

S_V [V/VT]: 0.01 … 0.05 (Si CMOS); 0.3 (GaAs); 1 ... 5 (InSb)

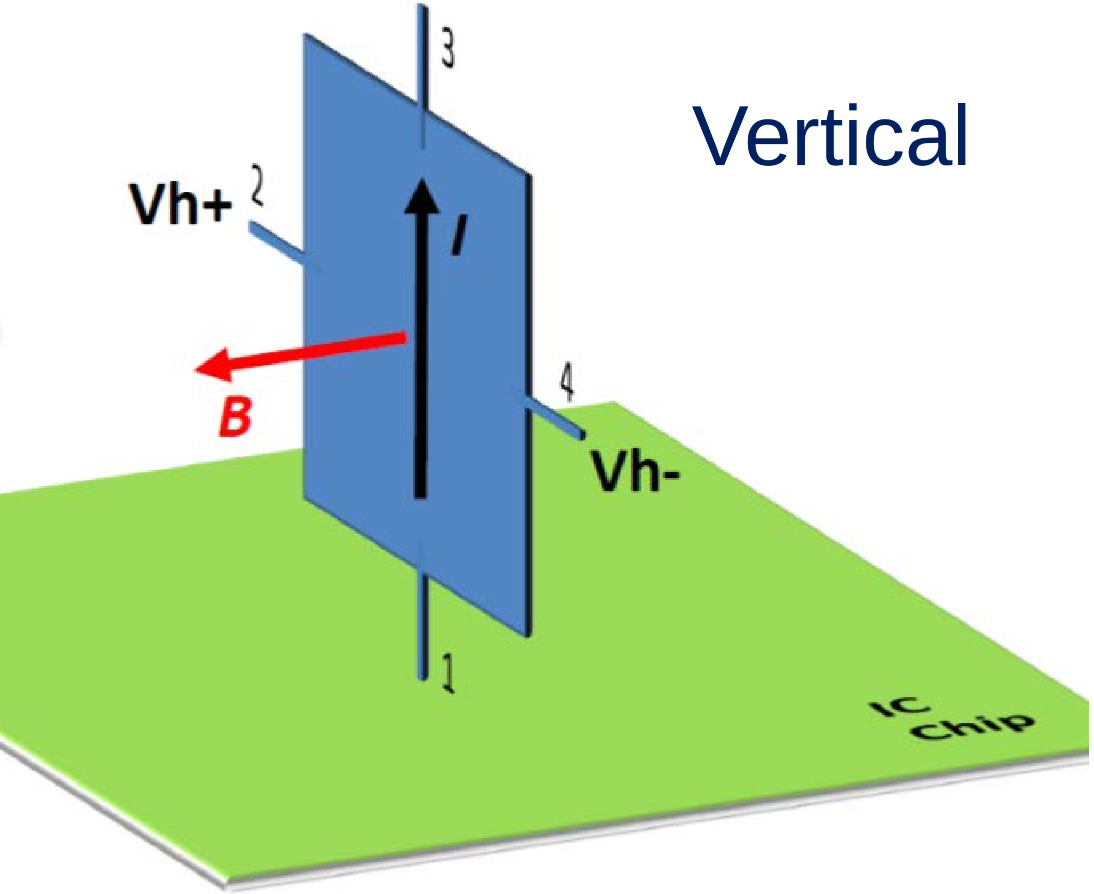
Shapes of Hall Devices



Positions of Hall Devices

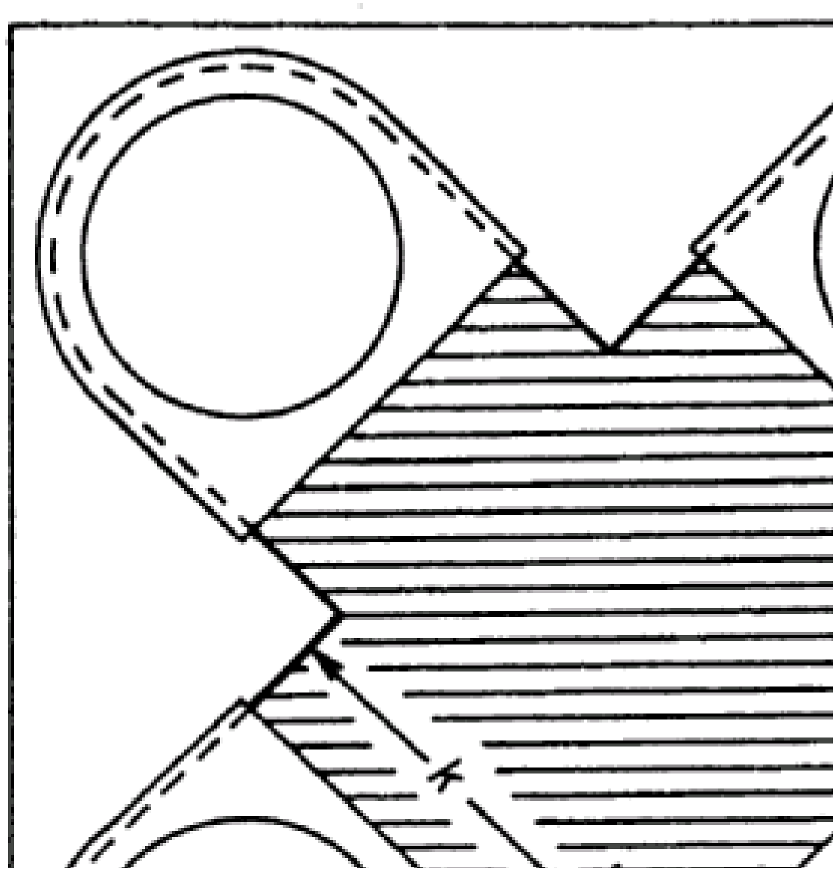


Horizontal



Vertical

GaAs Hall Device



1 : GaAs – active area

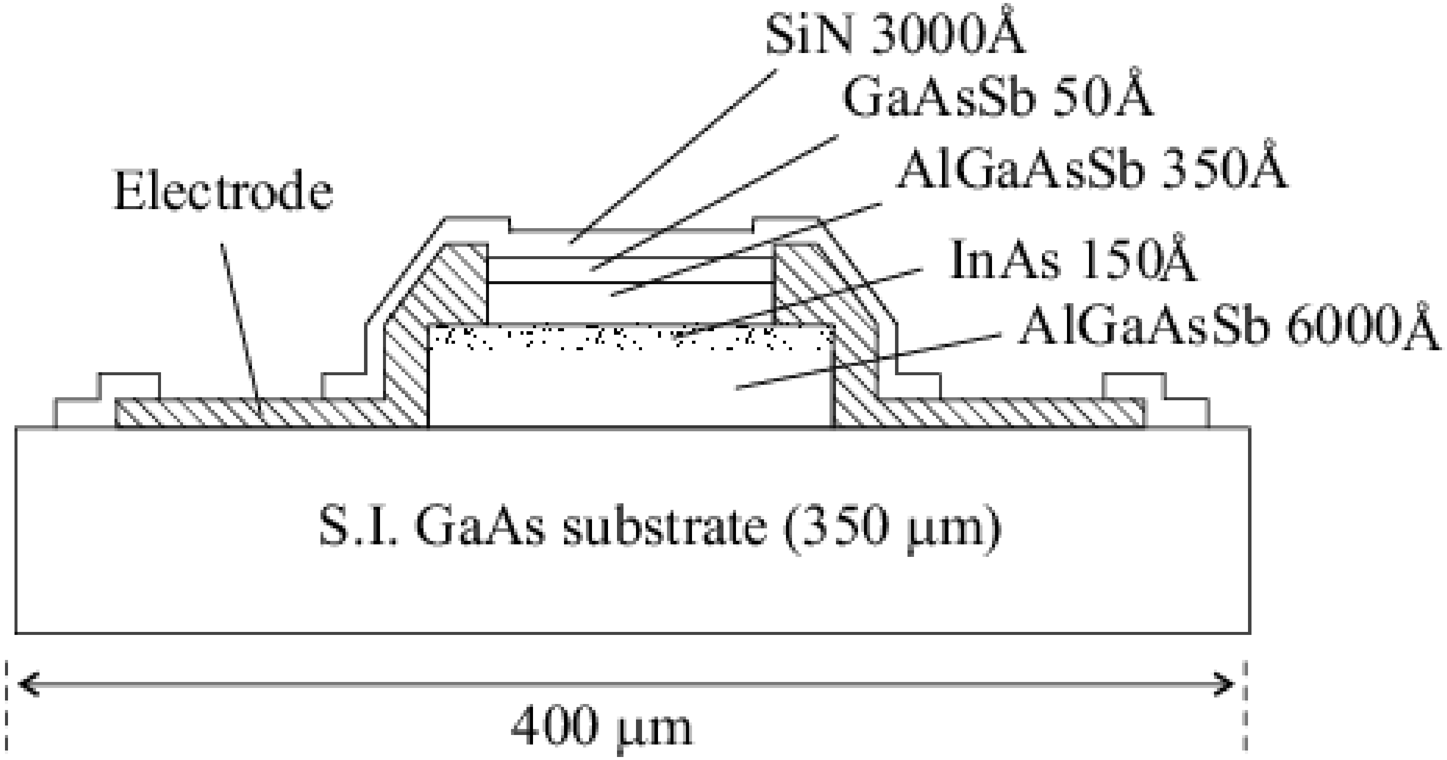
2 : Metalized region

3 : Contact region

Desired features of (1):

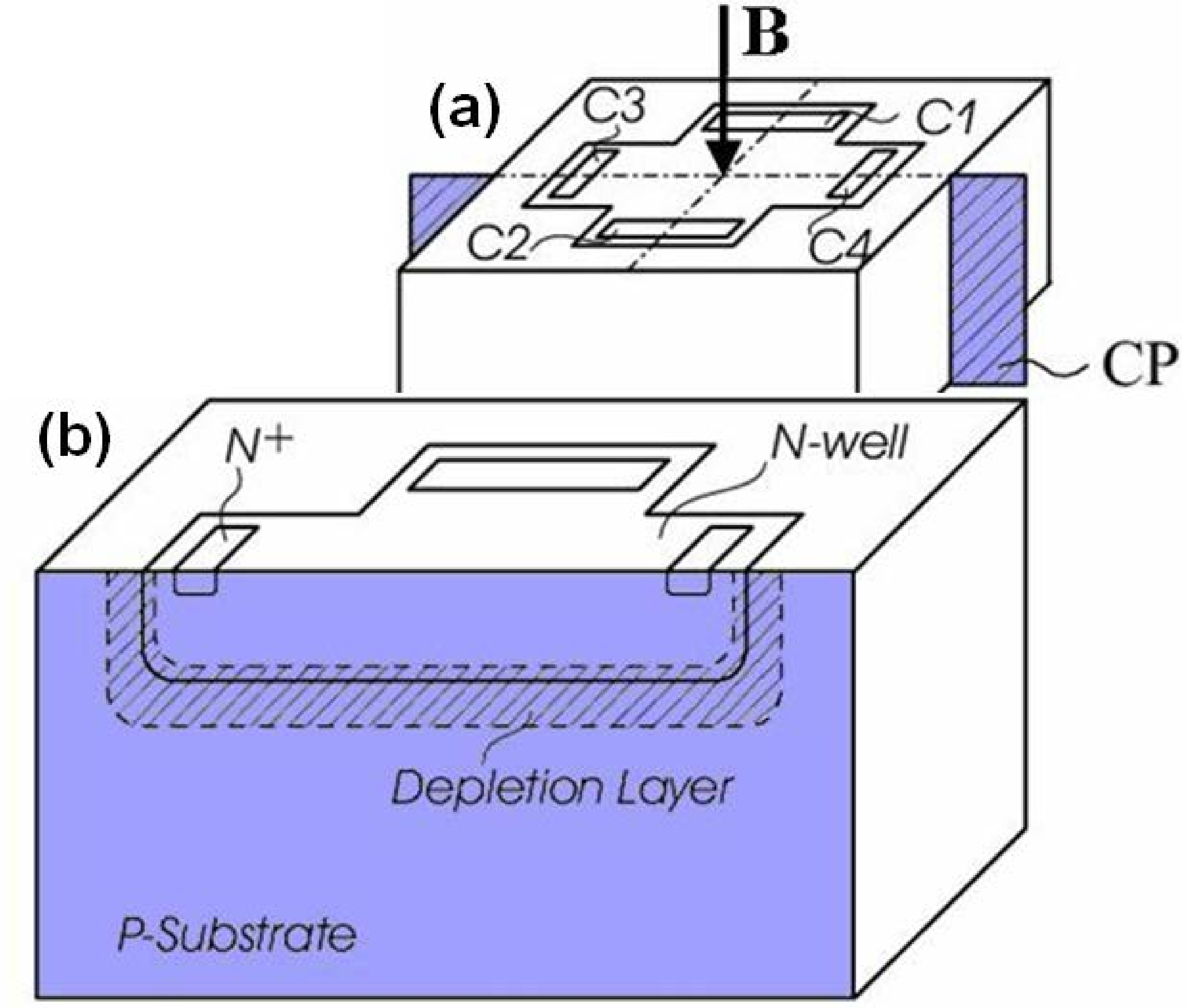
- High mobility
  ($\boldsymbol{E}_H = \mu\,[\boldsymbol{E} \times \boldsymbol{B}]$)
- Low carrier density
  ($\boldsymbol{E}_H = (1/qn)\,[\boldsymbol{J} \times \boldsymbol{B}]$)

High-mobility 2DEG Hall plate

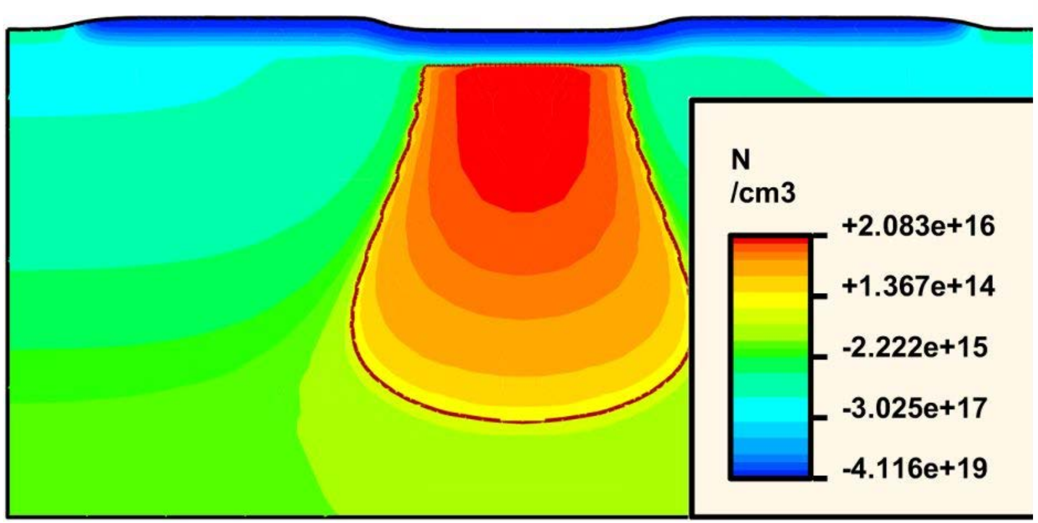


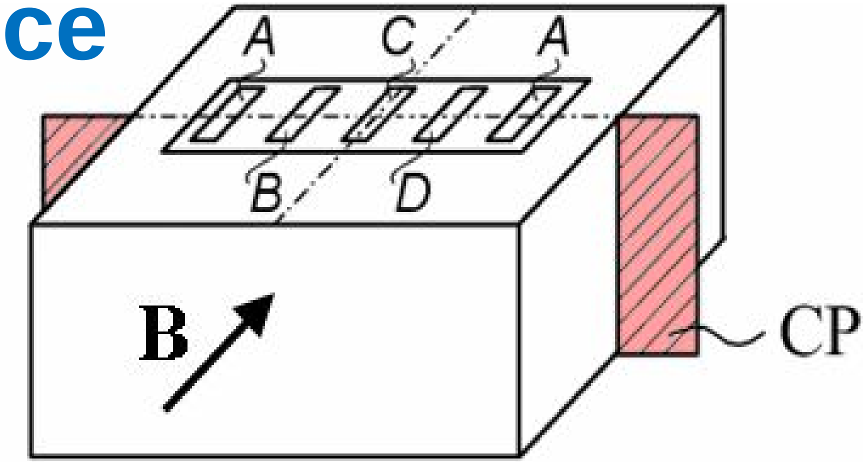
Silicon (Horizontal) conventional planar in Hall Device

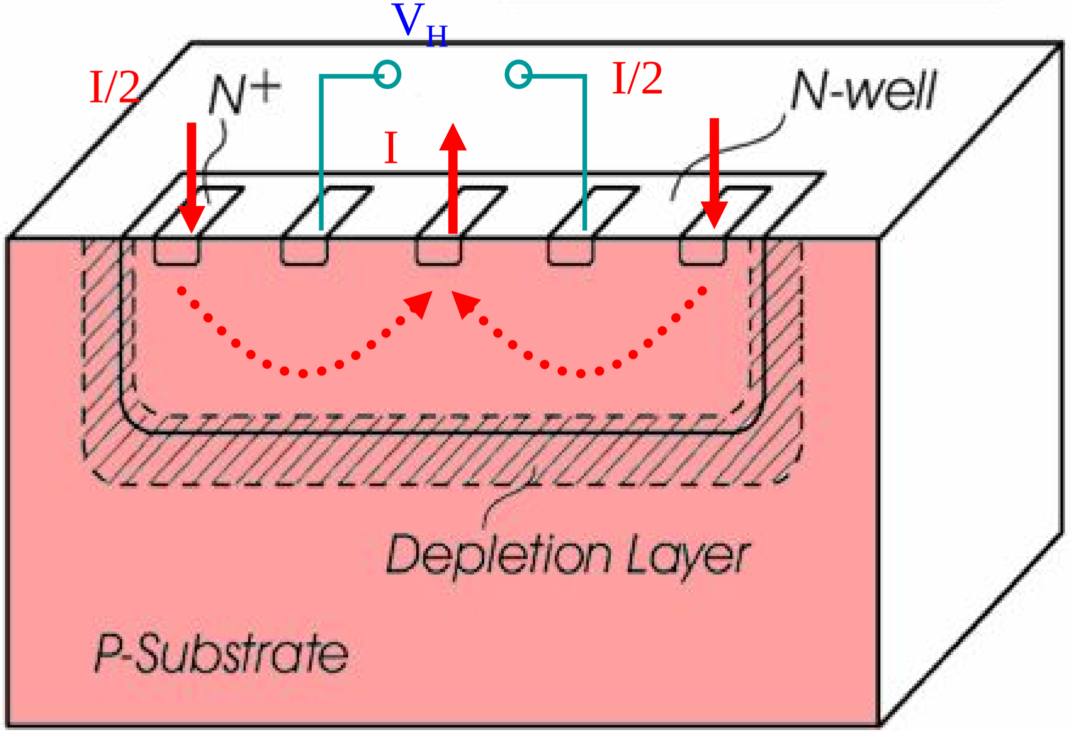
- Sensitive to the perpendicular field component **B**
- CMOS Technology: N-Well
- Depletion layer isolation



Silicon integrated Vertical Hall Device



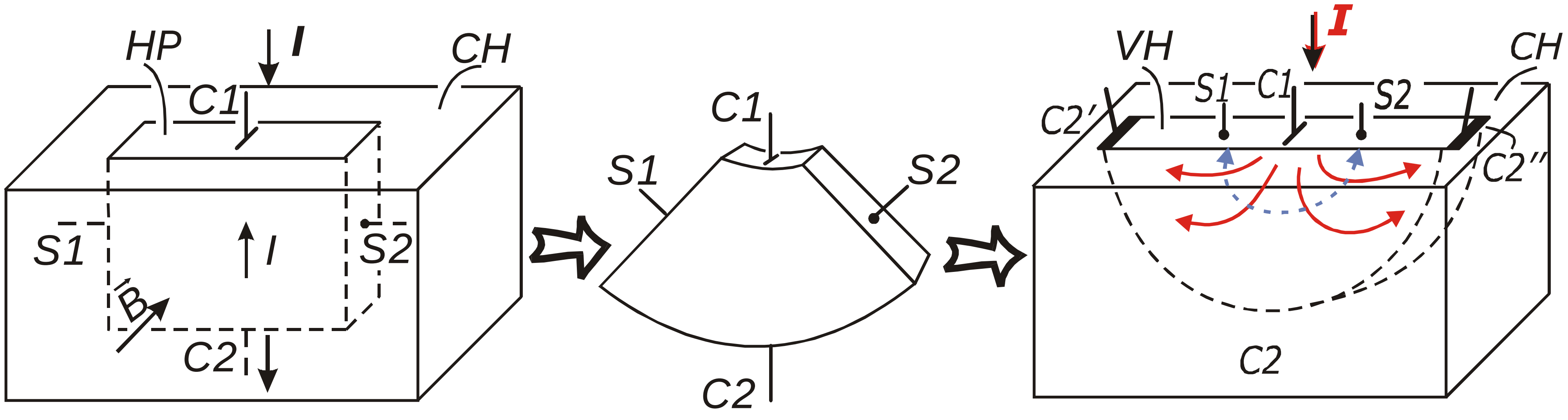




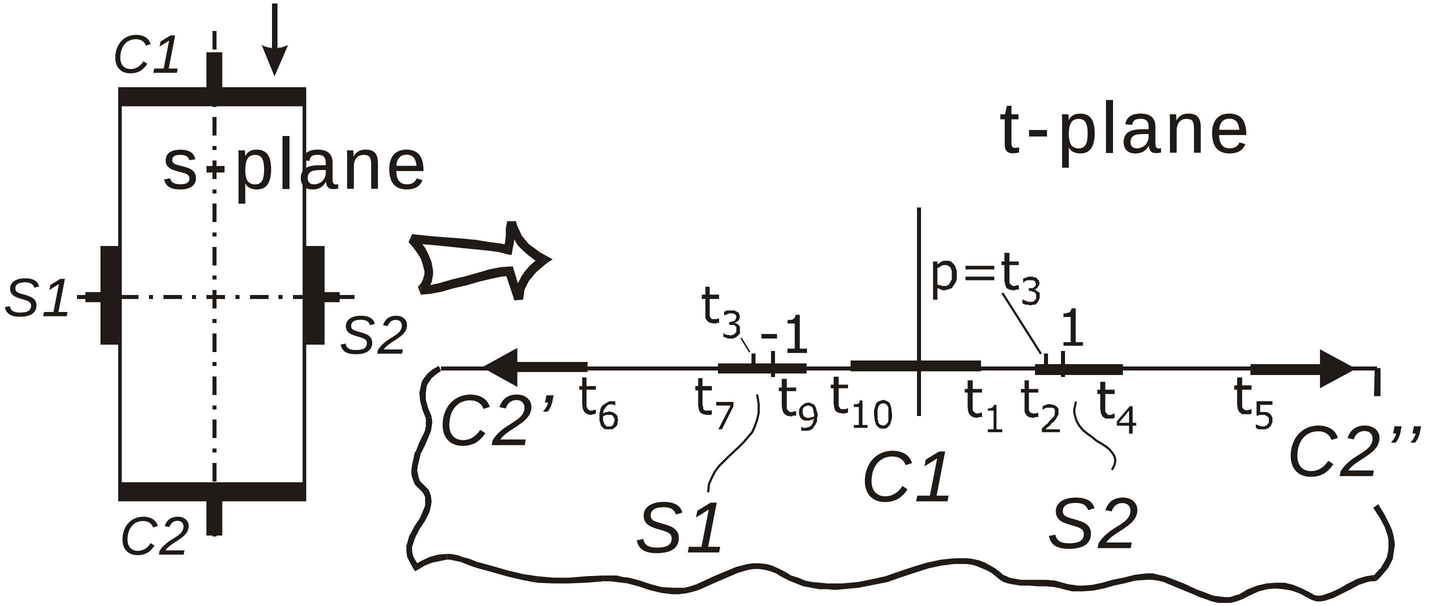
- **Sensitive to in-plane field component *B***
- **CMOS Technology: N-Well**
- **Depletion Layer Isolation**

GENESIS OF THE VERTICAL HALL DEVICE

INTUITIVE:

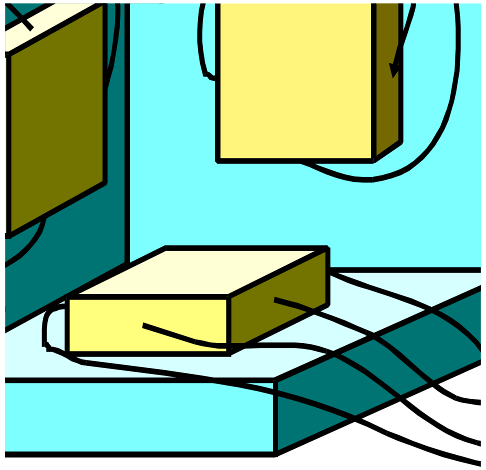


BY CONFORMAL MAPPING:



Multi-axis Hall magnetic sensors

Conventional:
3 Hall plates



- difficult alignment of axes
- pure spatial resolution
- many wires

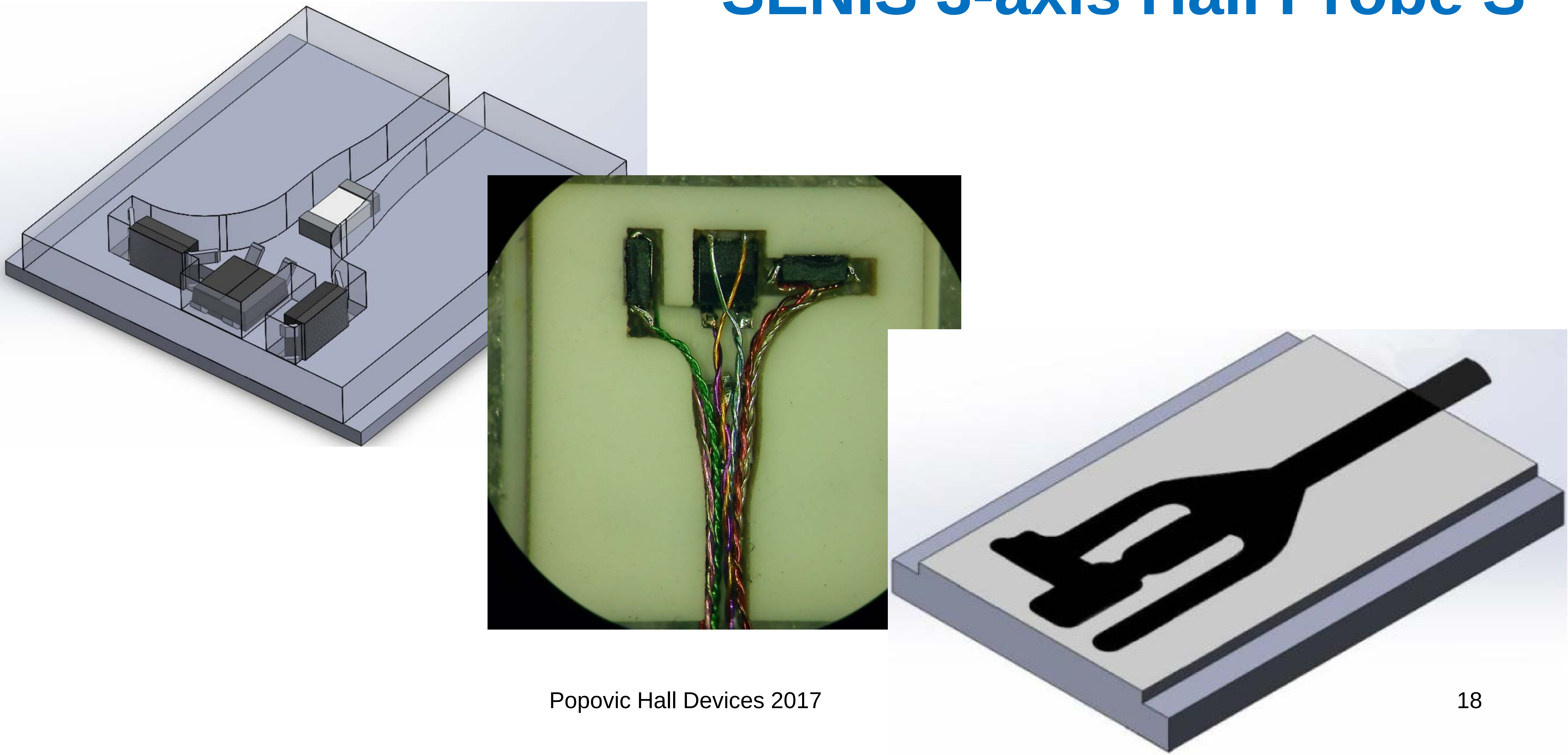
Integrated:
Single Chip

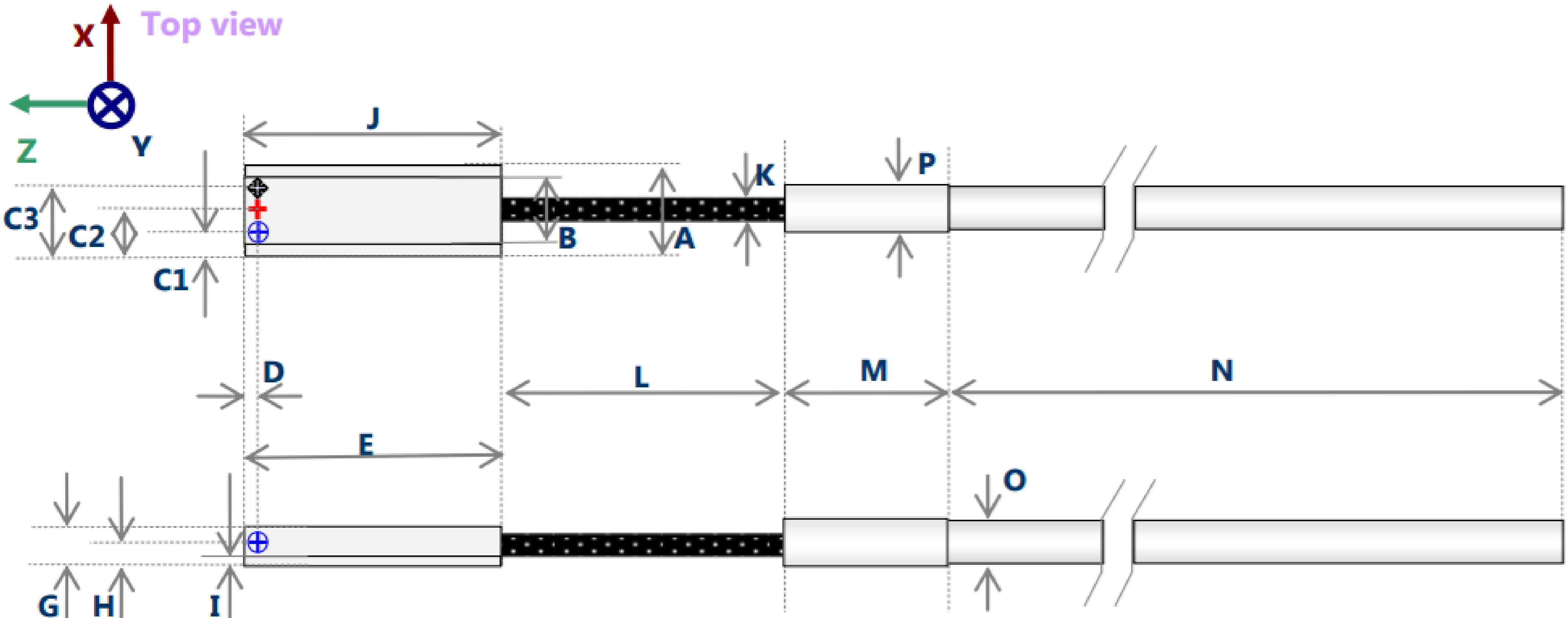
> VH + HH

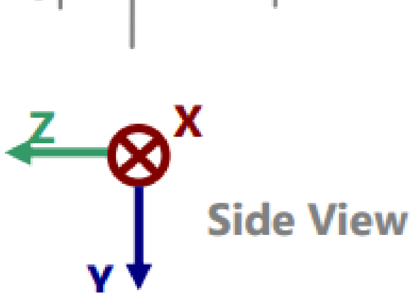
> IMC - Hall

- perfect alignment
- high resolution
- shared wires

SENIS 3-axis Hall Probe S



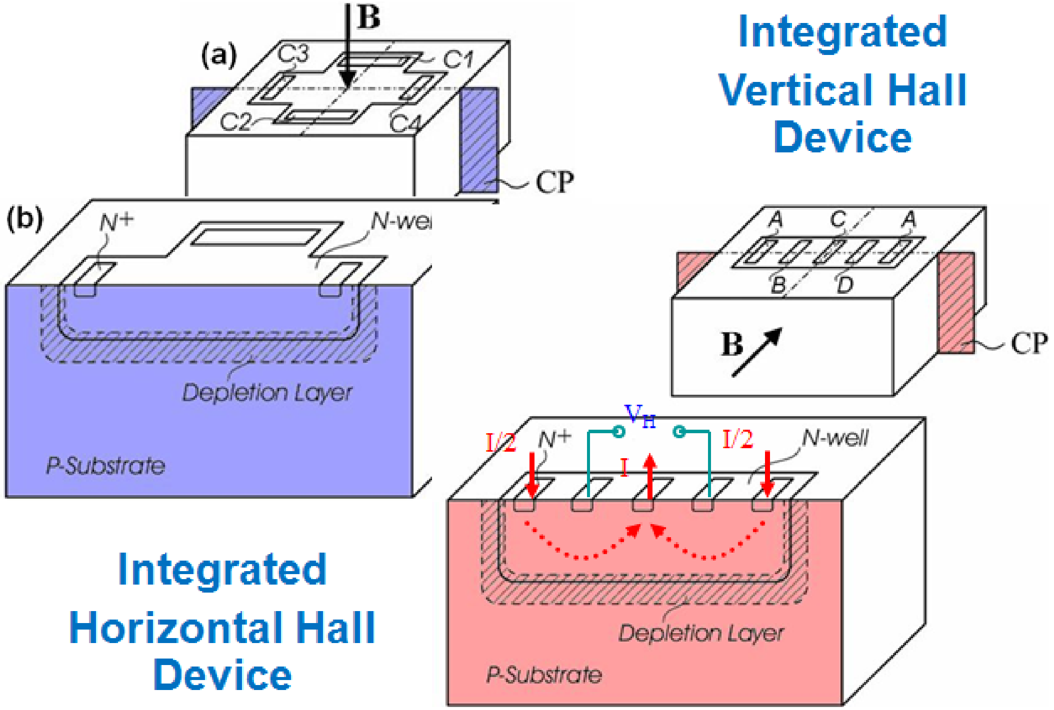




Probe Dimensions [mm]				Cable Dimensions [mm]	
A	10 ± 0.05	**E**	10 ± 0.05	**K**	1 ± 0.1
B	9.0 ± 0.05	**F**		**L**	200 ± 5
C1	3.0 ± 0.05	**G**	1.4 ± 0.05	**M**	20 ± 1
C2	5.0 ± 0.05	**H**	0.7 ± 0.05	**N**	10 000
C3	7.0 ± 0.05	**I**	0.38 ± 0.05	**O**	2.09
D	2.0 ± 0.05	**J**	10 ± 0.05	**P**	2.76

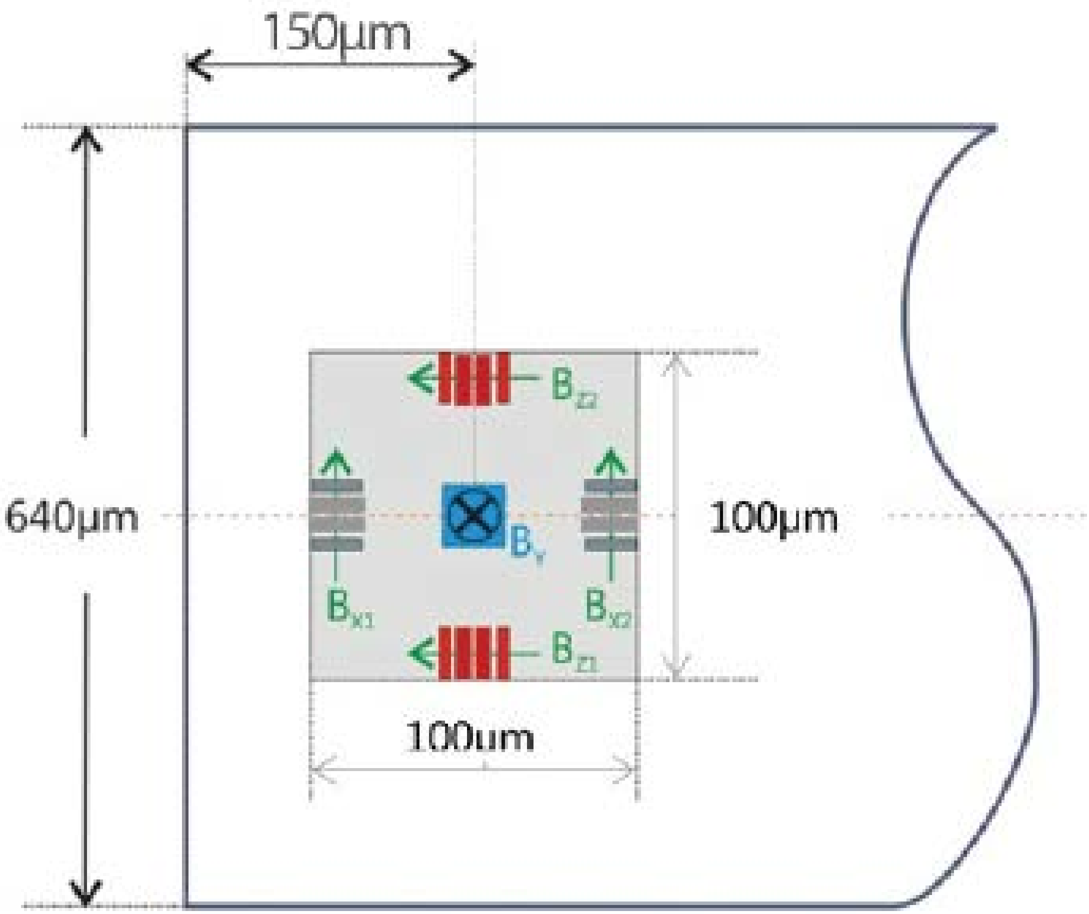
⊕ X-sensor
✚ Y-sensor
✥ Z-sensor

SENIS 3-Axis Integrated Hall Sensor



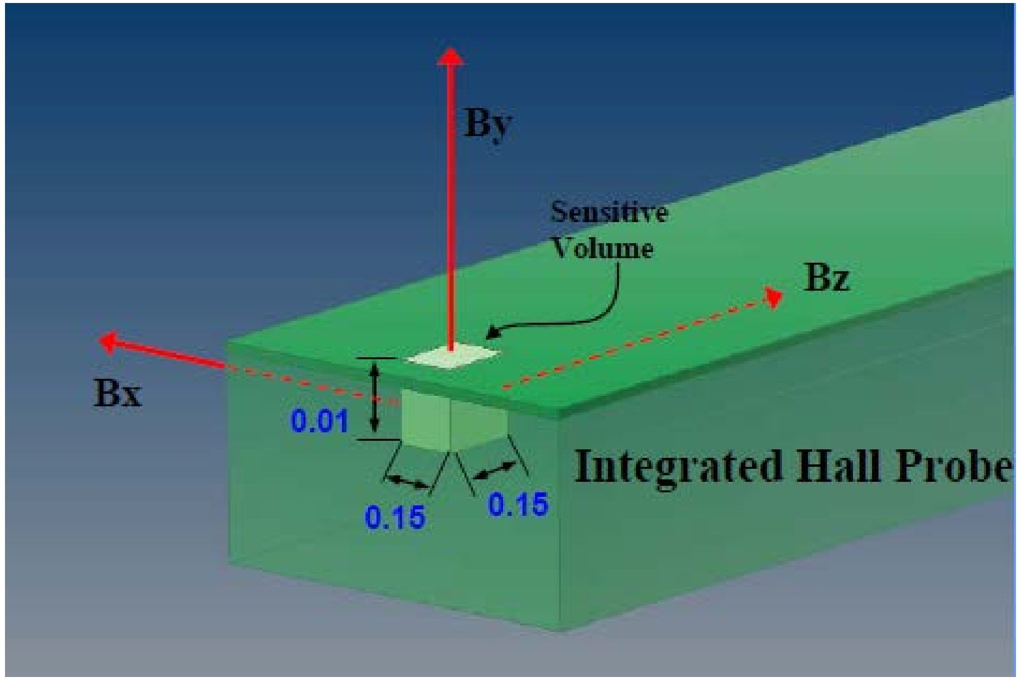
Integrated Vertical Hall Device

Integrated Horizontal Hall Device



Magnetic field sensitive volume:
100µm x 100µm x 10µm

Integrated 3-Axis Hall Probe

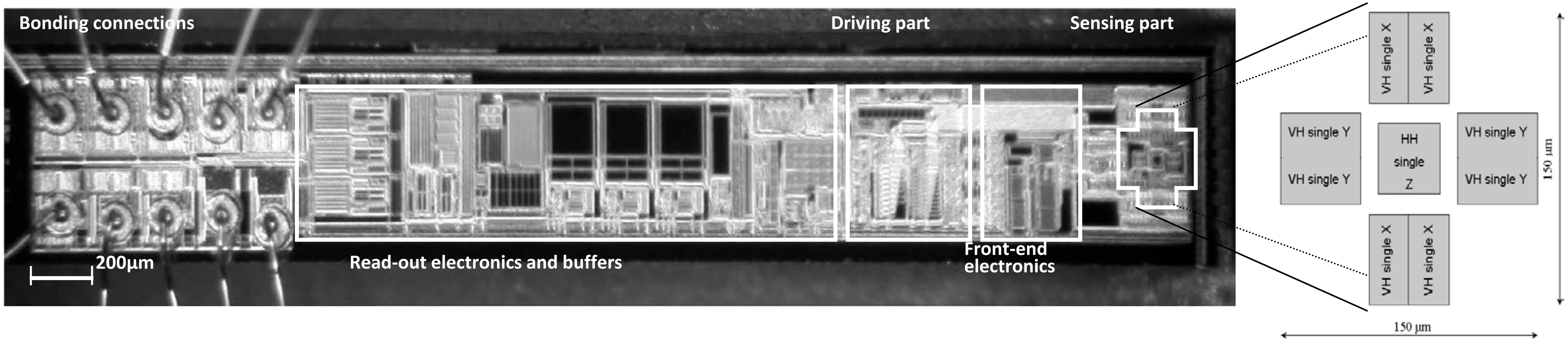


Sensing part composed of two types of micro-Hall sensors

- 4 planar Hall sensor – the perpendicular B-component
- 8 vertical Hall sensors – the in-plane B-components
- Mutual orthogonality: 0.1°

3D spatial resolution: 150 µm

SENIS fully integrated 3D Hall sensor



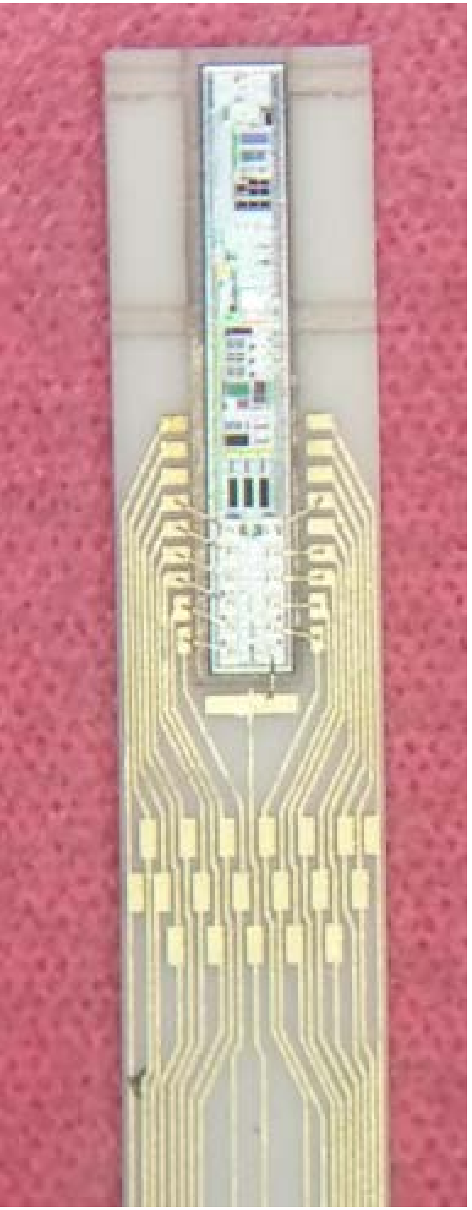
Precise 3D magnetic field measurements

- from militeslas up to tens of tesla
- in the frequency range from DC to 30 kHz
- spatial resolution of about 150 µm
- die dimensions: 4300 µm x 640 µm x 550 µm

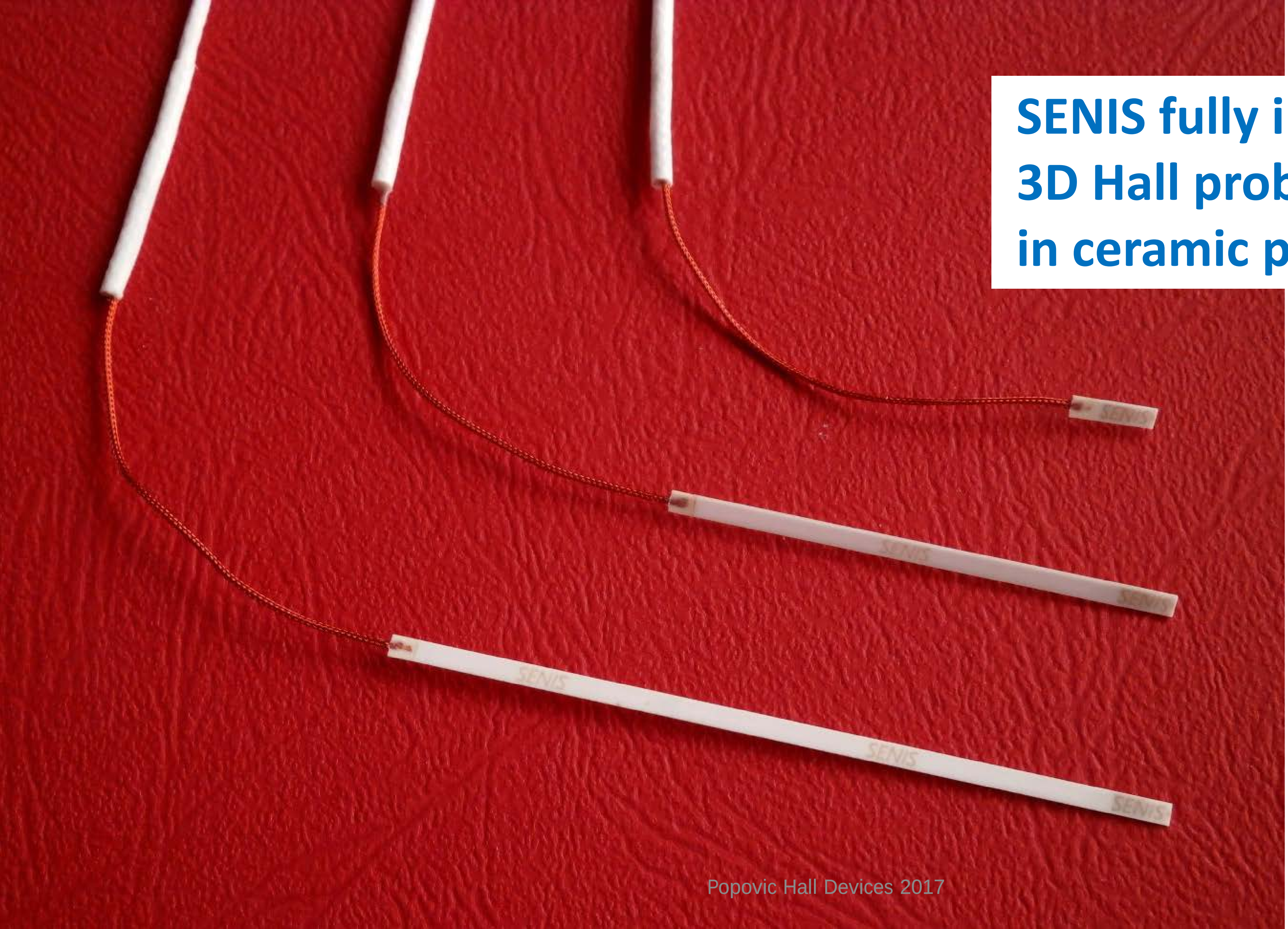
Sensing part composed of two types of micro-Hall sensors

- a planar Hall sensor – the perpendicular B-component
- 8 vertical Hall sensors – the in-plane B-components

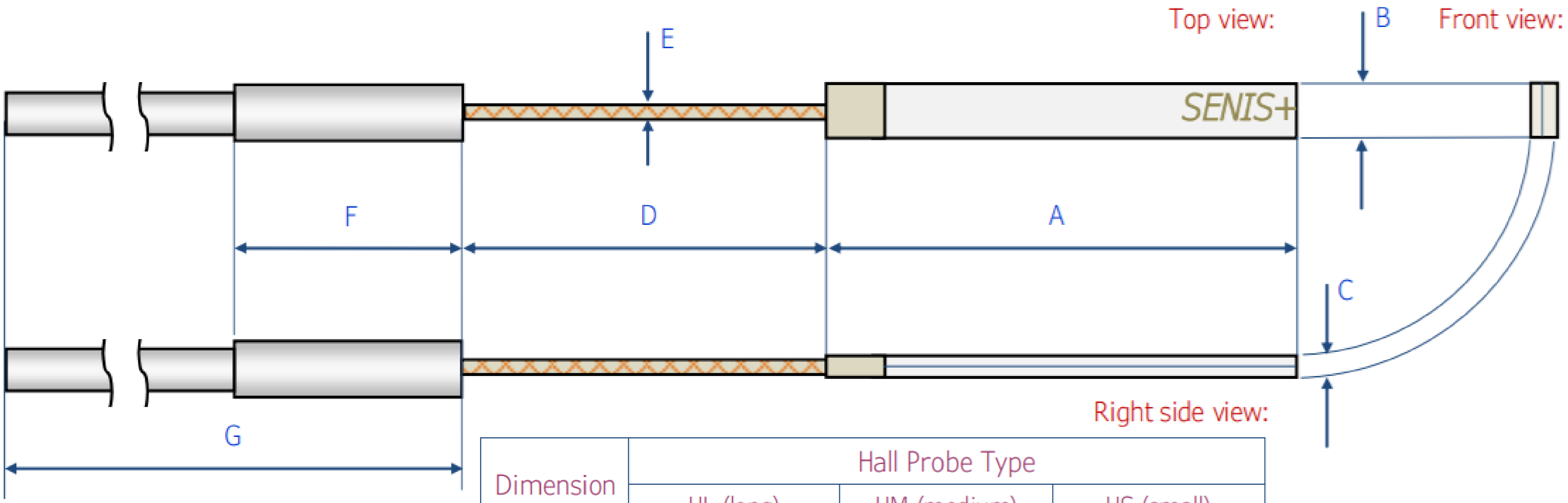
SENIS fully integrated 3D Hall probe in a ceramic package



SENIS fully integrated 3D Hall probes in ceramic packages

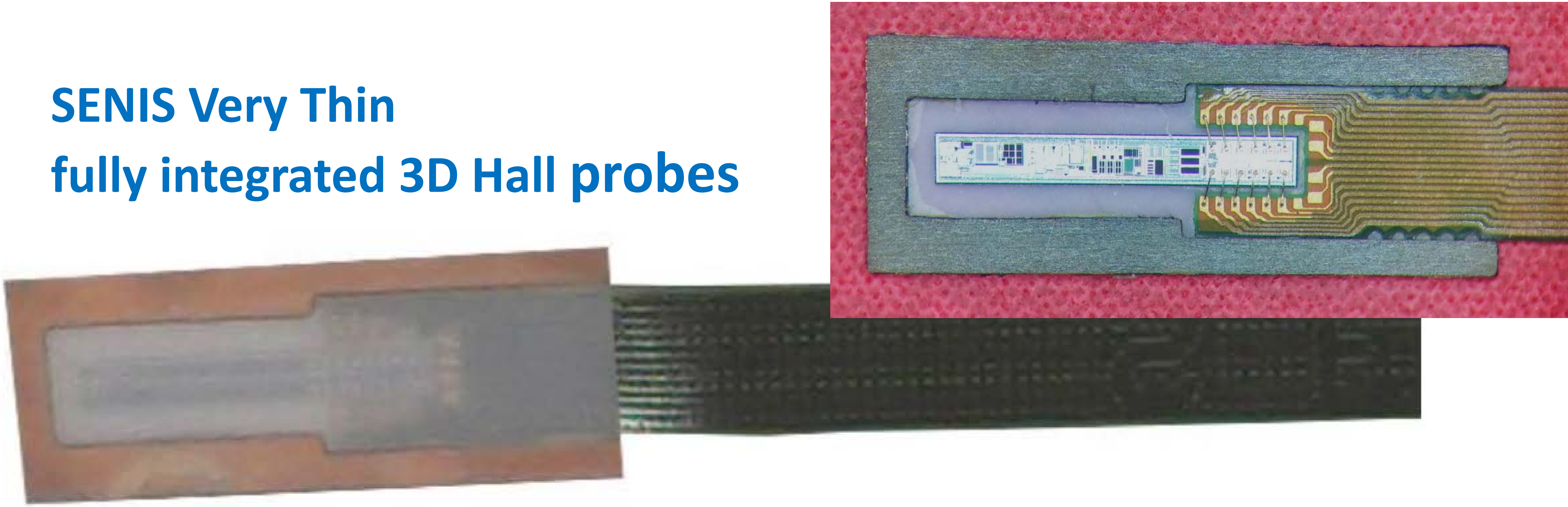


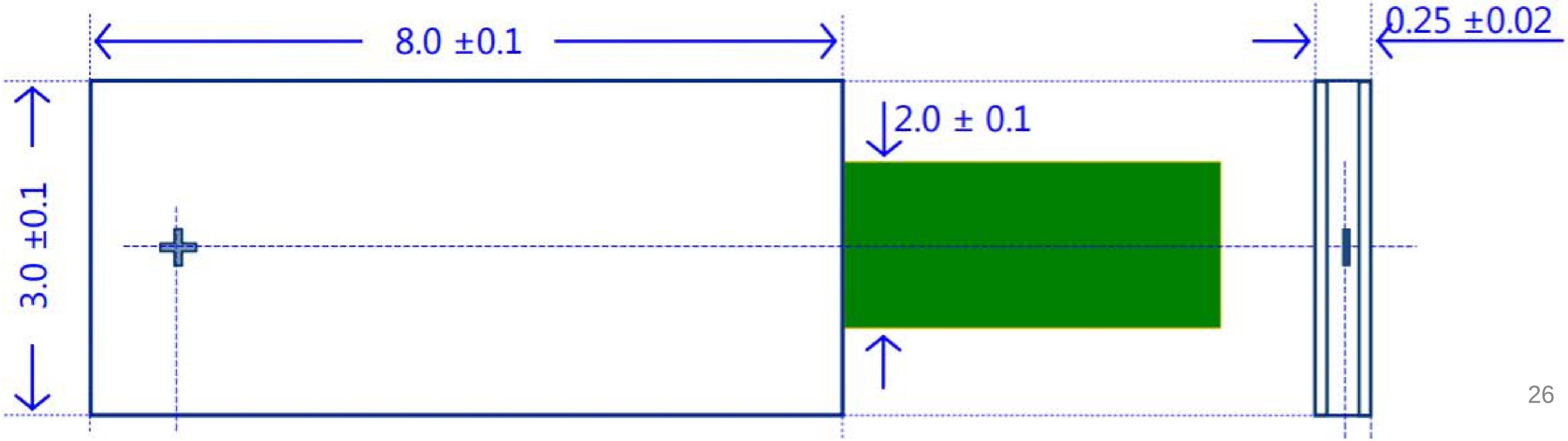
Fully integrated 3-Axis Hall Probe HL, HM, HS



Dimension	Hall Probe Type		
	HL (long)	HM (medium)	HS (small)
A	71.0 ± 0.5 mm	46.0 ± 0.5 mm	8.0 ± 0.2 mm
B	2.00 ± 0.05 mm		
C	0.50 +0.05/-0.00 mm		
D	50 ± 1 mm		
E	Ø 0.8 ± 0.1 mm		
F	25 ± 2 mm		
G	The standard Cable lengths are: 2m, 5m and 10m. Optionally, different cable lengths are available, on a demand.		

SENIS Very Thin
fully integrated 3D Hall probes



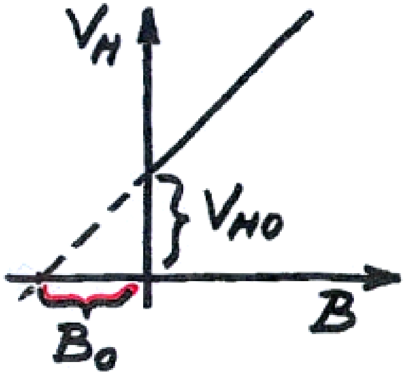


Probe Holders

Parasitic Effects in Hall Devices

- **Offset**
- **Noise**
- **Planar Hall effect**
- **Non-linearity**
- **Temperature dependence**
- **Stress dependence**
- **Inductive effects**
- **…**

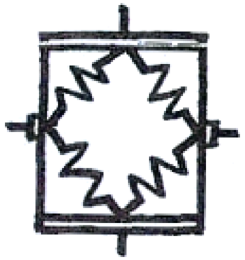
Offset
in a Hall Device



$V_{H0} \equiv V_H$ at $B=0$

$B_0 \equiv$ apparent B_{meas} at $B=0$

CAUSES: ASYMETRY DUE TO



- GEOMETRY
- DOPING
- TEMPERATURE GRAD.
- MECHANICAL STRESS
- SURFACE EFFECTS

TYPICAL VALUES:

$B_0 \sim 5 \ldots 50$ mT

OEMF:
Offset-Equivalent Magnetic Field

$OEMF = V_{\mathrm{off}} / S_{\mathrm{A}}$

V_{off}: Output offset voltage [V]

S_{A} : Absolute magnetic sensitivity [V/T]

Basic OEMF:

- Si integrated Hall elements: 5mT – 50mT
- High-mobility Hall elements: ca. 1mT

Offset Fluctuations and Noise

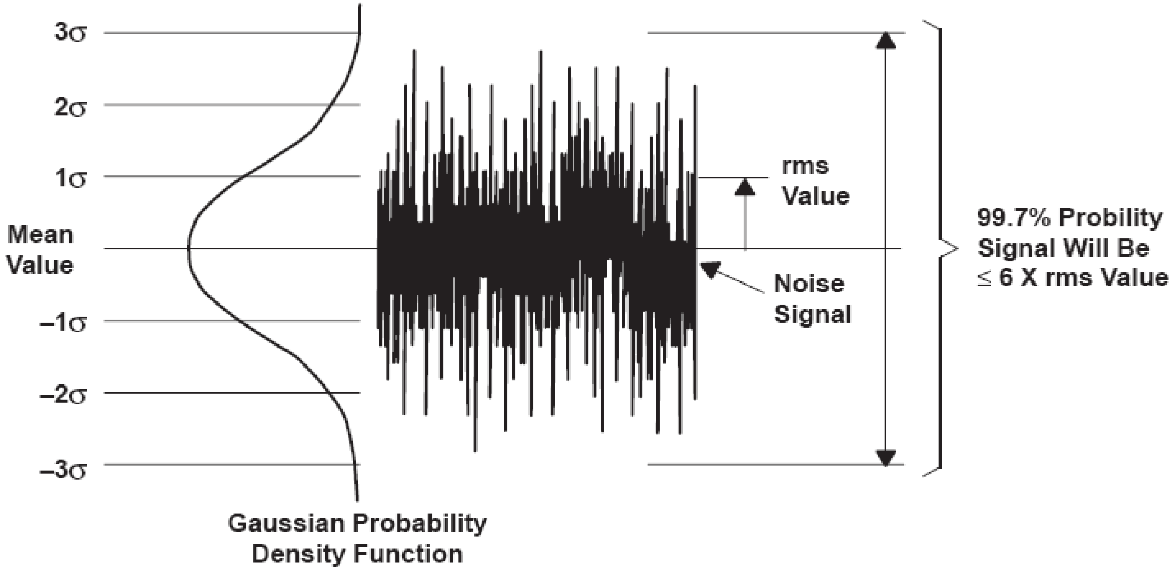


Figure 1. Gaussian Distribution of Noise Amplitude

σ^2:	Variance
σ:	Standard deviation
v_{nRMS}:	Root Mean Square noise voltage
$v_{nP\text{-}P}$:	Peak-to-Peak noise voltage

$$v_{nRMS} = \sigma$$

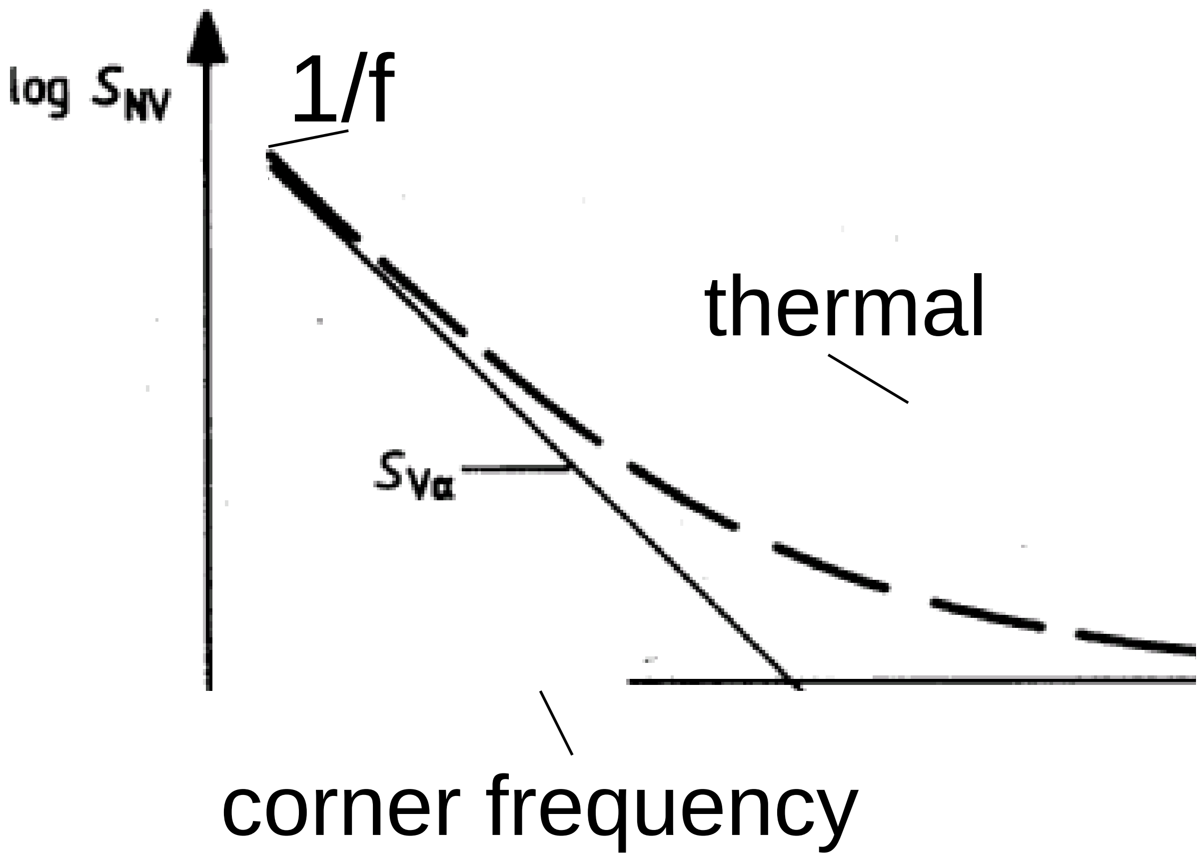
$$v_{nP\text{-}P} \approx 6\, v_{nRMS}$$

Noise Voltage Spectral Density of a Hall Device

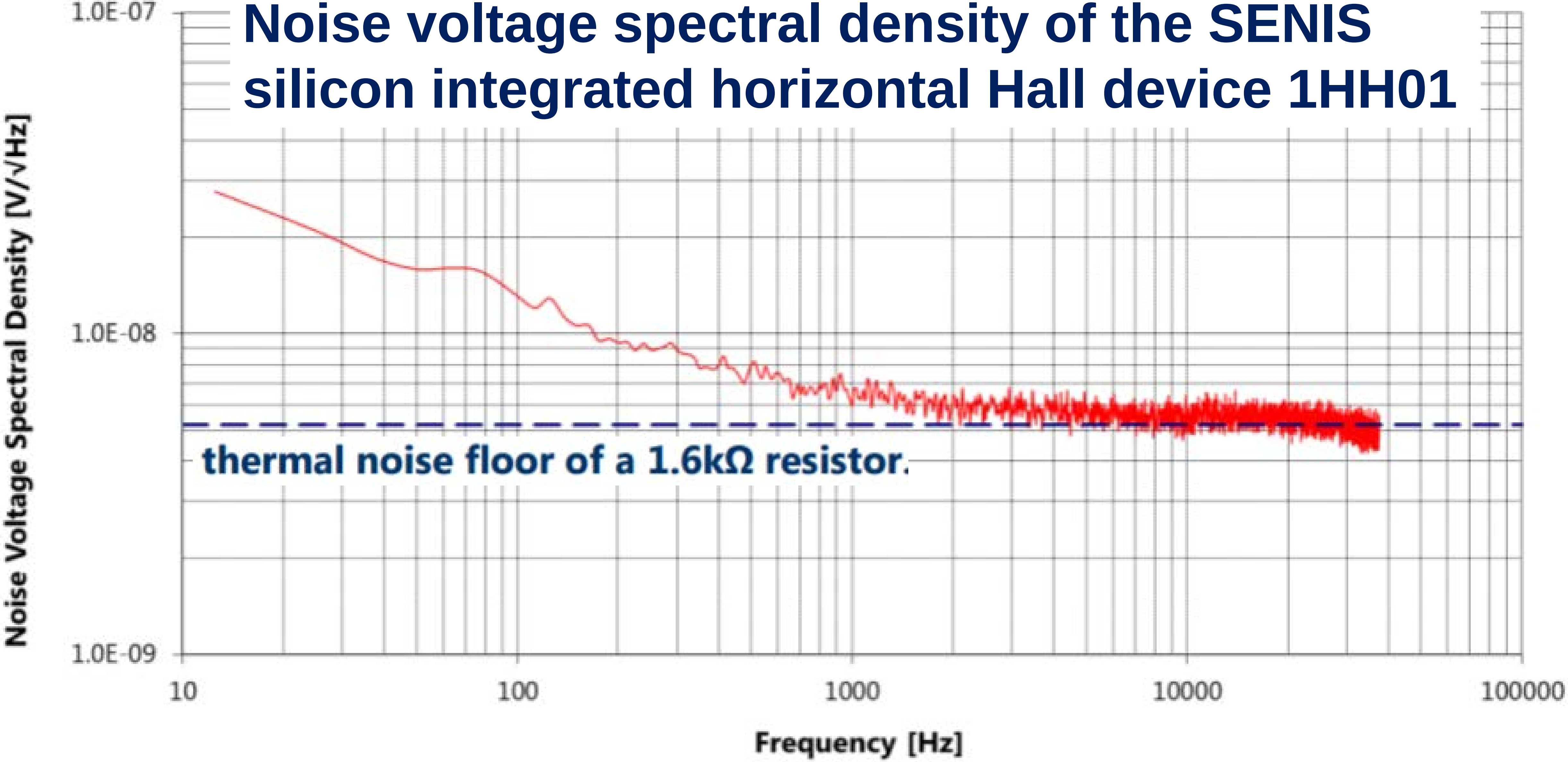
$S_{V\alpha} \propto (I^{2} / N) / f$

$S_{VT} \propto kTR$

$f_c \sim 1 \ldots 100$ kHz



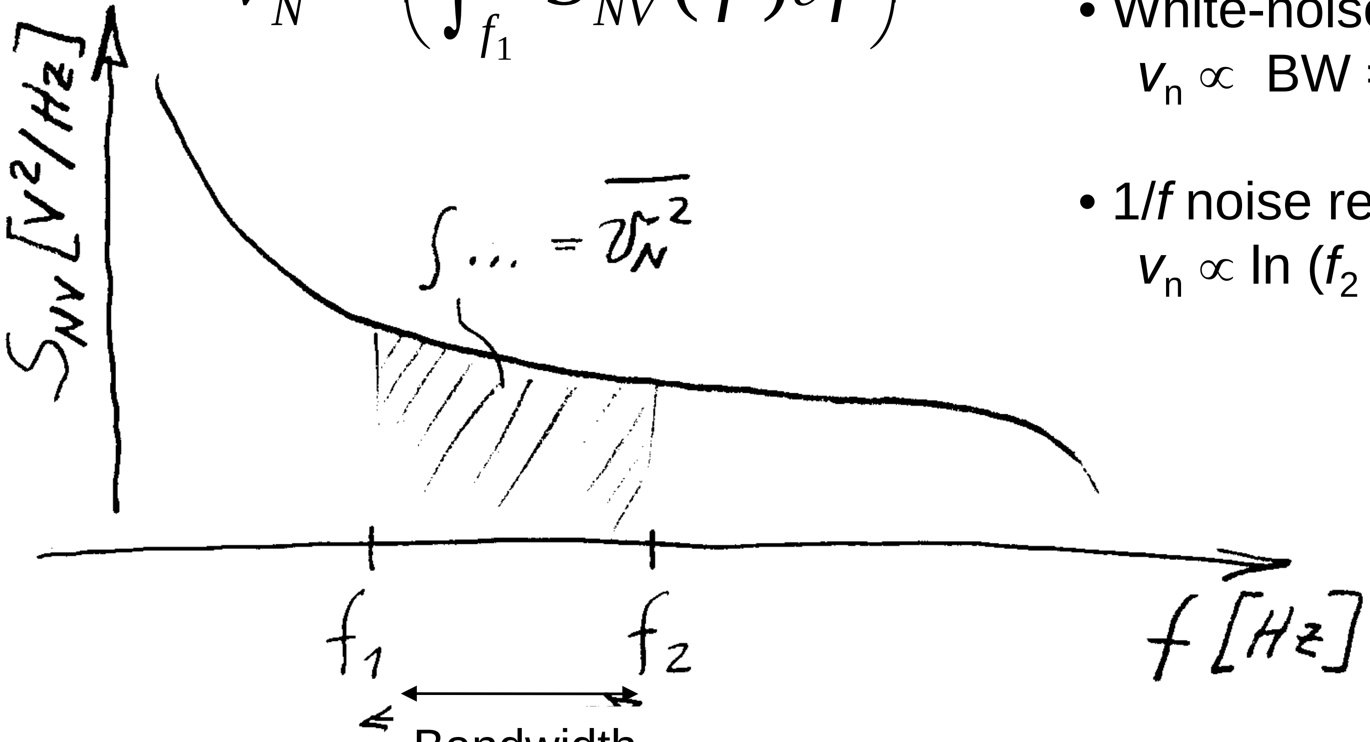
Noise voltage spectral density of the SENIS silicon integrated horizontal Hall device 1HH01



Noise Spectral Density and Noise Voltage

RMS noise voltage:

$$v_N = \left(\int_{f_1}^{f_2} S_{NV}(f)\,\partial f \right)^{\frac{1}{2}}$$



Bandwidth

- White-noise region:
  $v_n \propto$ BW $= f_2 - f_1$
- 1/*f* noise region:
  $v_n \propto \ln(f_2 / f_1)$

NEMF:
Noise-Equivalent Magnetic Field

$NEMF = V_n / S_A$ or $NEMF\ SD = V_n SD / S_A$

V_n: Output noise voltage [V]

V_n *SD:* Noise voltage spectral density [V/√Hz]

S_A : Absolute magnetic sensitivity [V/T]

NEMF[T] – depends on the frequency bandwidth

NEMF Spectral Density [T/√Hz] – a detailed spec.

Typical values of NEMF SD

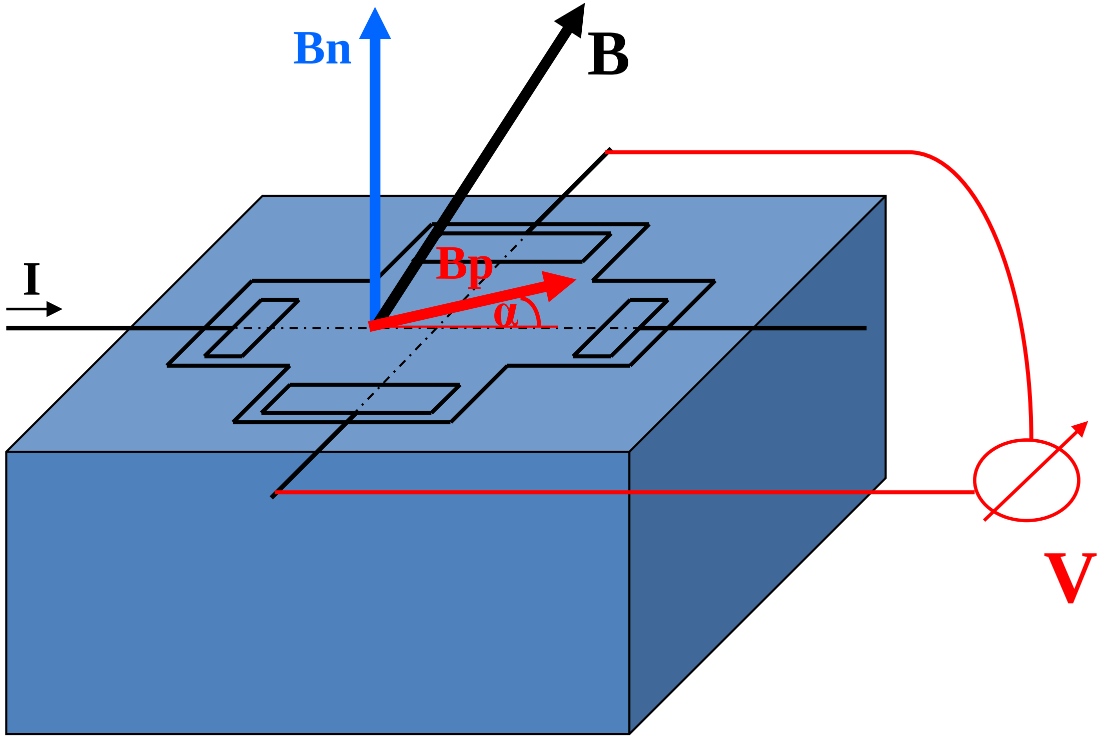
Thermal noise region, at room temperature:

- integrated silicon Hall elements: about 100nT/√Hz;
- GaAs epitaxial or 2DEG Hall elements: about 20nT/√Hz;
- high-mobility thin-film InSb Hall elements: about 1.5nT/√Hz.

Parasitic Effects in Hall Devices

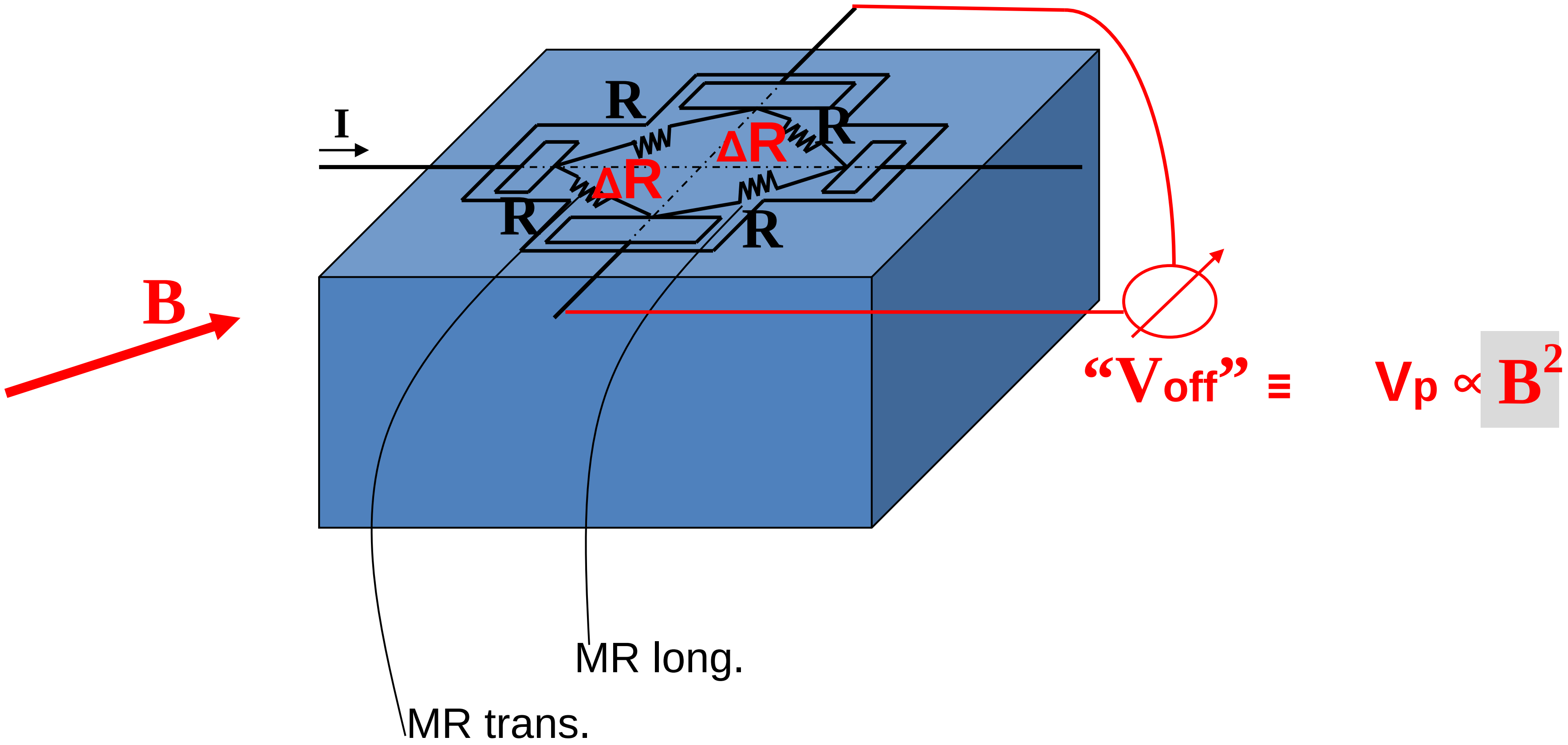
- Offset
- Noise
- Planar Hall effect
- Non-linearity
- Temperature dependence
- Stress dependence
- Inductive effects
- …

Planar Hall Effect



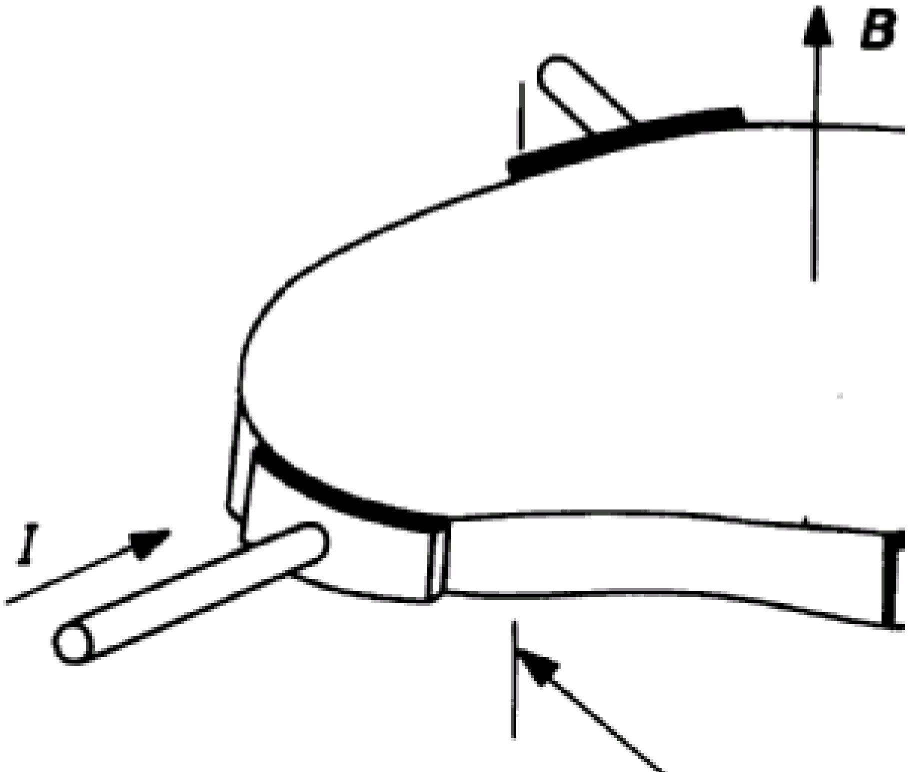
$V_p \propto I\, B_p^2 \sin 2\alpha$

MR Model of the Planar Hall effect



“V_{off}” ≡ $V_p \propto B^2$

Summary



- Hall Plate:
  4 Contacts, ***B*** ⊥ Plate
- Hall Voltage:

$$V_H = \mathrm{V}\, B_\perp$$
$$= S_I\, I\, B_\perp$$

- Errors: Offset, Noise, Planar Hall Effect, …

Where to get more information

R S Popovic:

“Hall Effect Devices”

2nd Edition, 2004

Institute of Physics Publishing, IOP, Bristol and Philadelphia

HALL MAGNETIC SENSORS
- SIGNAL PROCESSING

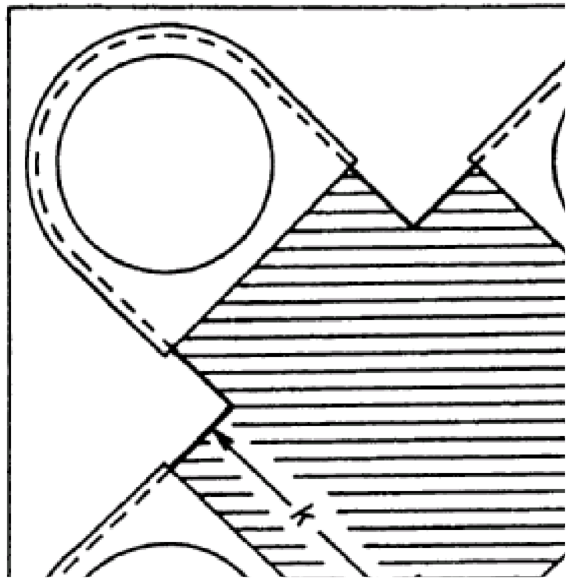
Radivoje S. Popovic

EPFL, Swiss Federal Institute of Technology
Lausanne, Switzerland,

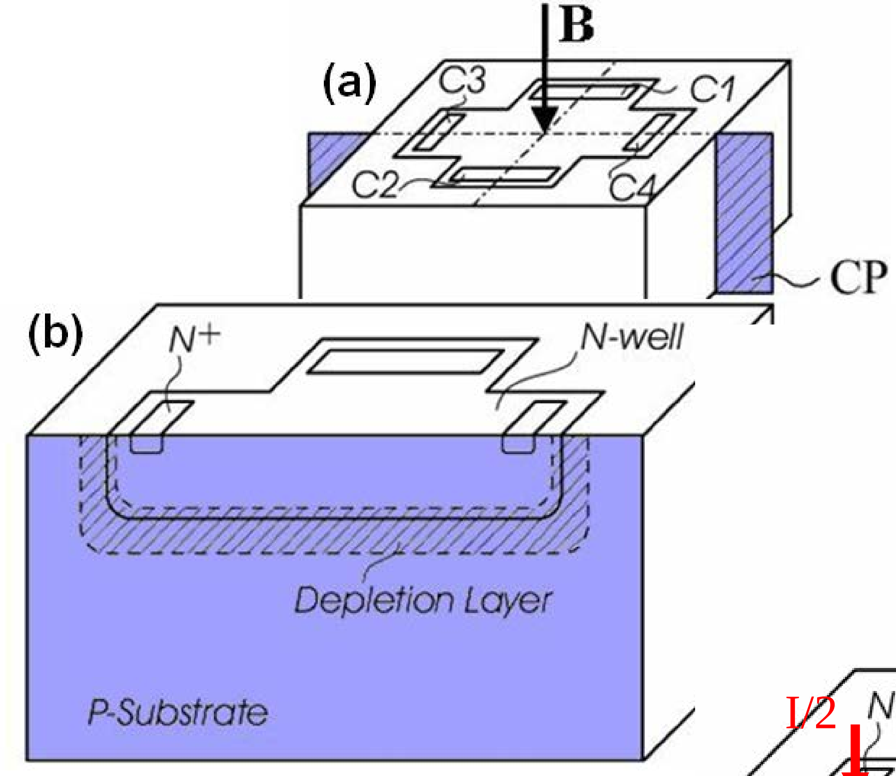
and

SENIS AG, Zug, Switzerland

Hall Devices

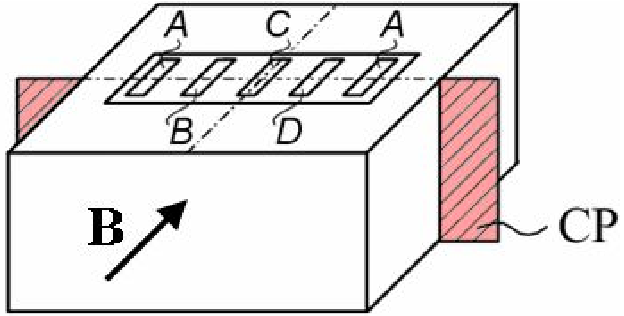


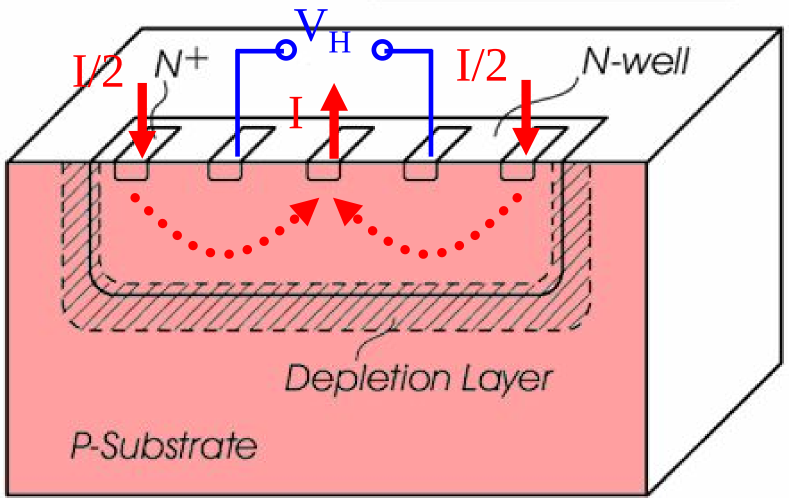
GaAs Hall Device



Integrated Horizontal Hall Device

Integrated Vertical Hall Device

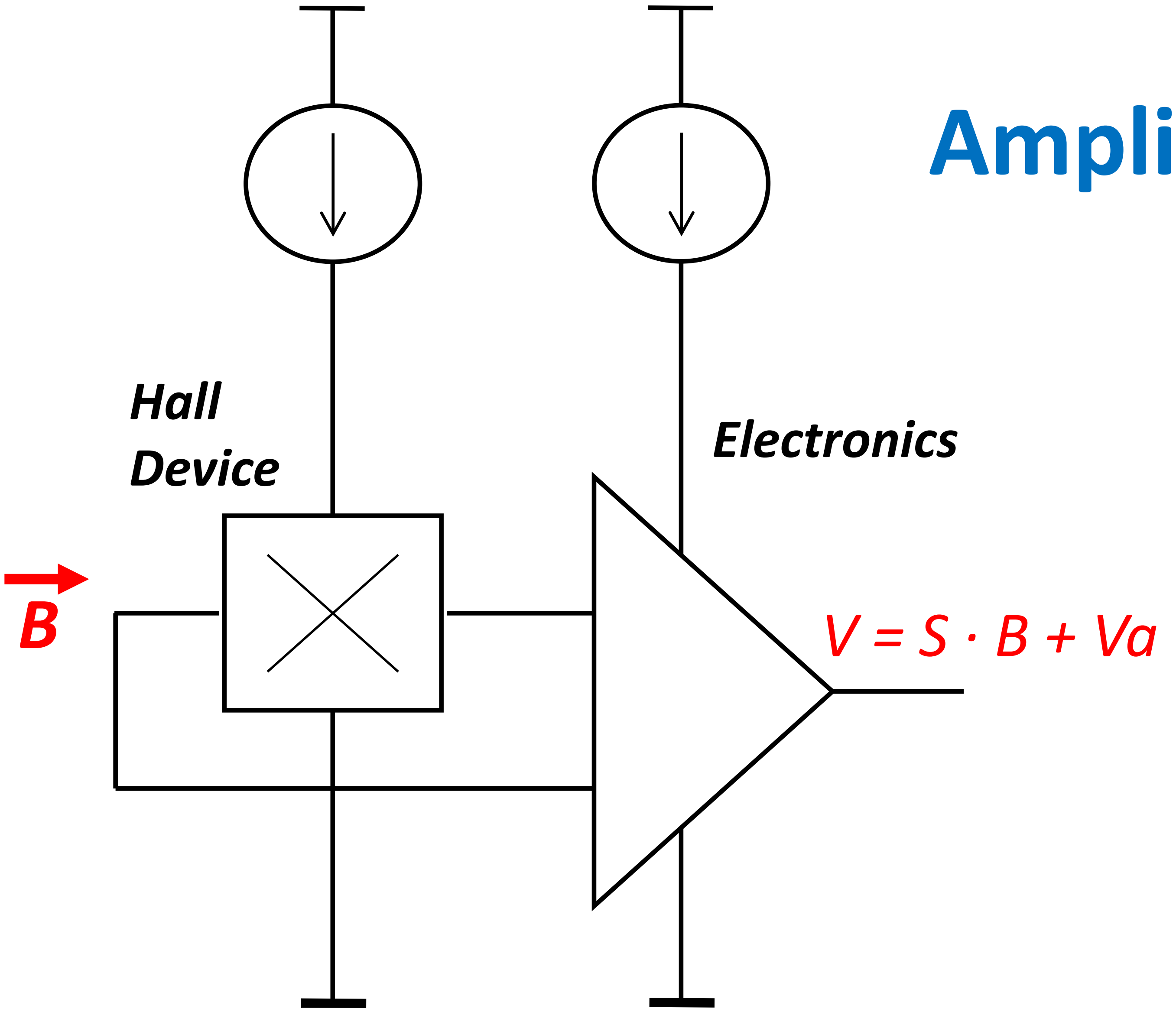




Outline

- Amplification of the Hall voltage
- Reducing offset, low-frequency noise, planar Hall effect, inductive effects, …
- Reducing angular errors
- Amplification of the magnetic signal
- Experimental Results

Amplifying the Hall voltage



S: absolute magnetic sensitivity of the transducer

Va: total artifact signal (noise voltage, offset, …)

Resolution limit:

when $S \cdot B \approx Va$, i.e.

$Bres \approx Va / S$

Magnetic Resolution Limit

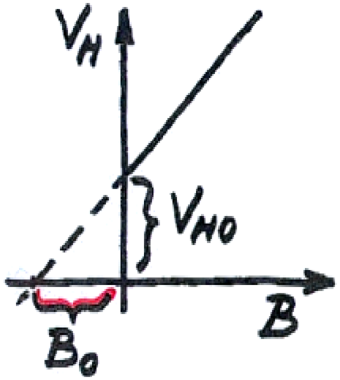
The magnetic resolution **limit – when Signal to Artifact Ratio ≈ 1**

Bres ≈ Artifact-Equivalent Magnetic Field, ***AEMF = Va / S***

Va: artifact signal (noise voltage, offset drift, …)

S: absolute magnetic sensitivity

- DC resolution: limited by
  - offset (if can not be zeroed)
  - offset drift (thermal, aging, …)
  - offset fluctuations (BW: ~ 0.1Hz to 10Hz)



- AC resolution: limited by noise
  - noise (thermal and 1/f)
  - bandwidth

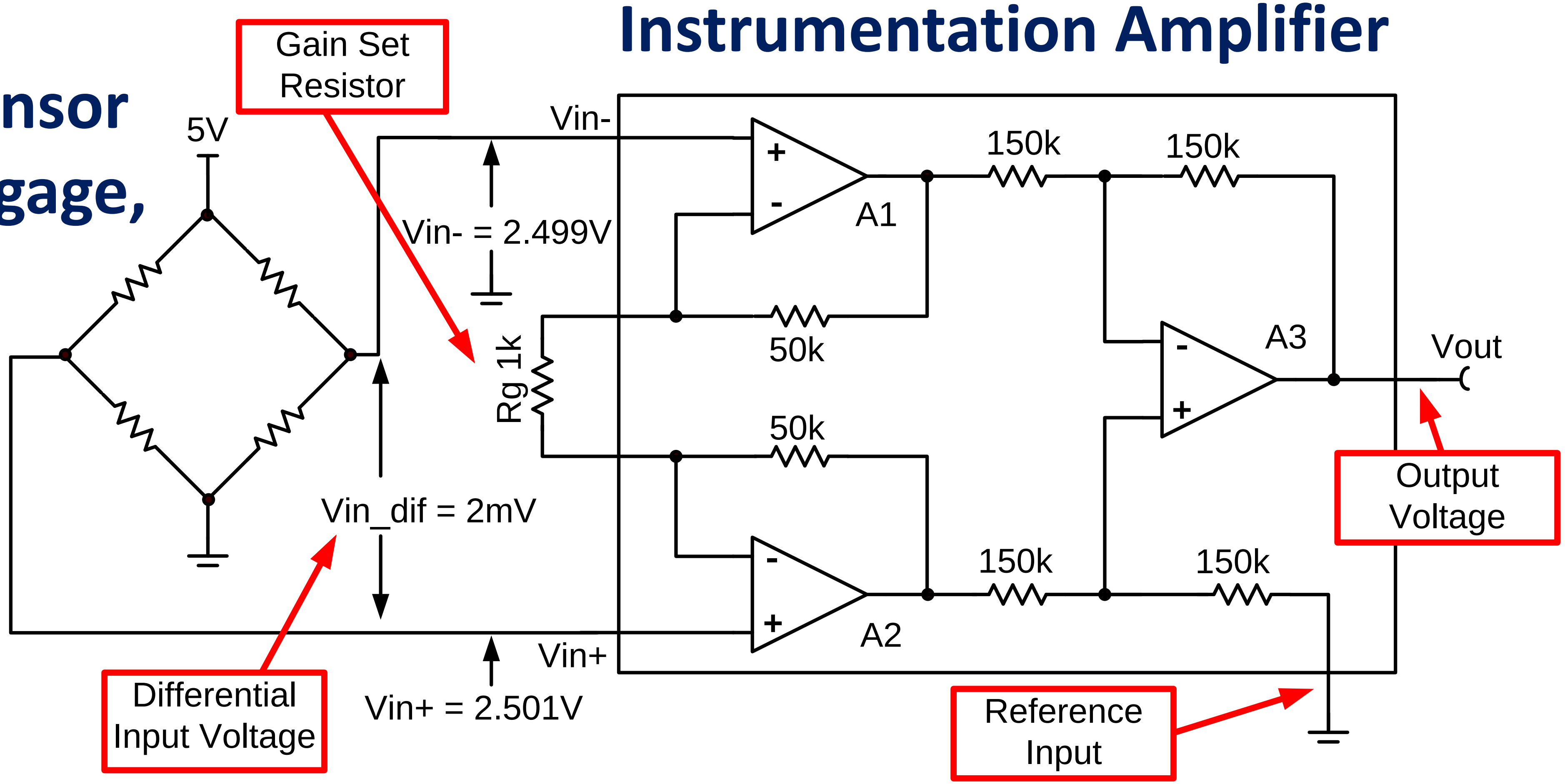
Amplifying the signal of a bridge-type sensor

Hall sensor

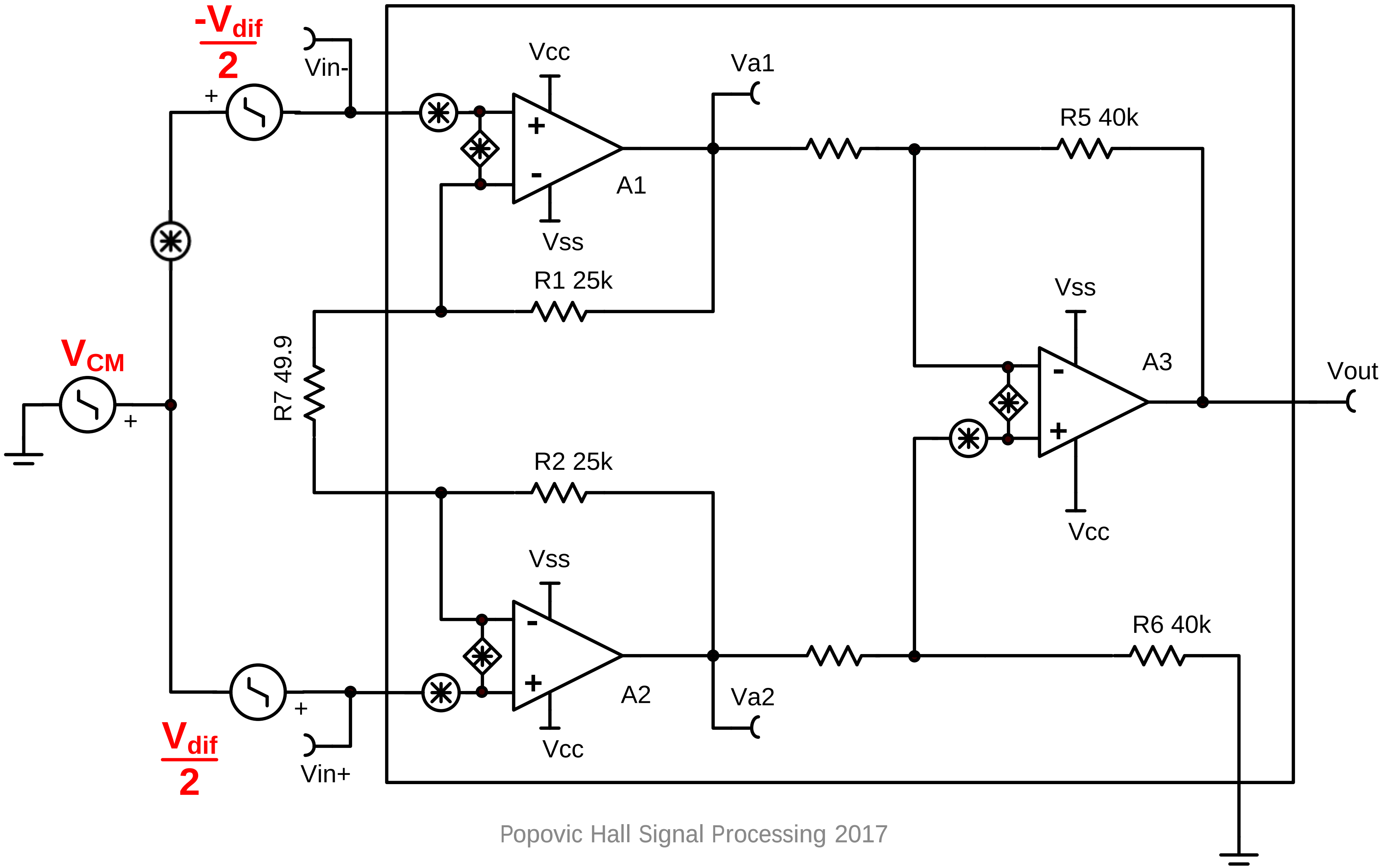
Strain gage,

…

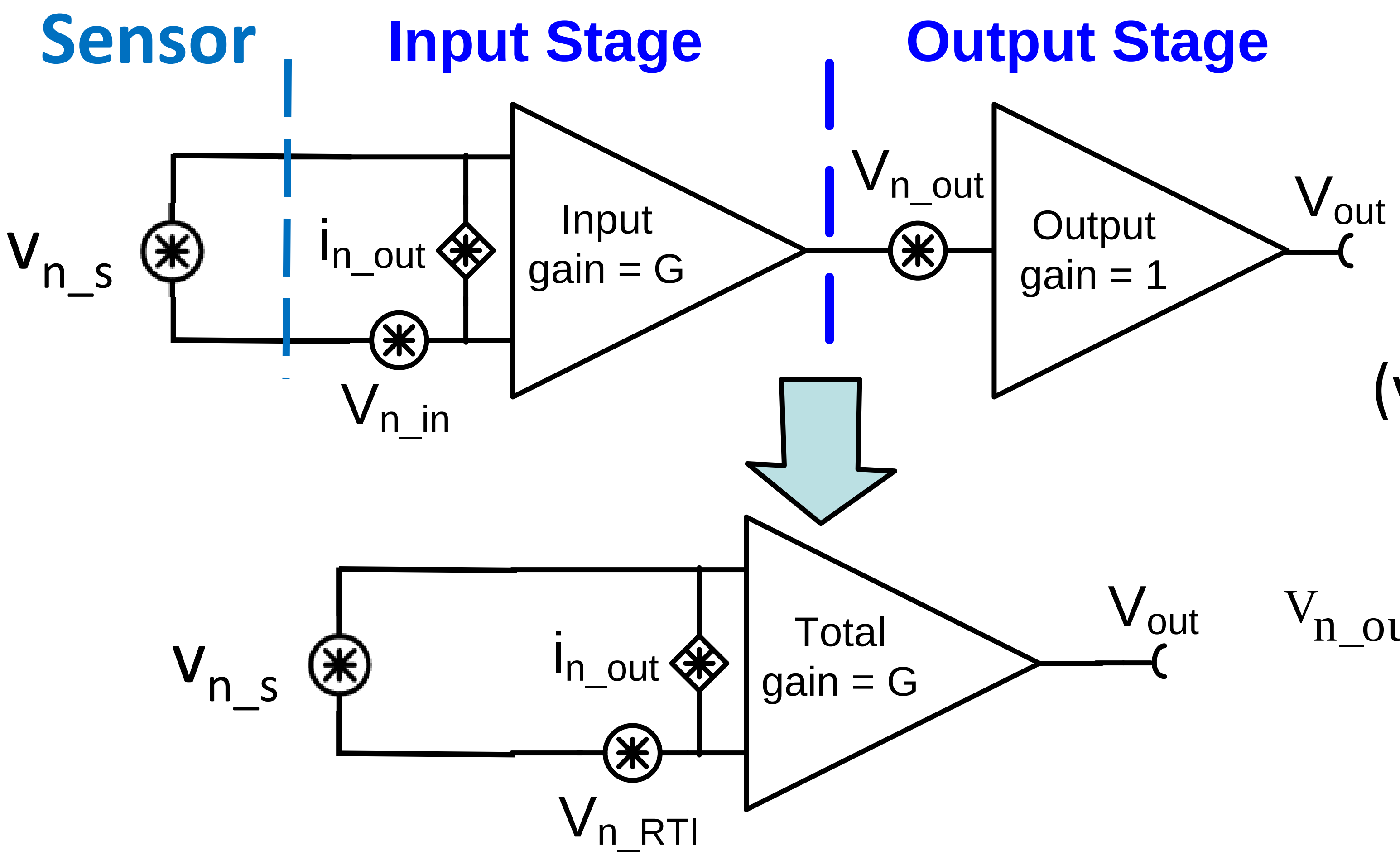
Instrumentation Amplifier



Noise model of a transducer



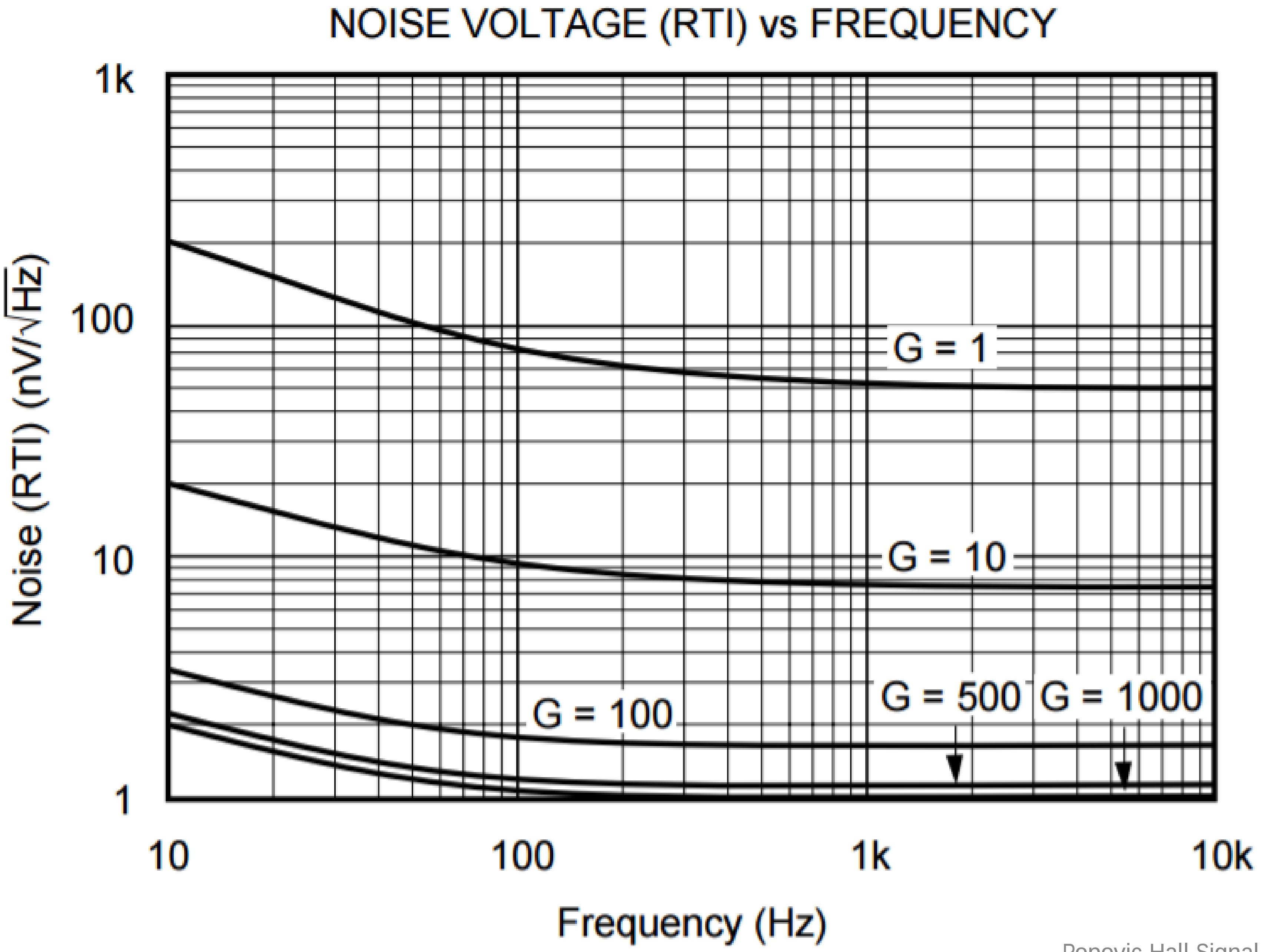
The Complex Model is Simplified



$$(v_{n\_in})^2 = (v_{n\_s})^2 + (v_{n\_ai})^2$$

$$V_{n\_out} = \sqrt{\left(V_{n\_out}\right)^2 + \left(V_{n\_in} \cdot G\right)^2}$$

$$V_{n\_RTI} = \sqrt{\left(\frac{V_{n\_out}}{G}\right)^2 + \left(V_{n\_in}\right)^2}$$



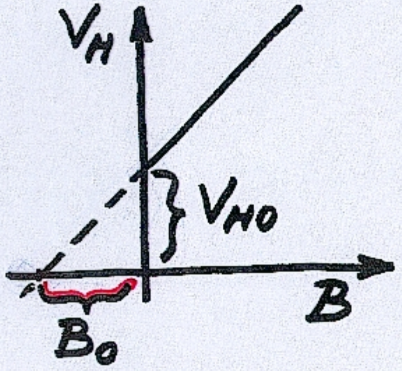
Example:

INA 163

&

$v_{n\_s} << v_{n\_ai}$

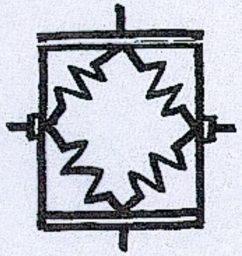
OFFSET
IN A HALL DEVICE



$V_{H0} \equiv V_H$ at $B=0$

$B_0 \equiv$ apparent B_{meas} at $B=0$

CAUSES: ASYMETRY DUE TO

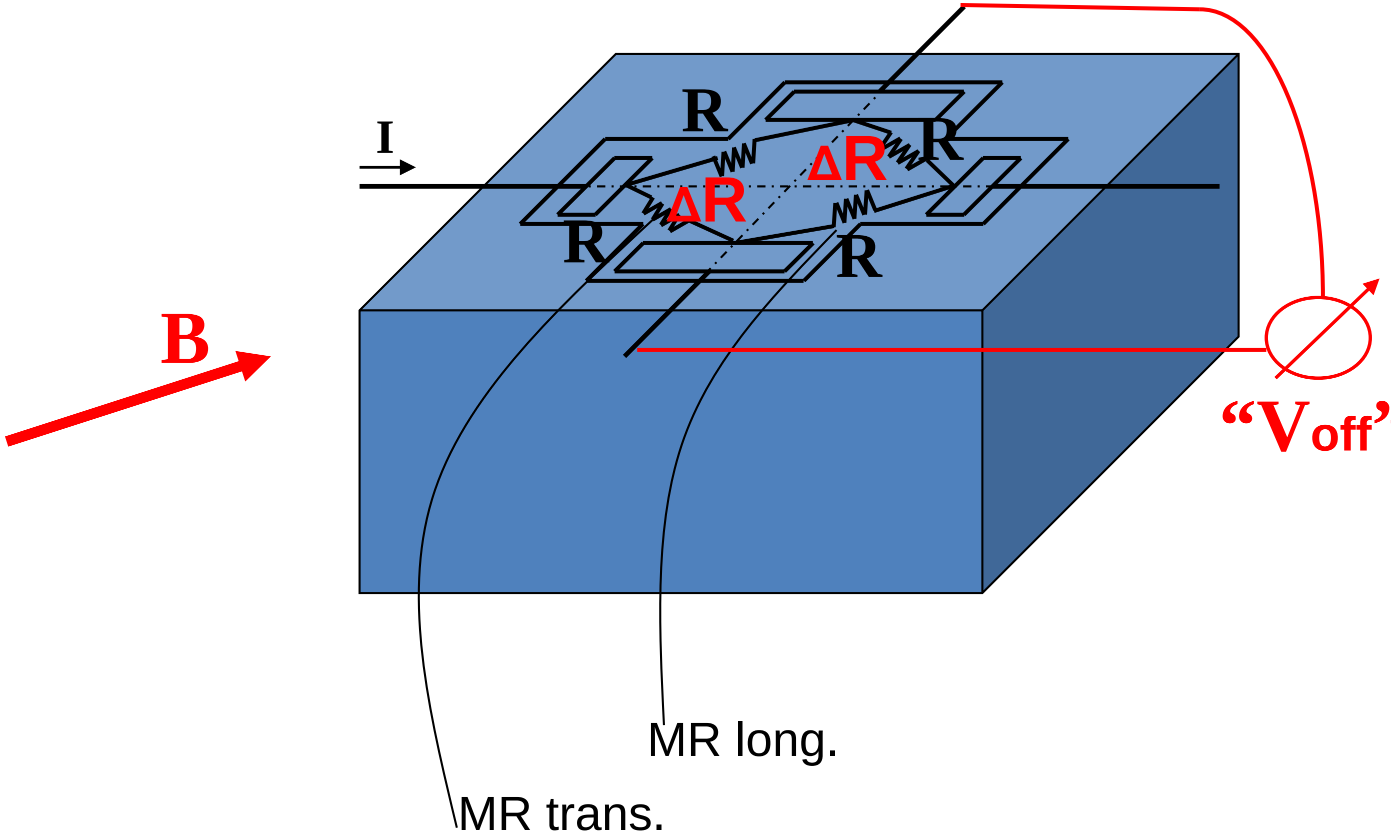


- GEOMETRY
- DOPING
- TEMPERATURE GRAD.
- MECHANICAL STRESS
- SURFACE EFFECTS

TYPICAL VALUES:

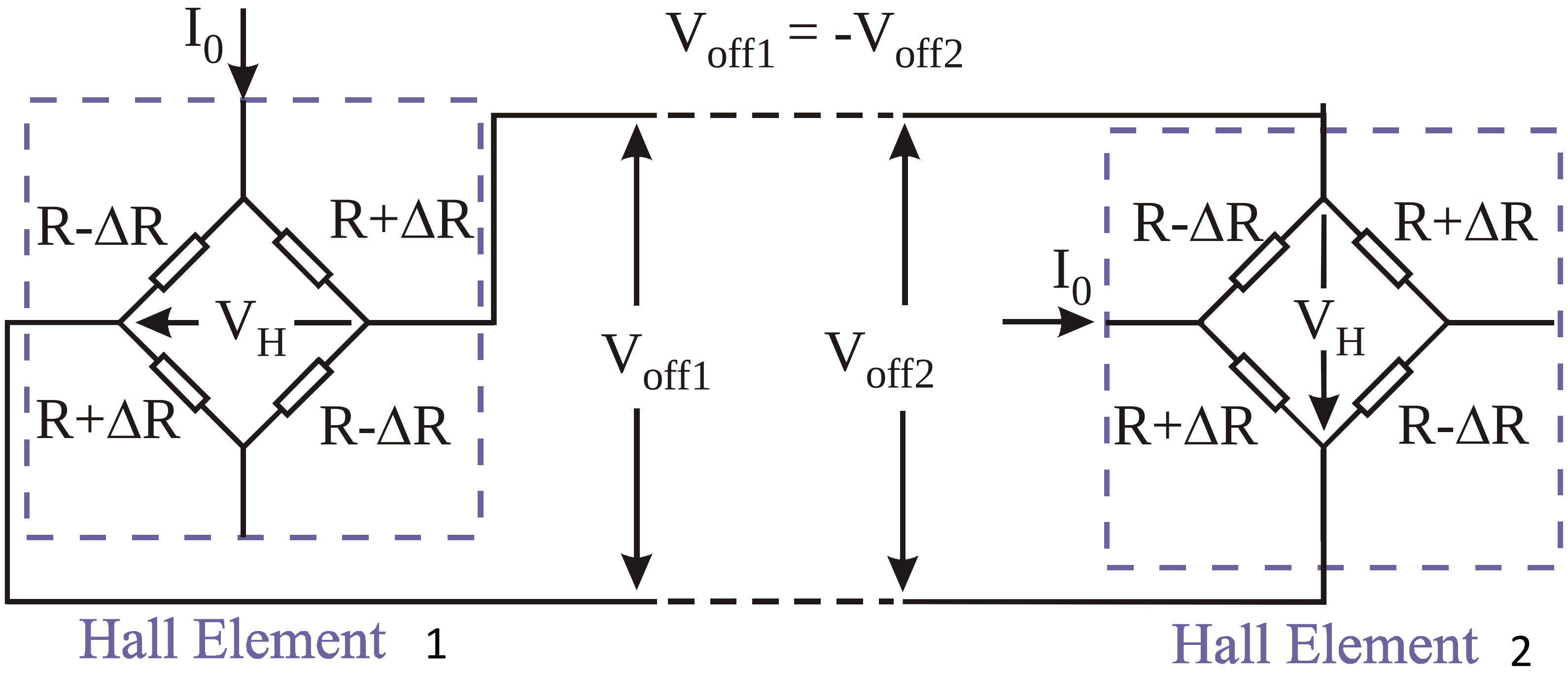
$B_0 \sim 5 \ldots 50$ mT

MR Model of the Planar Hall effect



"V_{off}" ≡ $V_p \propto B^2$

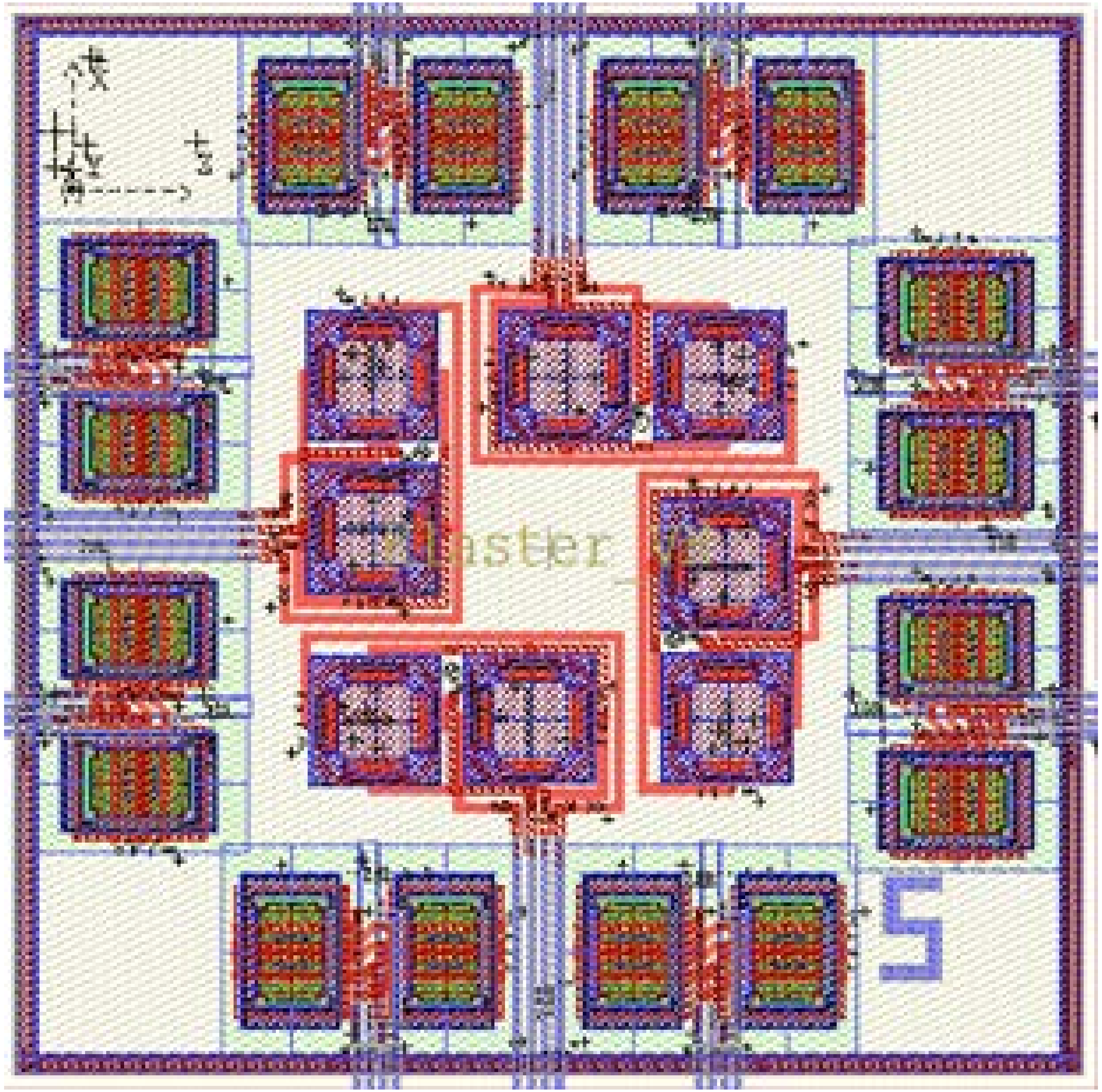
Reducing Offset and Noise:
Orthogonal-Parallel Coupling of Hall Elements



$V_{H1} = V_{H2}$

1 × Hall: $Vnoise1 = \sqrt{4kTR\Delta f}$; 2 × Hall: $Vnoise2 = \mathrm{Vnoise1} / \sqrt{2}$; ....

N × Hall: $\boldsymbol{VnoiseN = Vnoise1 / \sqrt{N}}$



SENIS integrated orthogonally coupled Hall elements

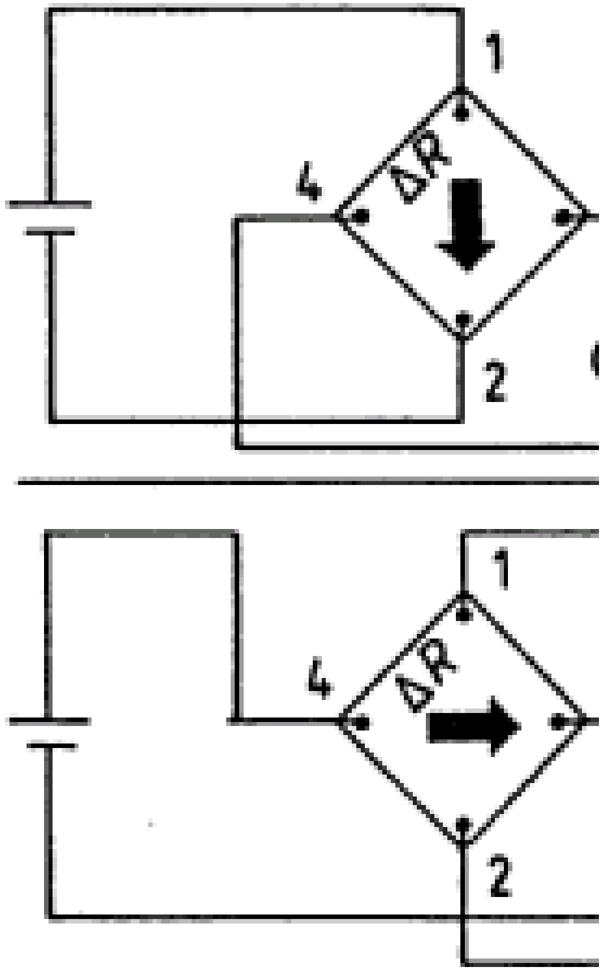
Reducing Offset and 1/f Noise by Current Spinning

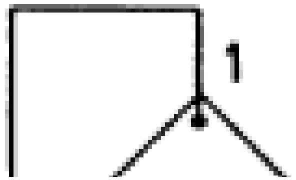
« Switched Hall »

or

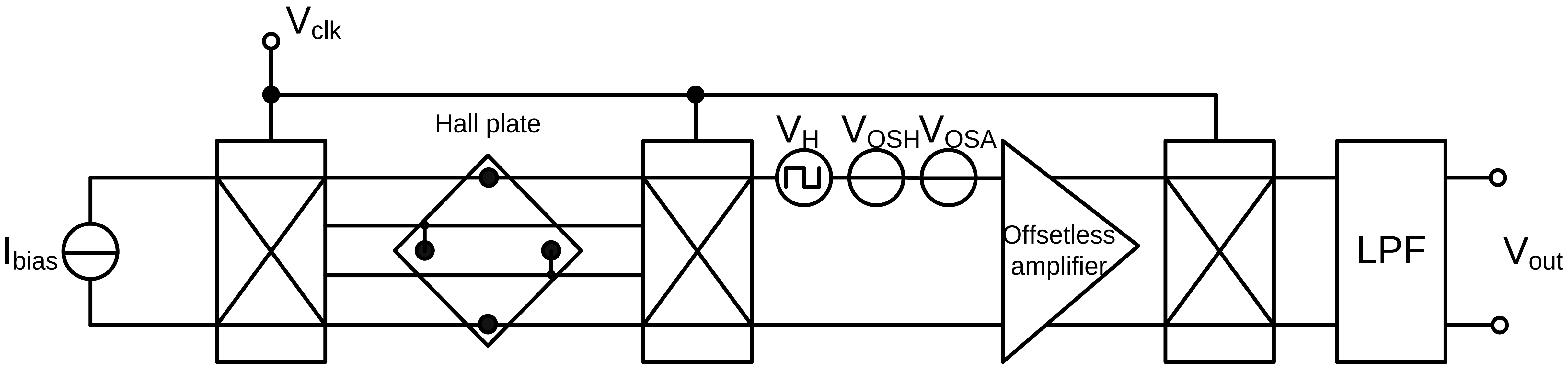
« Spinning Current »

Technique

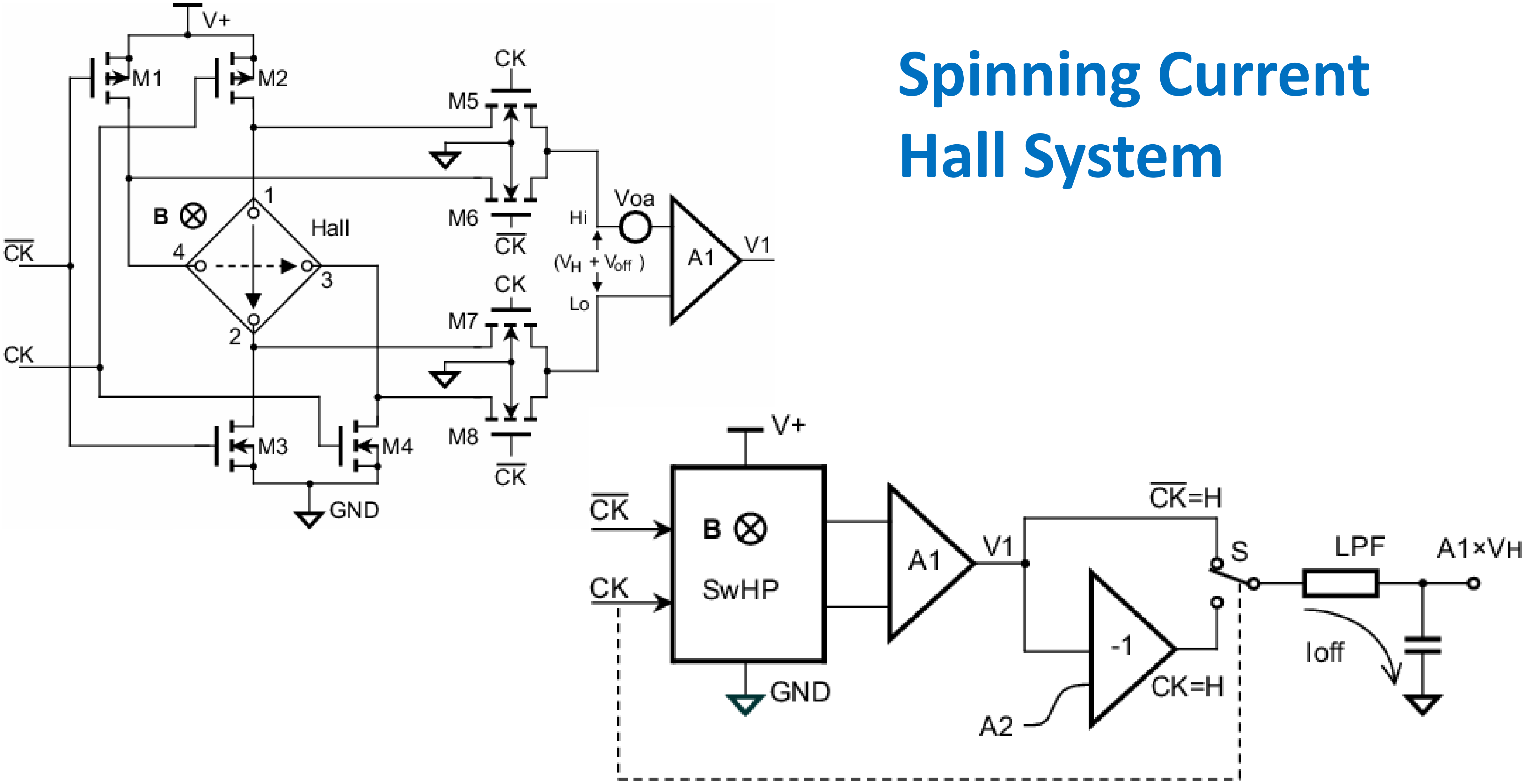




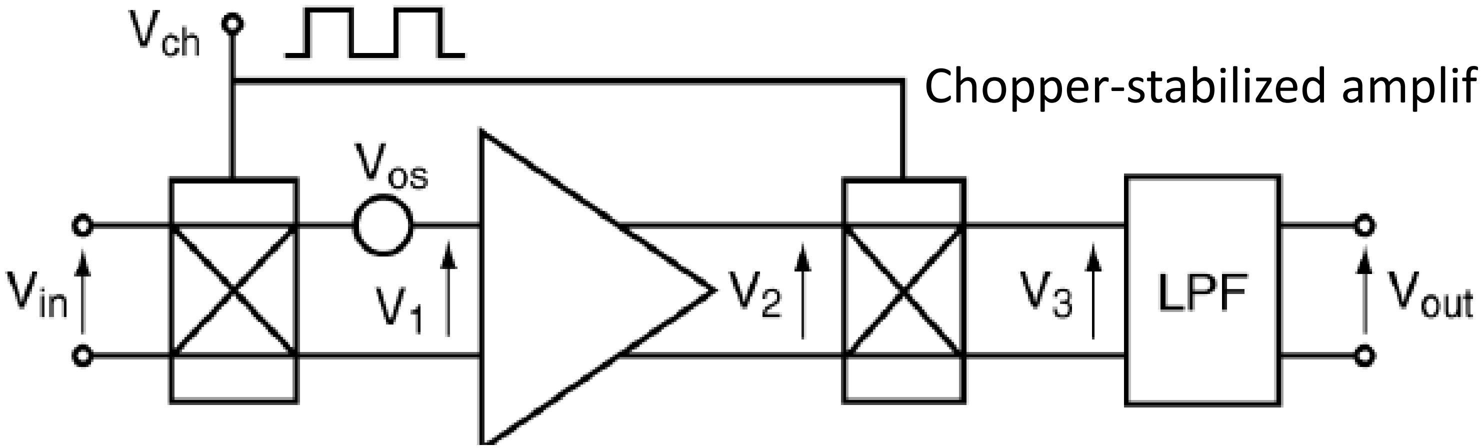
Spinning-Current Hall Sensor System



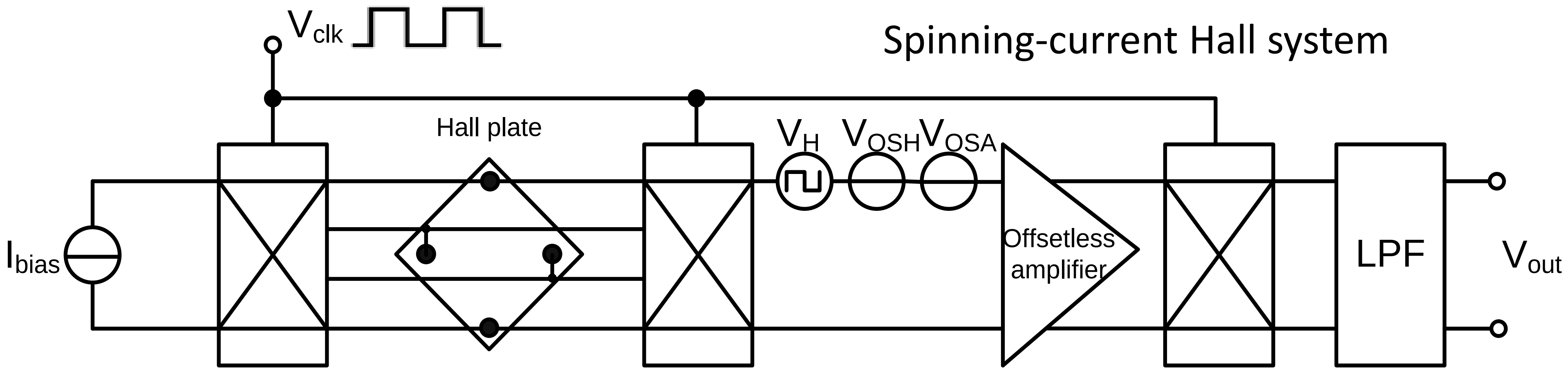
Spinning Current Hall System



Comparing Chopping with Spinning Current Technique

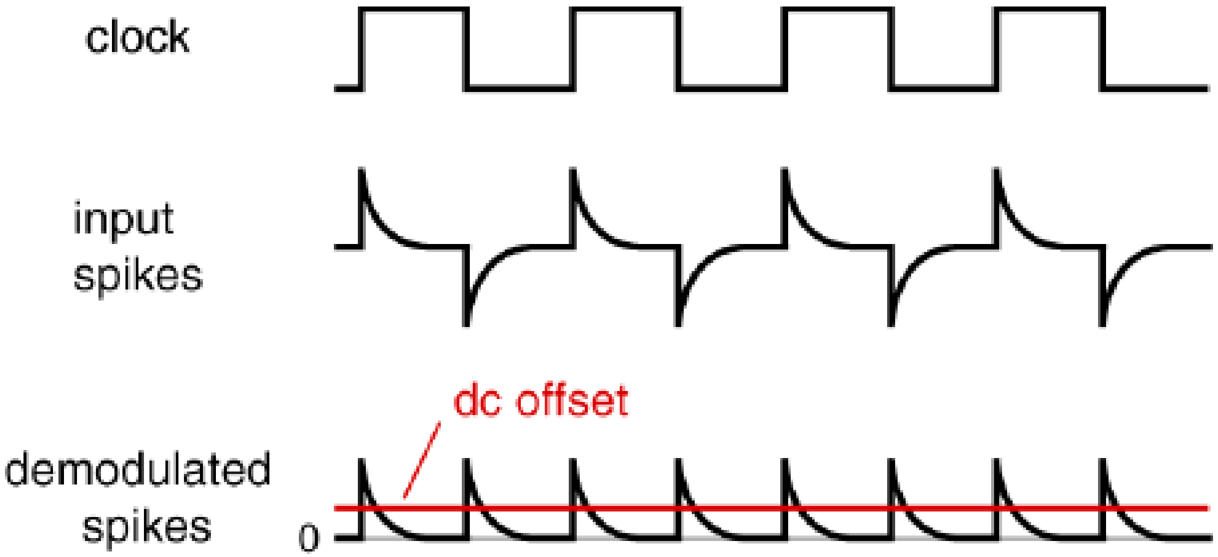


Chopper-stabilized amplifier



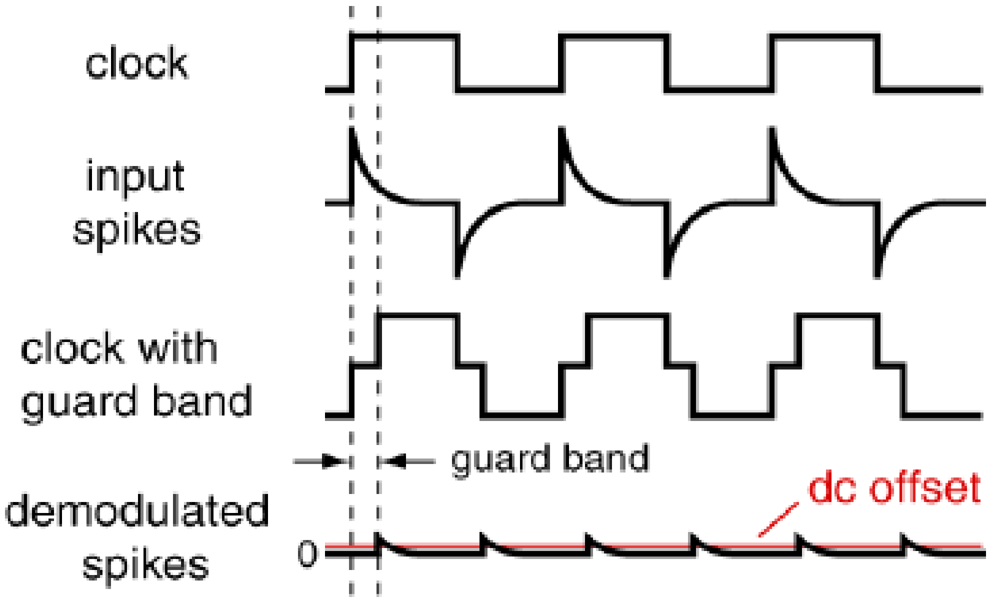
Spinning-current Hall system

Residual Offset of Chopping (1)



- Due to charge injection at the input chopper
- Causes a typical offset of a few μV
- Input spikes ⇒ bias current (a few tens of pA)

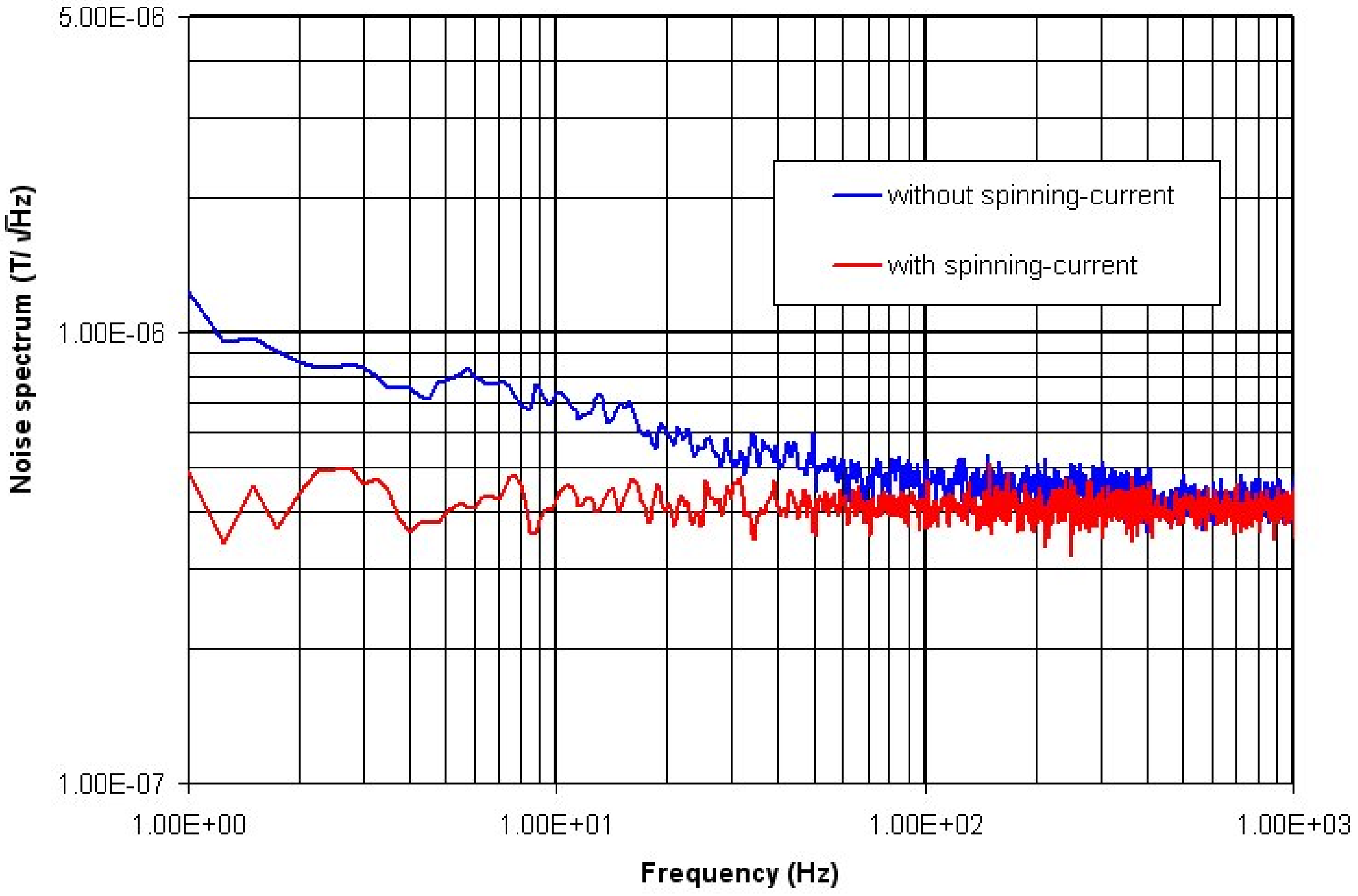
Chopper With Guard Band



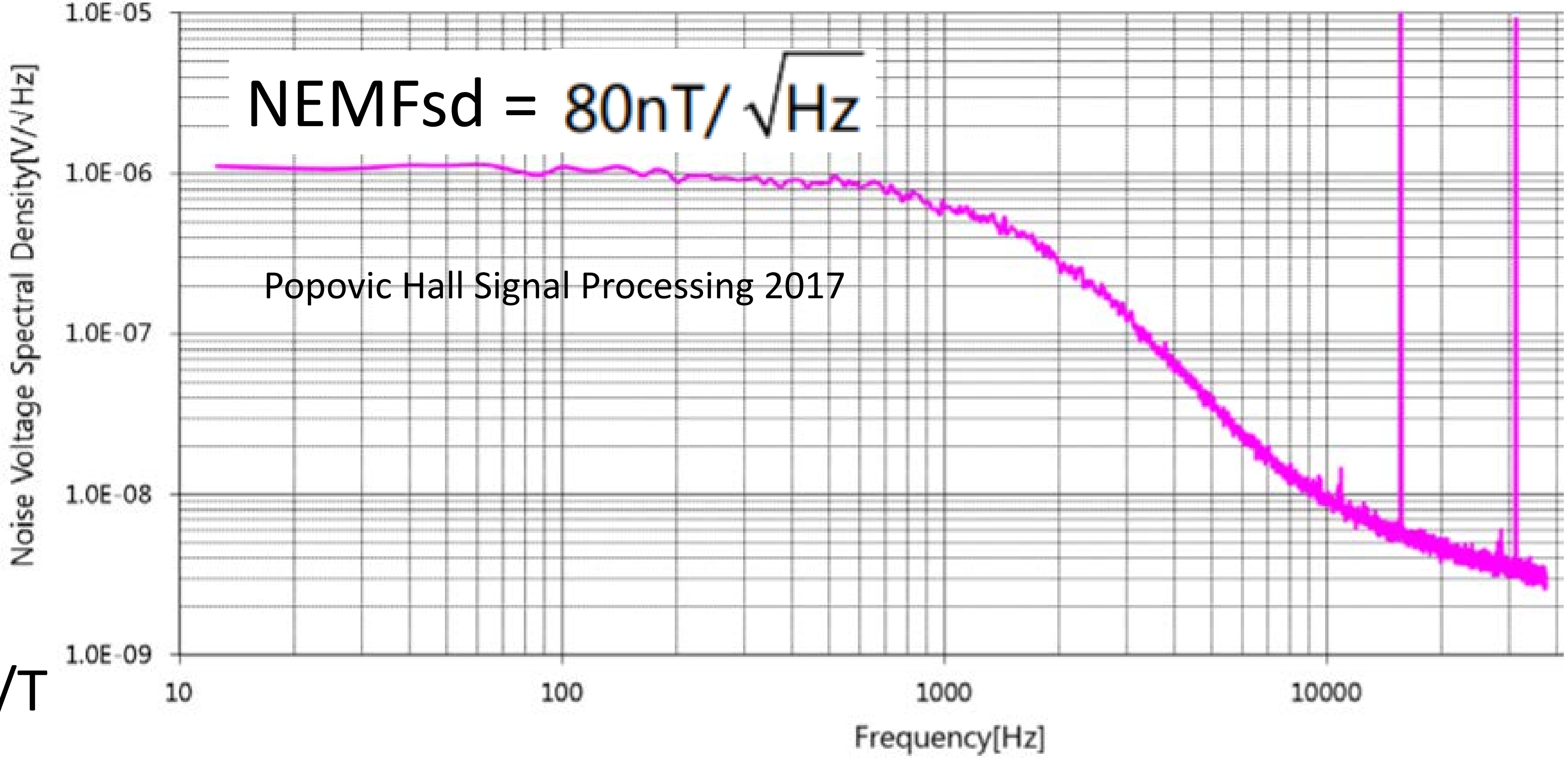
- During guard-band, output is shorted [15,16] or tri-stated [17]
- Residual offset ~ 200nV!
- Slightly worse noise performance

Smart Sensor Systems '02 Kofi A.A. Makinwa

1/f noise reduction in a Hall device by the spinning-current



SENIS integrated vertical Hall device: Noise voltage spectral density with spinning current

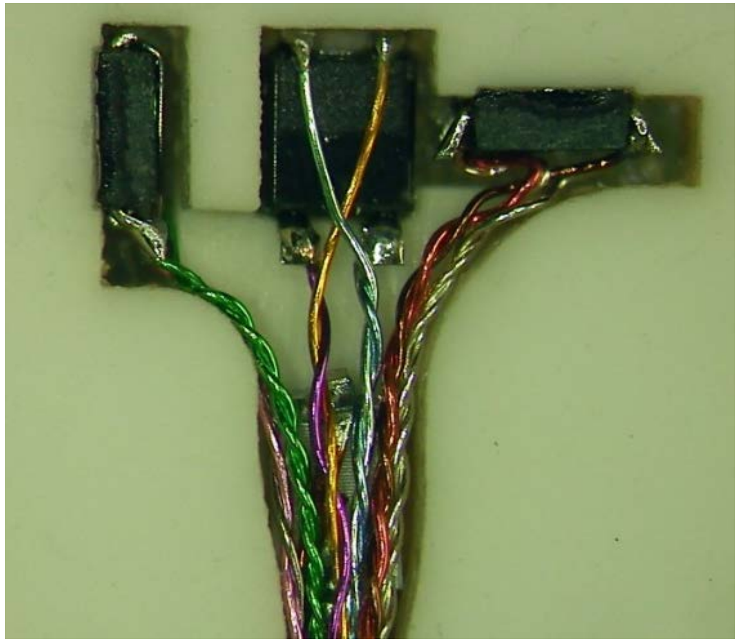


Gain: 200

F_{spin} = 16kHz

Sensitivity: 12.6V/T

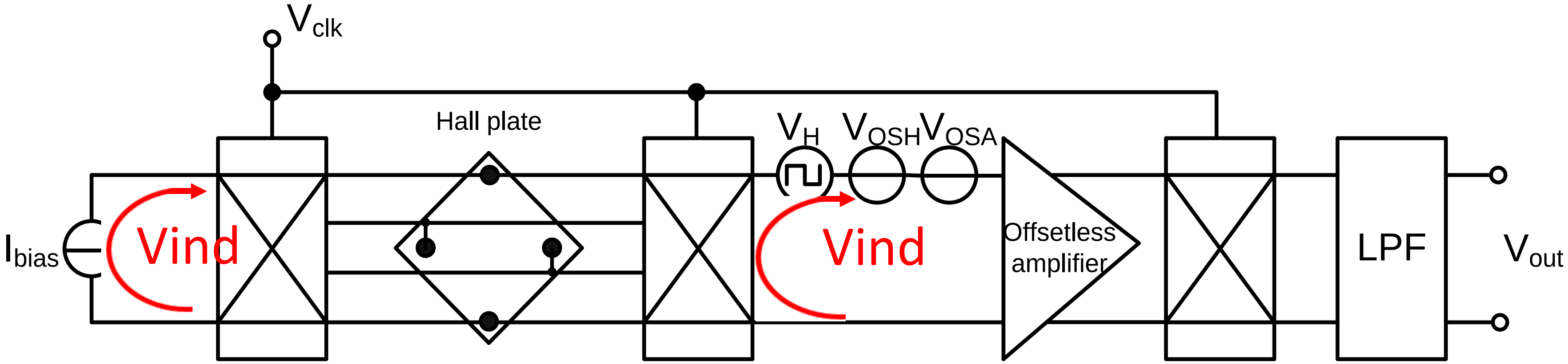
BW = 1kHz



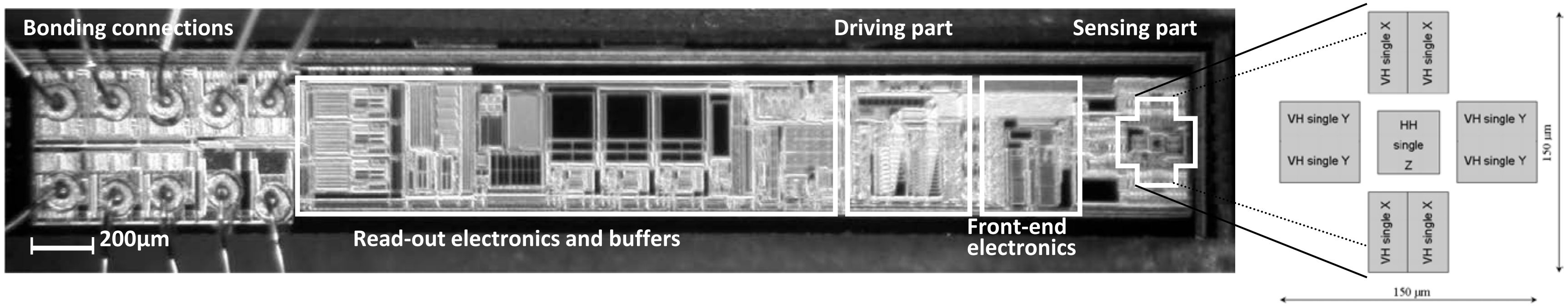
Reducing inductive effects

- Biasing by a constant current
- Spinning current

- Minimizing inductive loops
- Compensating inductive loops



Fully integrated 3D Hall probe



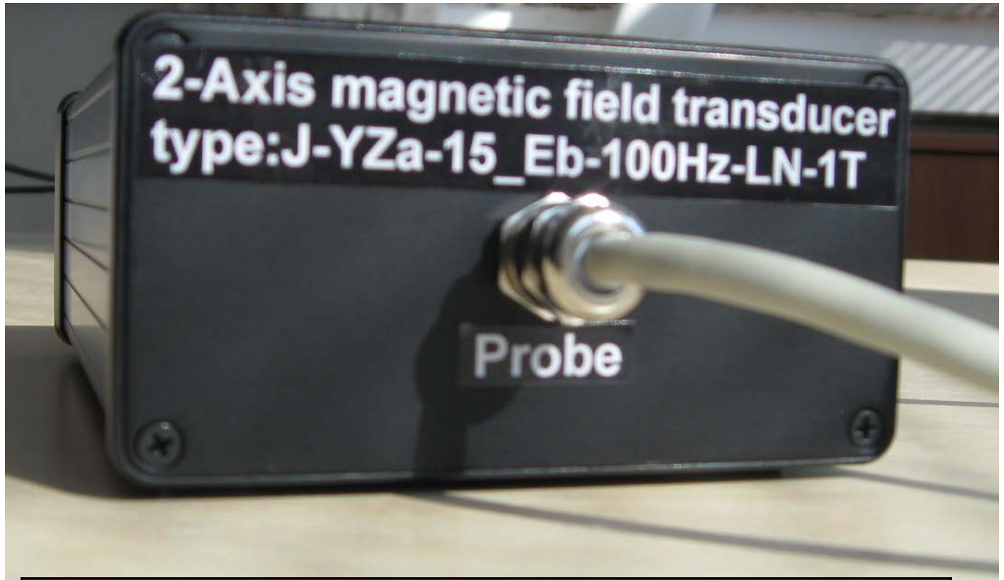
Precise 3D magnetic field measurements

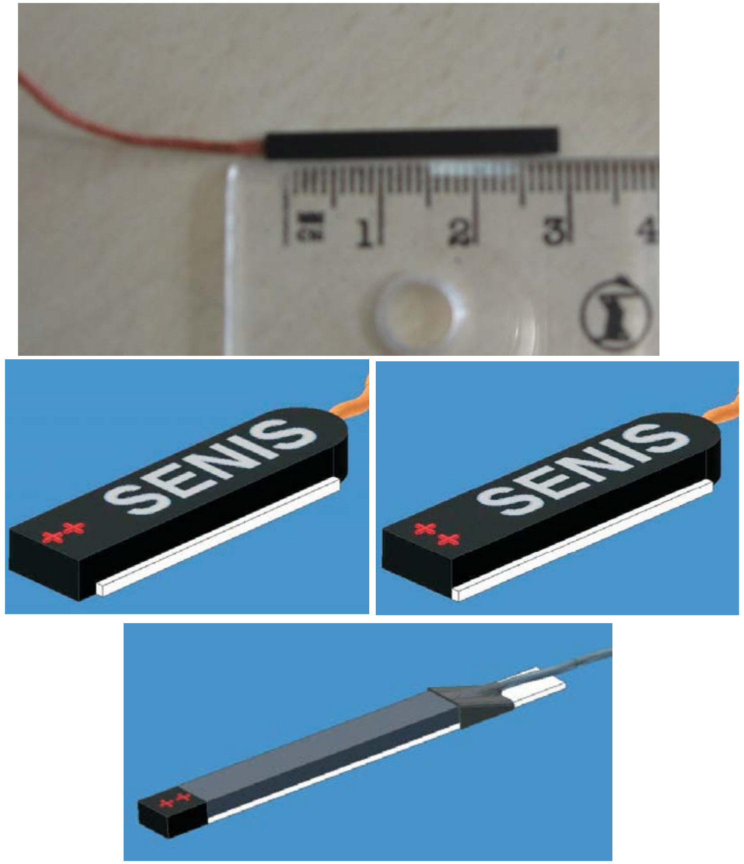
- from militeslas up to tens of tesla
- in the frequency range from DC to 30 kHz
- spatial resolution of about 150 µm
- die dimensions: 4300 µm x 640 µm x 550 µm

Sensing part composed of two types of micro-Hall sensors

- a planar Hall sensor – the perpendicular B-component
- 8 vertical Hall sensors – the in-plane B-components

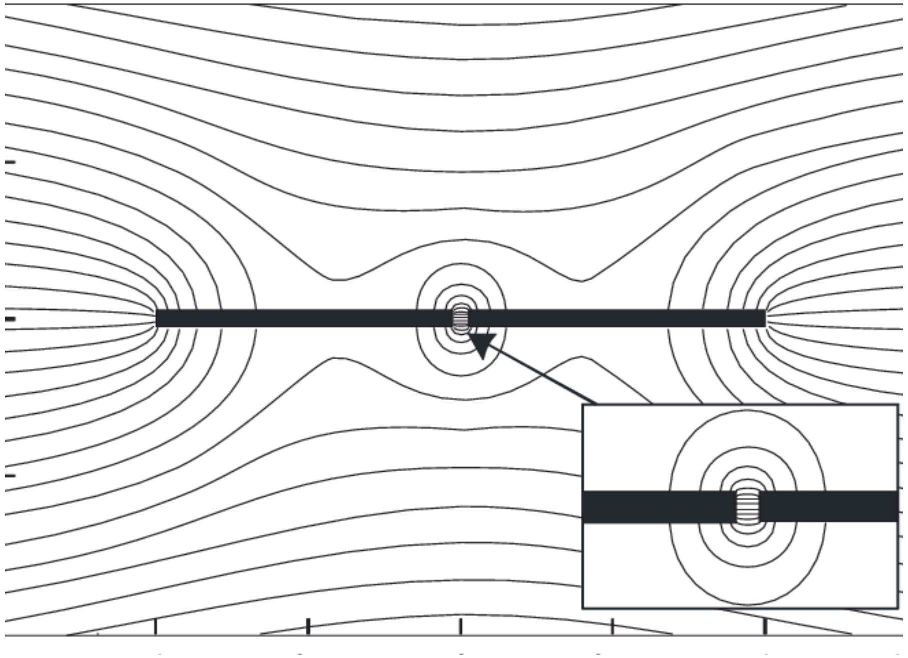
1ppm 2T Two-Axis Hall Transducer



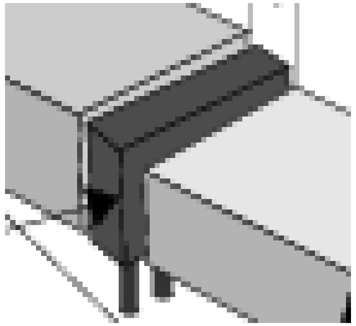


Key Features	
▪ **Measurement range**	**± 2T**
▪ **Frequency response**	**DC to 100Hz**
▪ **Broad-band Noise**	**$B_{RMS} < 0.5\mu T$**
▪ **Offset Drift**	**$B_{OF,RMS} < 0.4\mu T$**
▪ **Calibration Accuracy**	**10ppm**
▪ **Probe dimensions**	**$1.5 \times 3 \times 30\ mm^3$**

Resolution: NEMF < $0.25\ 10^{-6}$ B-range



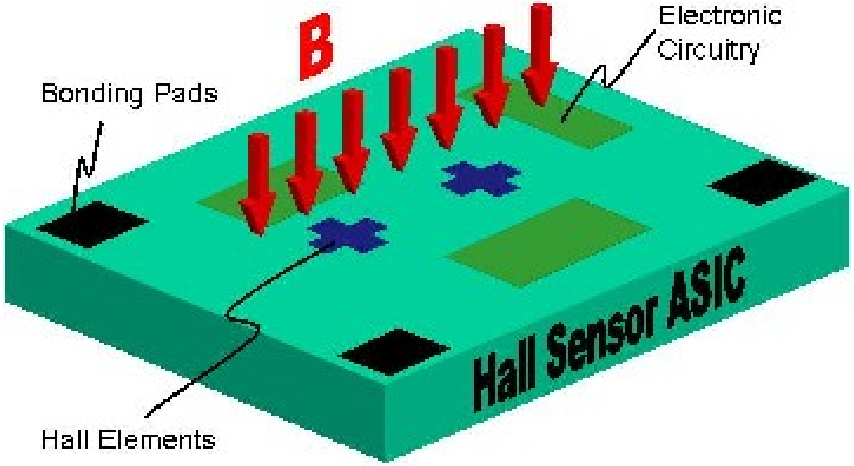
Amplifying the magnetic signal: the concept of 2 IMC - Hall

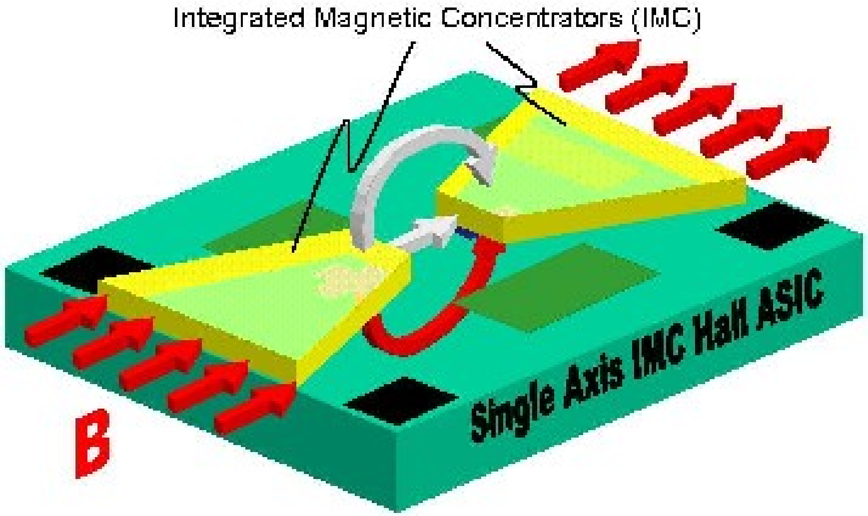


Magnetic Flux Concentration Gain:

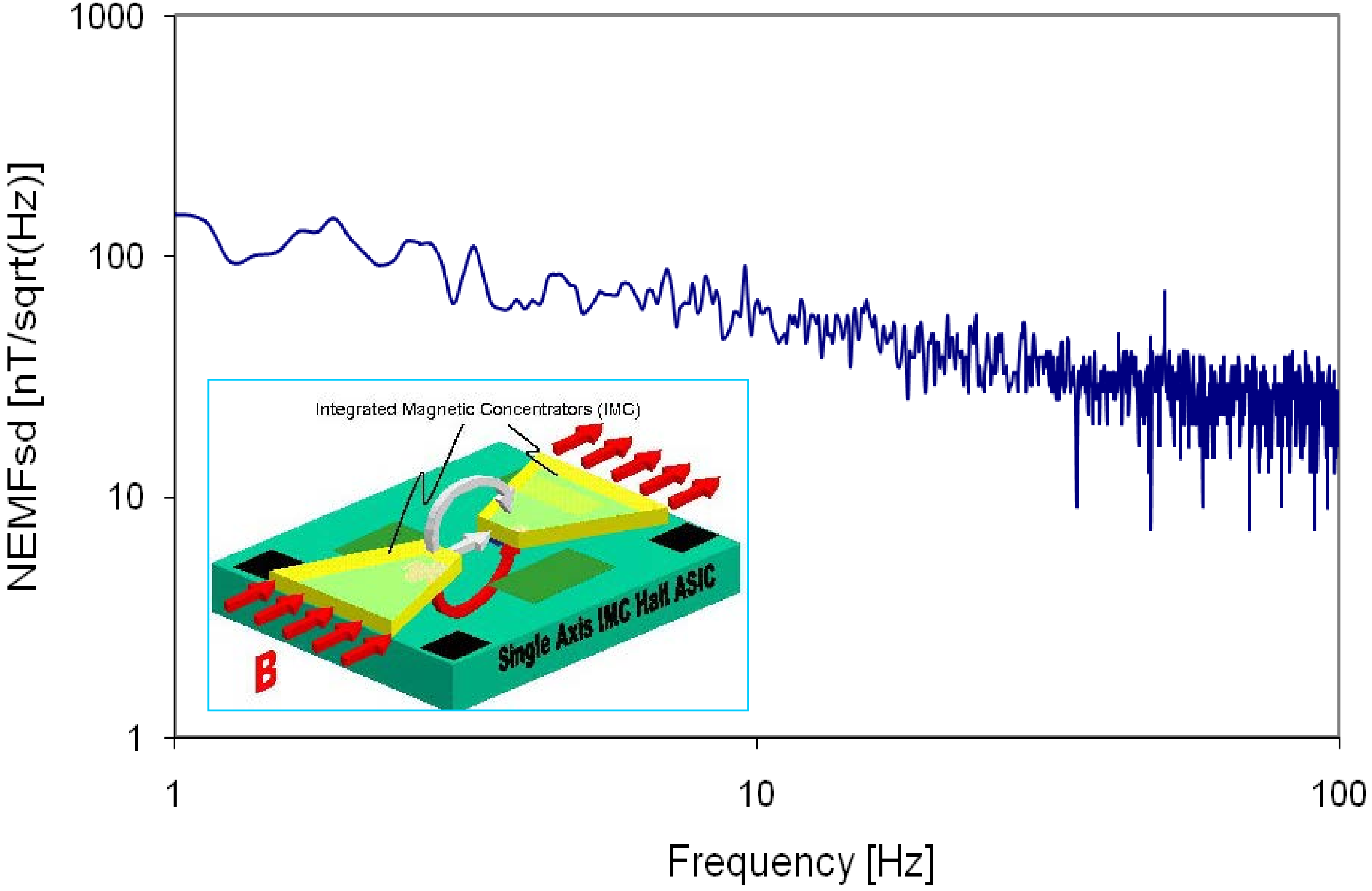
$G_{MC} = B_{Hall} / B_{ext}$

$G_{MC} = 1 \ldots. 10$

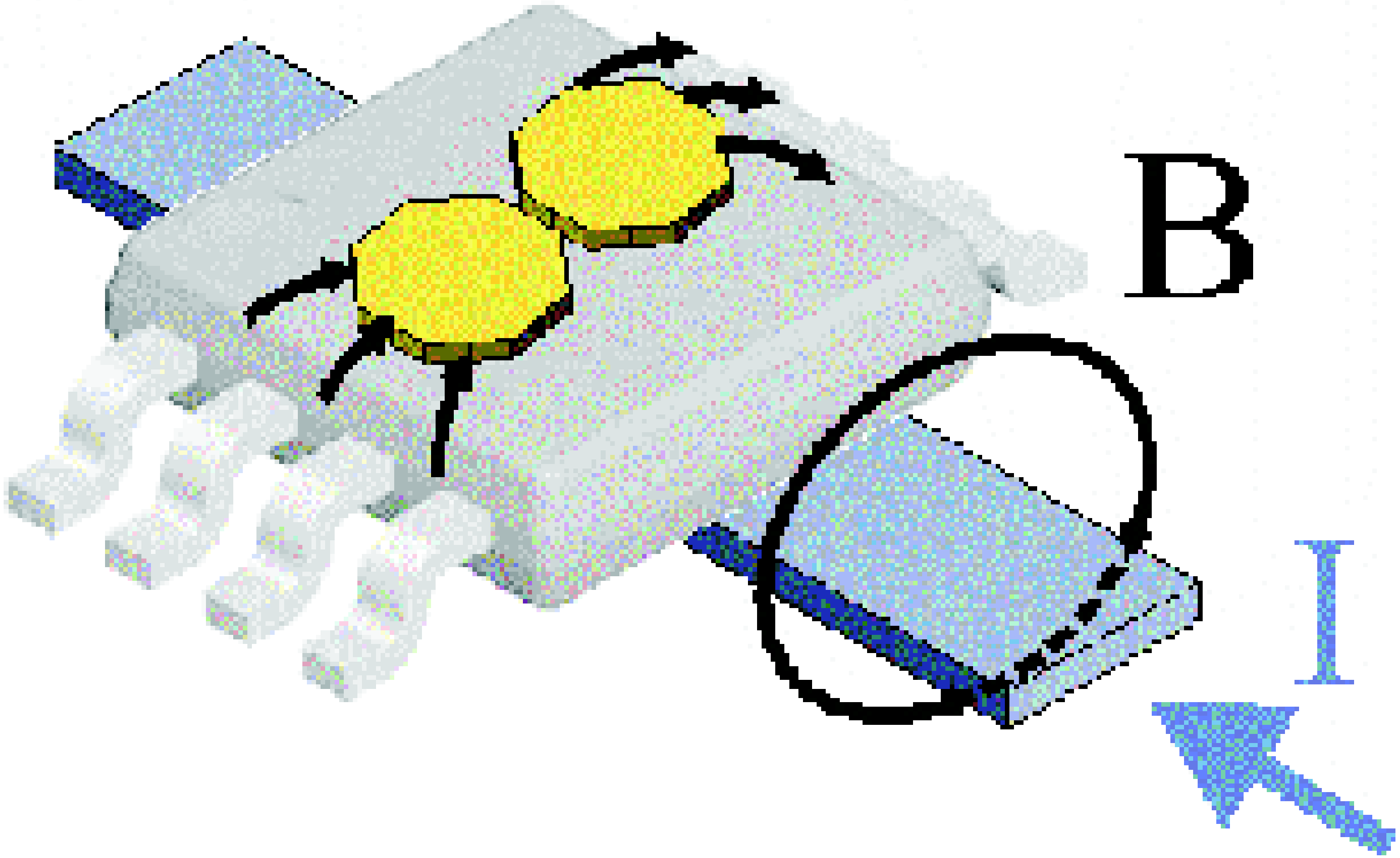




Measured NEMFsd
CSA-1V (Sentron)



Application: Low Cost Current Sensor



PHYSICAL LIMIT OF RESOLUTION

(Thermal) Noise-Equivalent Magnetic Field spectral density:

$$\text{NEMFsd,min} \geq \sqrt{4\,k\,T\,R_H}\;/\;(G_{MC}\;S_V\;V_b)$$

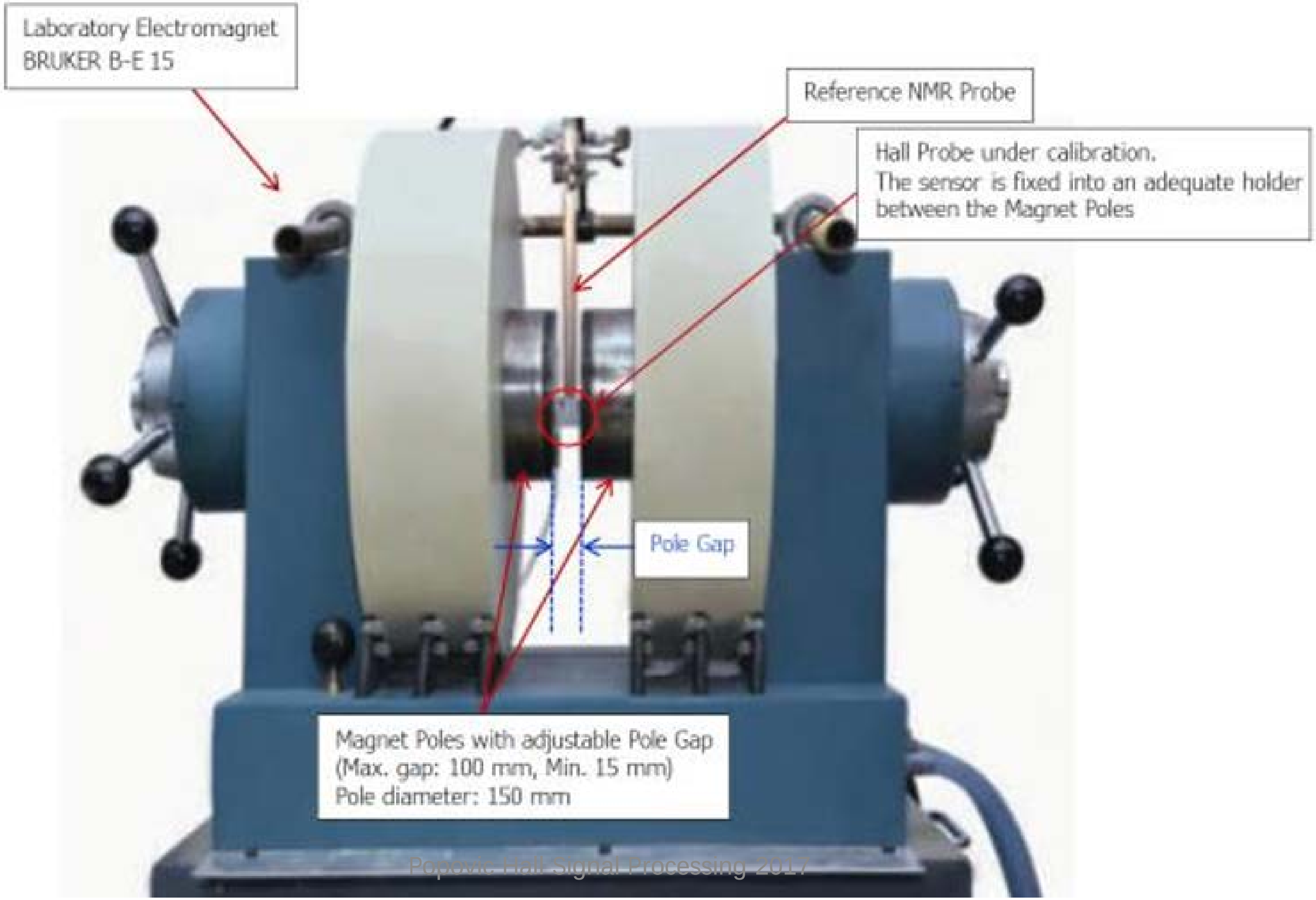
k – Boltz. constant; T – abs. temp.; R_H – resistance of Hall;
G_{MC} – magn. gain of IMC; S_V - volt-rel. sensitivity; V_b - bias volt.

$$\text{NEMFsd,min} \geq \sqrt{4\,k\,T}\;/\;(G_{MC}\;S_V\;\sqrt{P_b})$$

P_b : bias power of Hall, $P_b = V_b\,I_b$
For $S_V = 0.05$ (contemporary max for Si Hall) and $T = 300\text{K}$:

$$\mathbf{NEMFsd,min \geq 82\;nT/\sqrt{Hz\;mW}\;\;/\;G_{MC}}$$

Electromagnet for calibrating Hall probes



Laboratory Electromagnet
BRUKER B-E 15

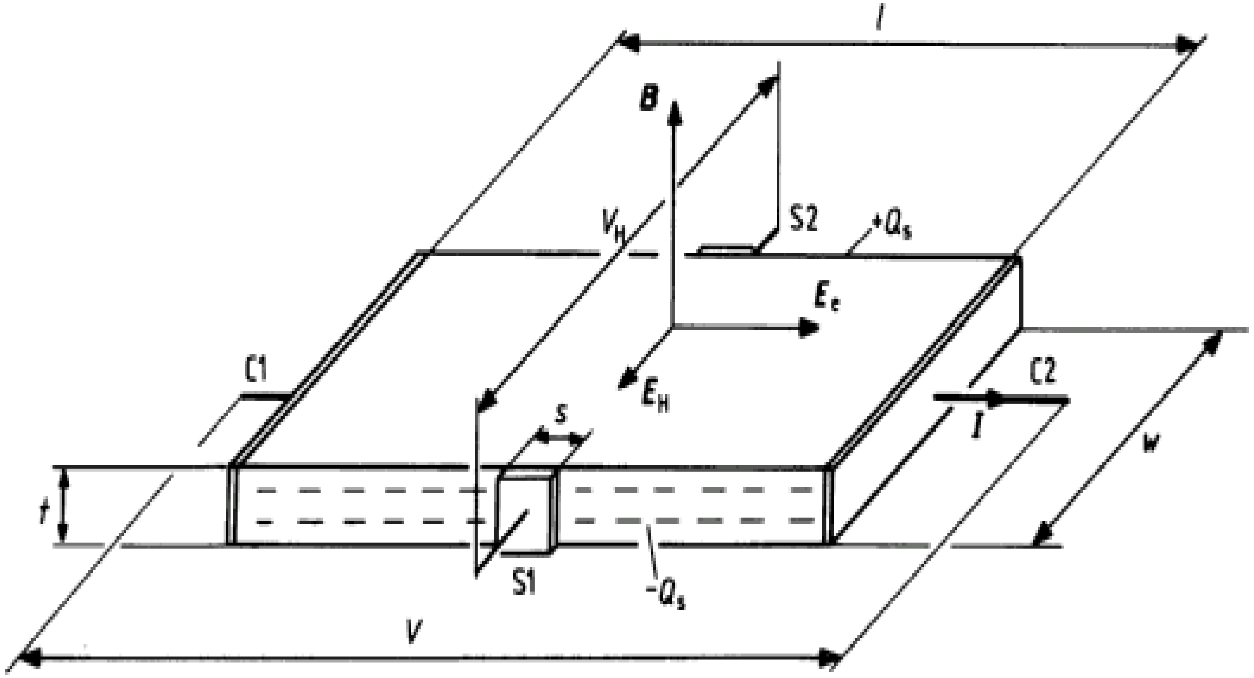
Reference NMR Probe

Hall Probe under calibration.
The sensor is fixed into an adequate holder between the Magnet Poles

Pole Gap

Magnet Poles with adjustable Pole Gap
(Max. gap: 100 mm, Min. 15 mm)
Pole diameter: 150 mm

Hall Voltage & Magnetic Sensitivity



Hall Voltage: $$V_H = \int_{S1}^{S2} \boldsymbol{E}_H \, \mathrm{d}\boldsymbol{w}$$

$$V_H = E_H w$$

$$\boldsymbol{E}_{Hn} = \mu_n [\boldsymbol{E} \times \boldsymbol{B}] \quad \Rightarrow \quad V_H = \mu_n \frac{V}{l} w \, B_\perp \quad \Rightarrow \quad V = RI = \frac{1}{q \mu_n n} \frac{l}{wt} I$$

$$V_H = S_V \, \mathrm{V} \, B_\perp \qquad\qquad V_H = S_I \, I \, B_\perp$$

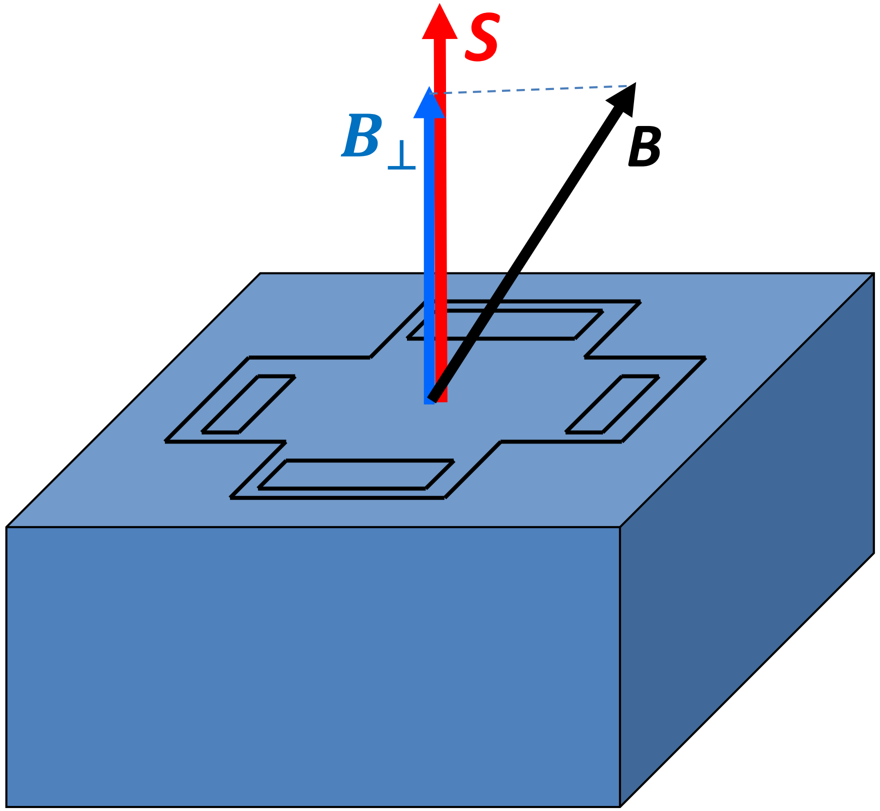
Voltage-Related Sensitivity:

$$S_V \approx \mu_n \frac{w}{l}$$

Current-Related Sensitivity:

$$S_I \approx \frac{1}{q\,n\,t} \approx \frac{R_H}{t}$$

Magnetic Sensitivity Vector



Since

$V_H = S_V \, \mathrm{V} \, B_\perp$ and

$V_H = S_I \, I \, B_\perp$

➡ $V_H = \boldsymbol{S} \cdot \boldsymbol{B}$ (the scalar product of $\boldsymbol{S}$ and $\boldsymbol{B}$)

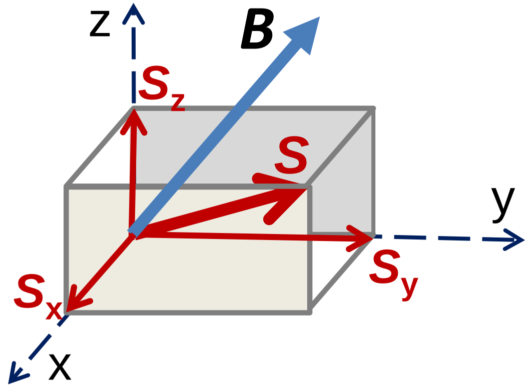
S : Magnetic Sensitivity Vector of a Hall device

$$U_{out} = S_X \cdot B_X + S_Y \cdot B_Y + S_Z \cdot B_Z$$

Magnetic Sensitivity Tensor

1 - axis Hall magnetic sensor:

$\boldsymbol{V_1 = S_1 \cdot B}$ ⇨ $V_1 = \begin{pmatrix} S_{1X} & S_{1Y} & S_{1Z} \end{pmatrix} \begin{pmatrix} B_X \\ B_Y \\ B_Z \end{pmatrix}$



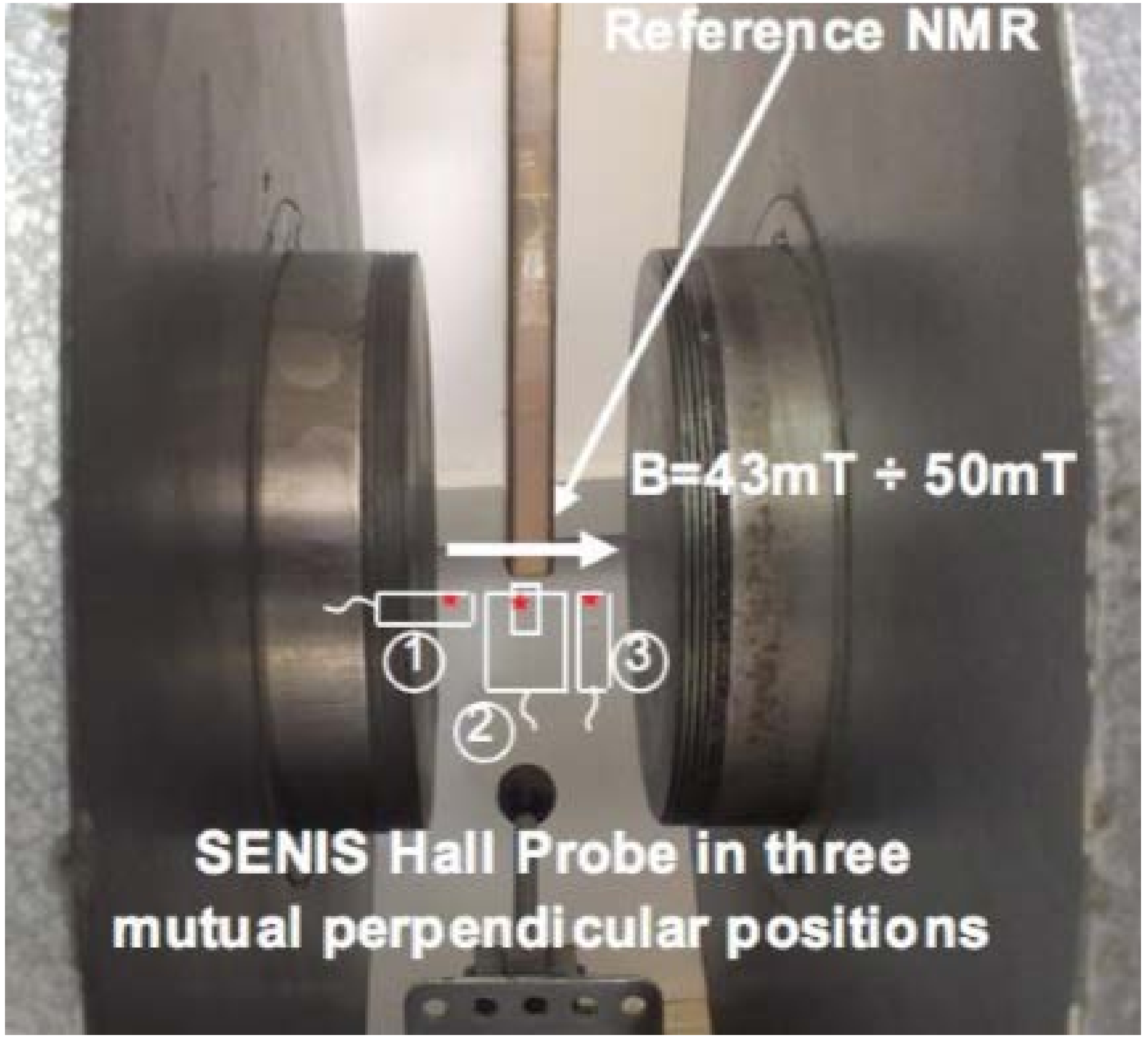
3 - axis Hall magnetic sensor:

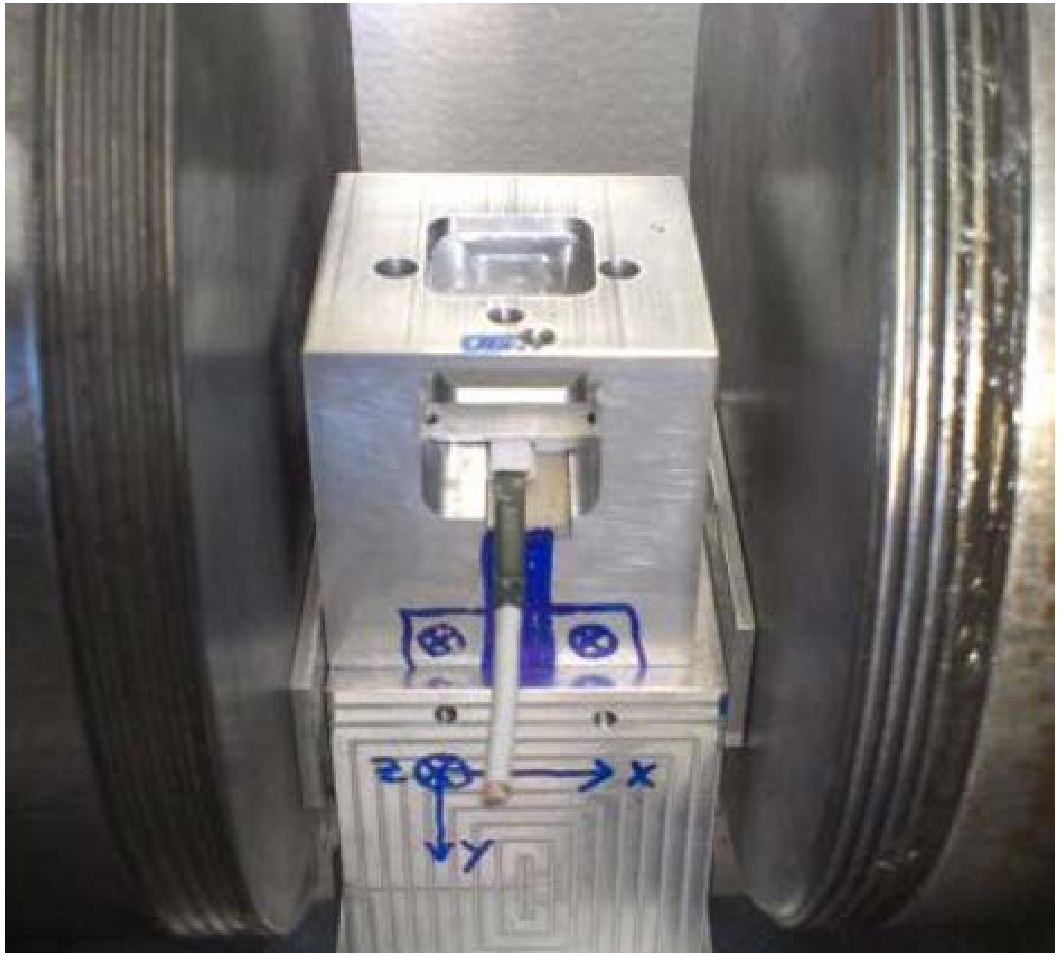
$$\begin{pmatrix} V_1 \\ V_2 \\ V_3 \end{pmatrix} = \begin{pmatrix} S_{1X} & S_{1Y} & S_{1Z} \\ S_{2X} & S_{2Y} & S_{2Z} \\ S_{2X} & S_{3Y} & S_{3Z} \end{pmatrix} \begin{pmatrix} B_X \\ B_Y \\ B_Z \end{pmatrix}$$

⇨ $\boldsymbol{V_3 = (S_3)\, B}$ ⇨ $\boldsymbol{B = (S_3)^{-1}\, V_3}$

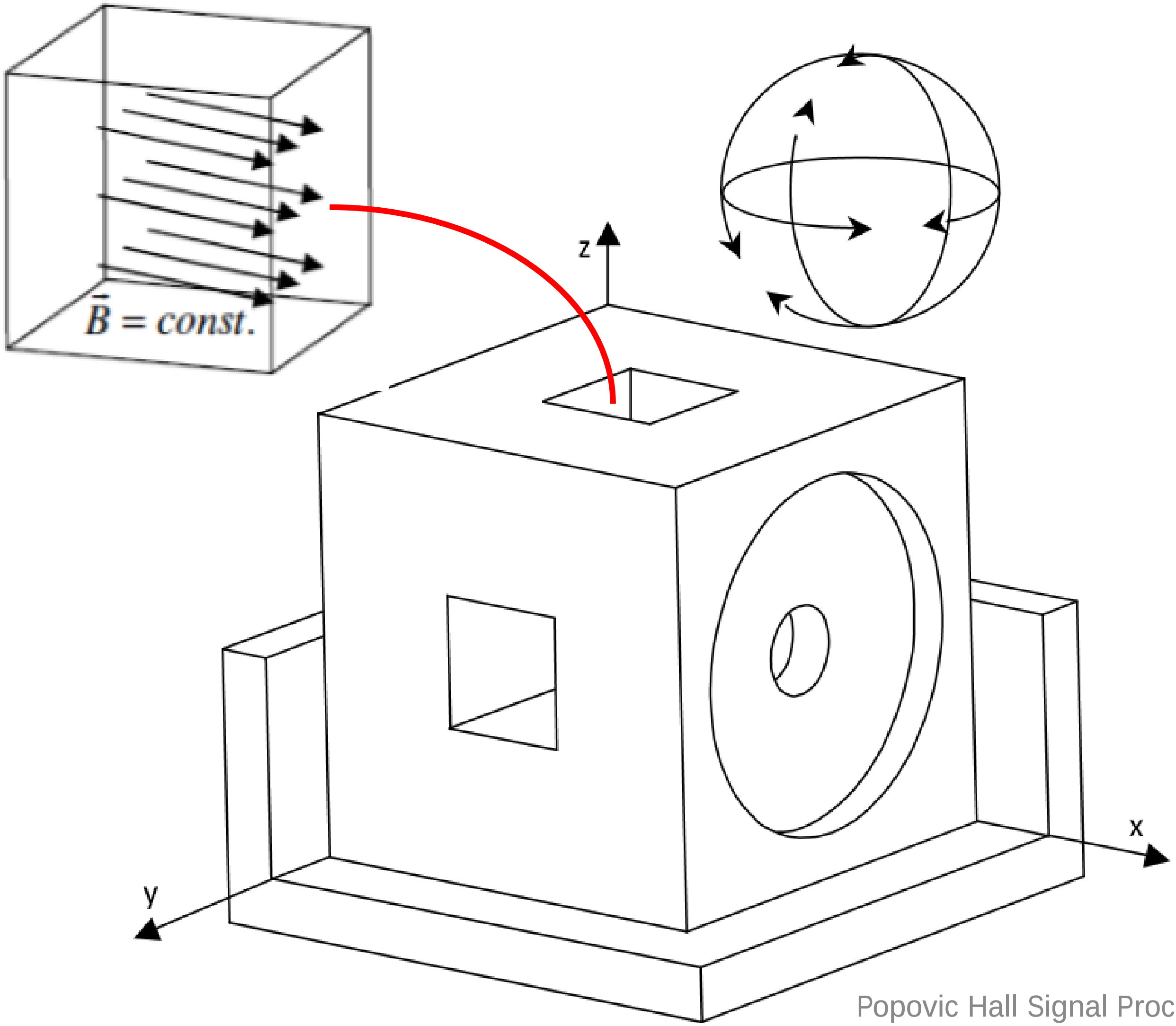
$(\boldsymbol{S_3})$: Magnetic Sensitivity Tensor of a 3-Axis Hall Probe

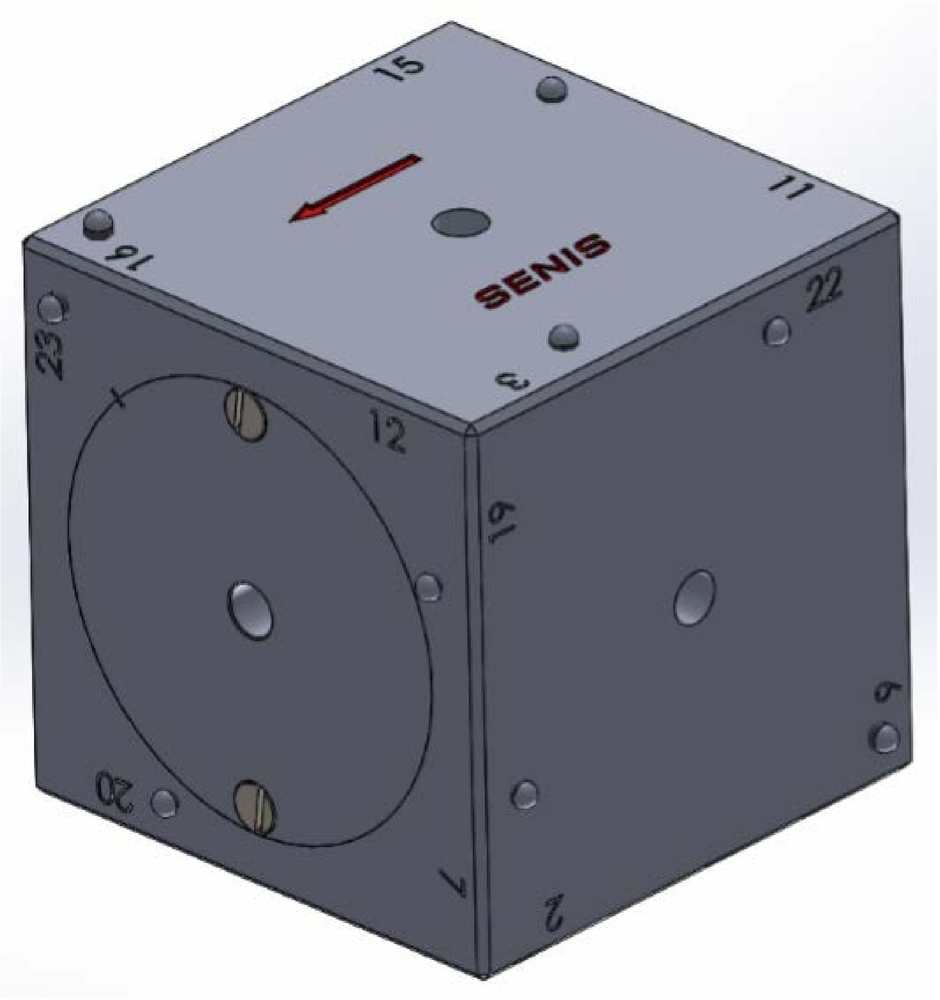
Calibrating the magnetic sensitivity tensor in an electromagnet



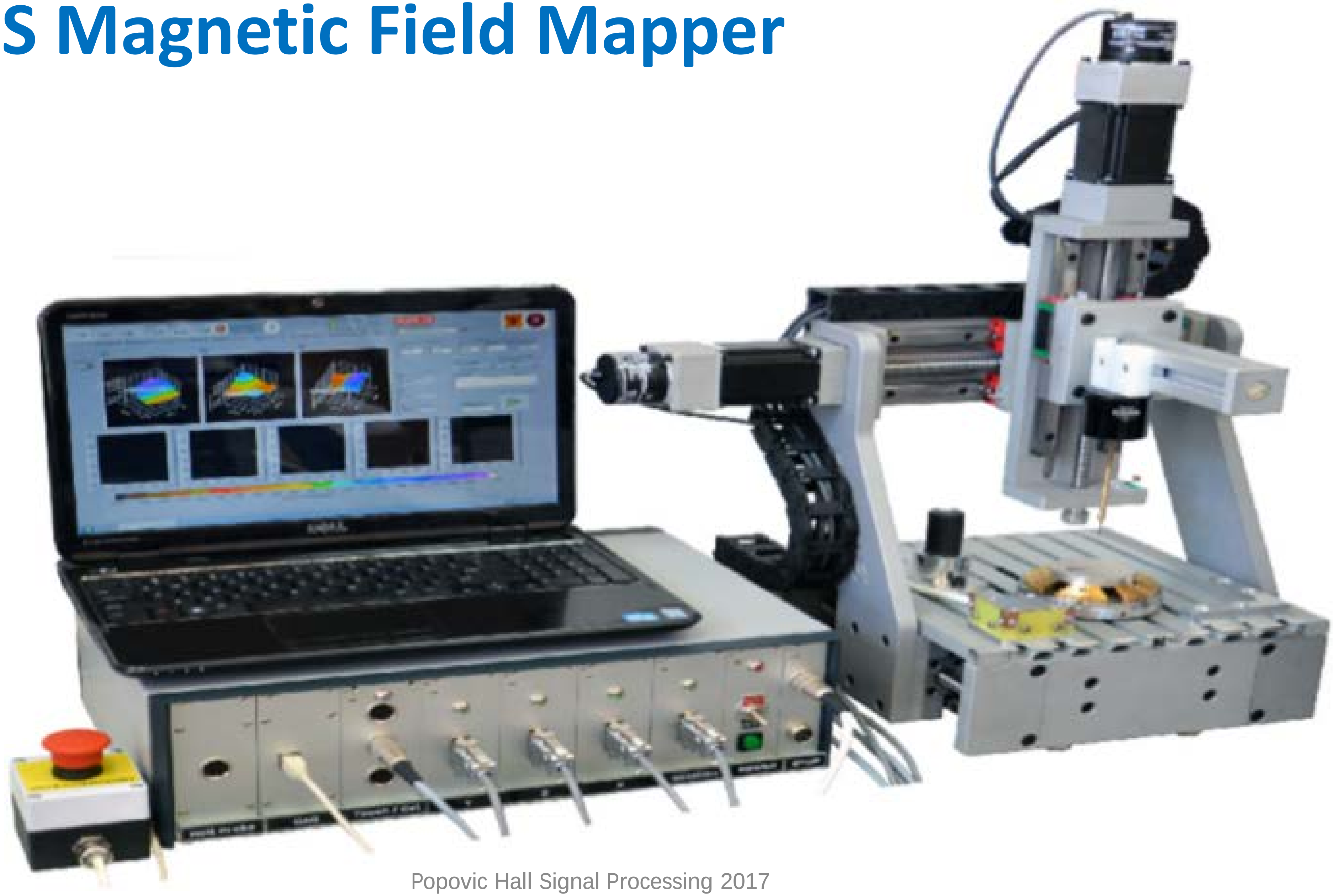


A tool for calibrating the magnetic sensitivity tensor

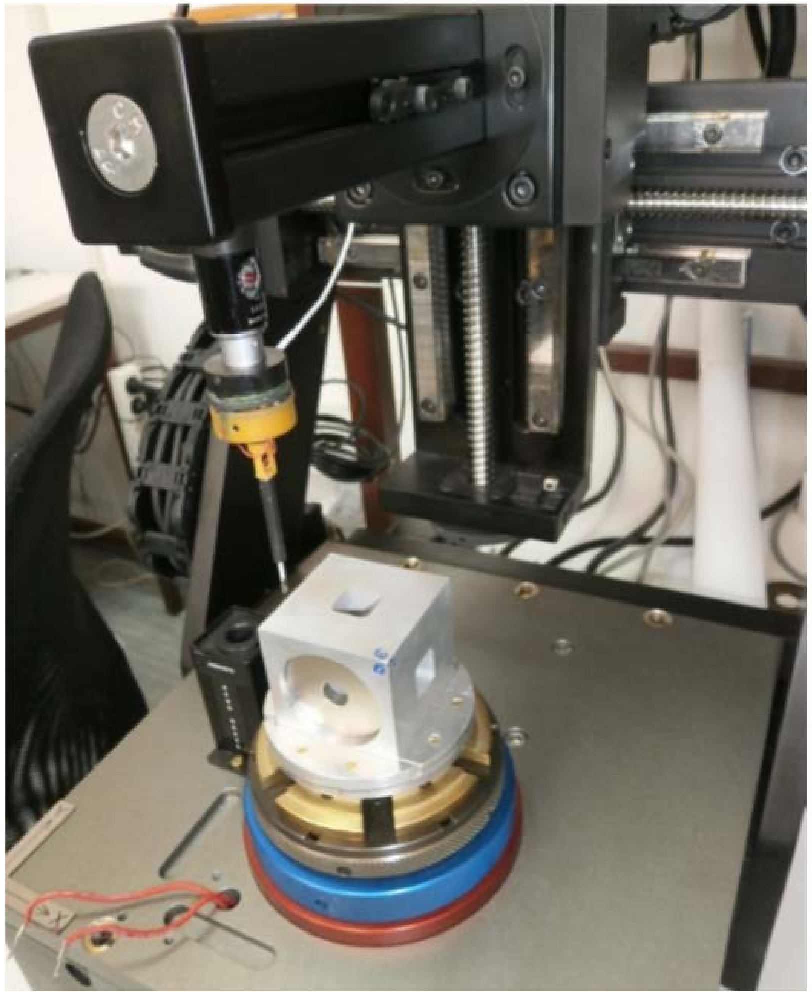


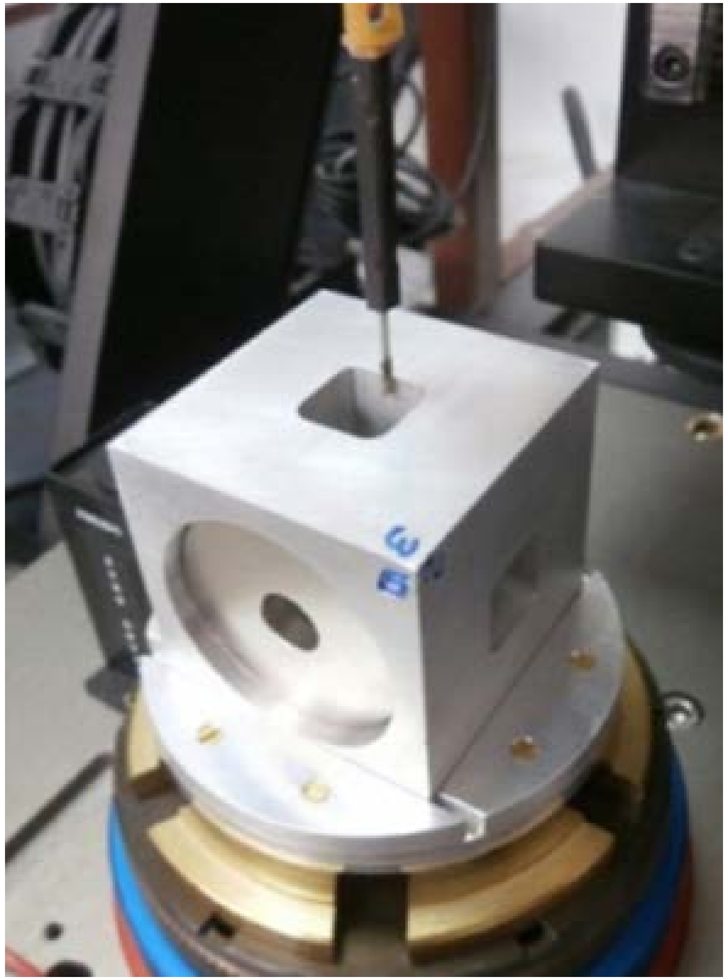


SENIS Magnetic Field Mapper



Calibration of the magnetic sensitivity tensor of a 3D Hall probe in the mapper





Calibration of the Magnetic Sensitivity Tensor
- an example

$$[S]=\begin{bmatrix} Sxx & Sxy & Sxz \\ Syx & Syy & Syz \\ Szx & Szy & Szz \end{bmatrix}=\begin{bmatrix} 96.6577 & 25.6285 & 2.44729 \\ -25.5293 & 96.6622 & 1.95327 \\ -2.4162 & -2.69085 & 99.9925 \end{bmatrix}$$

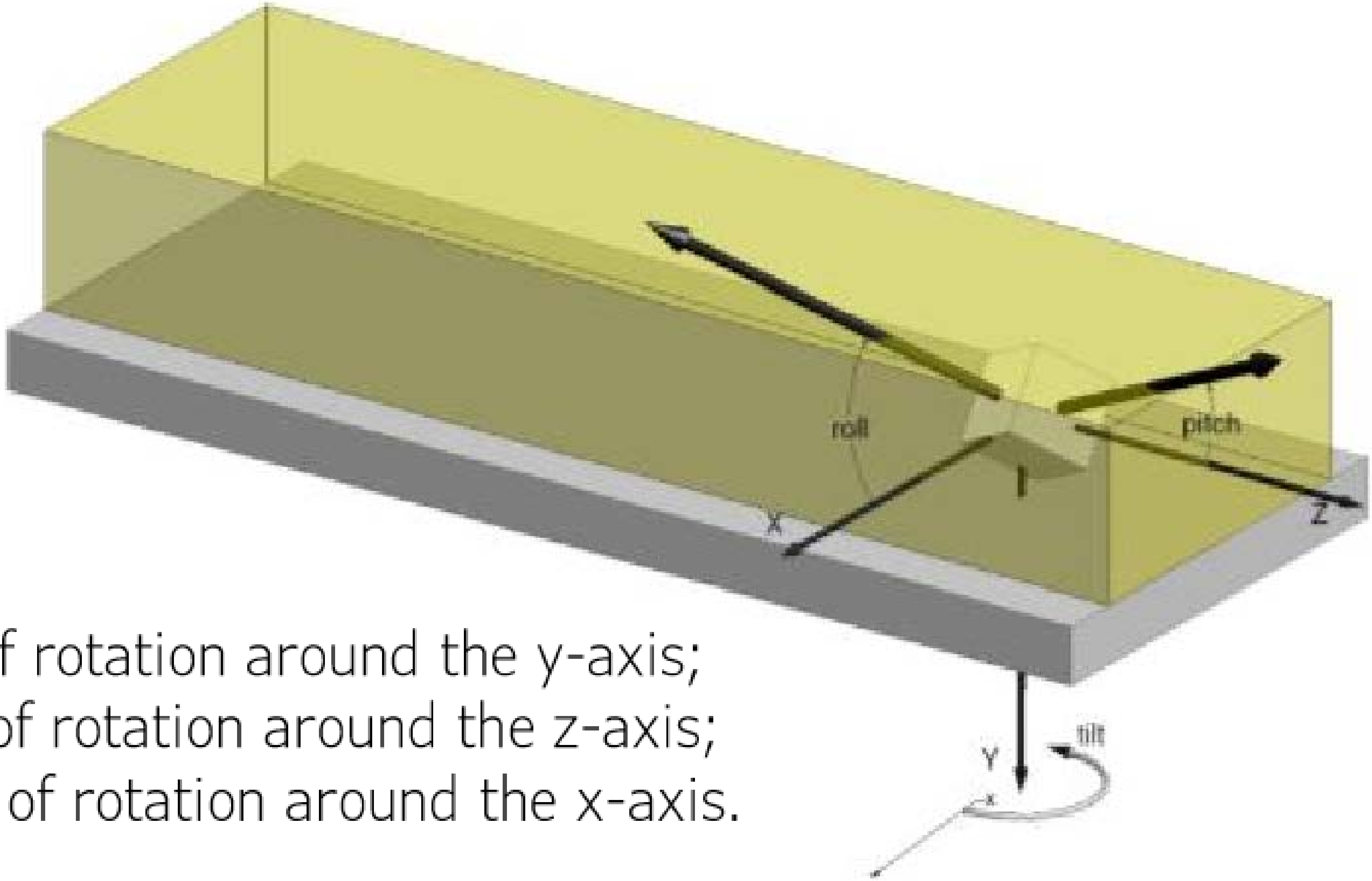
Before…

… and after Calibration

$$[S]=\begin{bmatrix} 100.002 & 0.0298746 & -0.00891582 \\ -0.103873 & 100.038 & 0.0110116 \\ 0.0138412 & -0.0328856 & 100.041 \end{bmatrix}$$

$$[S]\approx Ss\bullet[I] \qquad S_s = 100\text{V/T}$$

Definition of the angular errors of a probe



TILT is the angle of rotation around the y-axis;
ROLL is the angle of rotation around the z-axis;
PITCH is the angle of rotation around the x-axis.

Measurement of the angular errors of a 3D probe - an example

$$\left|\begin{array}{c|c|c} S_{XX} & S_{XY} & S_{XZ} \\ S_{YX} & S_{YY} & S_{YZ} \\ S_{ZX} & S_{ZY} & S_{ZZ} \end{array}\right| = \left|\begin{array}{rrr} 100.009 & -6.758 & -1.095 \\ 5.517 & 100.000 & 0.055 \\ 0.304 & -1.695 & 100.052 \end{array}\right|$$

…

$$B_c \cdot S_x = \sqrt{\frac{U_{xx}^2 + U_{xy}^2 + U_{xz}^2 + \sqrt{\left(U_{xx}^2 + U_{xy}^2 + U_{xz}^2\right)^2 - 4 \cdot U_{xy}^2 \cdot U_{xz}^2}}{2}}$$

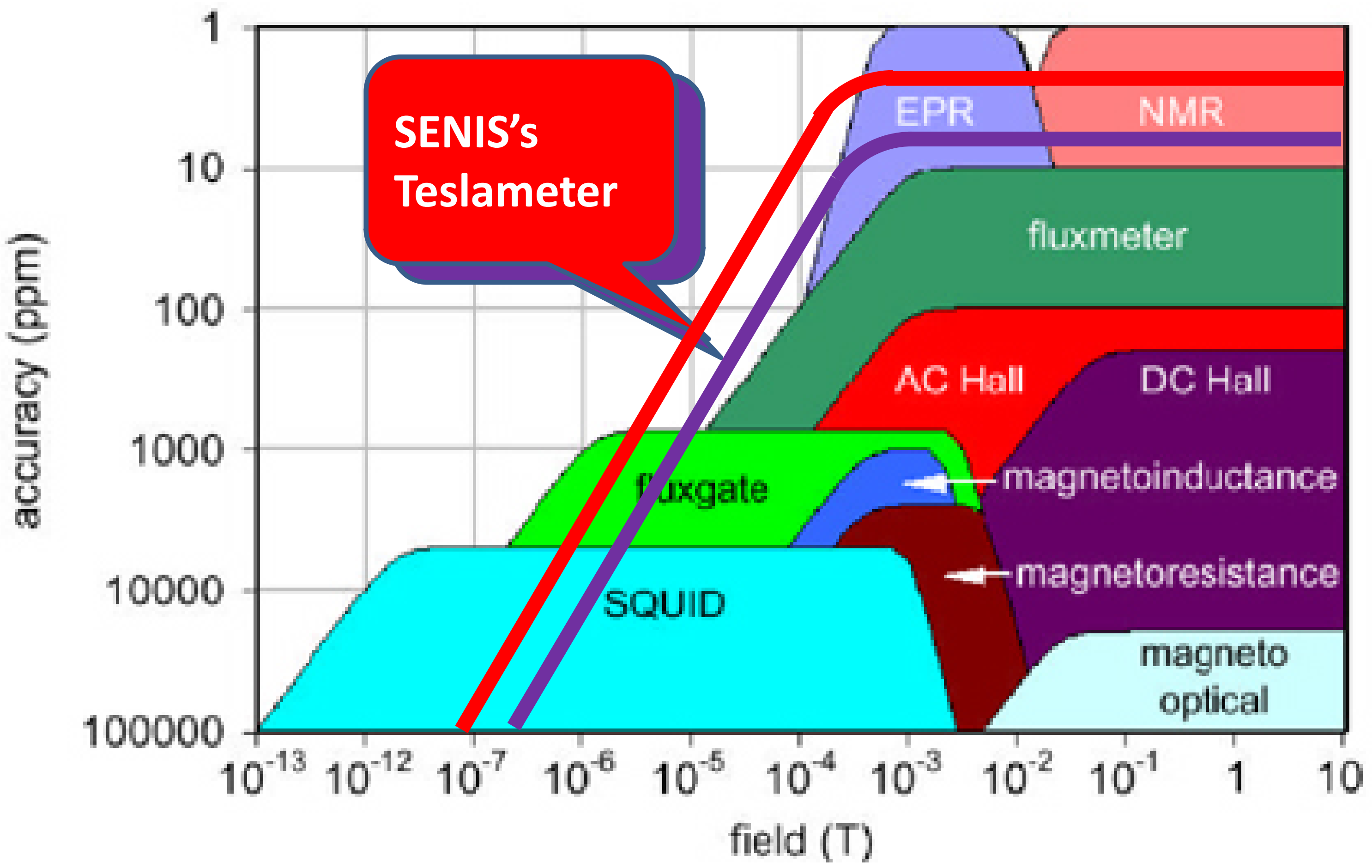
$$x_r = \arcsin\left(\frac{U_{xy}}{B_c \cdot S_x}\right)$$

$$x_t = \arcsin\left(\frac{U_{xz}}{B_c \cdot S_x}\right)$$

…

X_roll (°) = -3.87
X_tilt (°) = -0.63
Y_roll (°) = 3.16
Y_pitch (°) 0.03
Z_pitch (°) -0.97
Z_tilt (°) = 0.17

Up-dated classification of magnetic measurement technologies*



*Luca Bottura of CERN; Revised by SENIS 2011