Journées thématiques du Réseau Semi-conducteurs IN2P3-IRFU

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Microcapteurs magnétiques intégrés sur CMOS et applications

Laboratoire ICube

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Outline

CMOS compatible magnetic sensors

Hall effect magnetometers : from 1D to 3D sensing

Magnetic tracking of medical tools under MRI

Conclusion

Main approach

CMOS compatible sensors, even fully compatible (no post-process)

Sensing device + specific electronics = micro-sensor

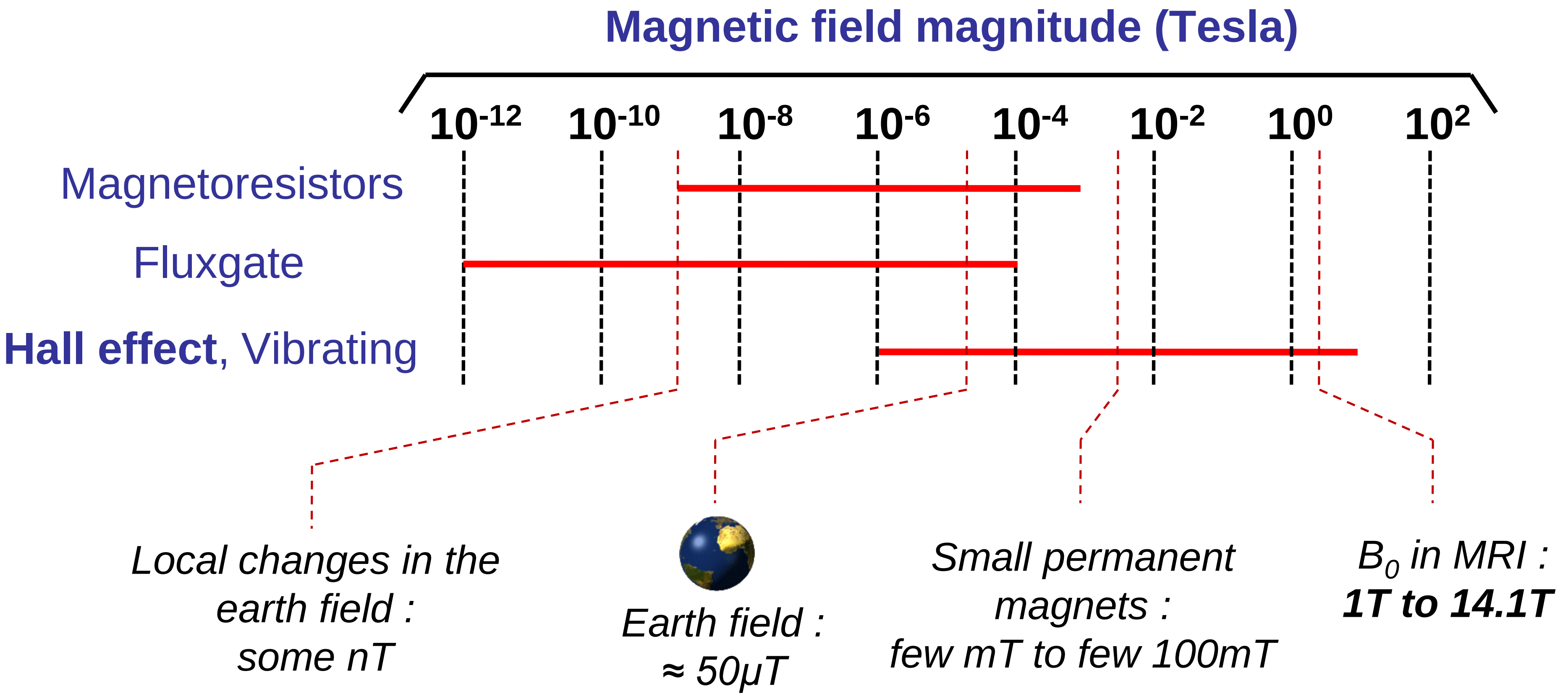
↑ simple post-process if required

Applied projects :

- Contactless current sensors
- Magnetic navigation of catheter
- ECG in MRI
- **Medical tool tracking/positioning in MRI**
- NMR microprobe

Magnetic navigation of catheter, ECG in MRI, Medical tool tracking/positioning in MRI } Medical applis → **3D sensor**

CMOS compatible magnetic sensors



Magnetic field magnitude (Tesla)

10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2}

Magnetoresistors

Fluxgate

Hall effect, Vibrating

Local changes in the earth field : some nT

Earth field : ≈ 50µT

Small permanent magnets : few mT to few 100mT

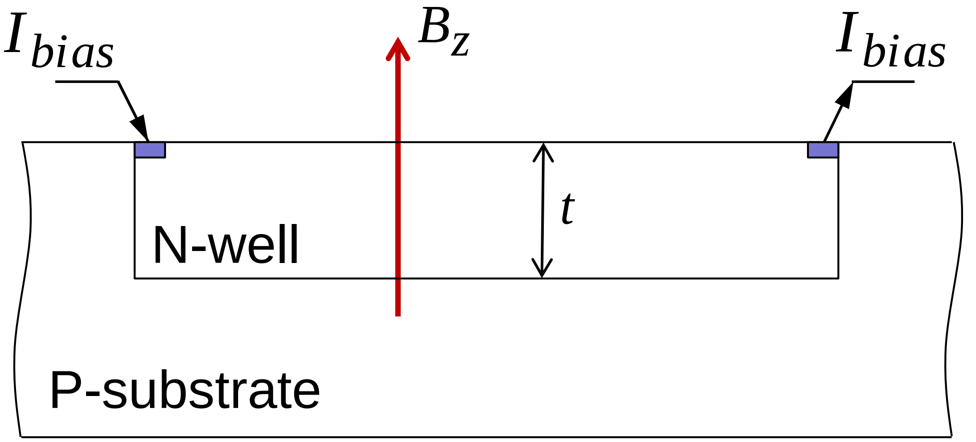
B_0 in MRI : ***1T to 14.1T***

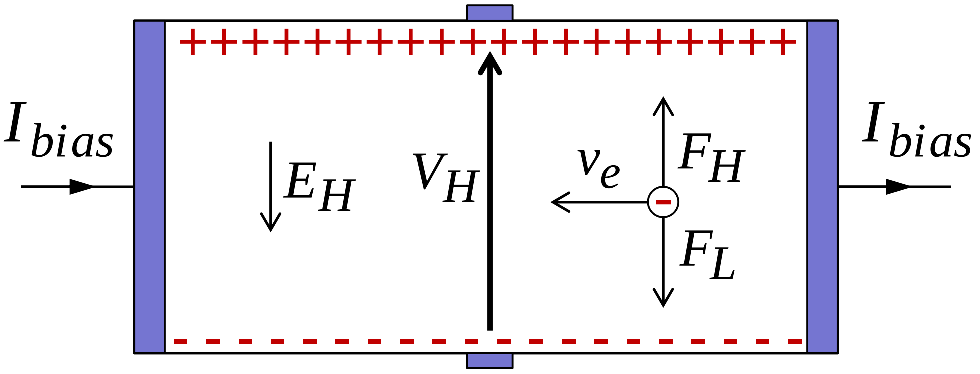
→ DC to a few kHz bandwidth magnetometers

Hall effect devices

- Fully compatible with CMOS processes → no post-processing
- Easy industrial outlets → the most produced micro-magnetometer (1D)
- Wide range of measurement : few 10µT to several Tesla
- Two types of Hall devices :
  - HHD : Horizontal Hall device → for B_z measurement
  - VHD : Vertical Hall device → for B_x and B_y measurement
- 3D Hall probe = 1 HHD + 2 VHD

Horizontal Hall Device





$$\boxed{V_H = \frac{G \cdot r}{n \cdot q \cdot t} \cdot I_{bias} \cdot B_z = S_I \cdot I_{bias} \cdot B_z}$$

S_I : current relative sensitivity

$G < 1$: geometrical factor

r : scattering factor ≈ 1.15 for Si

n : doping of the plate

t : plate thickness

Biasing current flowing « horizontally » $\Rightarrow$ **HHD**

Planar Hall Effect - PHE

➡ Accurate processing of the fluctuation of the mean free transit time τ

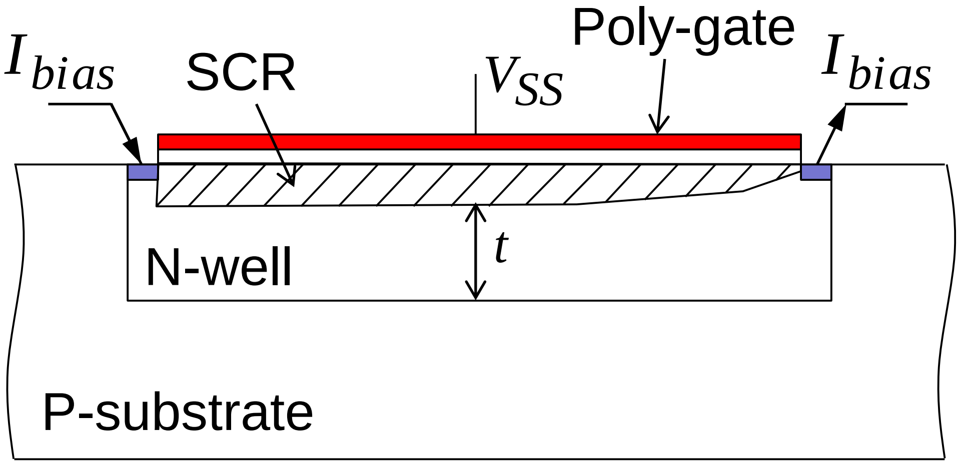
$$\boxed{V_H = \frac{G \cdot r}{n \cdot q \cdot t} \cdot I_{bias} \cdot B_z = S_I \cdot I_{bias} \cdot B_z + S_{IPHE} \cdot I_{bias} \cdot B_x \cdot B_y}$$

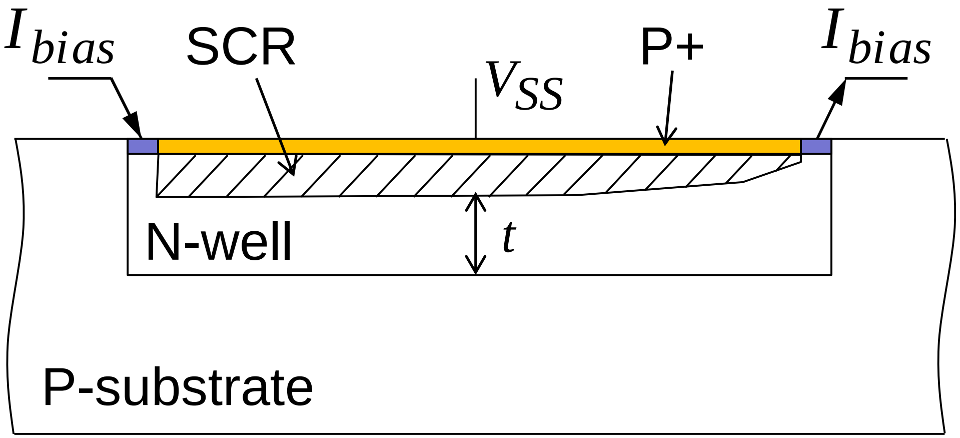
$$S_I = \frac{G \cdot r}{n \cdot q \cdot t} = \frac{G \cdot \left\langle \tau^2 \right\rangle / \left\langle \tau \right\rangle^2}{n \cdot q \cdot t} \qquad S_{IPHE} = \frac{\mu_n}{n \cdot q \cdot t} \cdot \left[\frac{\left\langle \tau^3 \right\rangle}{\left\langle \tau \right\rangle^3} - \frac{\left\langle \tau^2 \right\rangle^2}{\left\langle \tau \right\rangle^4} \right]$$

$S_{IPHE} / S_I \approx 8\%$ → not an issue when $B_x \approx B_y \approx B_z \approx$ a few mT

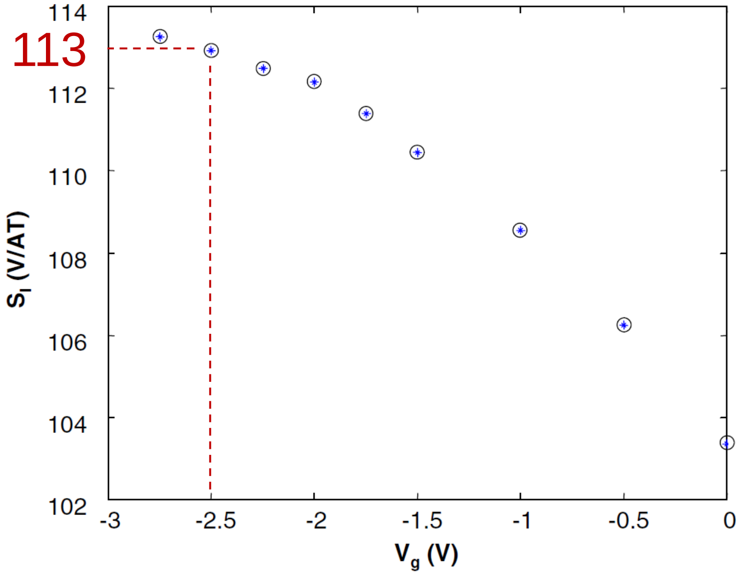
➡ Be careful when you measure a few mT over a few Teslas !

HHD current relative sensitivity





S_I improvement:

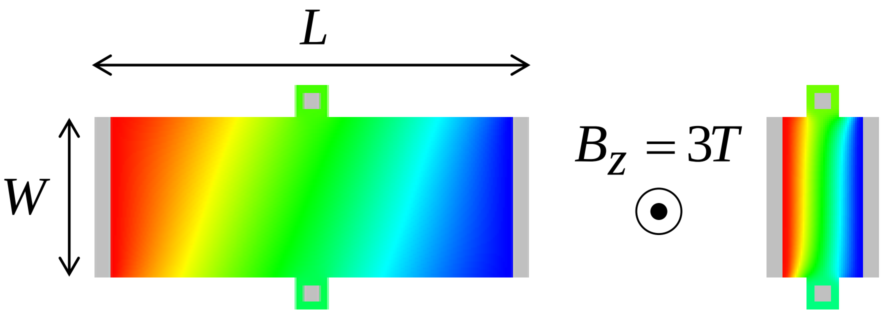


HHD in CMOS 0.6µm

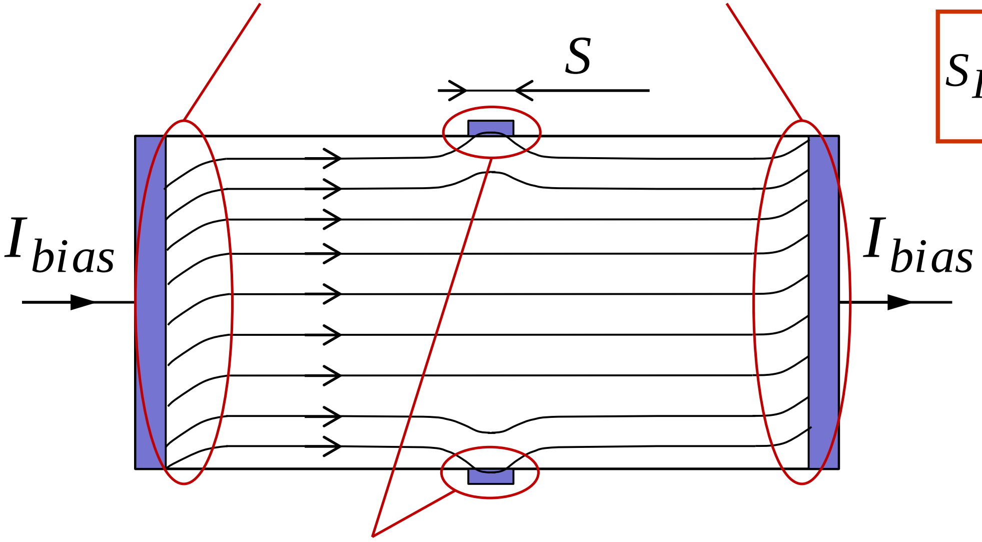
without any gate $S_I = 80\ V/(A \cdot T)$

$V_g = V_{SS} = \text{-}2.5V : S_I = \boxed{113\ V/(A \cdot T)}$

HHD geometrical factor

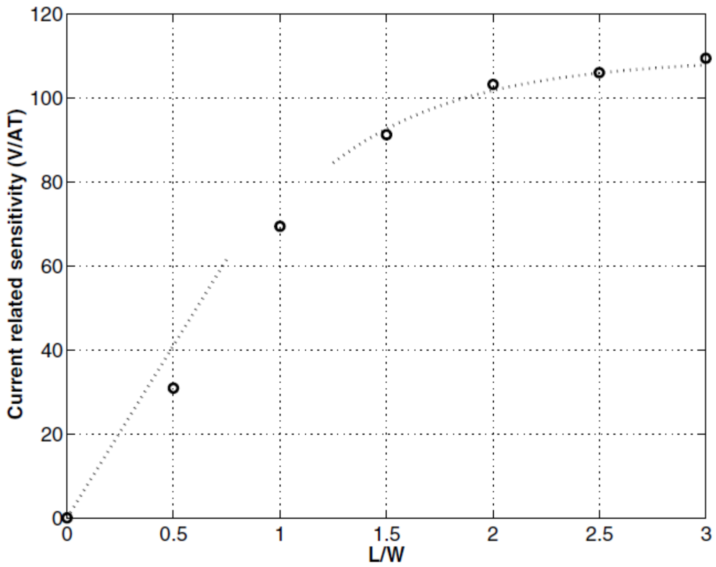


Short circuit by the biasing contacts



Short circuit by the sensing contacts

$$\boxed{S_I = \frac{G \cdot r}{n \cdot q \cdot t}}$$



$$G \approx 1 \text{ for } \begin{cases} L/W > 2 \\ W/S > 10 \end{cases}$$

$$\boxed{L = 20\mu m \text{ and } W = 10\mu m}$$

HHD biasing

Voltage biasing for highest I_{bias} ?

$$V_H = \frac{G \cdot r}{n \cdot q \cdot t} \cdot I_{bias} \cdot B_z$$

$$R_{in} = \frac{1}{n \cdot q \cdot \mu_n} \cdot \frac{L}{W \cdot t}$$

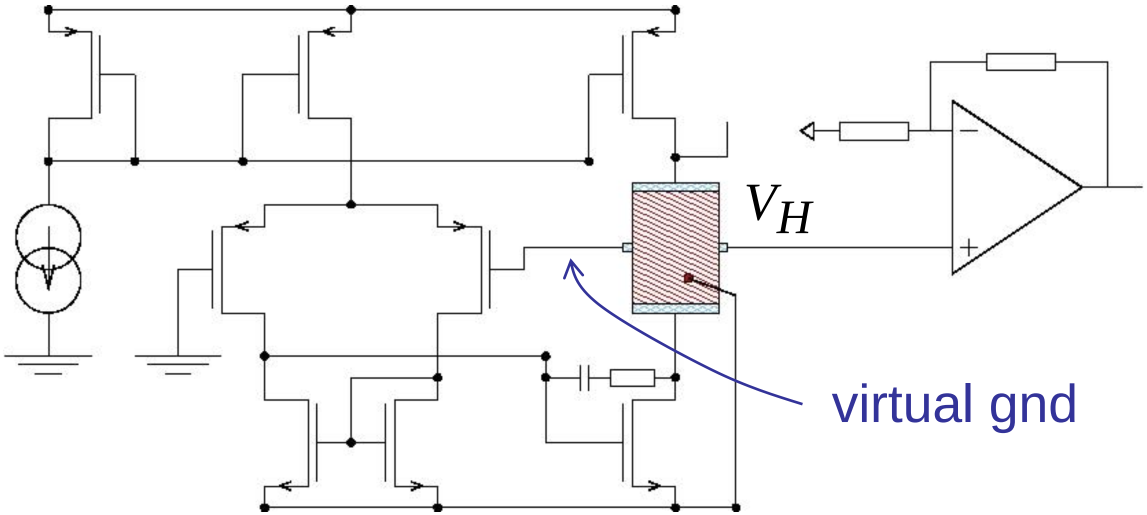
⬇

$$\boxed{V_H = G \cdot r \frac{W}{L} \cdot \mu_n \cdot V_{bias} \cdot B_z}$$

⬇

Very sensitive to temperature!

Current biasing is better



Easy to design I_{bias} insensitive to T

⬇

Low thermal drift of the sensor sensitivity

HHD offset

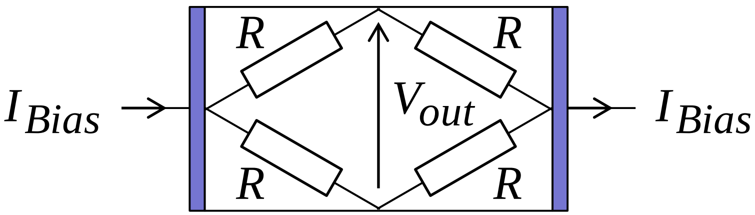
Three sources :

Sensing contact misalignment

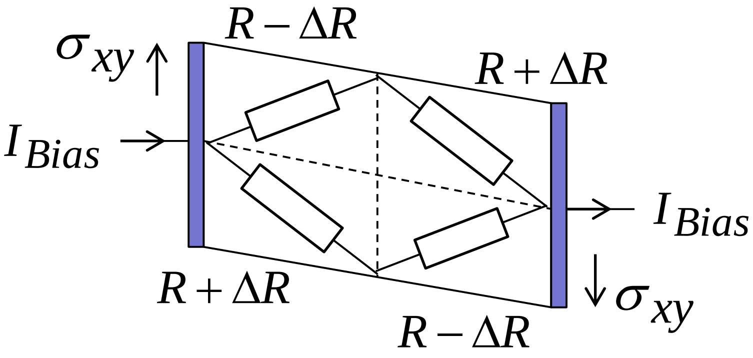
Doping gradients

Shear stress

$\Big\}$ → Unbalanced equivalent Wheatstone bridge



$$\boxed{V_{out} = 0}$$



$$\boxed{V_{out} = \Delta R \cdot I_{bias} = V_{off}}$$

Typical output $V_{off} = 1 \text{ to } 2\text{ mV}$

Typical sensitivity $S_A = 100\text{mV/T}$

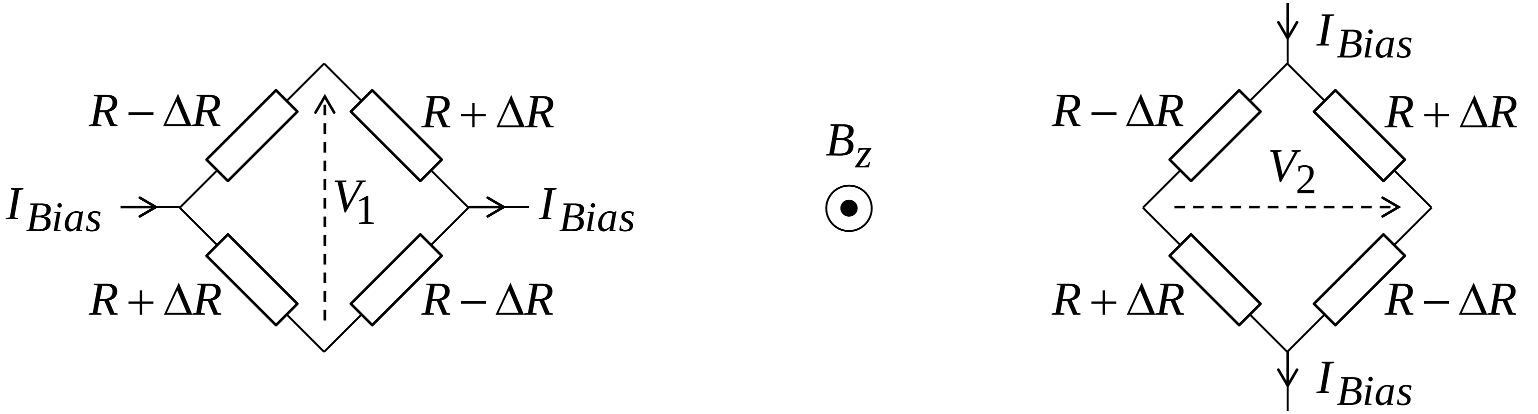
$\Big\}$ → Equivalent input offset of **10mT to 20mT** !!!

Spinning current – Offset canceling

Symmetrical HHD by a 90° rotation
Sensing and biasing contacts swap

→

V_H is unchanged
V_{off} is reversed

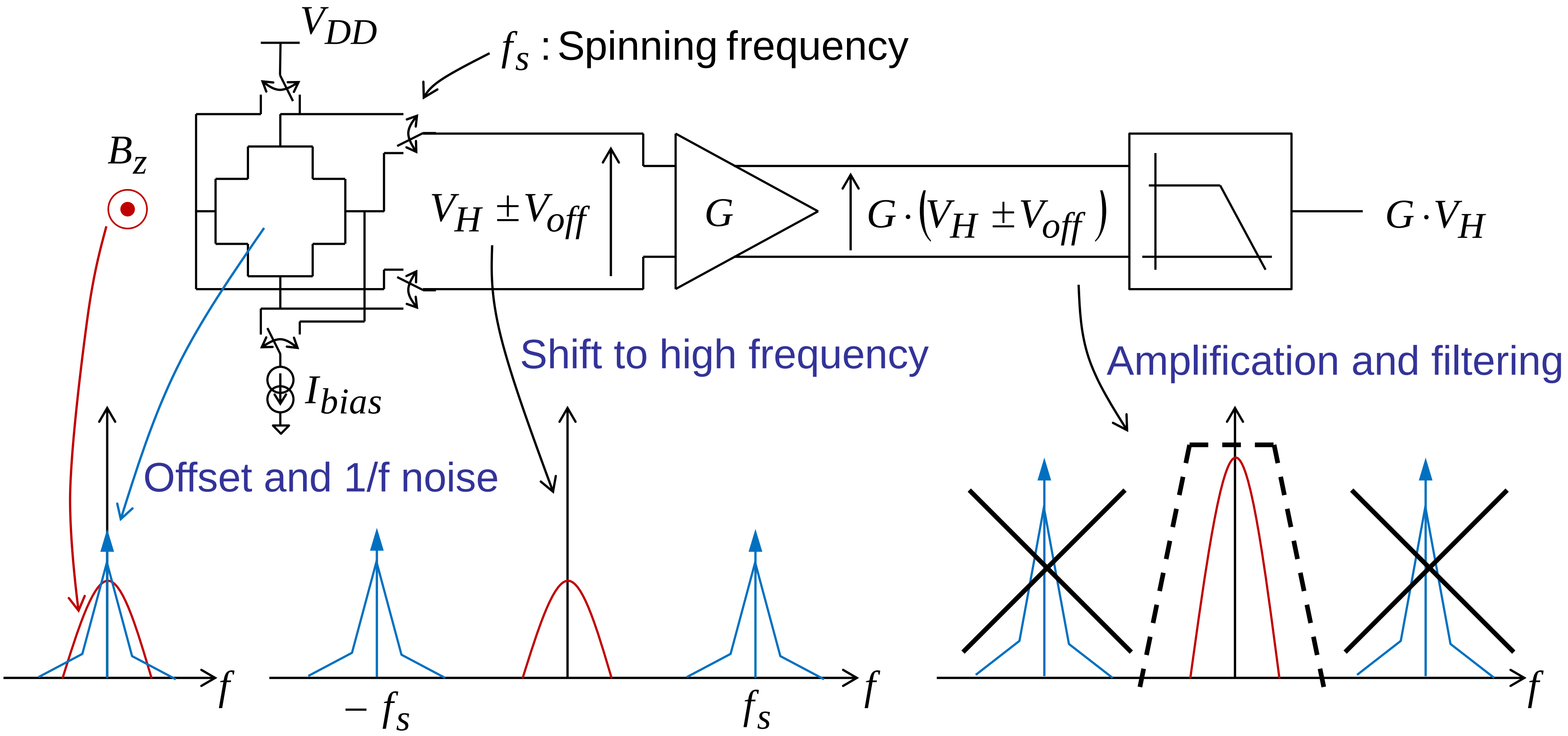


Phase 1: $V_1 = V_H + V_{off}$

Phase 2: $V_2 = V_H - V_{off}$

Cross-shaped HHD

Spinning current – 1/f noise canceling



f_s : Spinning frequency

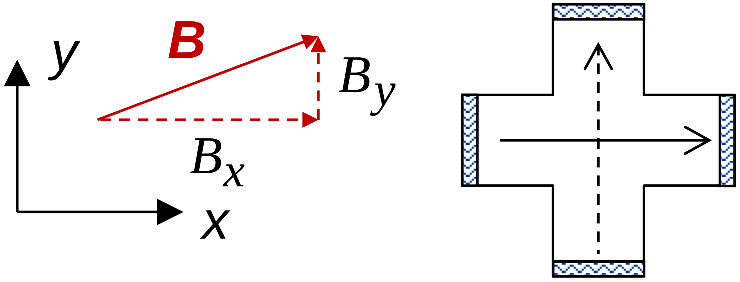
Offset and 1/f noise

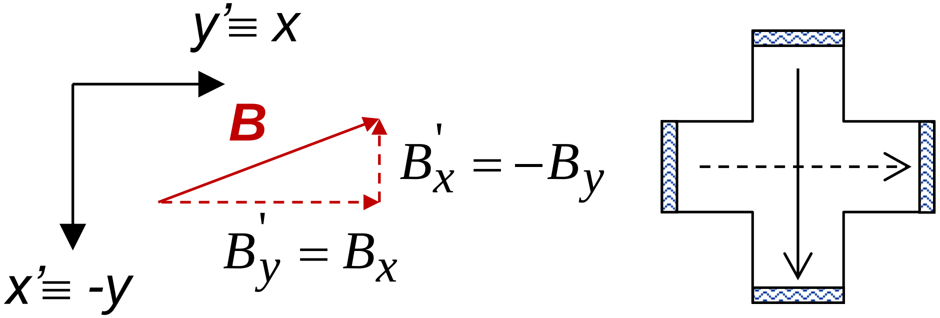
Shift to high frequency

Amplification and filtering

➡ 1/f noise cancelling → resolution of **10µT over a few kHz bandwidth**

Spinning current – PHE canceling





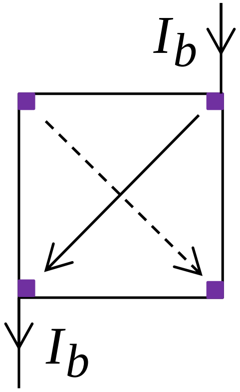
$$V_{PHE1} = S_{IPHE} \cdot I_{bias} \cdot B_x \cdot B_y$$

$$V_{PHE2} = S_{IPHE} \cdot I_{bias} \cdot \underbrace{B'_x \cdot B'_y}_{\boxed{-B_x \cdot B_y}}$$

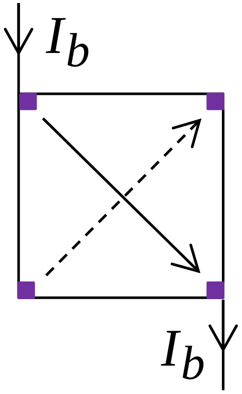
$$\boxed{V_{PHE2} = -V_{PHE1}}$$

➡ Spinning current is magic !

Spinning current versus HHD in series



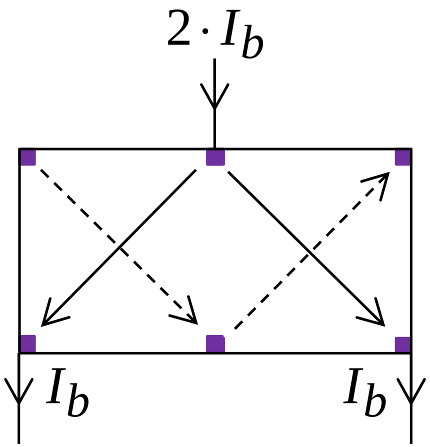
Two separate devices



$$V_1 = V_H + V_{off} + V_{PHE} + V_{1/f1}$$

$$V_2 = V_H - V_{off} - V_{PHE} + V_{1/f2}$$

Two HHD in series



$$V_{out} = 2 \cdot V_H + V_{1/f1} + V_{1/f2}$$

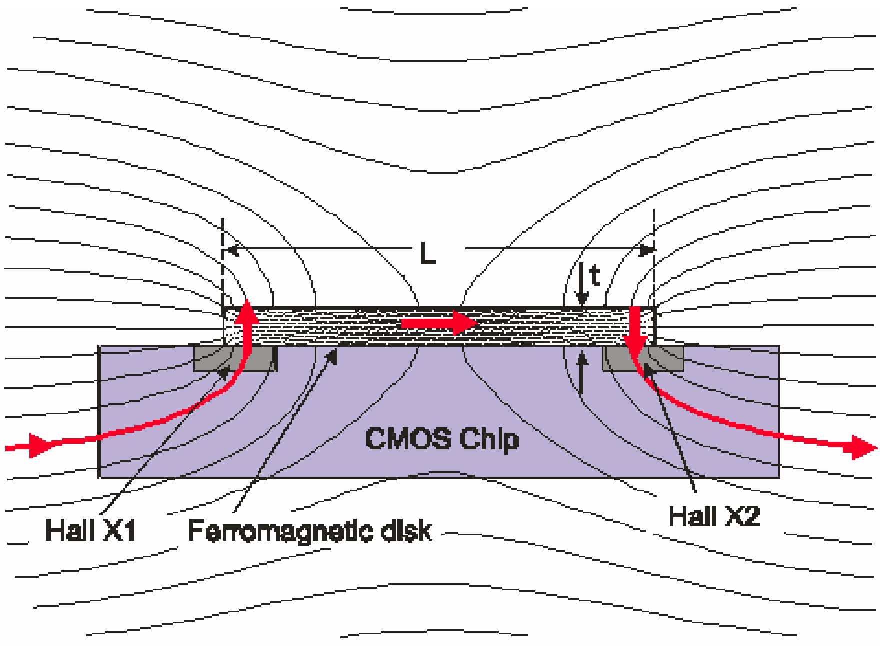
$$\boxed{V_{out} = 2 \cdot V_H + V_{1/f}}$$

Measuring *B* in the plane of the chip

Reproduced from C. Schott, and al., CMOS Three Axis Hall Sensor and Joystick Application, IEEE Sensor Conference, 2004

2001/2002 : Introduction of Integrated Magnetic Concentrators (ICM) – (*EPFL)*

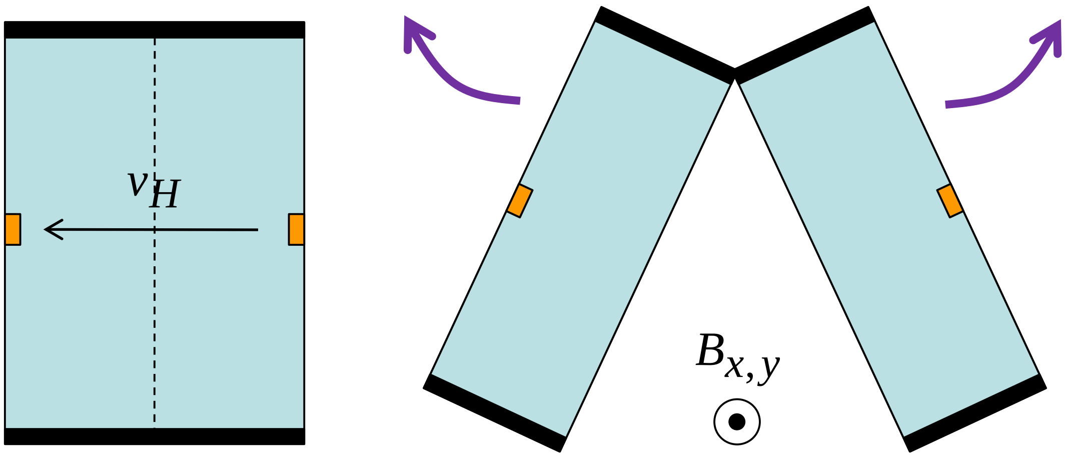
- Magnetic amplification by a factor of 10
- Soft magnetic material above CMOS
- Low hysteresis…
- Commercial product from Melexis

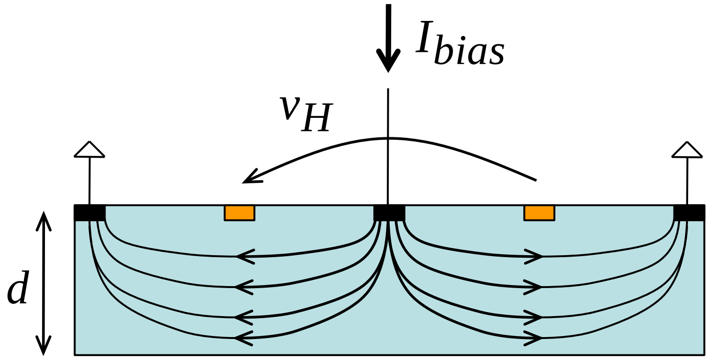


2002/2004 : Vertical Hall Device in the deep Nwell of HV-CMOS - (*EPFL)*

2008 : Vertical Hall Device in the shallow Nwell of LV-CMOS - (*ICube)*

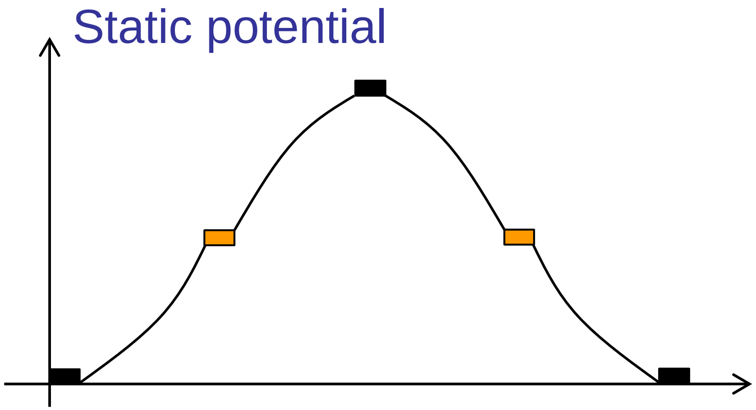
Vertical Hall Device – HV-CMOS



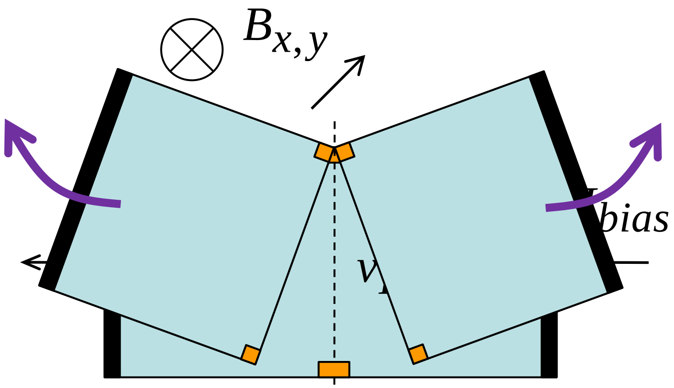


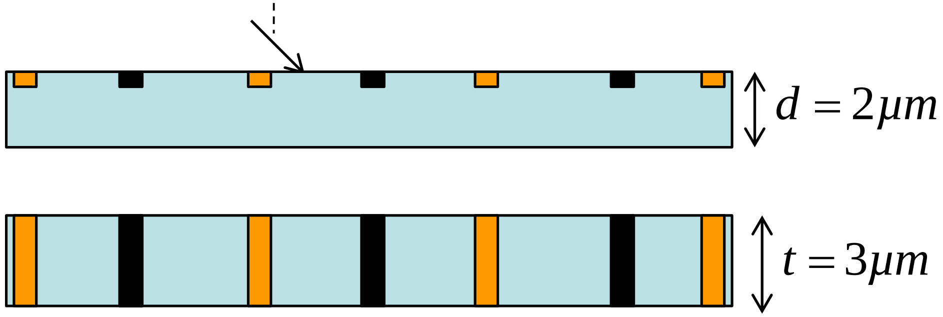
d has to be high to **avoid short-circuit by sensing contacts** !

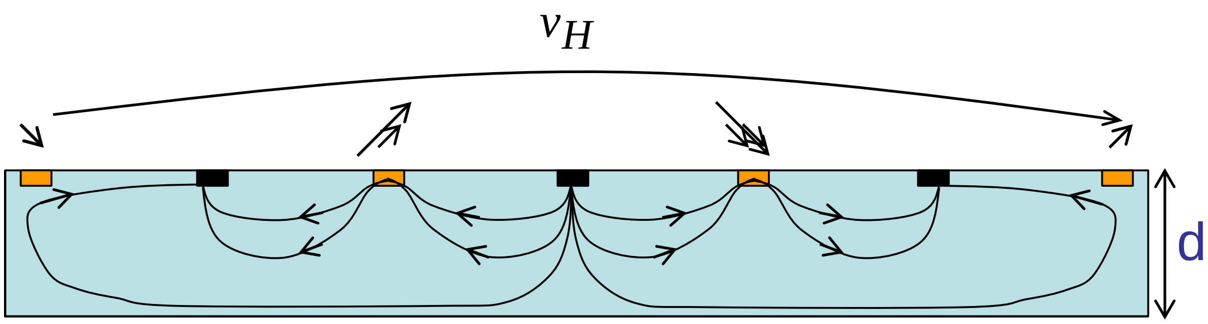
- 1984 – 2002 : VHD were discrete devices
- 2002 First VHD in HV-CMOS **(d = 7µm)**, but :
  - **Low sensitivity** (residual short-circuit)
  - **High offset** → amplifier saturation
  - **High *1/f* noise** → 1mT resolution

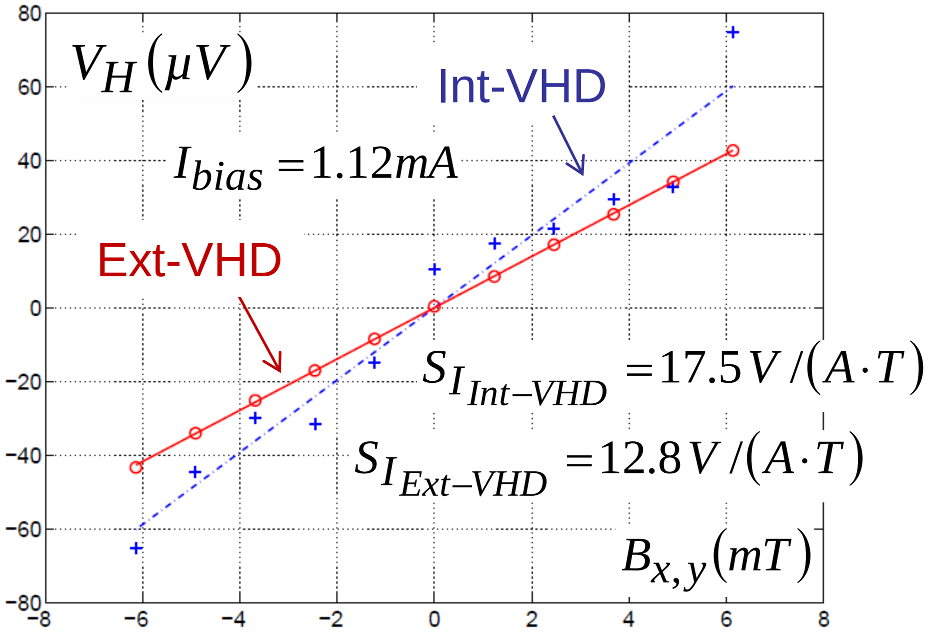


VHD in LV-CMOS





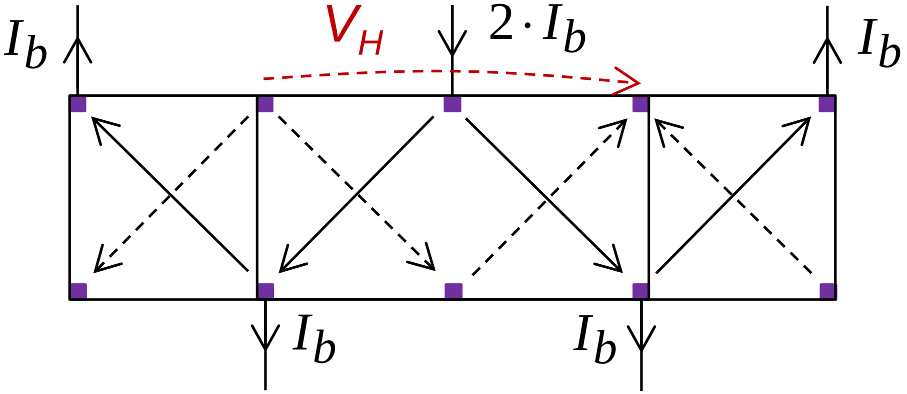


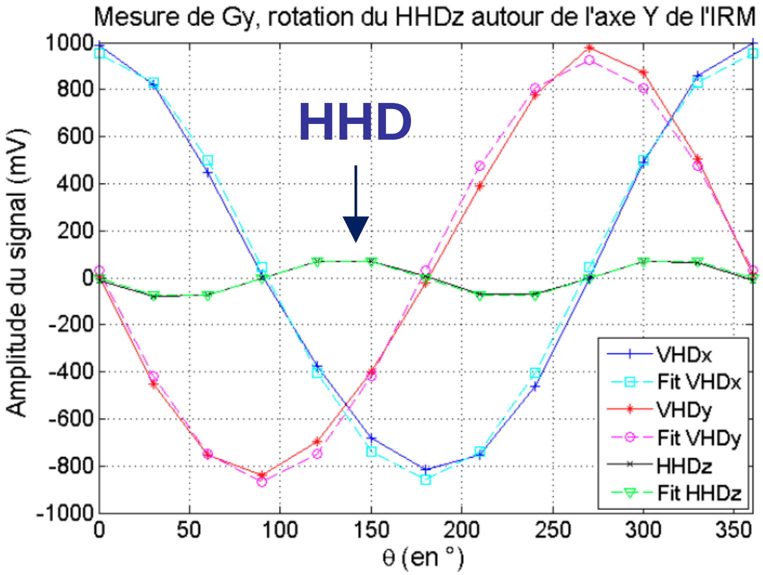


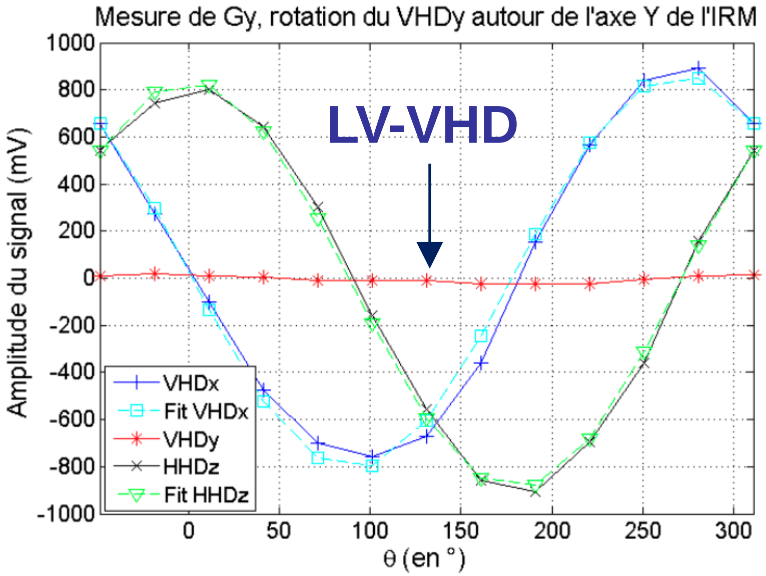
The Ext-VHD resolution of **80 µT** over 1.6 kHz without any electronics while it is of **800µT** for the **Int-VHD**

VHD Self-immunity to PHE

HV-VHD



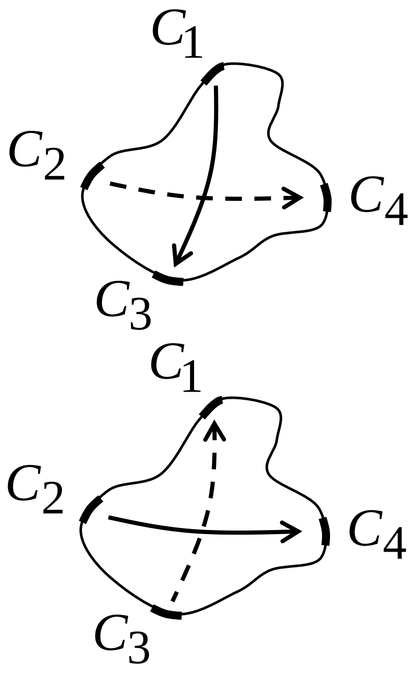




Spinning-current on VHD

⇨ **The only way to remove the *1/f* noise**, *as well as PHE, and offset*

From the Reverse Magnetic Field Reciprocity theorem, i.e. $\sigma(\boldsymbol{r},\boldsymbol{B}) = \sigma^t(\boldsymbol{r},-\boldsymbol{B})$, it can be shown that in a linear material :

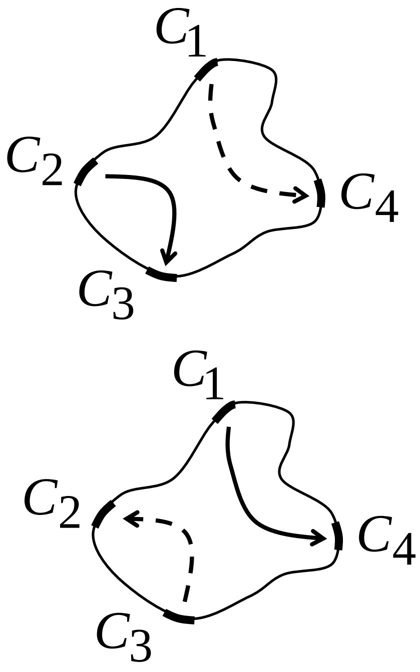


$$V_{out1} = V_H \boxed{+V_{off} + V_{1/f} + V_{PHE}}$$

⟶ I_B

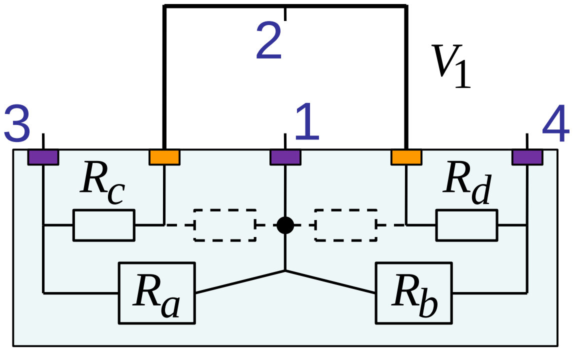
- - -> V_{out}

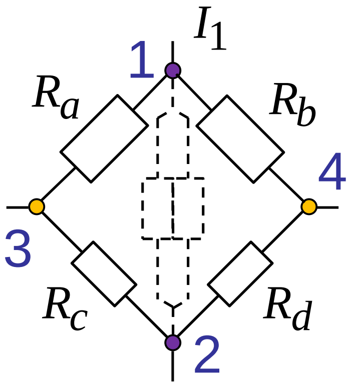
$$V_{out2} = V_H \boxed{-V_{off} - V_{1/f} - V_{PHE}}$$



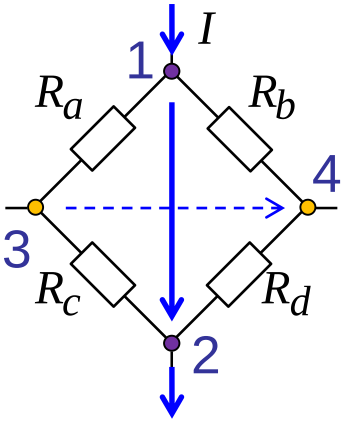
Spinning-current on LV-CMOS VHD

➡ You need to make the 5-contact LV-VHD a 4-contact sensor



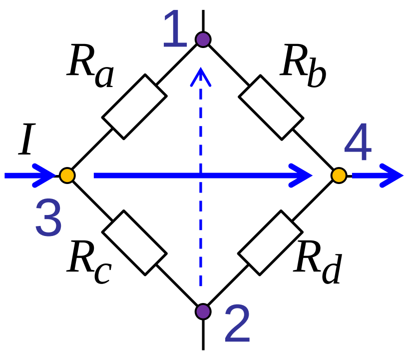


… and to exchange the biasing and sensing contacts periodically



Phi1

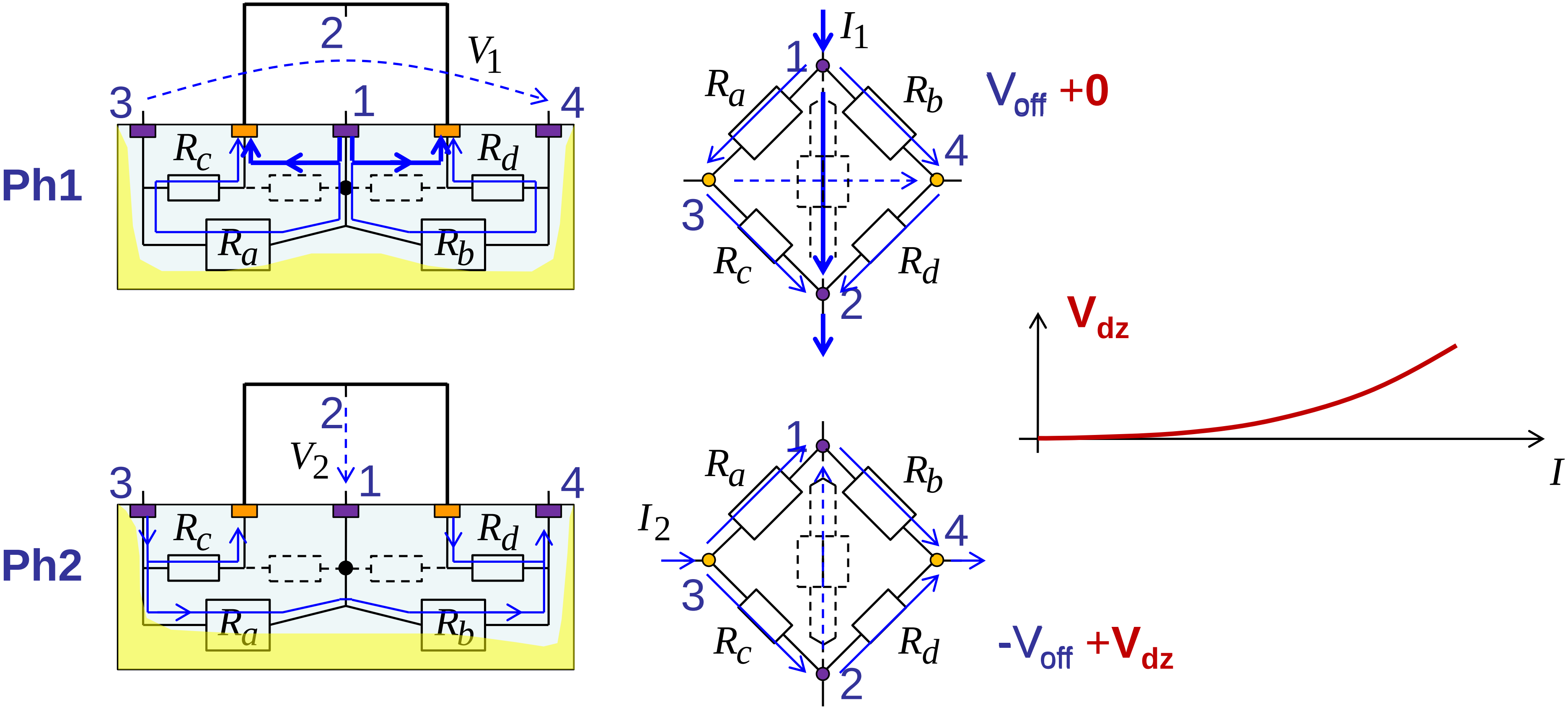
$$V_1 = V_{off} = \frac{R_a \cdot R_d - R_b \cdot R_c}{R_a + R_b + R_c + R_d} \cdot I$$



Phi2

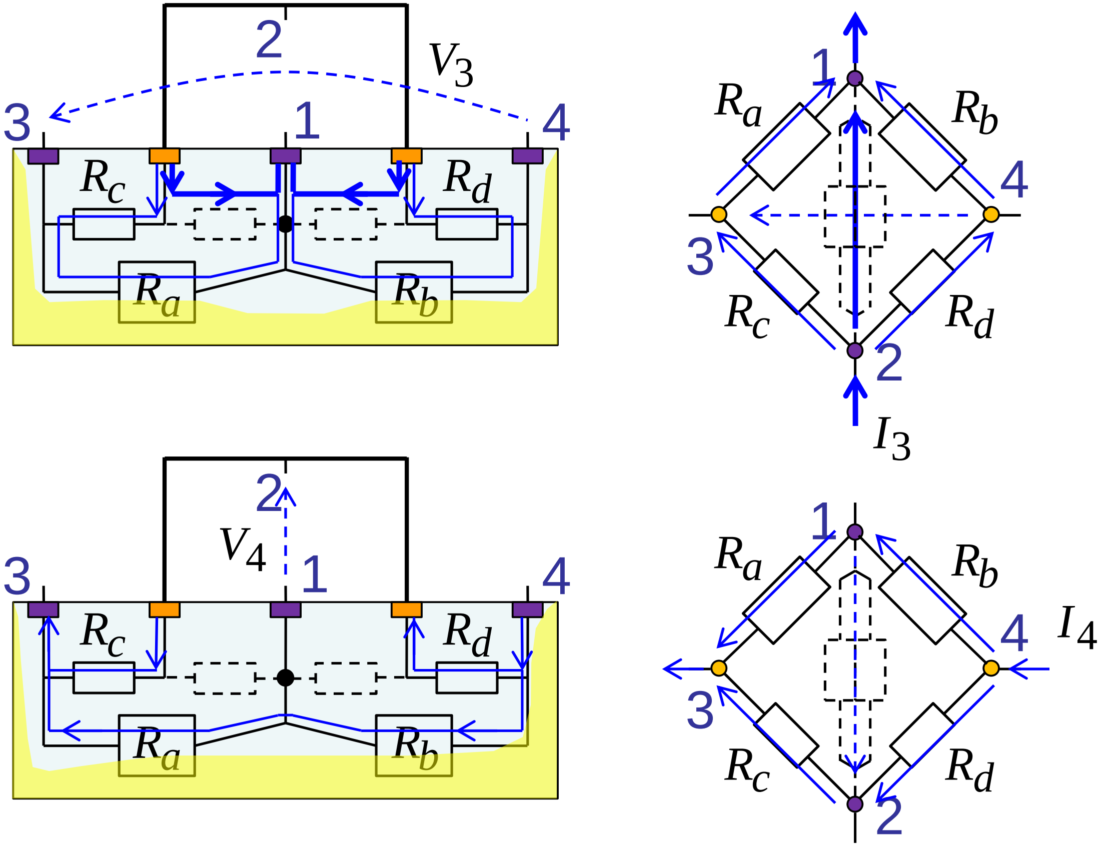
$$V_2 = -V_{off} = \frac{R_b \cdot R_c - R_a \cdot R_d}{R_a + R_b + R_c + R_d} \cdot I$$

Spinning-current on LV-CMOS VHD



$$I_{1max} > I_{2max} \quad \Rightarrow \quad I = I_1 = I_{2max}$$

Spinning-current on LV-CMOS VHD



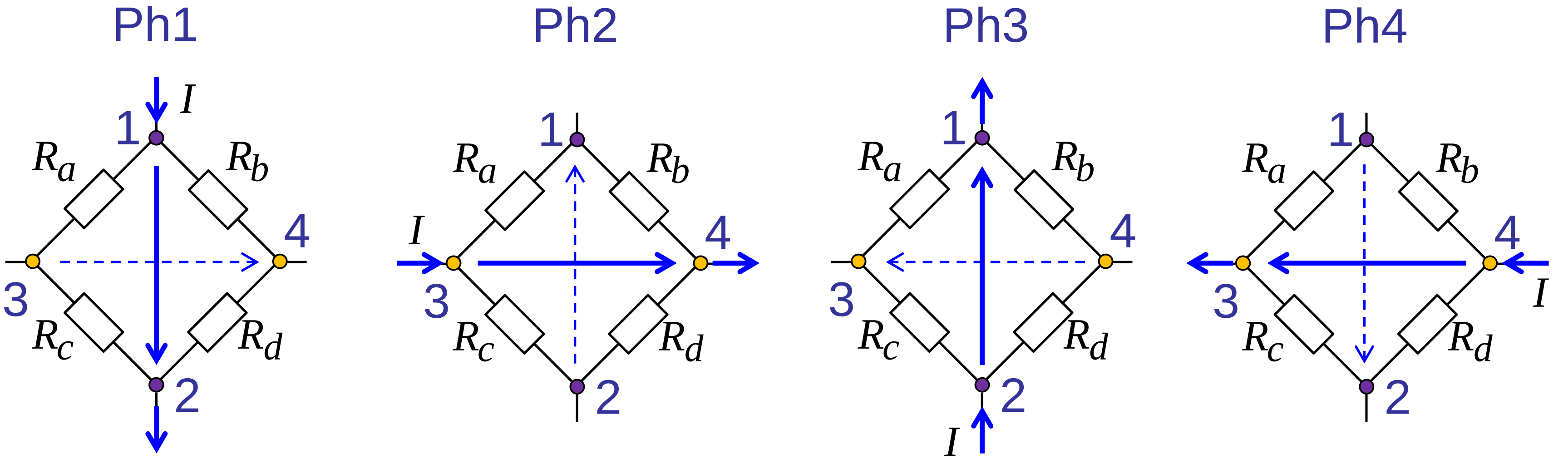
Ph3

V_{off} **+0**

Ph4

$-V_{off}$ **$-V_{dz}$**

Spinning-current on LV-CMOS VHD

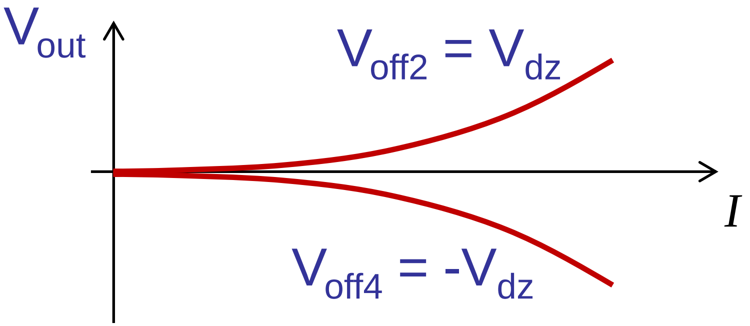


V_{off}

$- V_{off}$ **$+ V_{dz}$**

V_{off}

$- V_{off}$ **$- V_{dz}$**



We need a 4-Ph Spinning-current in VHD to remove the offset

Four-phase Bi-current SC

$I_{1\max} = I_{3\max} > I_{2\max} = I_{4\max}$ ➡ I_B (conventional SC) = $I_{2\max}$

However, offset, *1/f* noise and PHE are proportional to I_B !

Using the maximum current on each phase $\Rightarrow V_{off\,1} = -\frac{I_{1\max}}{I_{2\max}} \cdot V_{off\,2}$

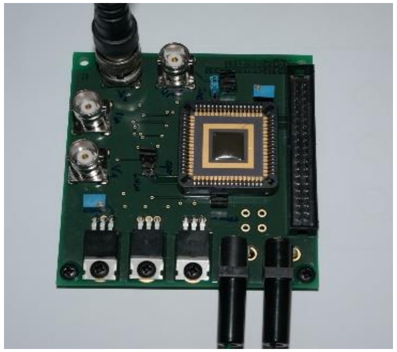
4-phase bi-current Spinning-current $\Rightarrow$

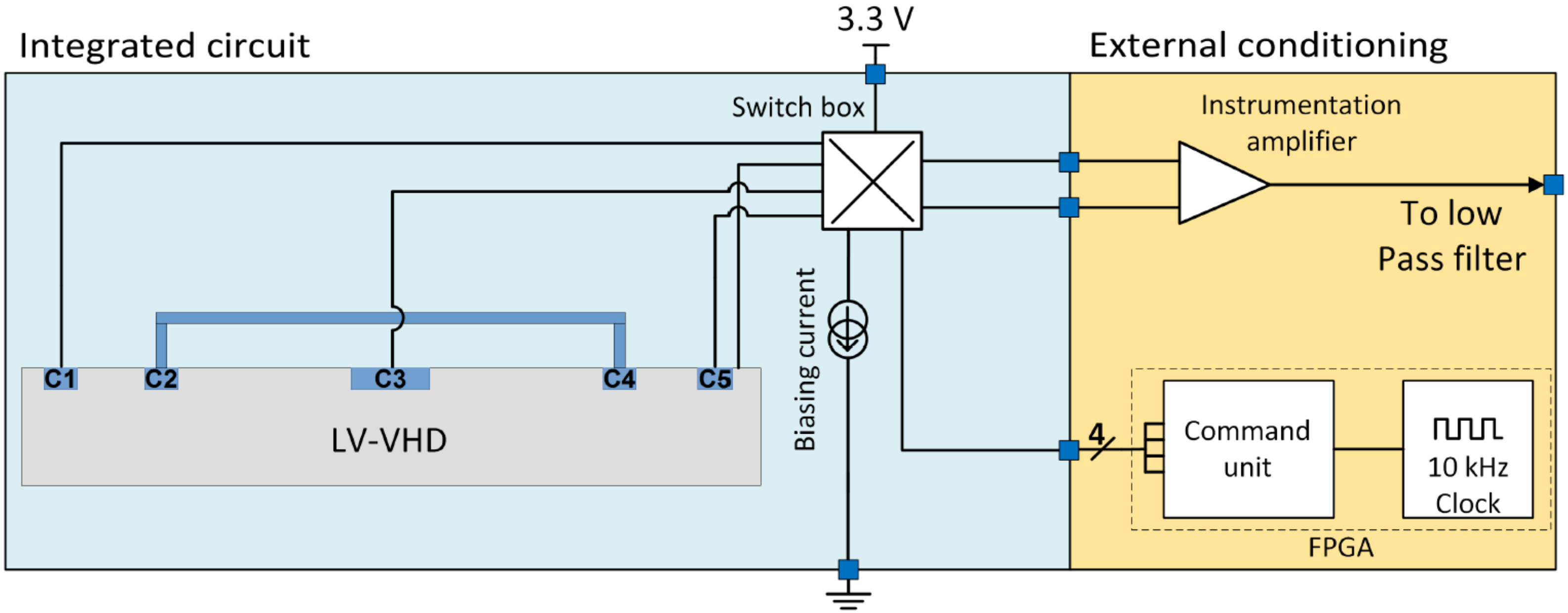
- Maximum current on each phase
- Amplify V_2 and V_4 by $I_{1\max}/I_{2\max}$
- Take the average

Experimental results

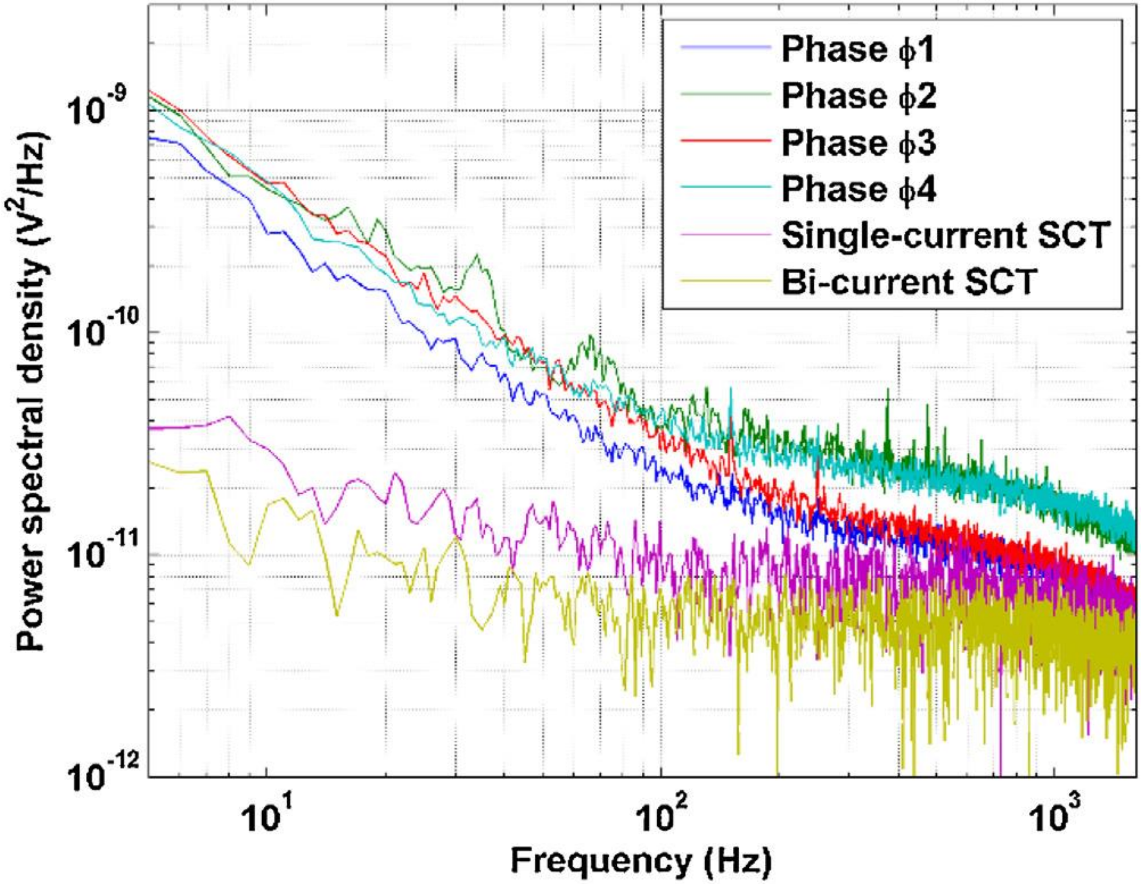
3 µm wide, 25 µm long and 2 µm deep

LV-VHD with external SC conditionning





Experimental results



I_{1max} = 1100 µA

I_{2max} = 550 µA

Over 1.6 kHz bandwidth

$R(1\text{-}I_B$ SC) = 64 µT

$R(2\text{-}I_B$ SC) = 51 µT

51 µT with an average I_B of 825 µA

Better results expected with Bi-current 4-Phase spinning-current **integrated on chip**

Commercial 3D Magnetometers

Most commercial Hall Devices are 1D HD switches, or 1D HDD for *B* measurement

A few 3D magnetometers are available commercially :

ST : LSM303D → based on AMR and a multi-chips package (with a 3D accelerometer)

2009

Melexis : MLX 90393 → based on HHD with Integrated Magnetic Concentrators *(Sentron acquired by Melexis on 2004)*

2005

Metrolab : MagVector MV2 → based on a HHD and two HV-VHD *(from Sensima founded in 2008 and delivered by Metrolab)*

2015

Allegro : ALS31300 → 3D Hall (3x3x0.8mm^3 DFN pack. ±200mT/100µT)

2017

AKM : AK09970N → 3D Hall (3x3x0.75mm^3 QFN pack. ±36mT/3µT)

2017

Magnetic tracking → XYZ-IRM

Advantages of MRI scanner :

- High tissue contrast
- Free imaging plane positionning
- No ionising radiation

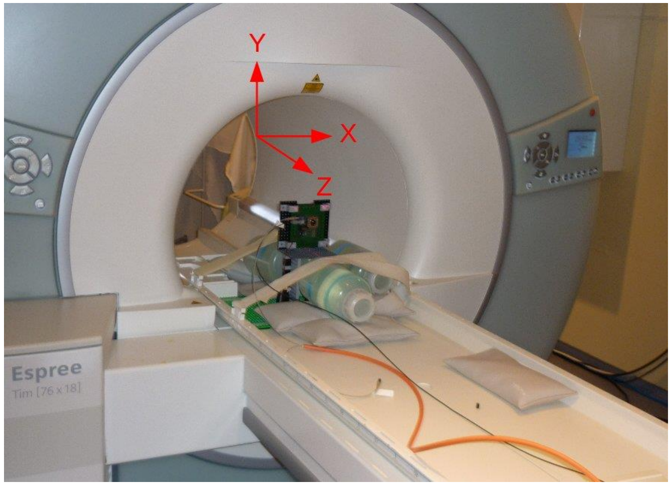
↓

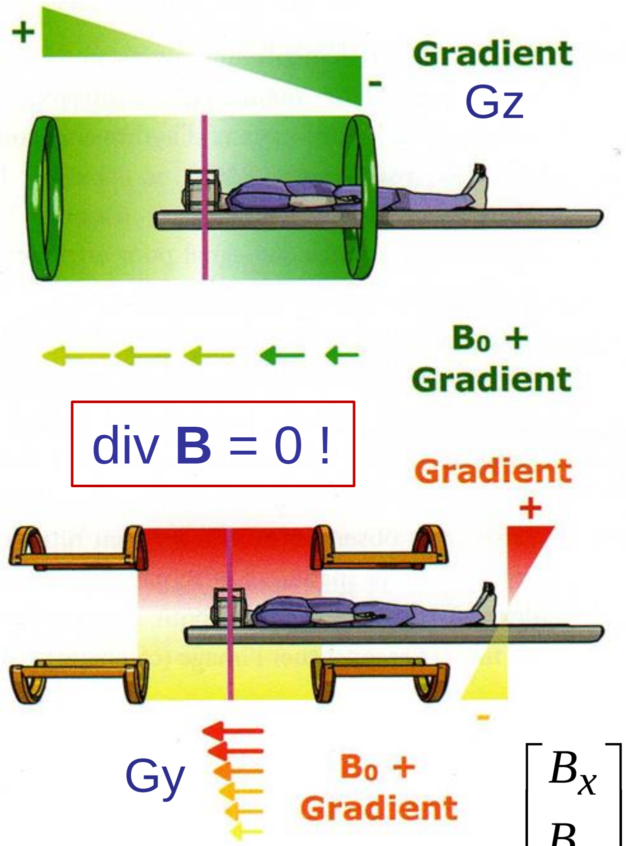
MRI for minimally-invasive surgery

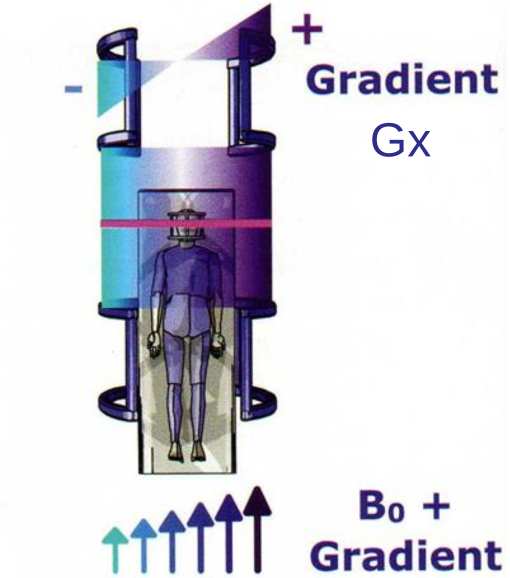
Need for fast tracking systems for MRI scanner

↳ **Magnetic localization device**

Magnetic tracking → XYZ-IRM







div **B** = 0 !

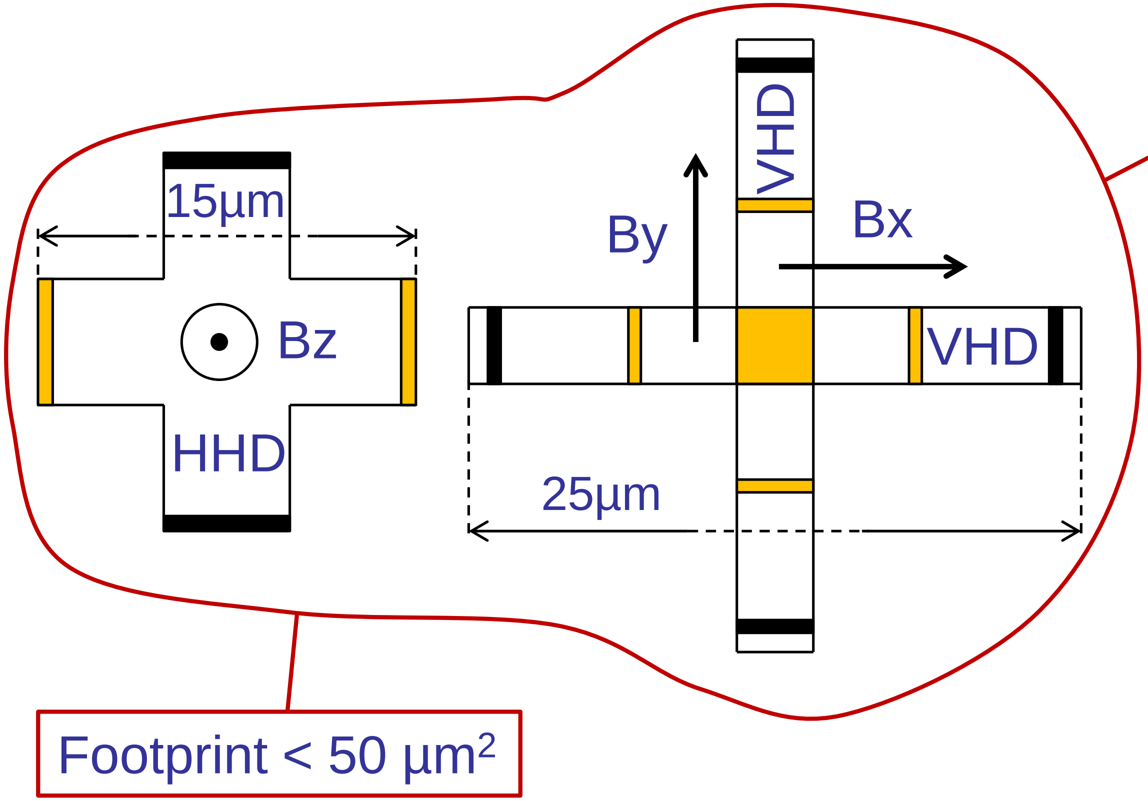
(Gx, Gy, Gz) stand for a space graduation.

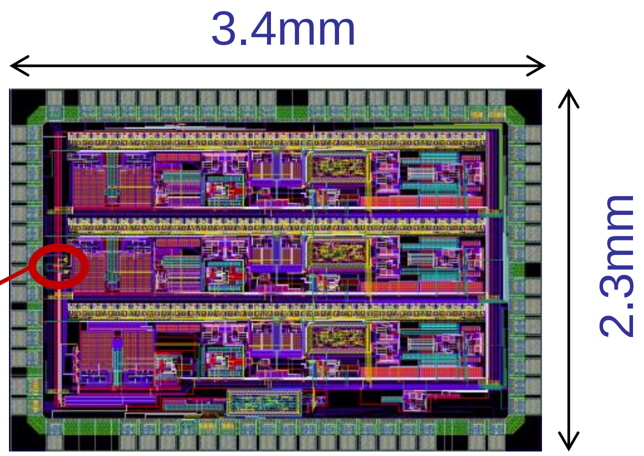
3D Hall probe to measure (Bx, By, Bz)

$$\begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} = \begin{bmatrix} -\frac{G_z}{2} & 0 & G_x \\ 0 & -\frac{G_z}{2} & G_y \\ G_x & G_y & G_z \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

Magnetic tracking → XYZ-IRM

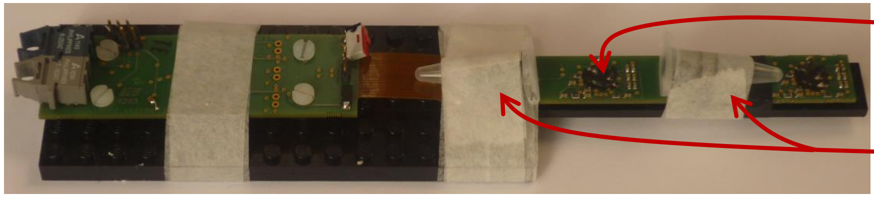
J.-B. Schell, and al., « Hall effect magnetic tracking device for Magnetic Resonance Imaging », IEEE Sensors Conference, Baltimore, Maryland-USA, Nov. 4-6, 2013, pp. 1382-1385





- 0.35µm AMS LV-CMOS
- B_0 removing
- Bx, By, Bz measured in 1ms
- 1.5T or 3T MRI scanner

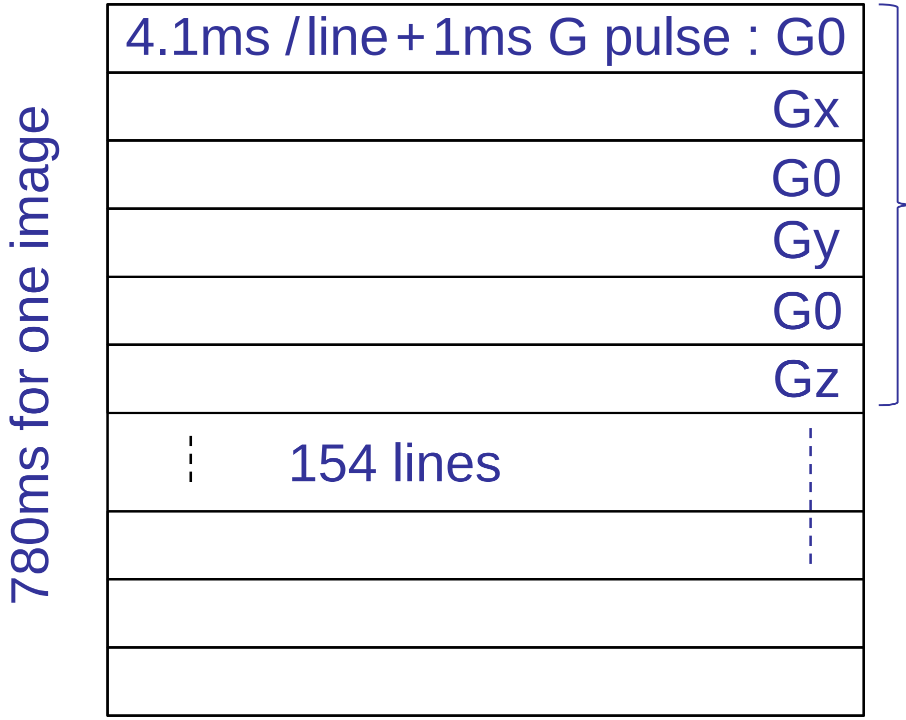
Magnetic tracking → XYZ-IRM



Used 3D Hall probe

Markers with gadolinium + a coil

Spoiled gradient echo sequence



12 measurements averaged → 367ms

\+

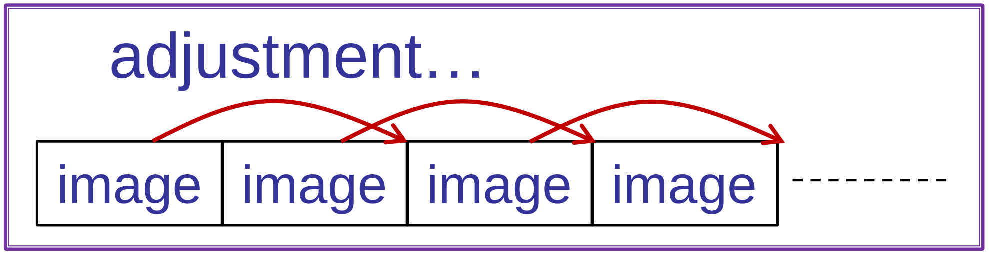
240ms for position computation

\+

400ms at least for image adjustment by the scanner

↓

Total = 1s



Magnetic tracking → XYZ-IRM

Conclusion

Fluxgate → the best resolution, but macroscopic device (a few cm-3)

Micro-fluxgate → in the future ?

~10pT

Magnetoresistances : a few nT to a few mT, resolution around 1 nT

Magnetoresistance are CMOS compatible, but multi-chip design remain the state-of-the art

~10nT

Hall devices remain the state-of-the-art magnetomer for co-integration on CMOS

3D magnetometers now available in LV as well as HV-CMOS

Hall effect in silicon → a few µT to tens of Tesla

Hall device resolution : a few µT over a few kHz of BW

~10µT

➡ New applications expected with 3D Hall devices

Thanks to my colleagues

J.-B. Schell, J. Pascal,

V. Frick, J.-B. Kammerer, M. Madec

Thanks for your attention