Sensor devices

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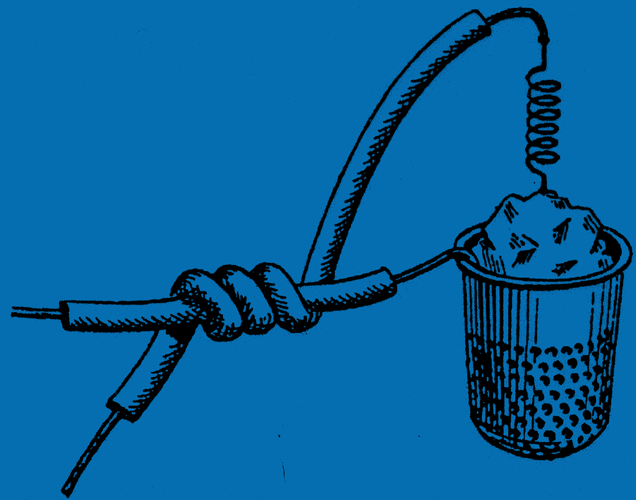
Magnetic sensors

ELECTRONICS

Design Division



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Outline

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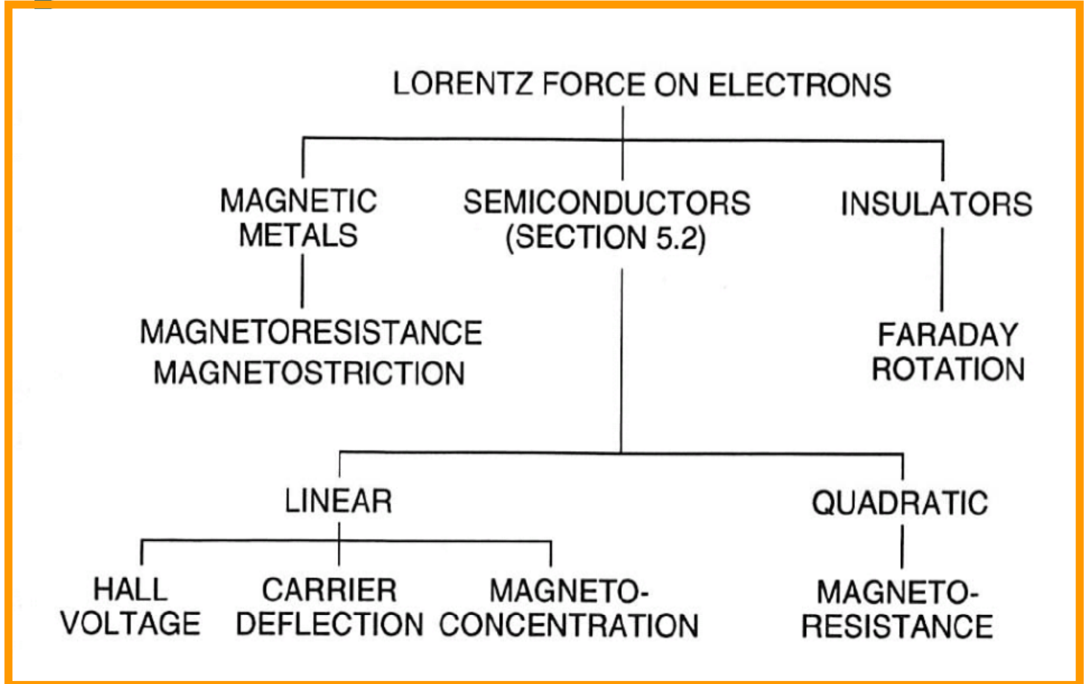
- 5 Magnetic Sensors
  - Introduction
  - Theory
    - Galvanomagnetic Effects
  - Applications

Introduction

- A magnetic sensor is a transducer that converts a magnetic field into an electrical signal
- Galvanomagnetic effects occur when a material carrying an electrical current is exposed to a magnetic field
- Hall effects, An electric field are generated when a perpendicular magnetic field plus a feeding current in a semiconductor (The effect are small in metal)
- Lorentz deflection, A current vector are generated caused by a perpendicular magnetic field
- Magnetoresistance, a modulation of the resistance by a magnetic field
- Magnetoconcentration, produce a gradient of carrier perpendicular to the magnetic field and the original current

Theory

Lorentz Force (electric field and magnetic field)



$$\boxed{F = q(E + v \times B)}$$

B magnetic induction vector

q charge of a carrier

v is the electron velocity (vector)

F the force acting on the electron (vector)

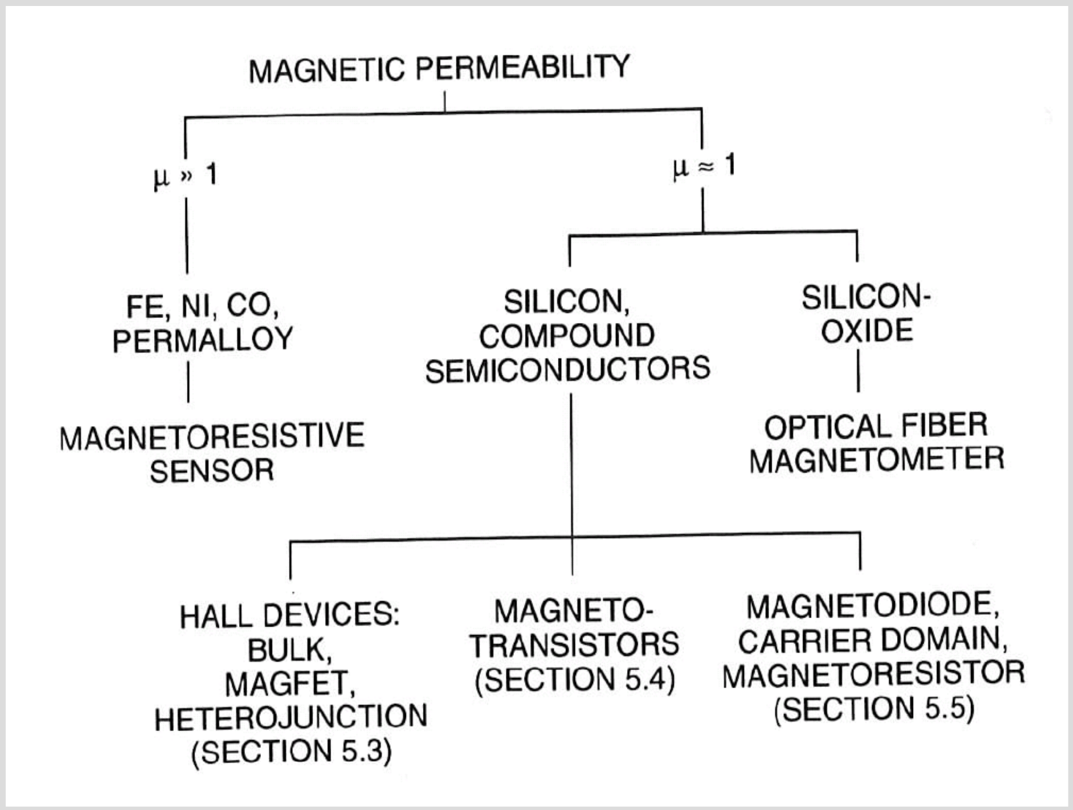
X vector product

$$\boldsymbol{B} = \mu\mu_0 \boldsymbol{H}$$

u_o is the permeability of free space

u is the relative permeability

Theory



- $\mu >> 1$
  - ferro or ferrimagnetic materials
    - NiFe
- $\mu \sim 1$
  - Dia- or paramagnetic materals
    - Galvanomagnetic effects in semiconductor

Theory

- Drift-diffusion approximations (semiconductor)
  - ***B*=0**

$$J_n(0) = \sigma_n \mathscr{E} + qD_n \nabla n,$$

$$\boxed{\sigma_n = q\mu_n n}$$

Electric drift

Diffusion

σ= conductivity

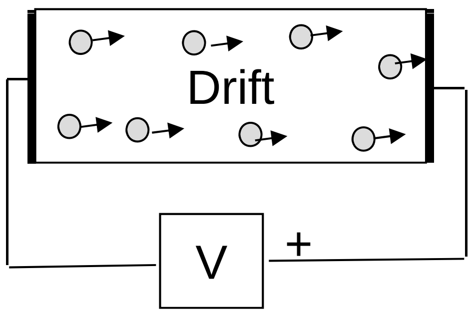
q= charge

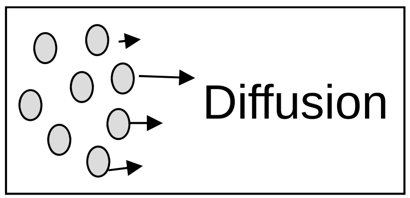
μ= mobility

n= carrier concentration

D= diffusion coefficient

∇n=gradient of electrons





Theory

Introduce Lorentz force in the drift diffusion approximation

$$J_n(0) = \sigma_n \mathscr{E} + qD_n \nabla n,$$

$$E \longrightarrow E + v \times B$$

$$J_n(B) = q\mu_n nE + qD_n \nabla n + qu_n n v_n \times B$$

Theory

$$\boxed{v_n = -\frac{J_n}{qn}}$$

replace

$$\boxed{J_n(B) = q\mu_n nE + qD_n\nabla n - u_n J_n(B)\times B}$$

Result in

$$\boxed{J_n(B) = J_n(0) - u_n J_n(B)\times B}$$

Theory

Solving with respect to $J_n(B)$

$$\boldsymbol{J}_n(\boldsymbol{B}) \approx [\boldsymbol{J}_n(0) + \mu_n \boldsymbol{B} \times \boldsymbol{J}_n(0) + (\mu_n)^2 \boldsymbol{B} \cdot \boldsymbol{J}_n(0) \boldsymbol{B}][1 + (\mu_n \boldsymbol{B})^2]^{-1}$$

Both cross product and scalar product

Scattering mechanism

< > Means average

$$r_n = \langle \tau^2 \rangle / \langle \tau \rangle^2$$

Low doped silicon
$r_n \sim 1.15$

Theory

$$\mu_n^* = r_n \mu_n.$$

Adjusting the mobility with respect to scattering factors

$$\boldsymbol{J}_n(\boldsymbol{B}) = [\boldsymbol{J}_n(0) + \mu_n^* \boldsymbol{B} \times \boldsymbol{J}_n(0) + K(\mu_n^*)^2 \boldsymbol{B} \cdot \boldsymbol{J}_n(0)\boldsymbol{B}][1 + (\mu_n^* B)^2]^{-1}.$$

Theory

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Semiconductor sample without concentration gradients

$$J_n(B) = \sigma_{nB}[\mathscr{E} + \mu_n^* B \times \mathscr{E} + K(\mu_n^*)^2 (B \cdot \mathscr{E}) B]$$

$$\sigma_{nB} = \sigma_n [1 + (\mu_n^* B)^2]^{-1}.$$

Magnetic field dependent conductivity

If magnetic field ***B*** is parallel to ***E*** then

$$\overline{J}_n(B) = \sigma_{nB}\left[1 + K(\mu_n^* B)^2\right]\overline{E}$$

Which is the longitudinal magneto resistance effect.

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Theory

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B is perpendicular to ***E,*** scalar product is therefore zero. The diffusion is also assumed to be negligible, then

$$J_n(B) = \sigma_{nB}(\mathscr{E} + \mu_n^* B \times \mathscr{E}).$$

The Electric field and the current density is assumed to be in the x-y plane. Result in;

$$J_{nx} = \sigma_{nB}(\mathscr{E}_x - \mu_n^* B \mathscr{E}_y) \qquad J_{ny} = \sigma_{nB}(\mathscr{E}_y + \mu_n^* B \mathscr{E}_x).$$

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Theory, Hall Effect

In the case of a long (in x-direction) sample, then the J_{ny}=0

The Hall field is then:

$$\mathscr{E}_y = -\mu_n^* B \mathscr{E}_x = R_H J_{nx} B,$$

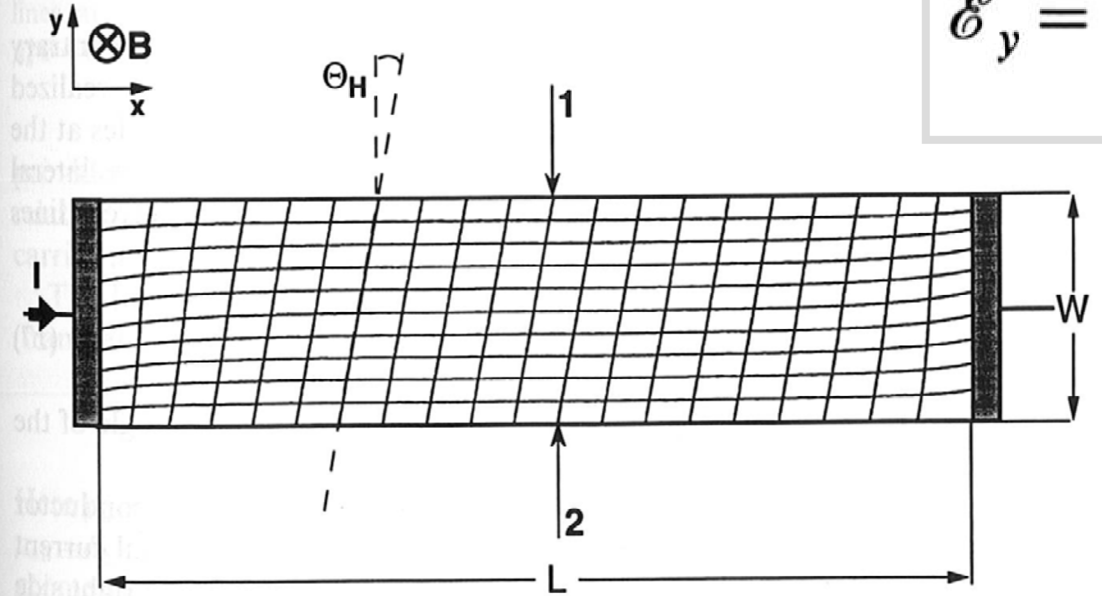

Fig. 3 Hall effect in a long semiconductor plate ($L=4W$). Current lines connect (shaded) ohmic contacts. Equipotential lines are deflected from vertical direction by Hall angle θ_H. The Hall voltage appears between border locations 1 and 2. The curves originate from numerical modeling with $\mu_n^* B=0.21$. (After Ref. 3)

$$R_H = -\mu_n^*/\sigma_n = -r_n/qn$$

Low doping gives a high hall-coefficient

Hall voltage

$$V_H = R_H IB/t.$$

Theory, Ideal Hall Effect

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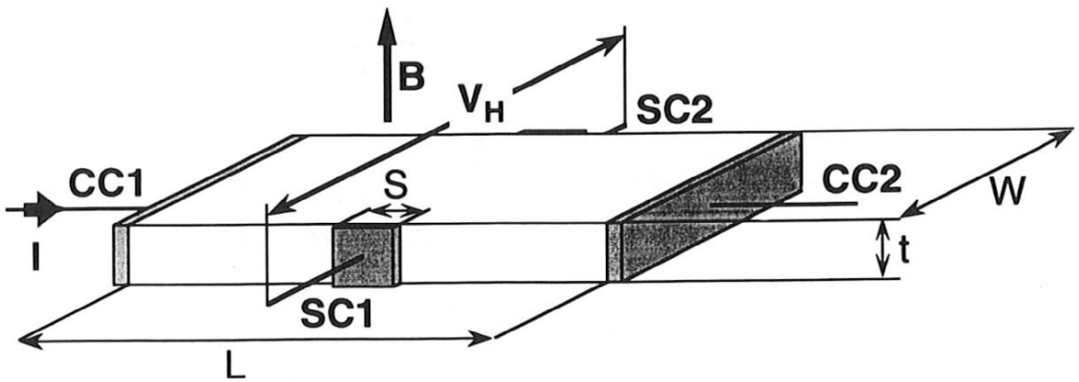
$$V_H = R_H G t^{-1} I B = -G I B r_n (qnt)^{-1}.$$

G: a geometrical factor



A long, thin and low doped sensor should give a high efficiency, but the voltage (between L) drop can then be unrealistic high

$$V = (I/qn\mu_n^*)(L/Wt)$$

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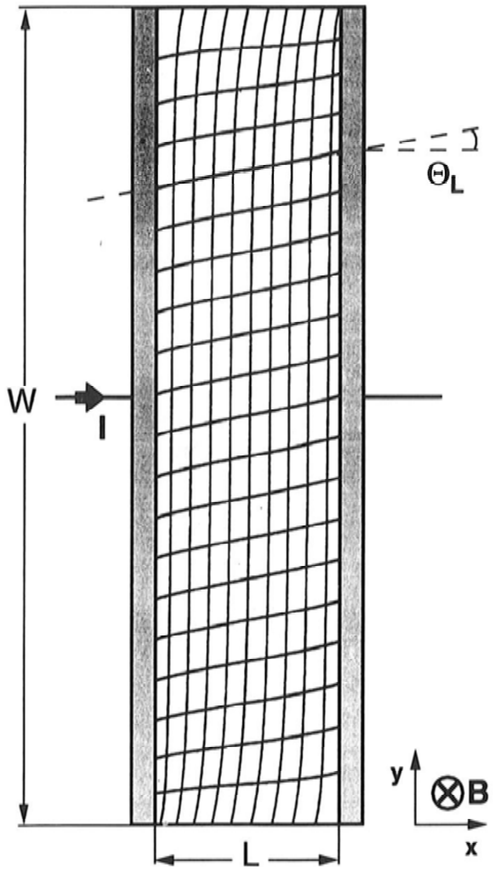
Theory, Lorentz deflection

In the case of a short sample, Hall field is zero and $\boldsymbol{E_y}$=0



A lateral current component is present, the current is therefore deflected

$$-J_{ny}/J_{nx} = \mu_n^* B = \tan\theta_L.$$

Current imbalance caused by the deflection

$$I_L = \mu_n^*(L/W)IB,$$

The semiconductor must have a high mobility for high sensitivity, InSb and InAs are good candidates

Theory, Magnetoconcentration

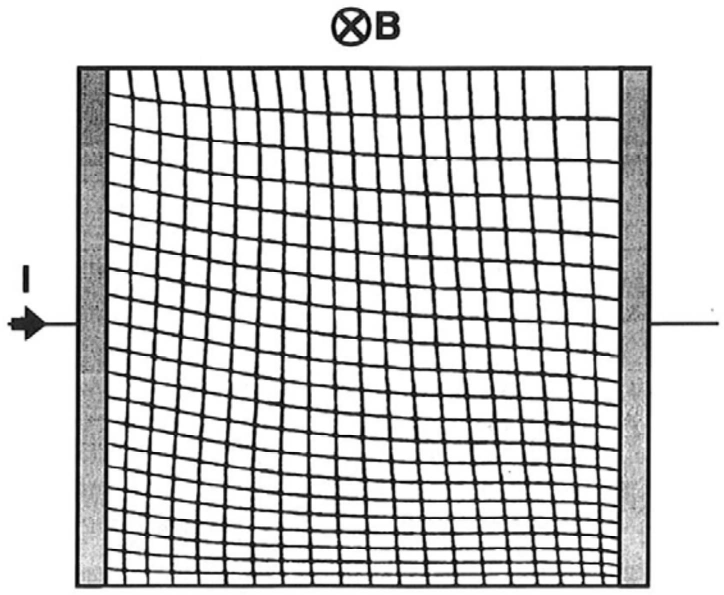
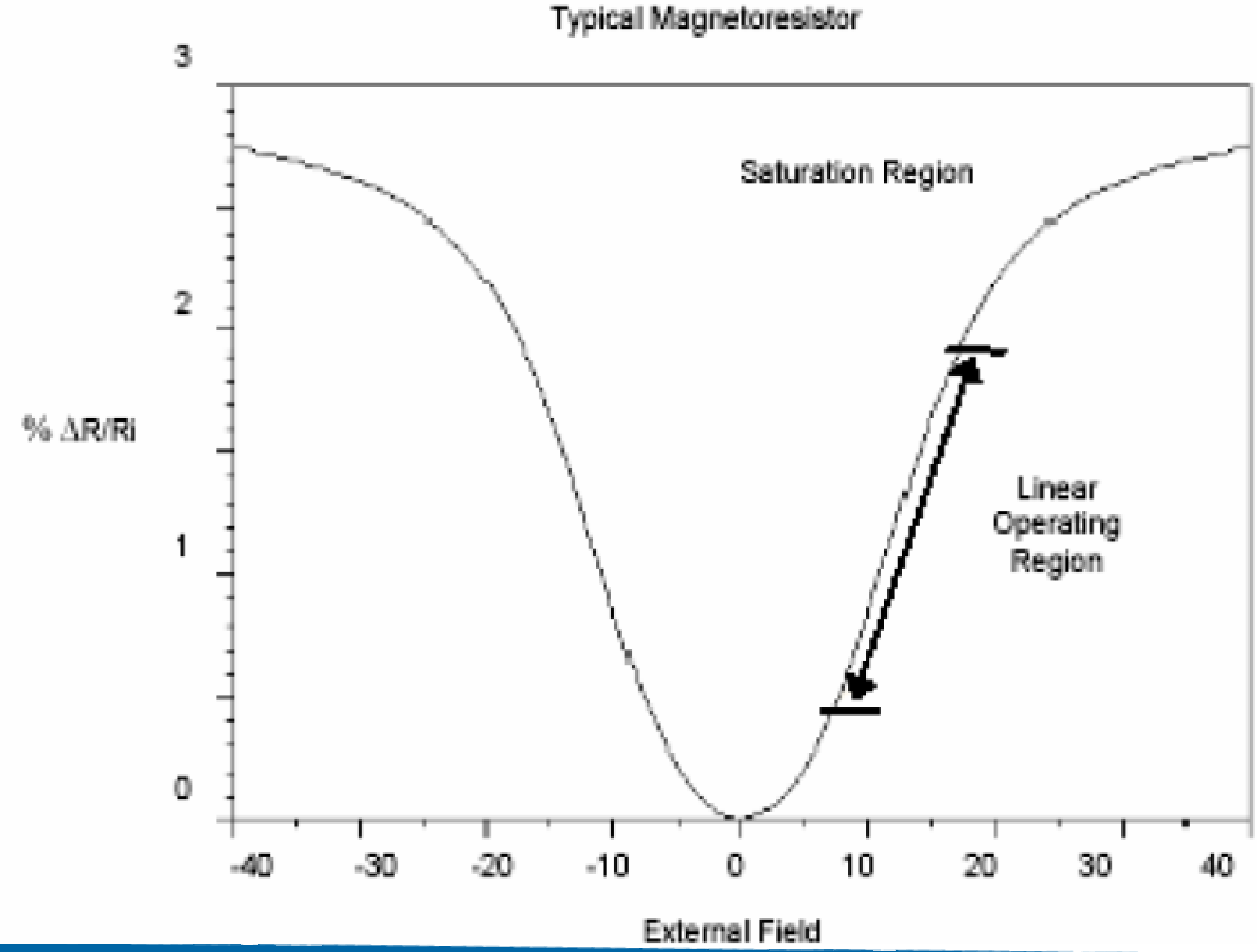


Fig. 6 Magnetoconcentration in a nearly intrinsic ($T = 500$ K) bulk silicon plate. Current lines connect ohmic contacts and crowd near bottom. Equipotential lines are approximately parallel to the contacts. The curves originate from modeling with $\mu_n^* B = 0.21$ and $\mu_p^* B = 0.07$. (After Ref. 3)

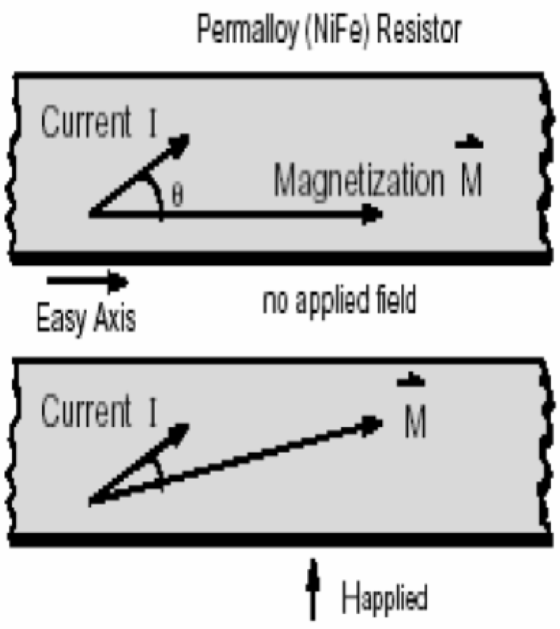
Current crowding because of local increase in conductivity

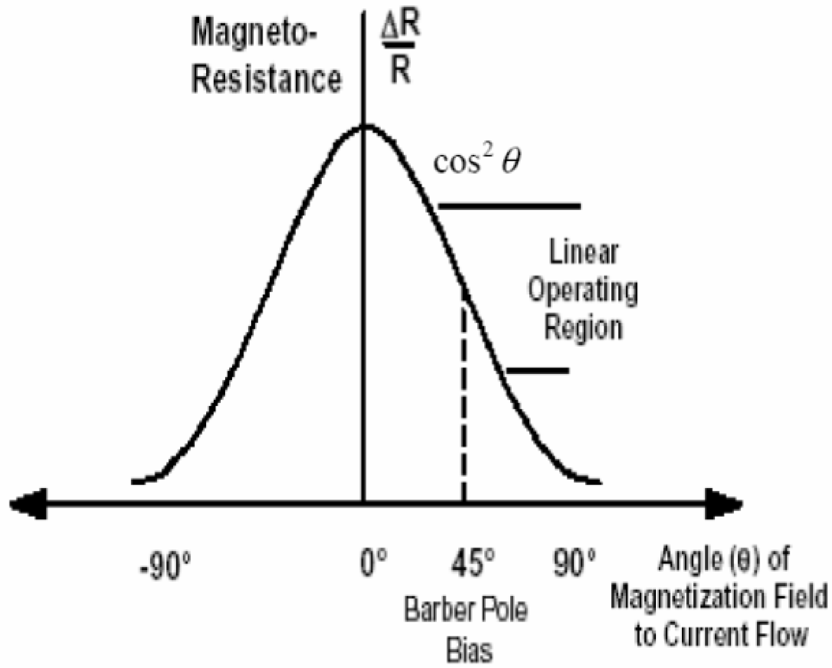
Important in devices like magnetodiodes and magneto-transistors

Theory, magnetoresistive



Theory, magnetoresistive





Barber Pole Bias

Theory, magnetoresistive, bridge

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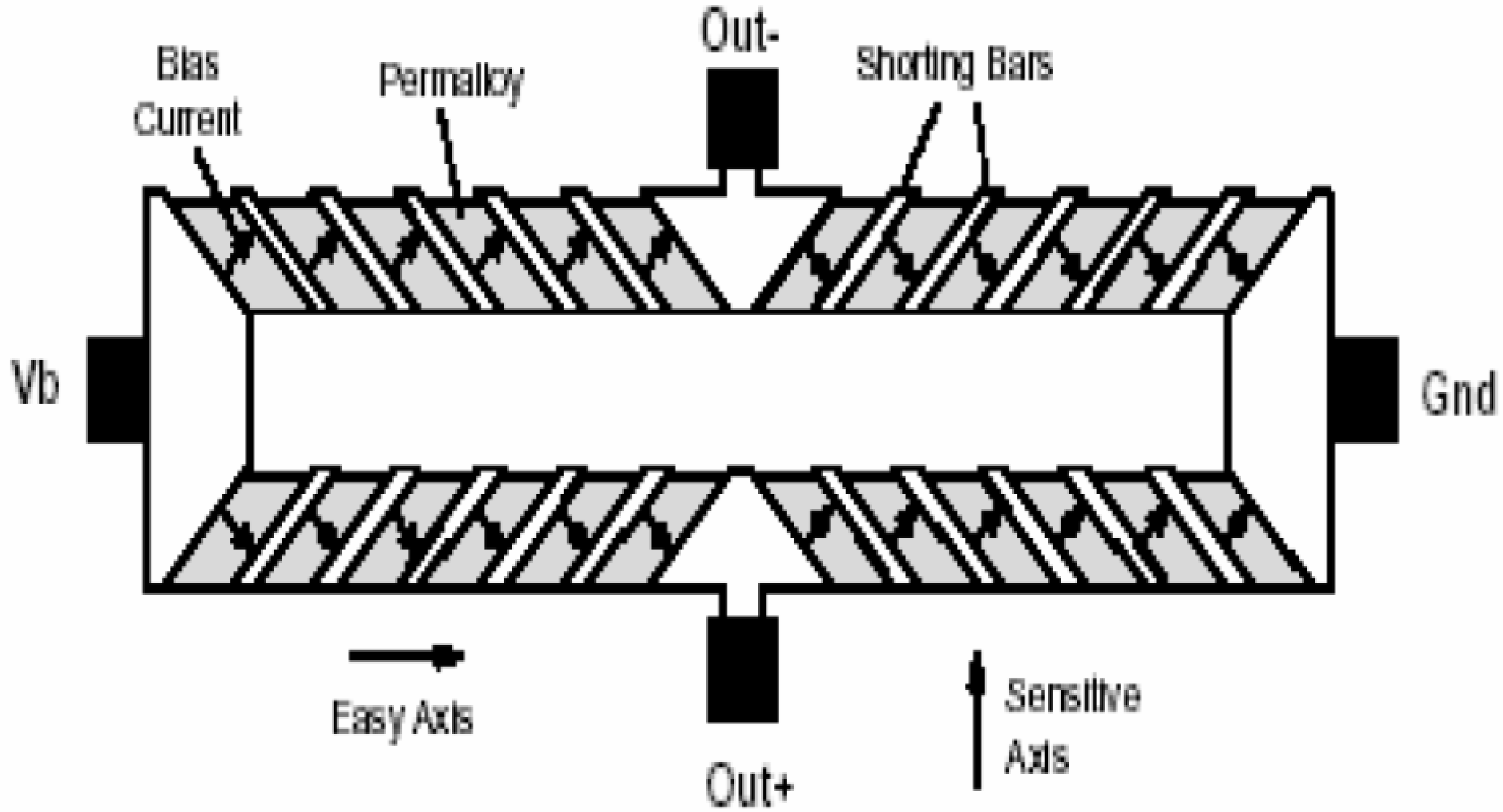
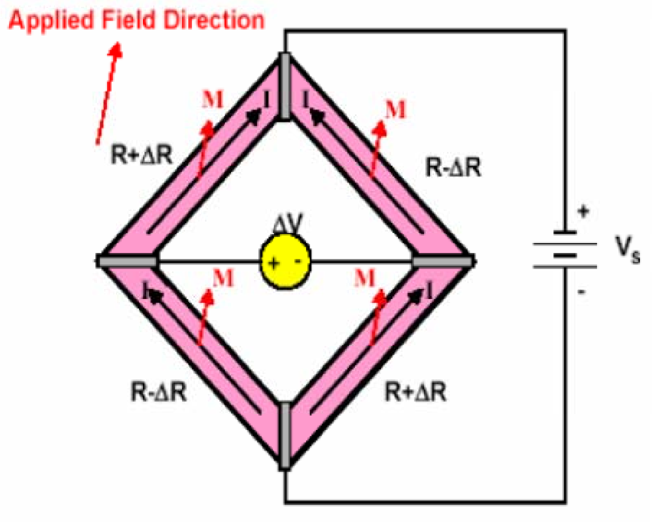
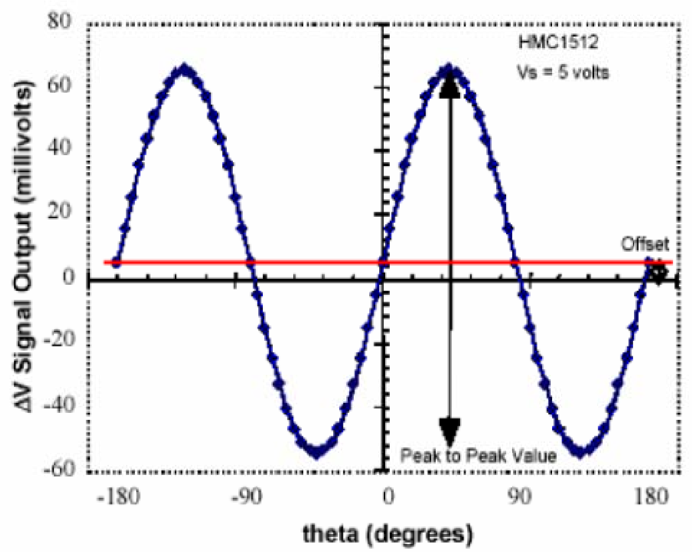


Theory, magnetoresistive, typical signal output

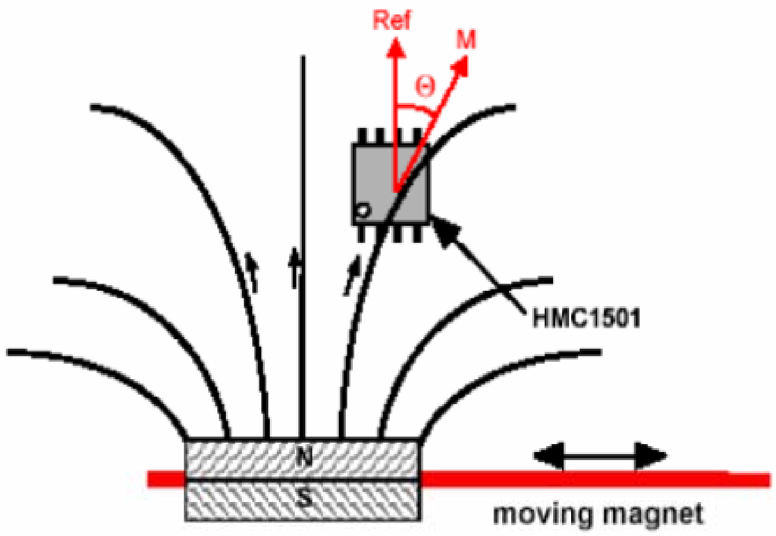


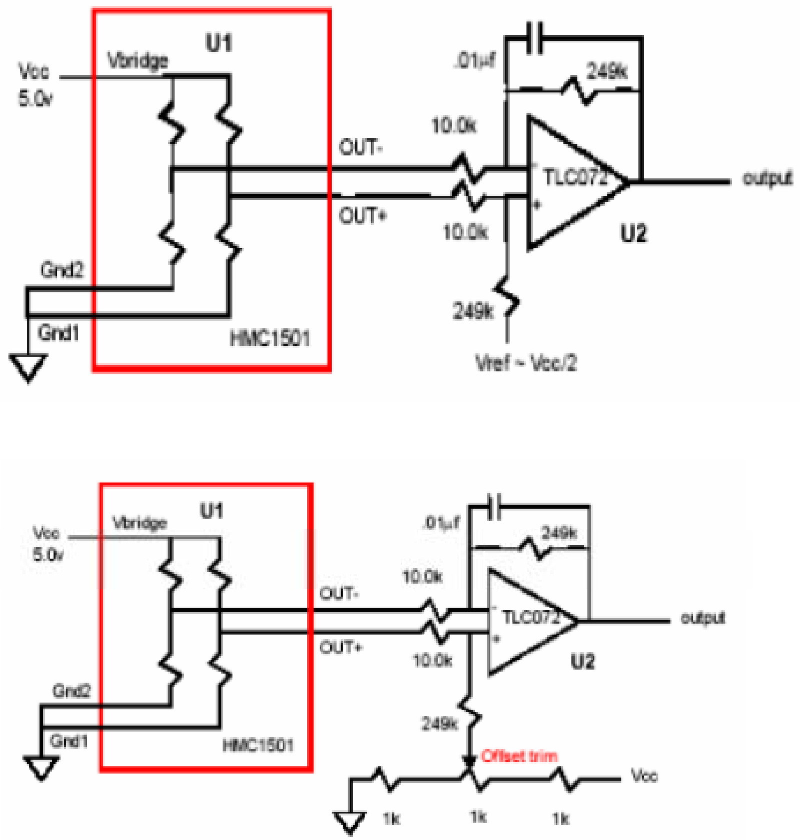
$\Delta V = -V_s\, S \sin(2\theta)$

Vs = Supply Voltage (volts)
S = Material Constant (12mV/V)
θ = Reference to Magnetic Field Angle (degrees)

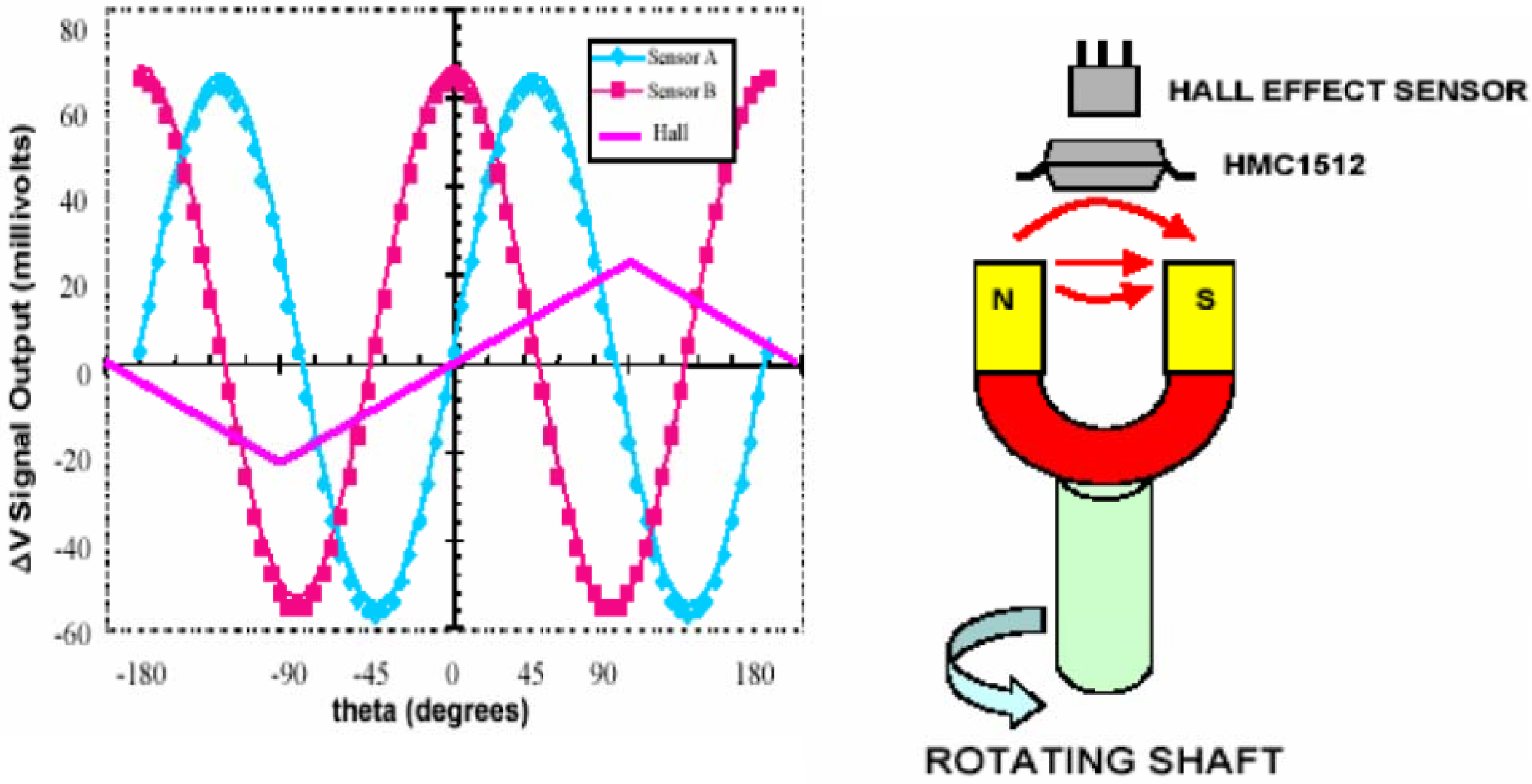


Theory, magnetoresistive, Read out circuit



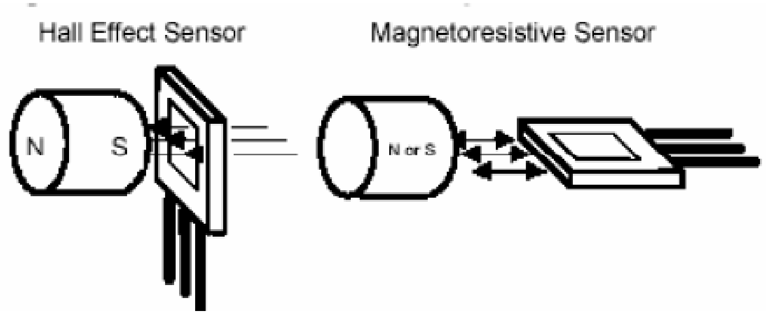


Applications

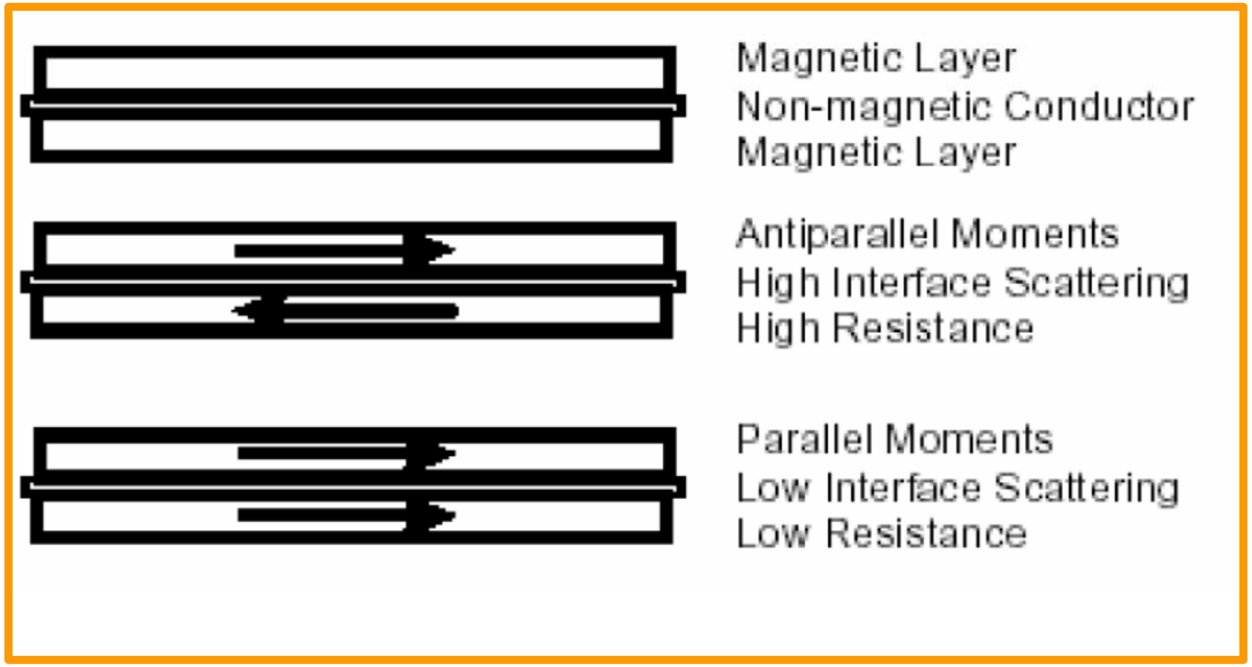


Applications

	Hall	MR
Process Technology	Silicon IC	NiFe Thin Film
Sensitivity	10uv/v/g	2 mv/v/g
Saturation Field	None	10 - 100g
Linearity	< 1%	$COS^2 \Theta$
Sensitive Axis	Perpendicular to plane of chip	Parallel to plane of chip
Output for Constant Field	Yes	Yes



Giant magnetoresistivity

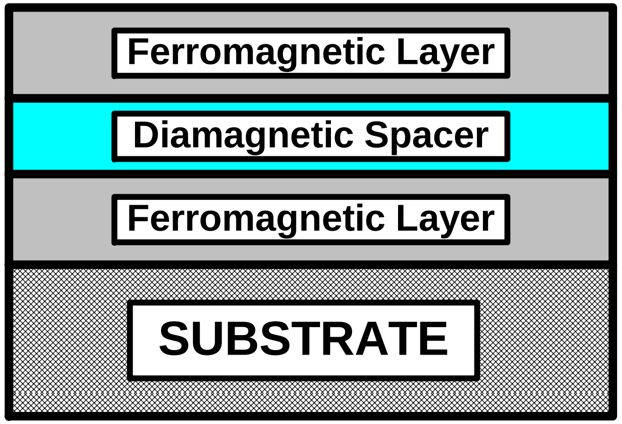


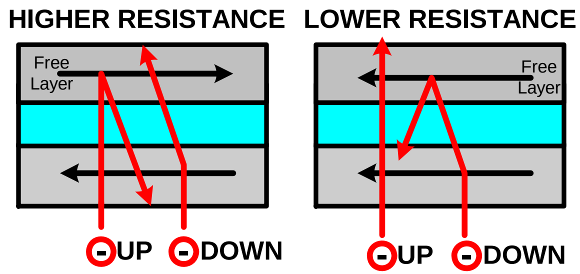
Giant Magnetoresistivity Basics

Sandwich structures combining ferromagnetic and diamagnetic metallic thin films

Giant Magnetoresistive Effect (GMR)

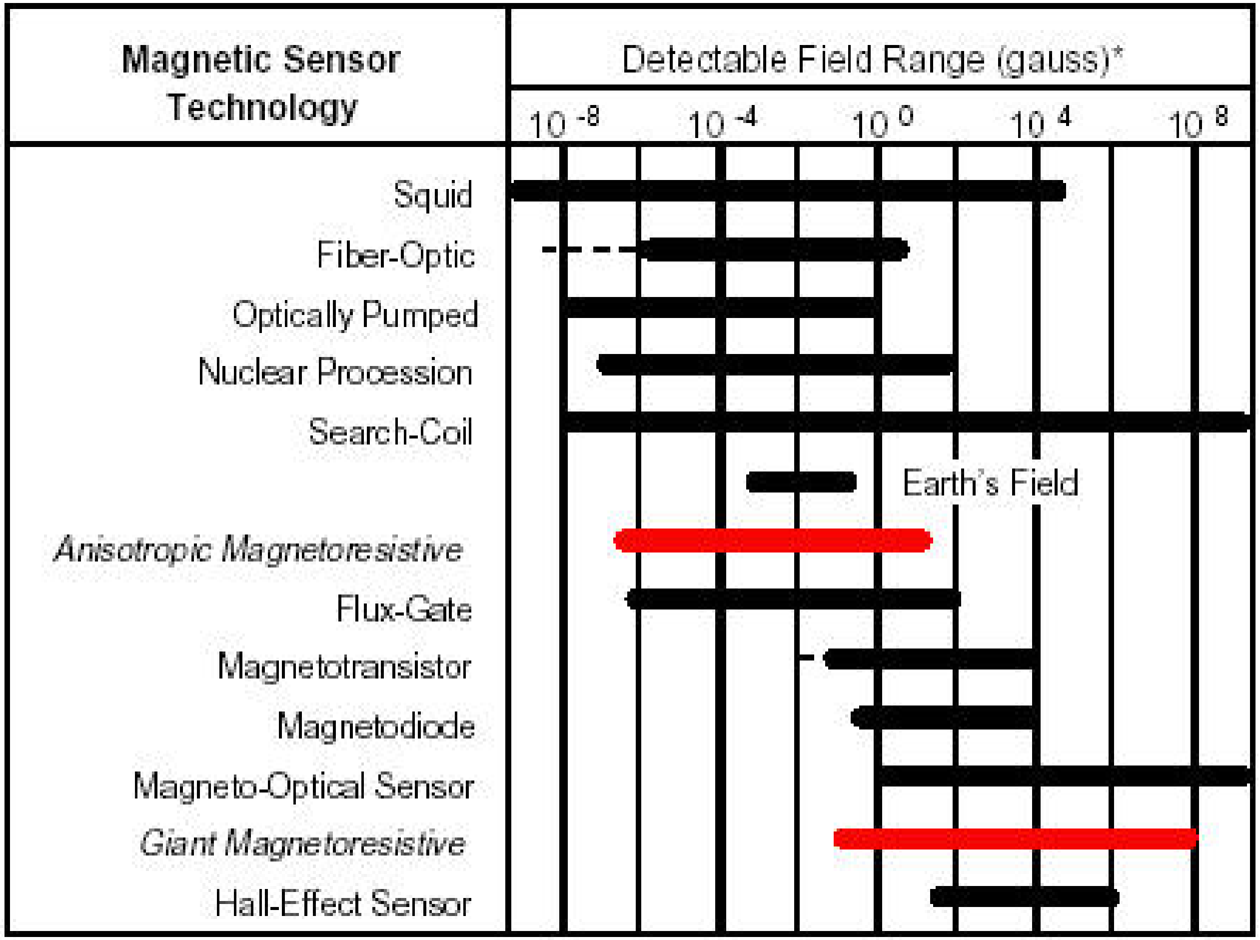
- **Significant change in the electrical resistance (10 – 15%) when the structure is subjected to the external magnetic field.**
- **Caused by spin dependent scattering of electrons in thin film sandwich structure.**
- **External magnetic field changes the magnetic orientation of the ferromagnetic layers and thus affects the flow of electrons.**





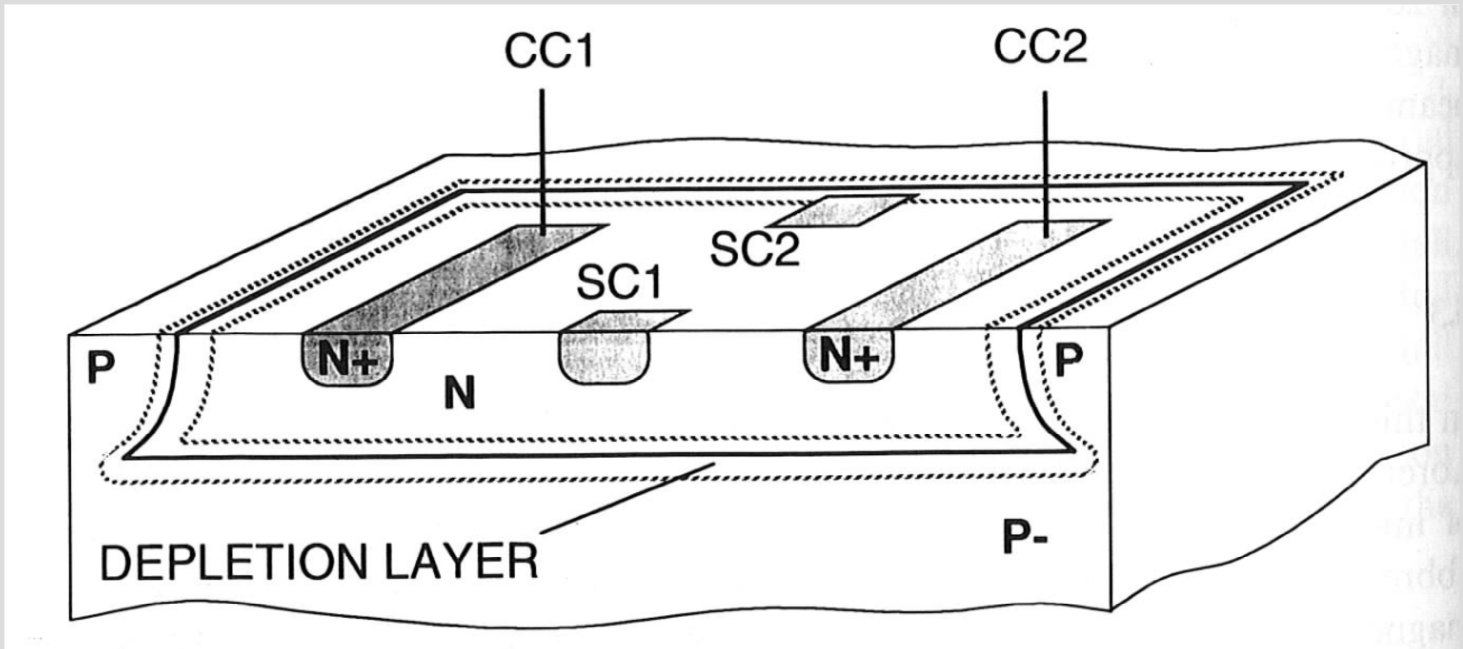
The mobility of electrons with the parallel spin is higher than those with anti-parallel spin.

Application Comparison



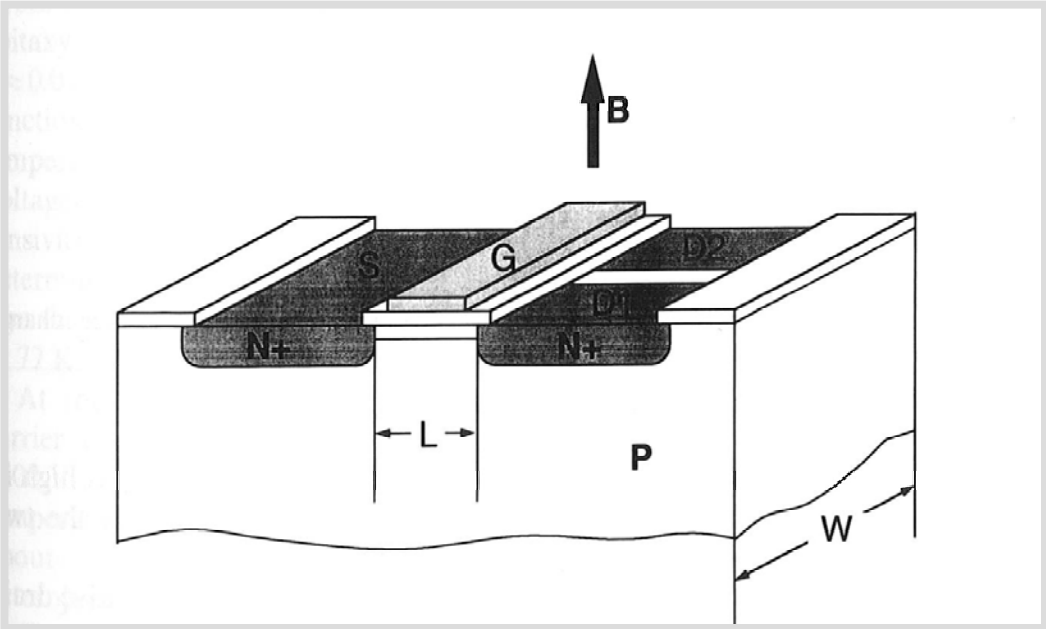
* Note: 1gauss = 10^{-4}Tesla = 10^{5}gamma

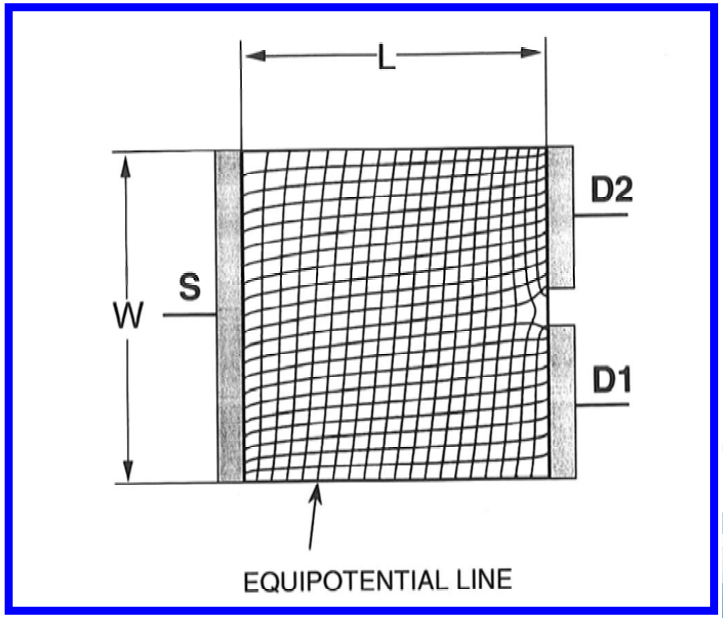
Applications, integrated bulk hall devices



Cc current contact, sc sensing contact

Applications, dual-drain MAGFET





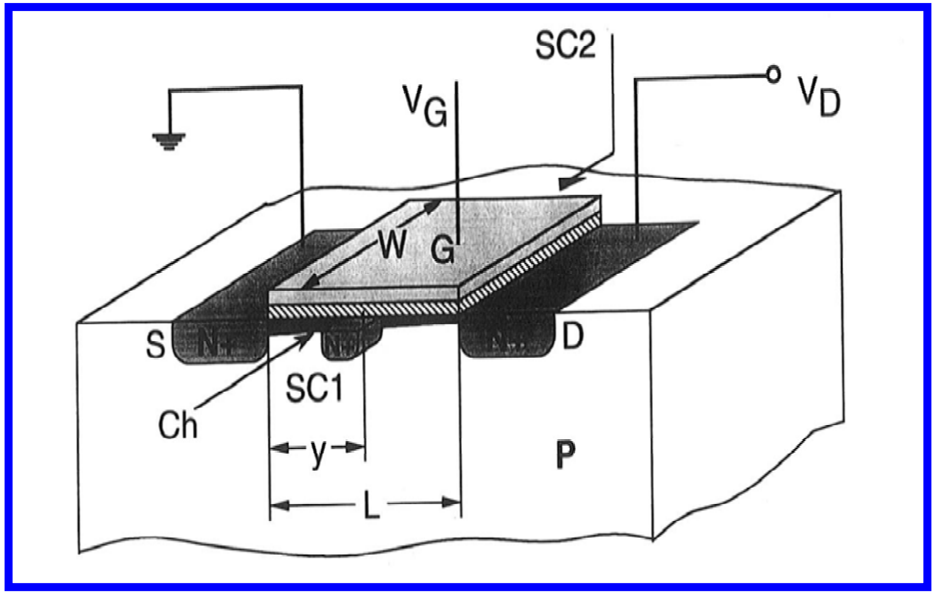
Working principle Lorentz current (deflection)

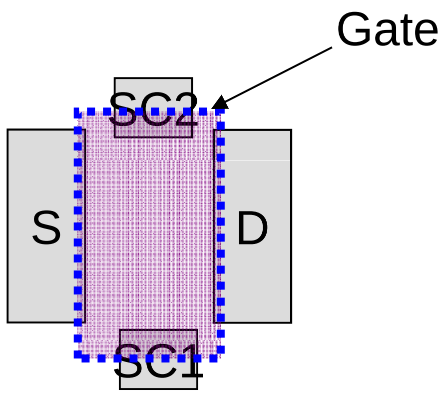
High 1/f noise

Applications, Hall MAGFET

The channel is used as a extremely thin hall plate.

High 1/f noise

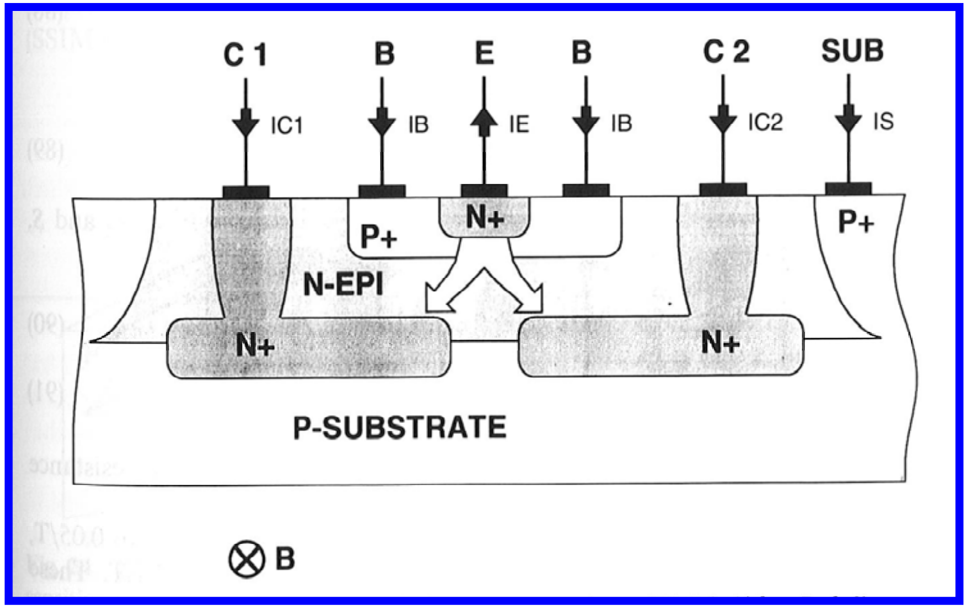




Applications, Vertical Magneto transistors

Lorentz deflection

Sensitivity similar as for dual-drain MAGFET

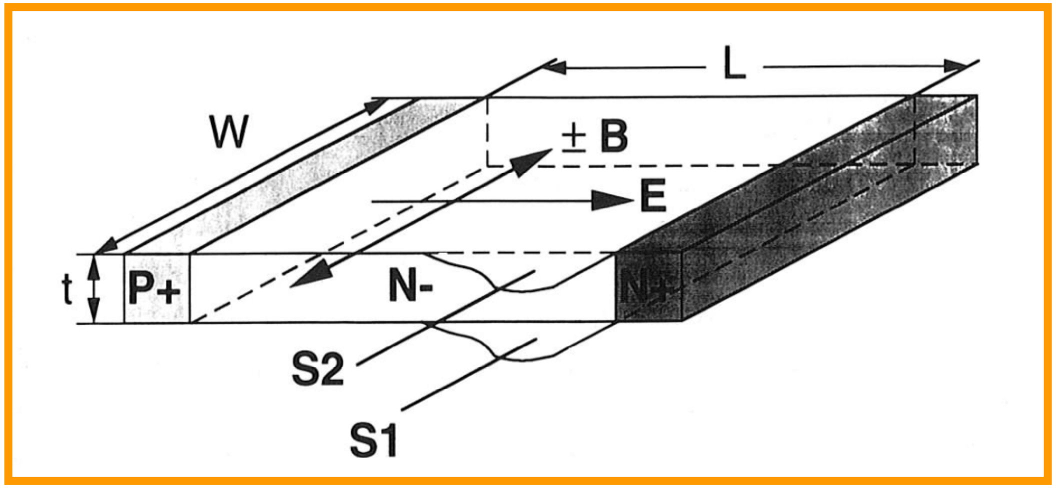


Applications, Magnetodiodes

- Magnetoconcentration
- Use of a high and a low recombination surface

S1 respectively S2

The current change in the device caused by the deflection towards low recombination or high recombination surfaces



Exercise

1)

An Si plate is doped with phosphorus and boron. $N_D = 4 \times 10^{14}$ cm^{-3}, $N_A = 4.001 \times 10^{14}$ cm^{-3}, $r_n = 1.15$, $r_p = 0.7$, $\mu_p = 0.047$ T^{-1}, $\mu_n = 0.138$ T^{-1}. What is the value for R_H?

2)

A Hall plate is integrated using a standard bipolar IC process (Fig. 11). The epi layer defining the plate has a thickness of 10 μm and a sheet resistance $\rho_s = 1000\ \Omega$/sq. Assume $L = 600\ \mu$m, and $W = 200\ \mu$m. The supply current is $I = 10$ mA and the presence of a magnetic induction $B = 100$ Gauss. Calculate:

a) the Hall coefficient, R_H

b) the Hall voltage, V_H

c) the Hall angle, θ_H

d) the supply-voltage related sensitivity, S_V.

Exercise

3) Hall structure ,V_L=0.1 V, Bz=10*E-5 Wb/cm2, Vsc_{12}=
-2mV, t=10um, L=5mm, w=0.1 mm, I=1 mA, find the type, concentration, and mobility of the majority carrier.

answer; electrons, 3.125E17 cm^{-3}, u_n= 10000 $cm^2(Vs)^{-1}$

Magnetic Sensors

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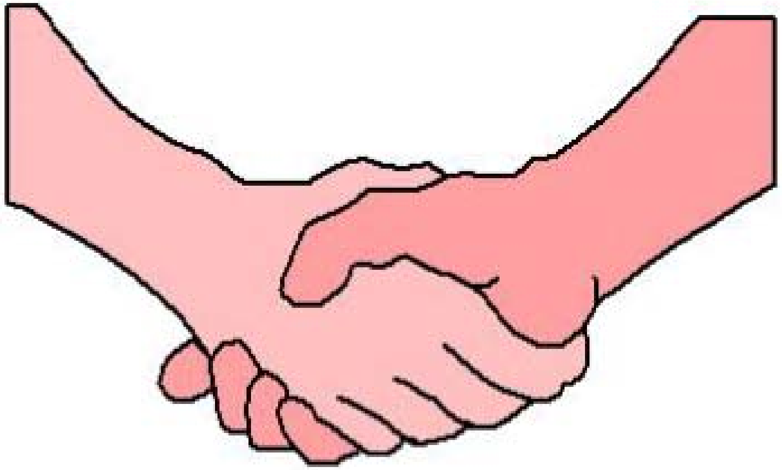

Thank you