

磁感測器技術研究與應用

Research on Magnetic Sensor Technologies and its Applications

鄭振宗 (Jen-Tzong Jeng)



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Department of Mechanical Engineering,
National Kaohsiung University of Applied Sciences



微磁技術實驗室
Micro Magnetic Technologies Laboratory
(MMT Lab)

微磁技術實驗室-研究主題

◆磁強計 (magnetometers)

- 超導量子干涉元件 (Superconducting Quantum Interference Devices, SQUID)
- 巨磁阻 (giant magnetoresistance, GMR)
- 通量閘 (fluxgate)

◆渦電流偵測器 (eddy-current detectors)

- 低頻(10 Hz~10 kHz)：渦電流缺陷偵測器
- 高頻(10 kHz~10 MHz)：非接觸式距離偵測器

◆磁感測器應用

- 心臟磁場量測：SQUID
- 磁場圖掃描、磁源電流逆算：GMR
- 硬幣辨識：高頻渦電流偵測器

◆結語

合作研究群(Co-workers)



國立高雄應用科技大學

National Kaohsiung University of Applied Sciences

鄭振宗 教授 - 微磁技術實驗室(MMT Lab)

SQUID sensor, magnetic simulation: 陳博能, 魏世峰

GMR, fluxgate, and MTJ driving circuits: 張進雄, 賈孟寰, 洪聖芳

Eddy-current sensors: 馮珙鉸(碩專)

Magnets for electric vehicles: 陳信忠(碩專)



國立台北科技大學

National Taipei University of Technology

呂志誠 教授 - 先進微系統元件實驗室 (AMD Lab)

Microfluxgate: 邱士良

GMR driving circuits (ASIC): 廖唯佐, 邱柏凱

Coin validator: 康峻菁

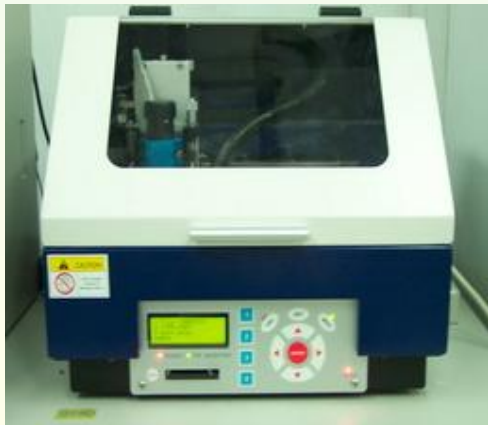
微磁技術實驗室-主要儀器



二維磁場掃描系統



磁控濺鍍、離子束蝕刻系統



電路板彫刻機



頻譜分析儀

磁控濺鍍、離子束蝕刻系統



規格：

(1)磁控濺鍍

- 交、直流磁控濺鍍電源
- 雙濺鍍槍(2")
- 溫控加熱器(800°C, PID)

(2)離子束蝕刻

- 離子槍(3 cm, Ar)
- 可旋轉蝕刻台(360°)

用途：

- 成長YBCO磊晶薄膜
- 銀薄膜製作
- 氬離子束蝕刻
- 晶片退火(O₂, N₂, Ar)

微磁技術實驗室-其它儀器設備

- 晶片(鋁線)鐳線機(wire bonder) – 在無塵室內
- 任意波形產生器(arbitrary wave form generator)
- 微波訊號產生器(microwave signal generator)
- 鎖相放大器(lock-in amplifier)
- 可程式濾波放大器(programmable filter, DC~1 MHz)
- 射頻放大器(radio-frequency amplifier, DC~350 MHz)
- 光遮斷器(optical chopper)
- 數位儲存示波器(digital storage oscilloscope)
- 六位半多功能電表(multimeter, 6½ digits)
- 阻抗量測儀(LCR meter)
- 三軸通量閘(triaxial fluxgate, 10^{-4} T~ 10^{-10} T)

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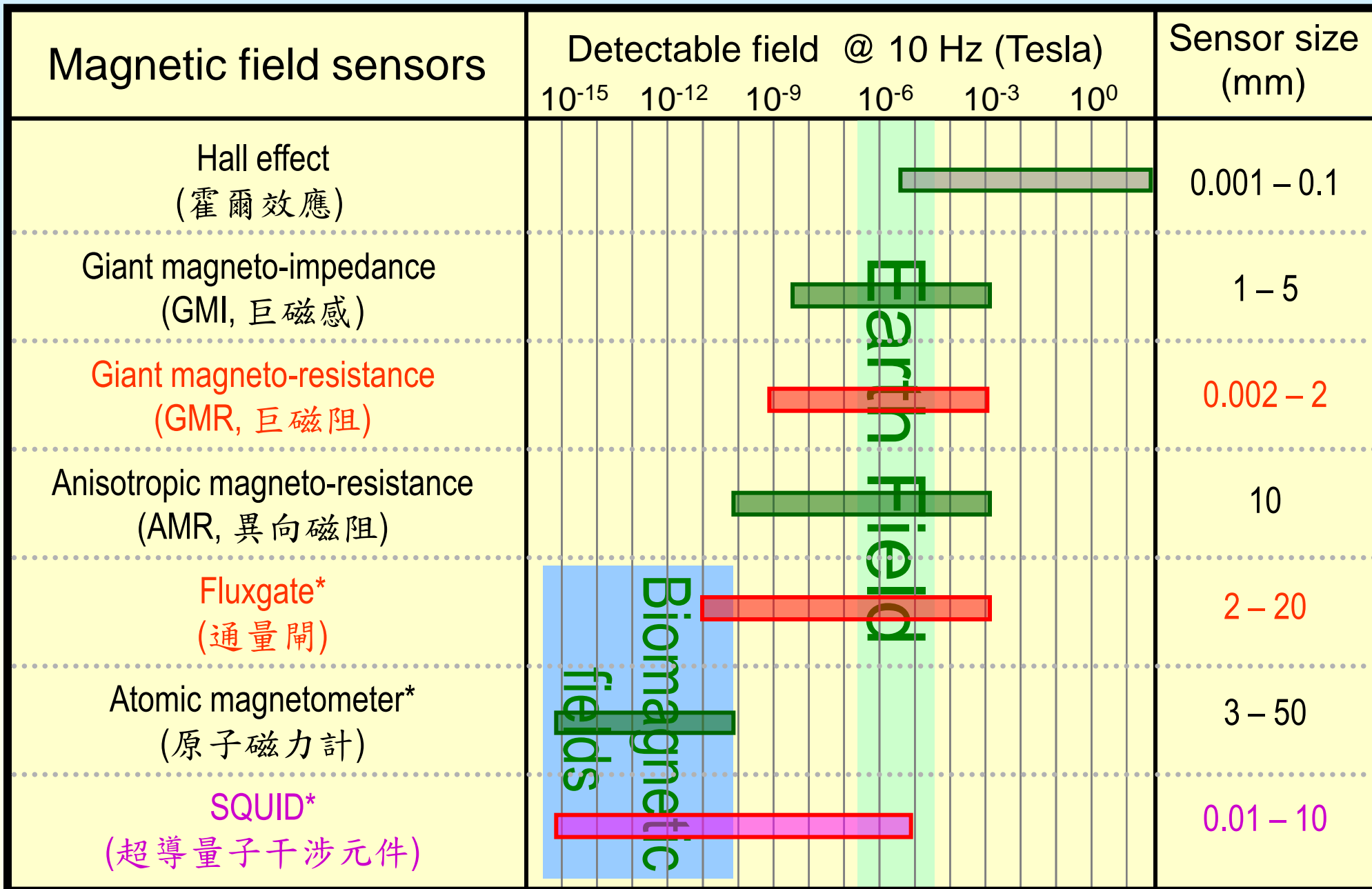
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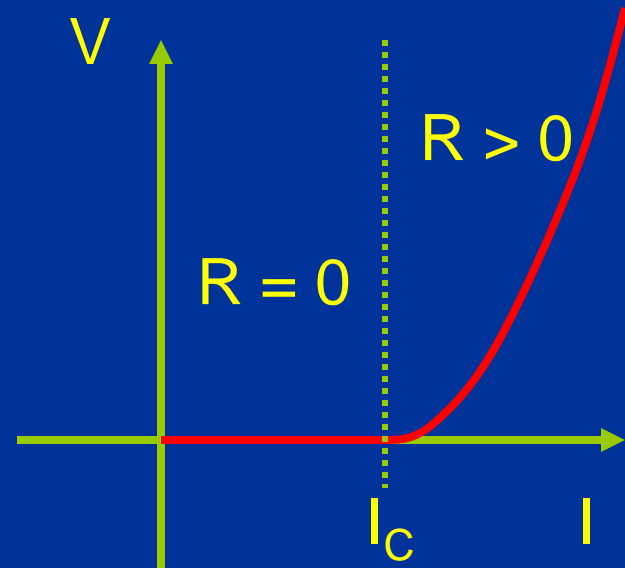
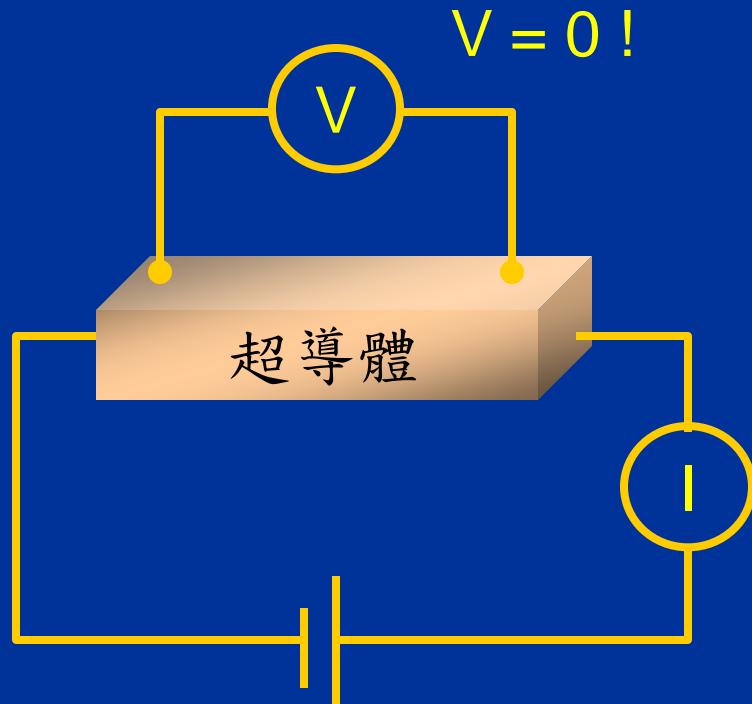
◆結語

磁強計之感測範圍比較



何謂超導體

❄️ 超導體 = 沒有電阻的導體, $R = \frac{V}{I} = 0$



臨界電流

超導材料

傳統超導體 (金屬)

Al (1.2 K), Sn (3.7 K), Pb (7.2 K), Nb (9.3 K)

Nb₃Sn (18 K), Nb₃Ge (23 K)

高溫超導體 (陶瓷)

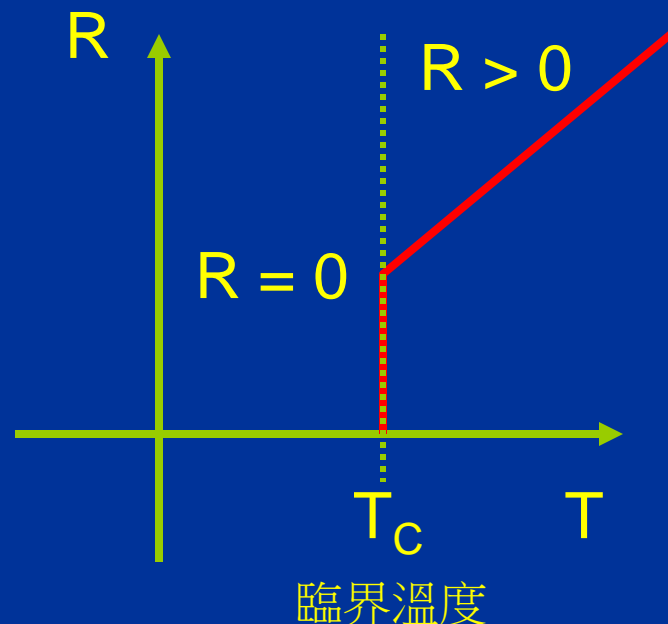
La_{1.8}Sr_{0.2}CuO₄ (40 K)

YBa₂Cu₃O_{7-y} (92 K)

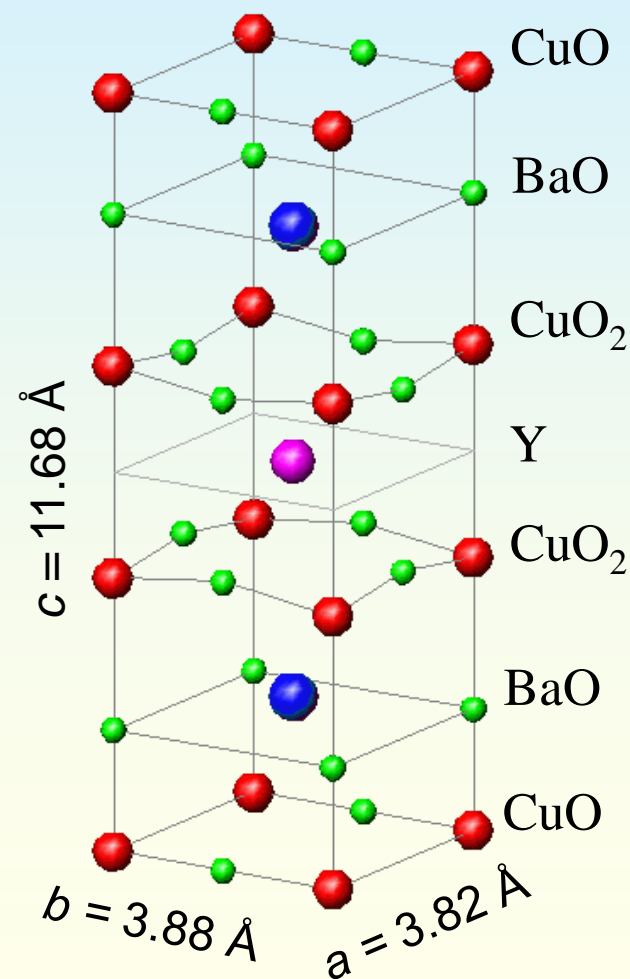
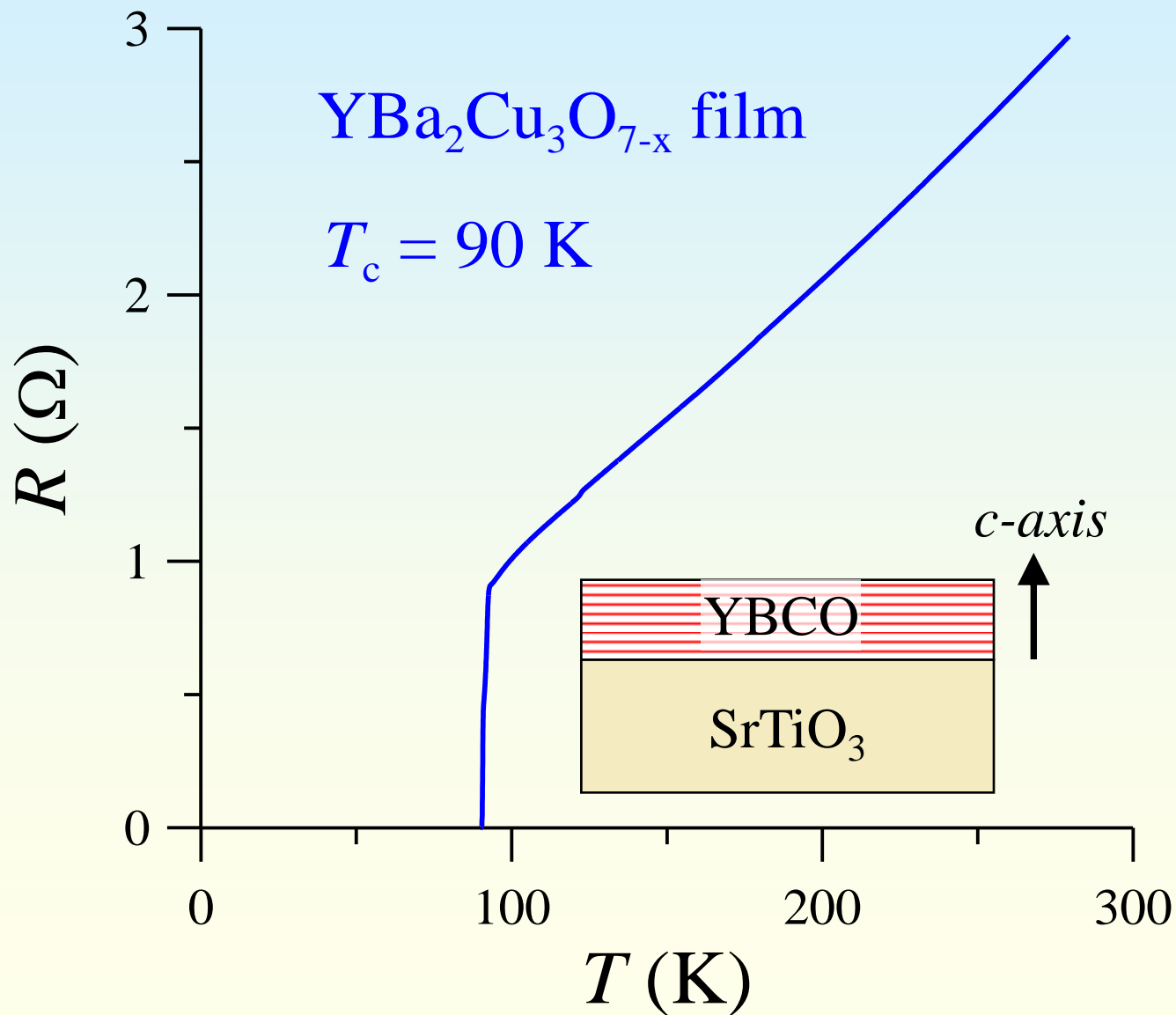
(Tl_{0.5}Pb_{0.5})Ba₂Ca₂Cu₃O_{10-y} (125 K)

HgSr₂Ca₂Cu₃O_{10-y} (150 K)

MgB₂ (40 K)



Crystalline $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) Superconductor Film

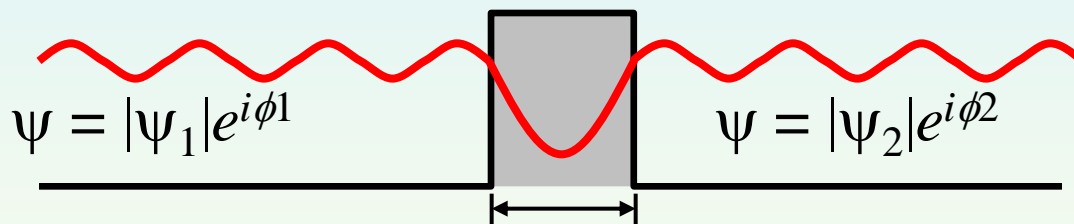


High- T_c $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) Josephson junctions

約瑟夫森界面

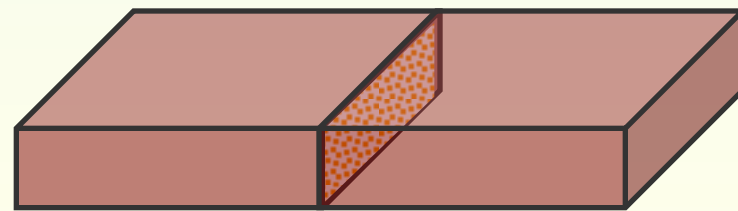
$$\begin{cases} I = I_0 \sin \delta & \text{Current-phase relation (CPR)} \\ \frac{d\delta}{dt} = \frac{2\pi}{\Phi_0} V & \text{Voltage-phase relation} \end{cases}$$

$$\delta = \phi_1 - \phi_2$$



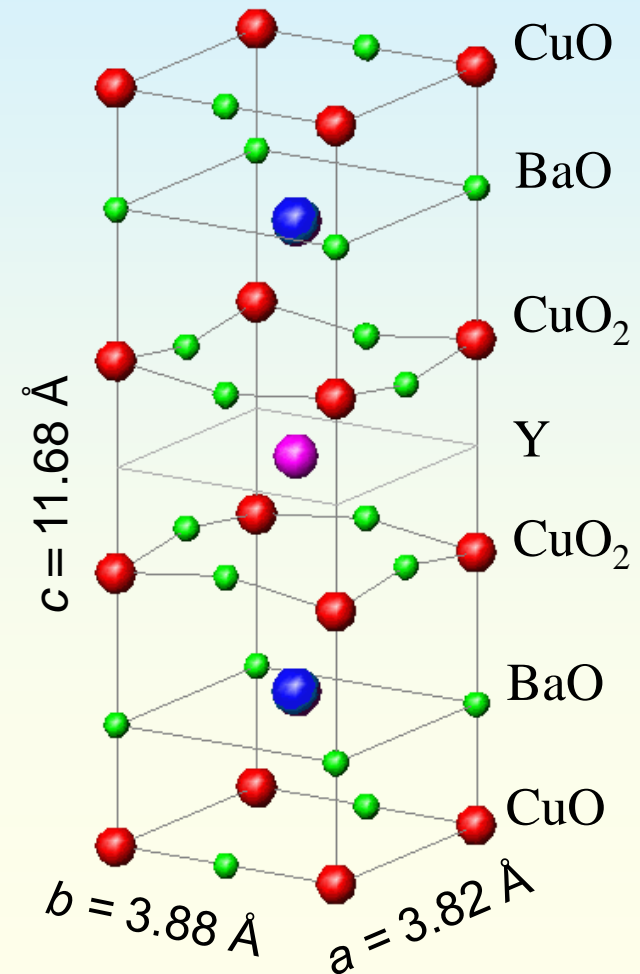
Coherence lengths ~ 3 nm in the a - b plane
 ~ 0.4 nm along the c -axis

c -axis



Bi-crystal Josephson junction

Junction area
 $= 2 \mu\text{m} \times 0.15 \mu\text{m}$
 $= 0.3 \mu\text{m}^2$

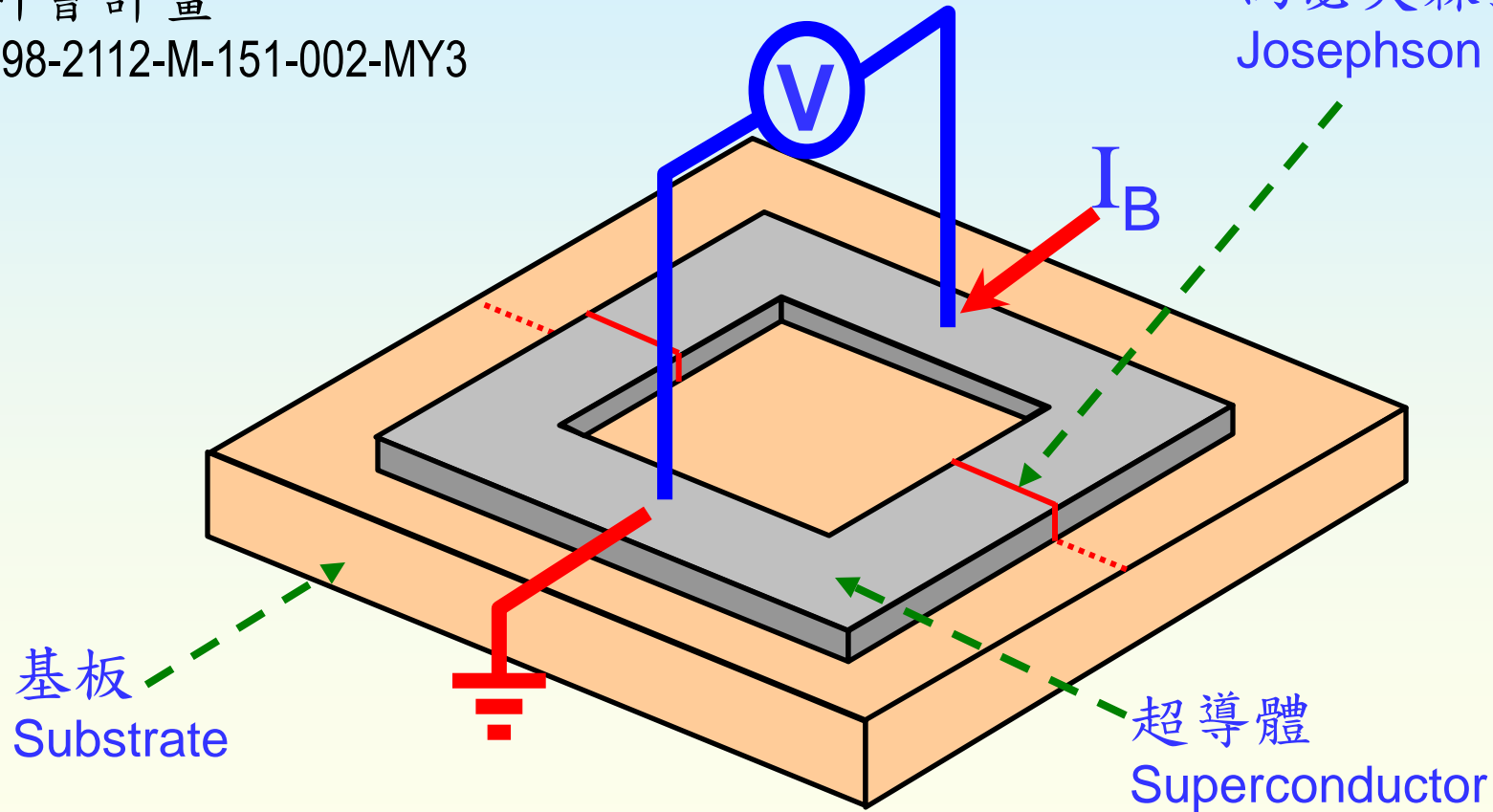


超導量子干涉元件 (SQUID)

國科會計畫

NSC98-2112-M-151-002-MY3

約瑟夫森接面
Josephson Junctions

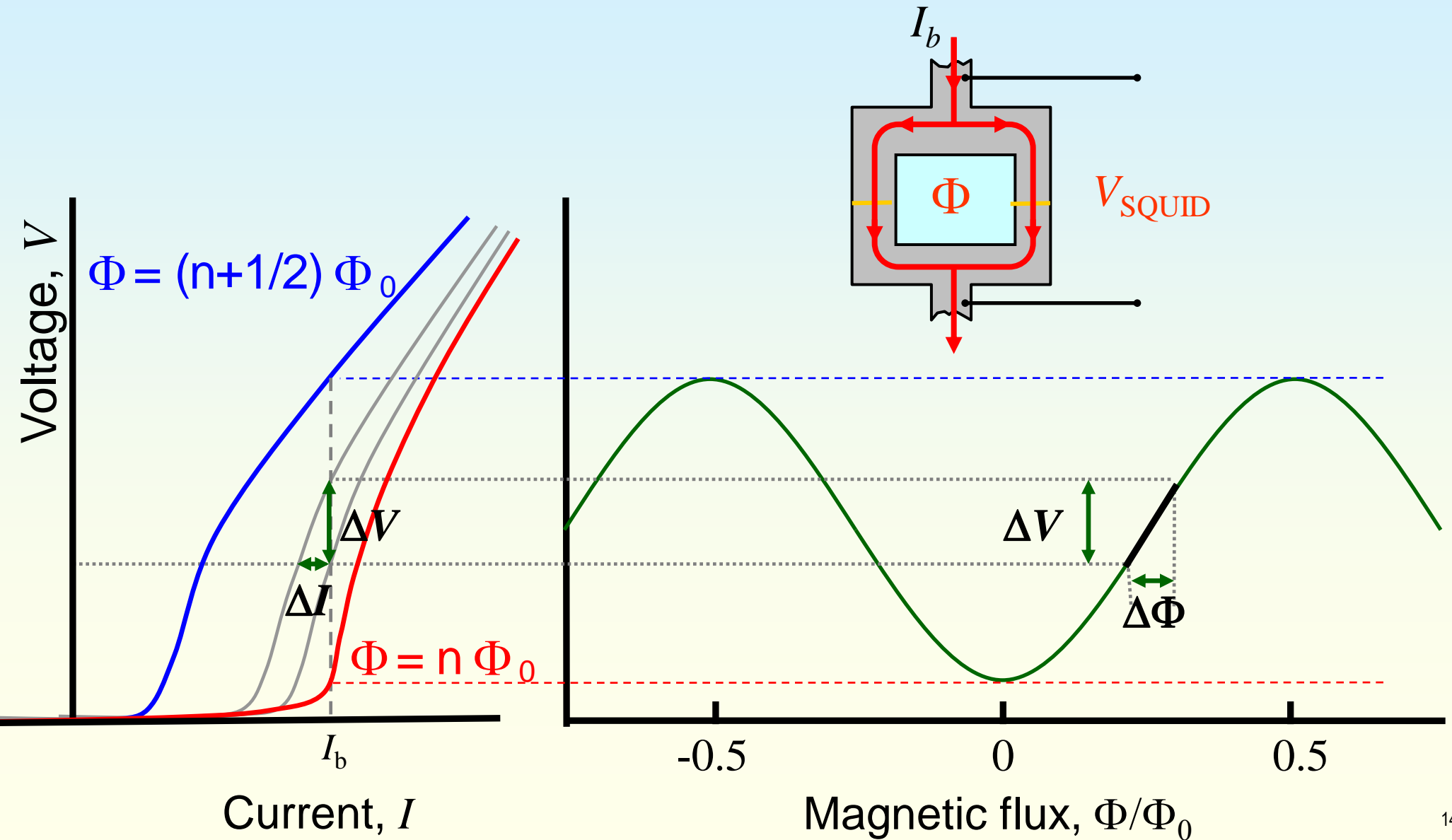


SQUID = Superconducting QUantum Interference Device

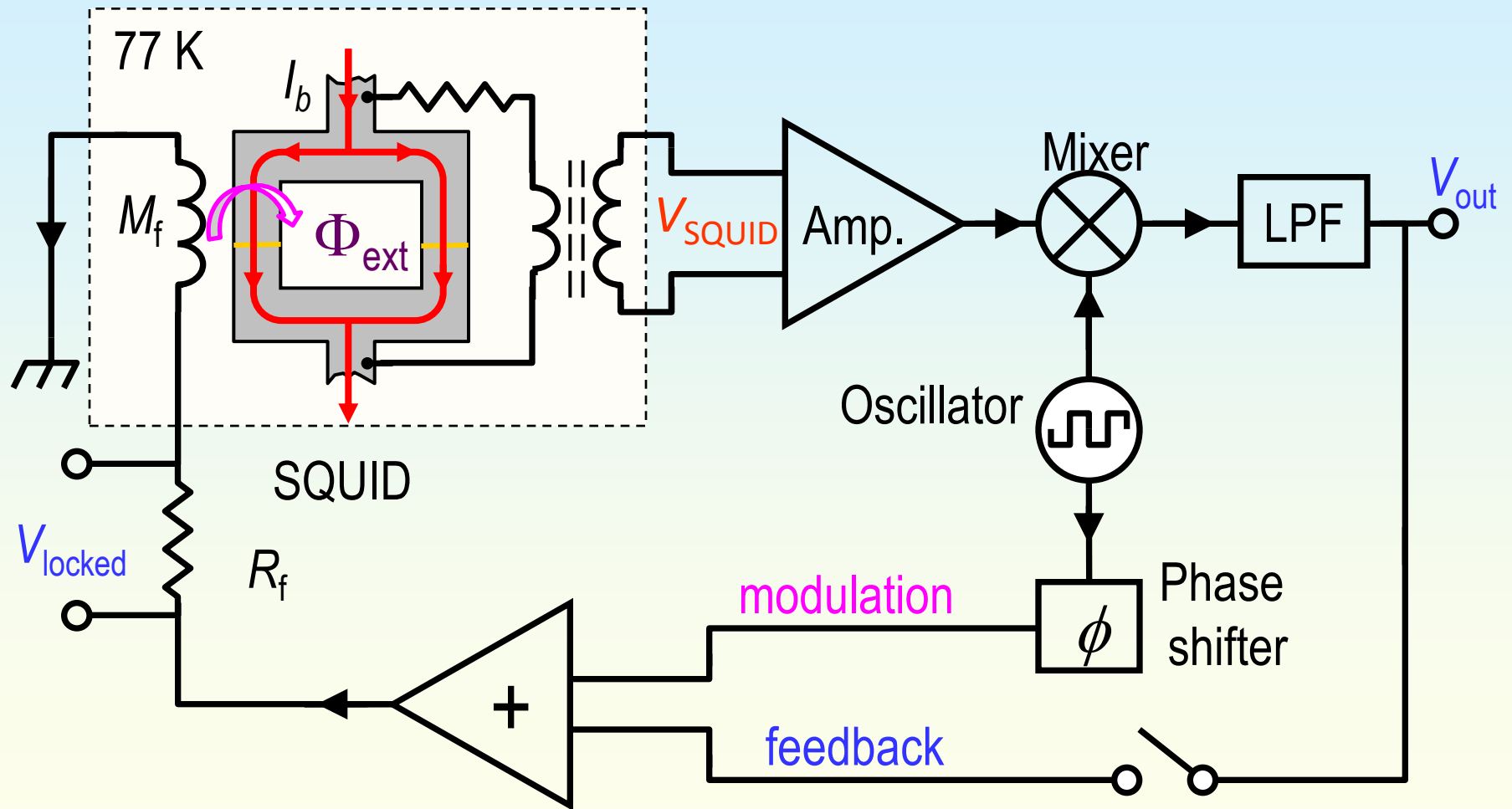
超導

量子

SQUID之磁通-電壓轉換特性

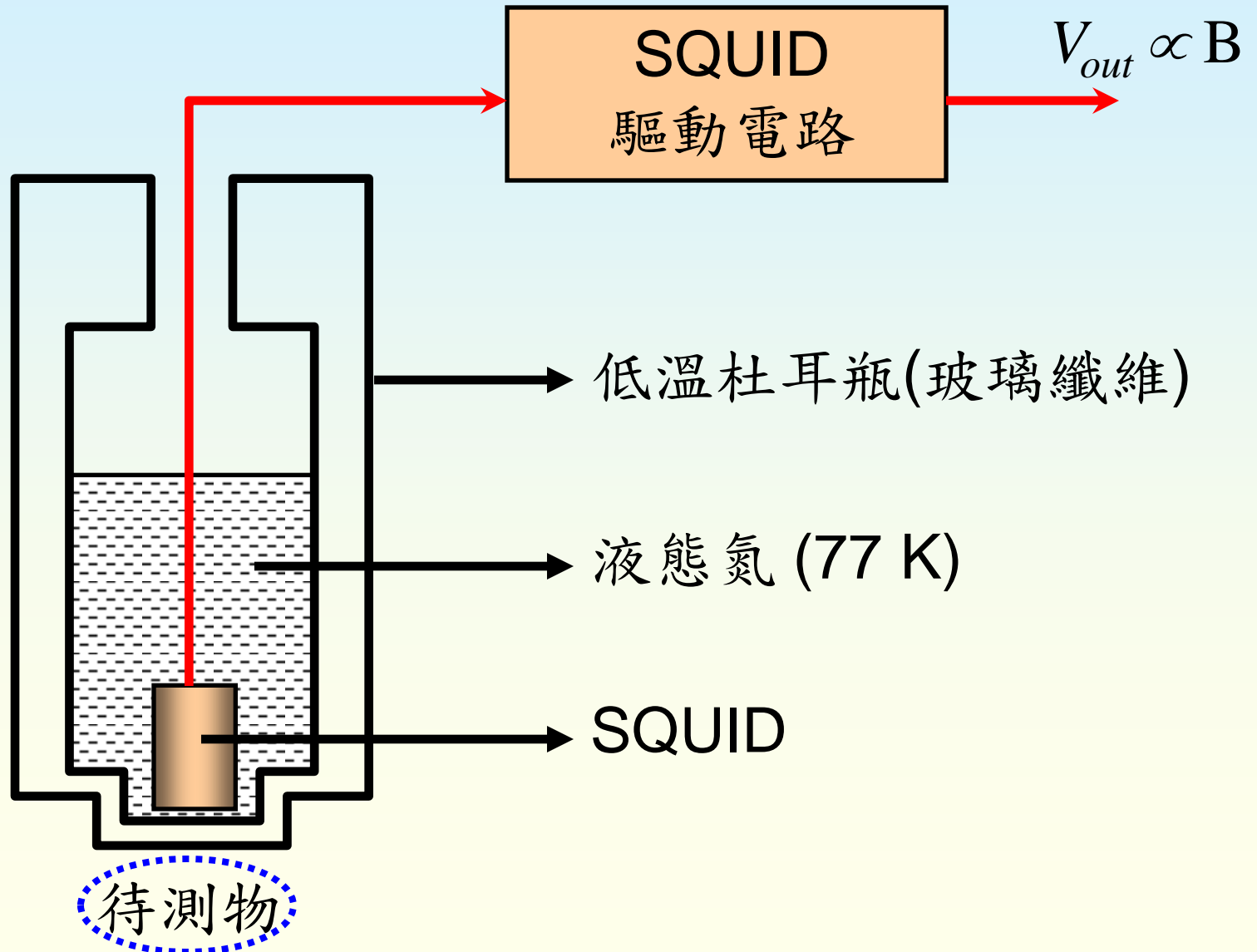


Flux-locked loop for dc SQUID

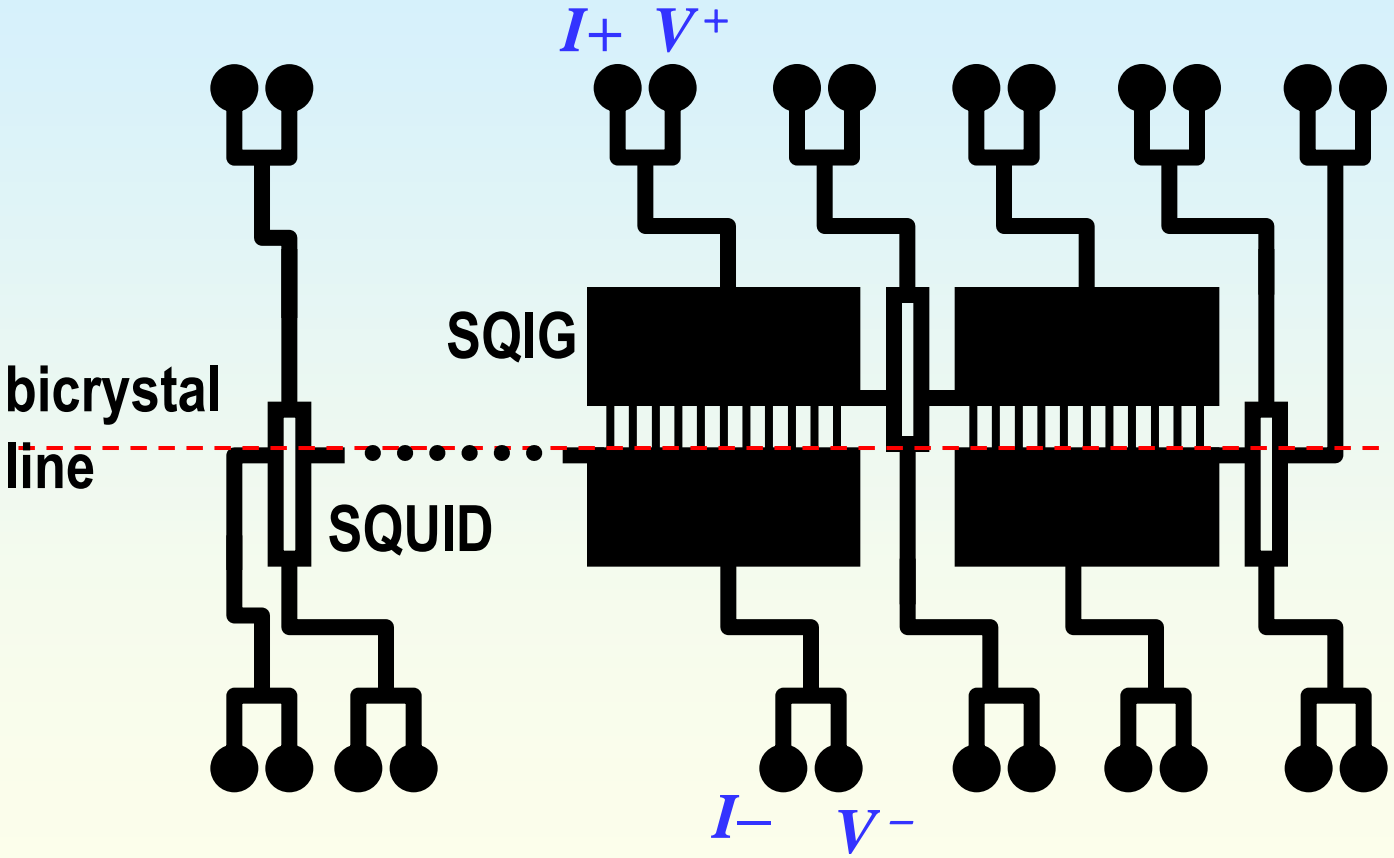


$$\rightarrow V_{out} \propto \Phi_{ext} : \quad V_{out} = (R_f / M_f) \Phi_{ext}$$

SQUID 磁場測量系統



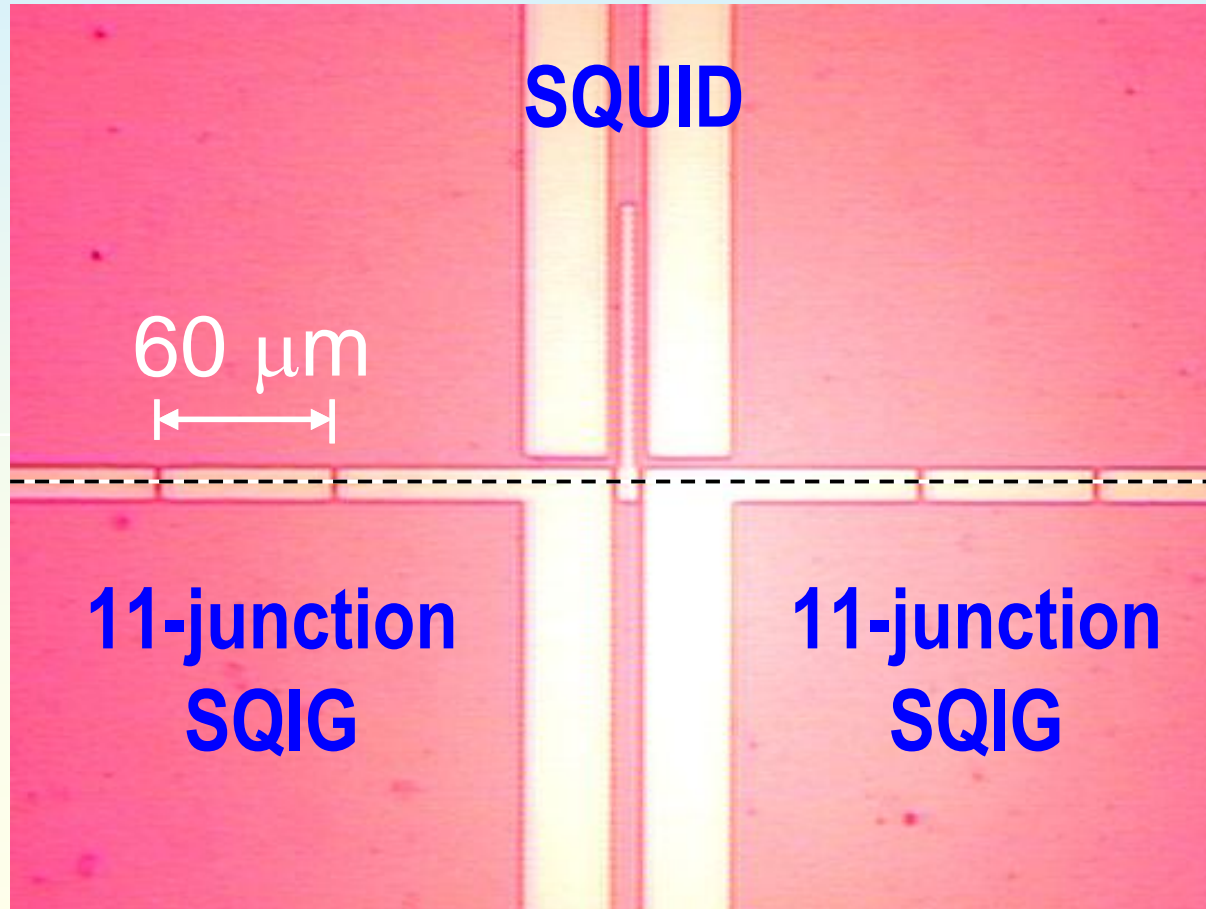
Superconducting Quantum Interference Grating (SQIG)



J. T. Jeng et al., IEEE Trans. Appl. Supercond. 17, 691 – 694 (2007).

SQIG and SQUID with bicrystal junctions

($\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ on a $12^\circ/12^\circ$ SrTiO_3 bicrystal substrate)



■ SQIG

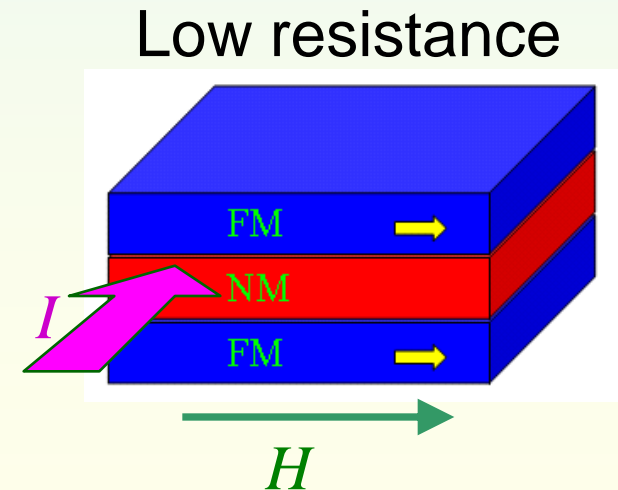
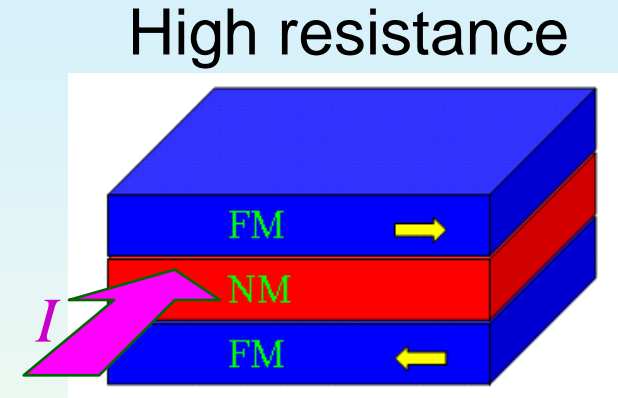
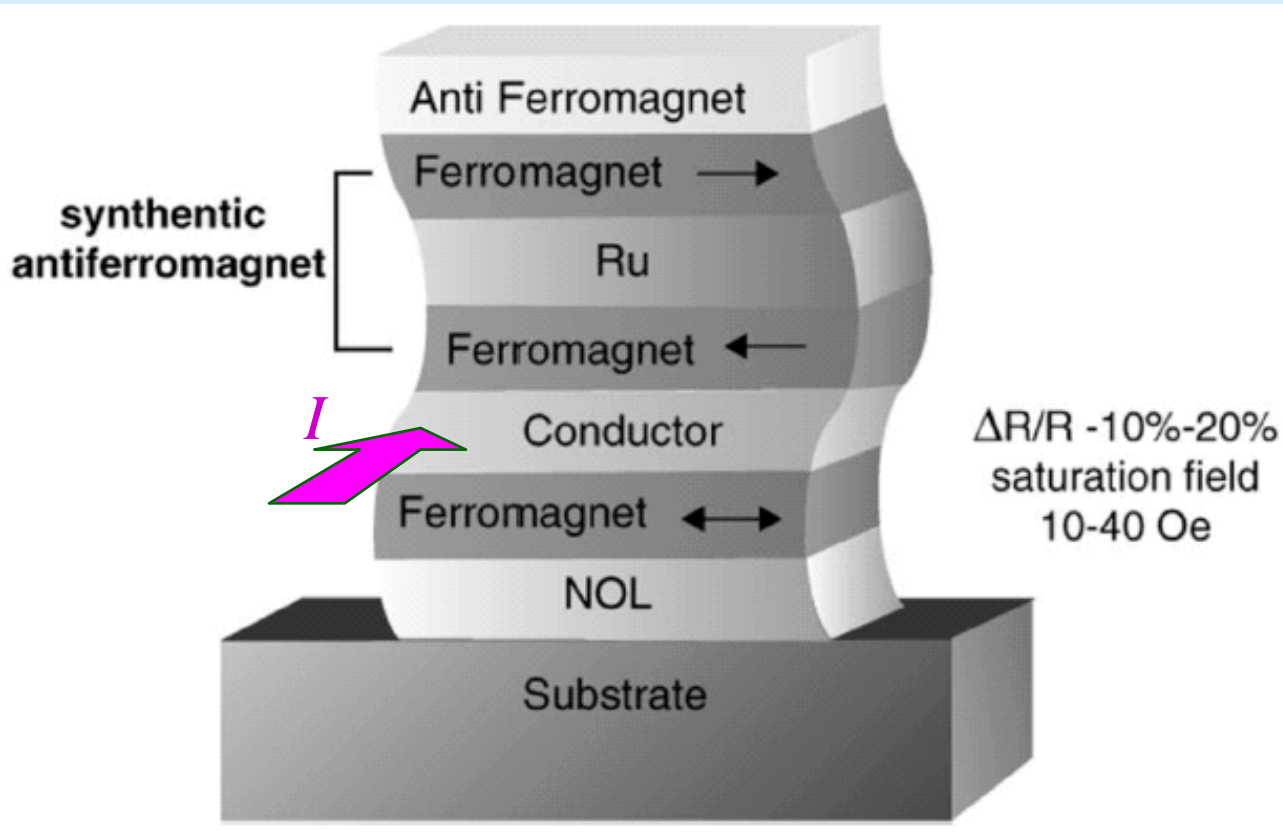
- 11 Josephson junctions in parallel (2 μm in width)
- $A_{\text{eff}} \approx 0.0083 \text{ mm}^2$

bicrystal boundary

■ SQUID

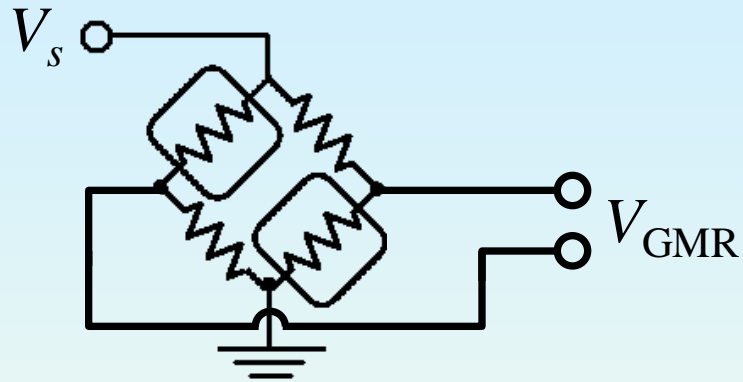
- two Josephson junctions in parallel (2 μm in width)
- $A_{\text{eff}} \approx 0.0015 \text{ mm}^2$

巨磁阻 (giant magneto resistance, GMR) 元件

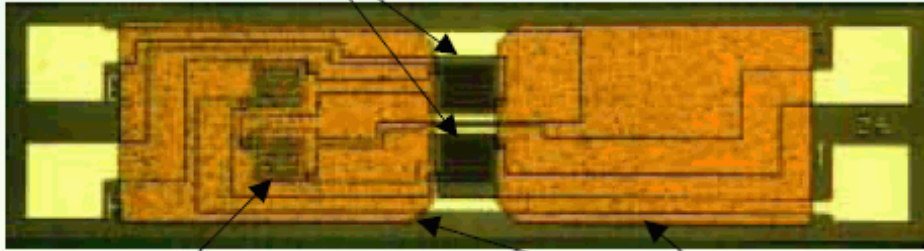


Jim Daughton, "Spin-Dependent Sensors",
Proc. IEEE, **91**, 681, (2003)

GMR磁場感測元件



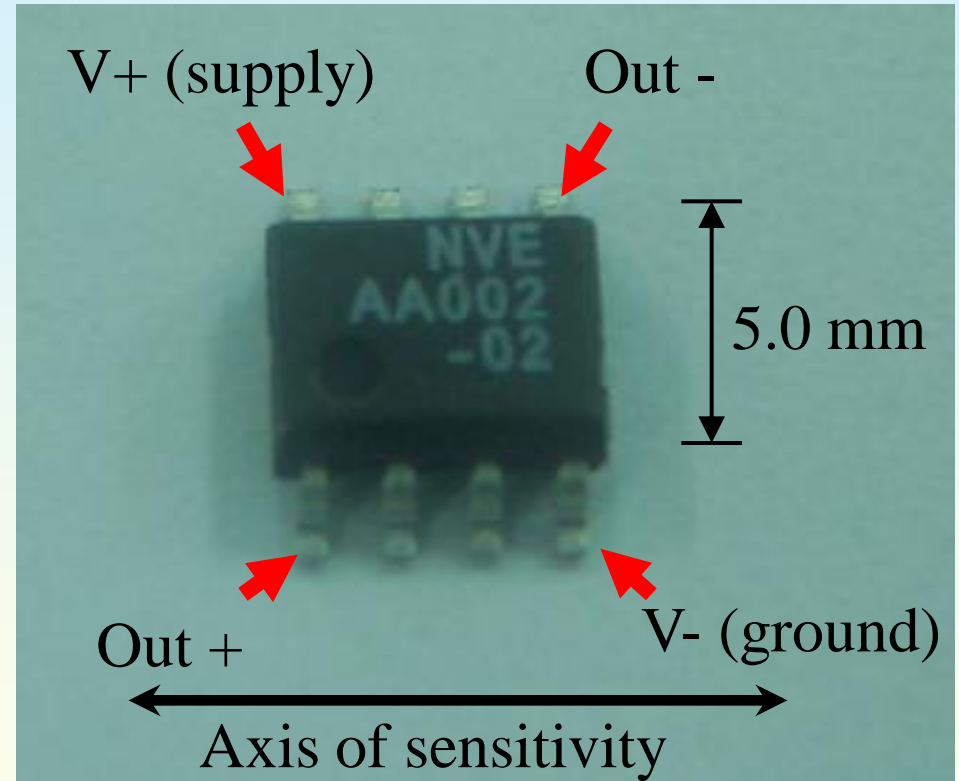
5K GMR Resistors
(Sensing Elements)



5K GMR Resistors
(Reference Elements)

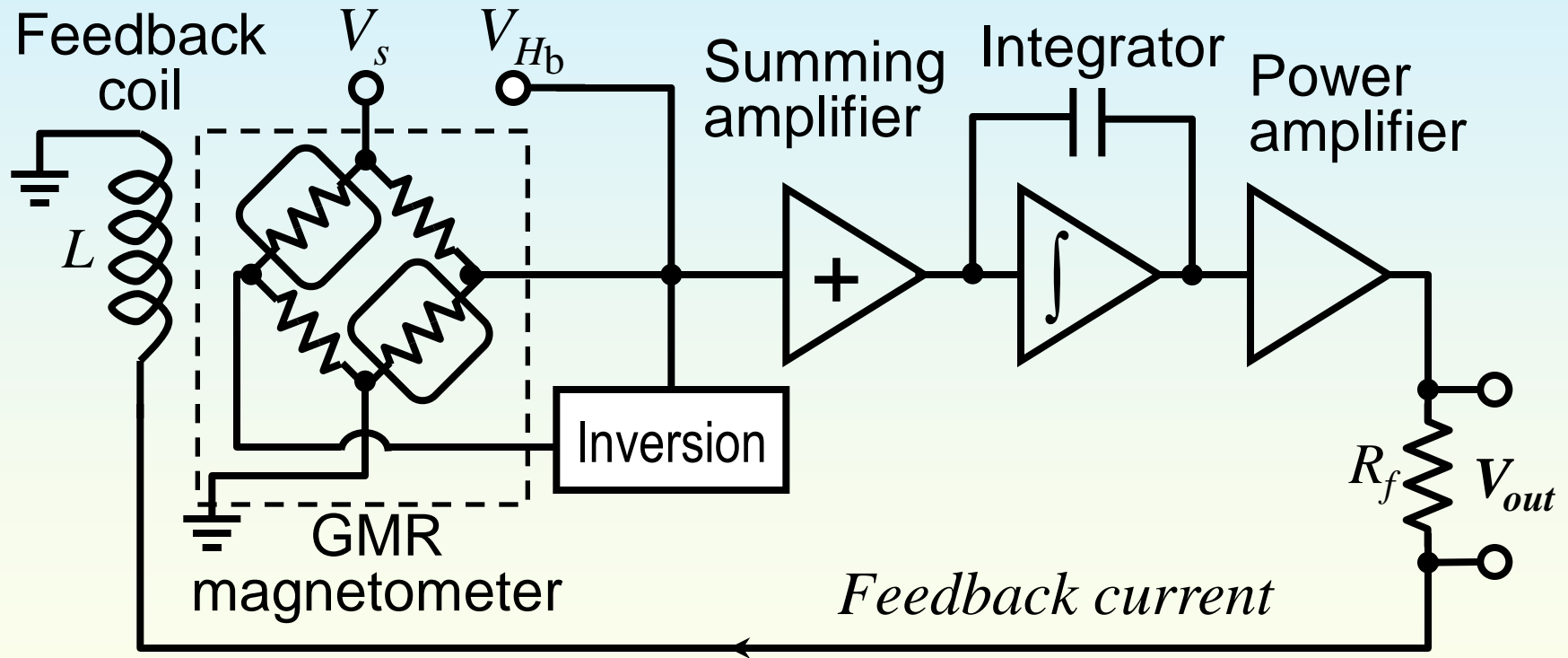
1.4 mm

Flux Concentrators



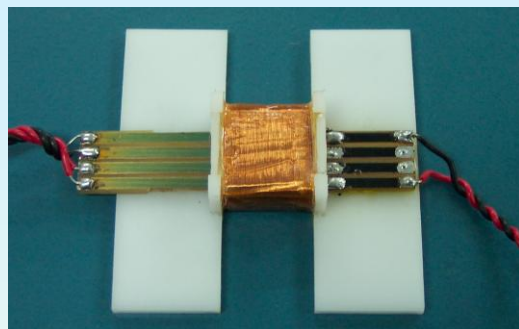
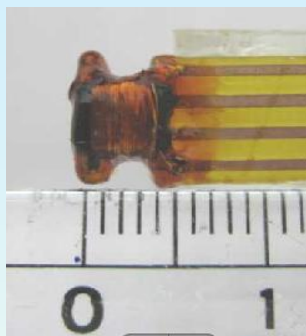
GMR sensor from Nonvolatile Electronics, <http://www.nve.com/>

GMR磁強計之磁場回授電路

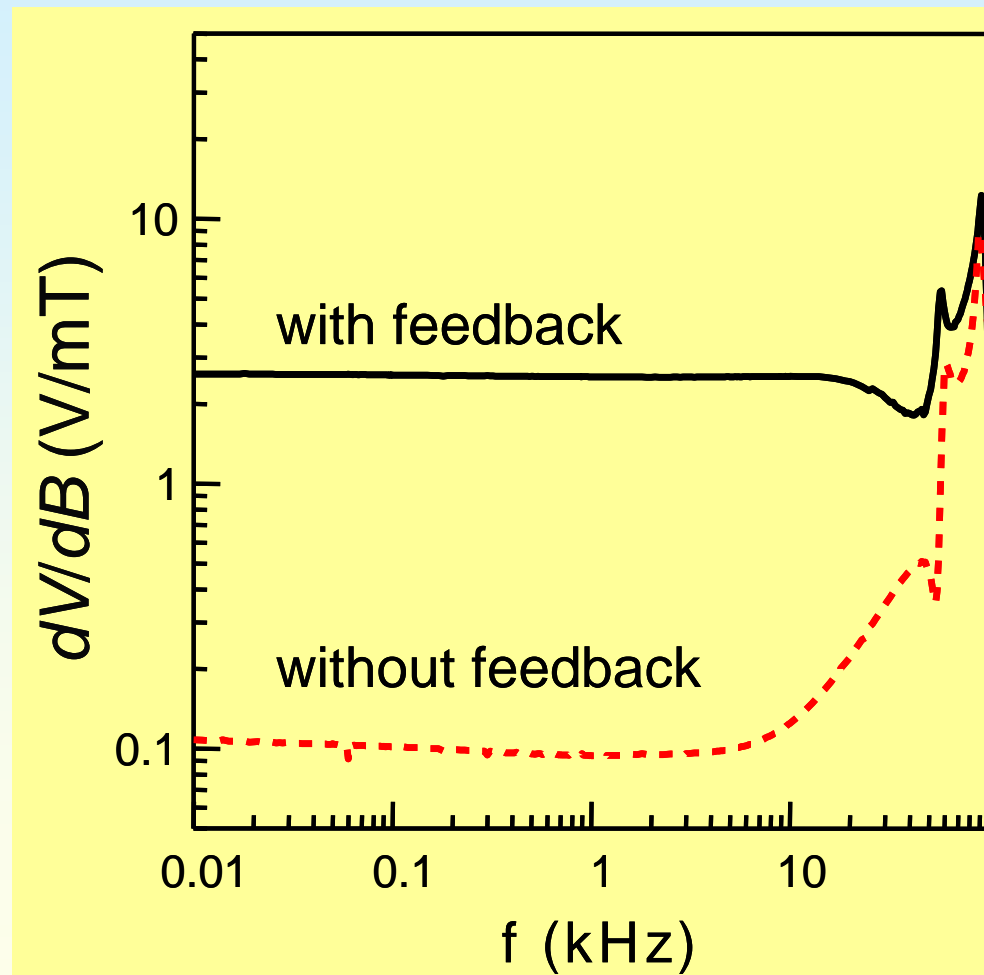


The GMR sensor is the AA-002 available from the Nonvolatile Electronics (NVE)

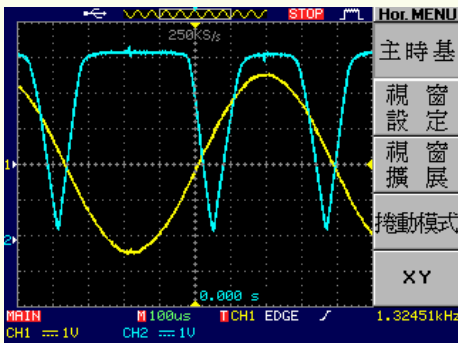
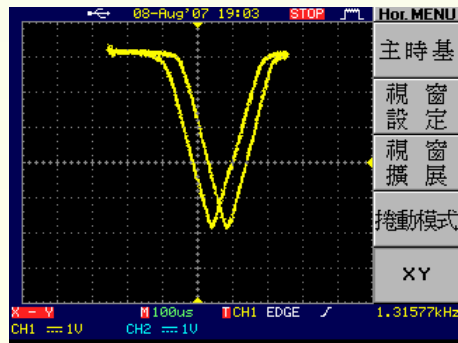
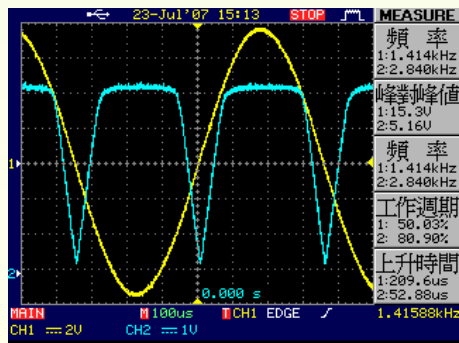
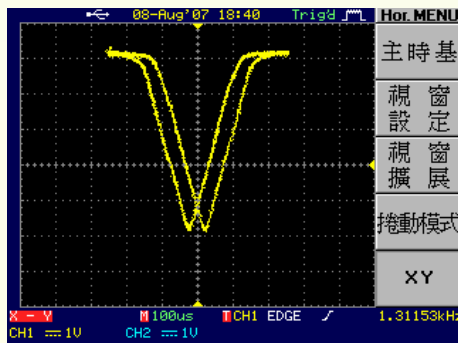
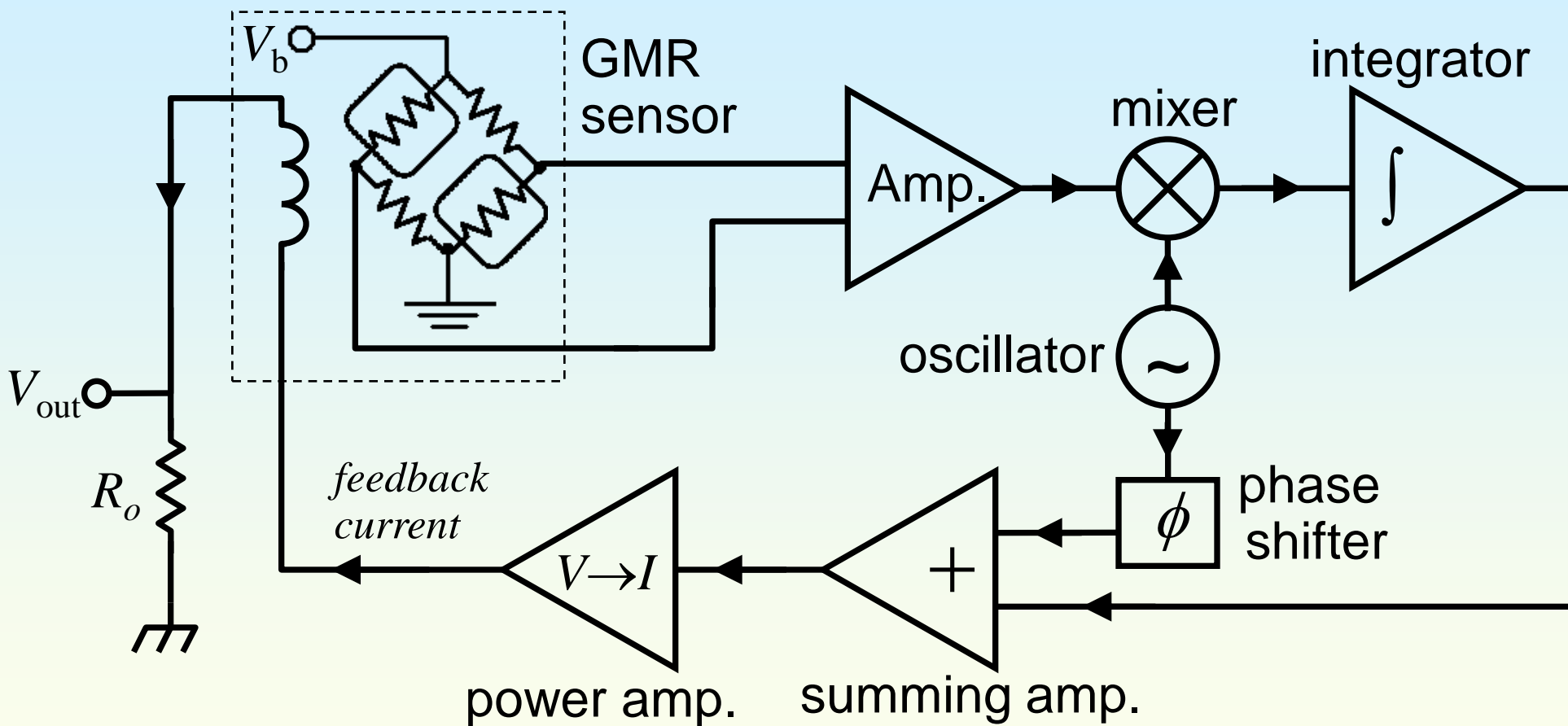
有磁場回授之GMR磁強計的特性



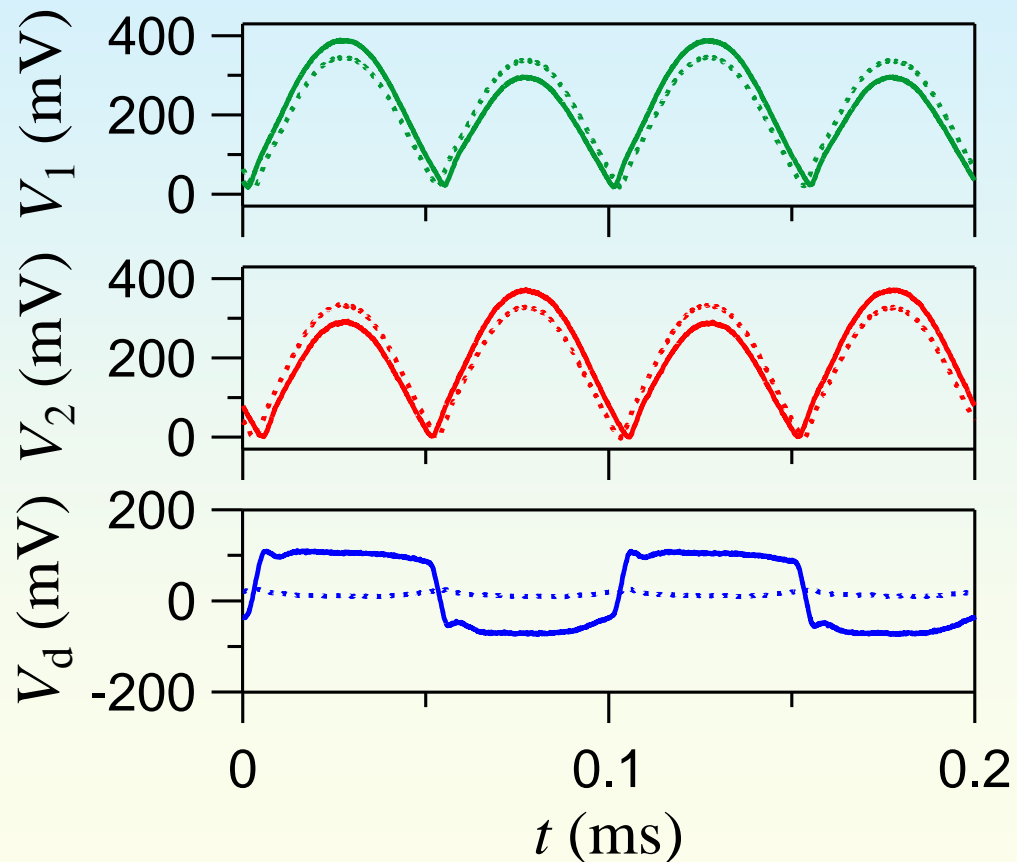
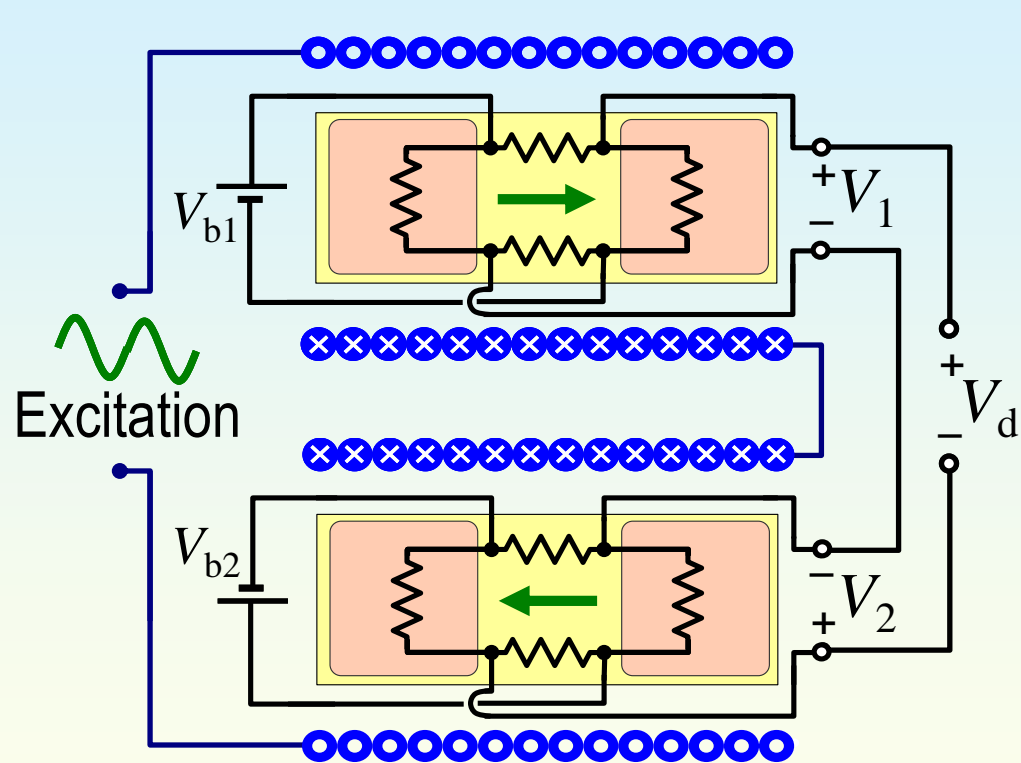
Sensor #	V_B (V/mT)	$S_B^{1/2}$ @1 kHz (nT/Hz ^{1/2})
GMR 1	2.80 ± 0.025	1.5
GMR 2	2.83 ± 0.028	1.8
GMR 3	2.94 ± 0.013	2.7



交流驅動之GMR磁強計電路



雙電橋巨磁阻感測器 (dual-bridge GMR sensor)



磁穿隧接面(magnetic tunneling junction, MTJ)

Ag (wiring)

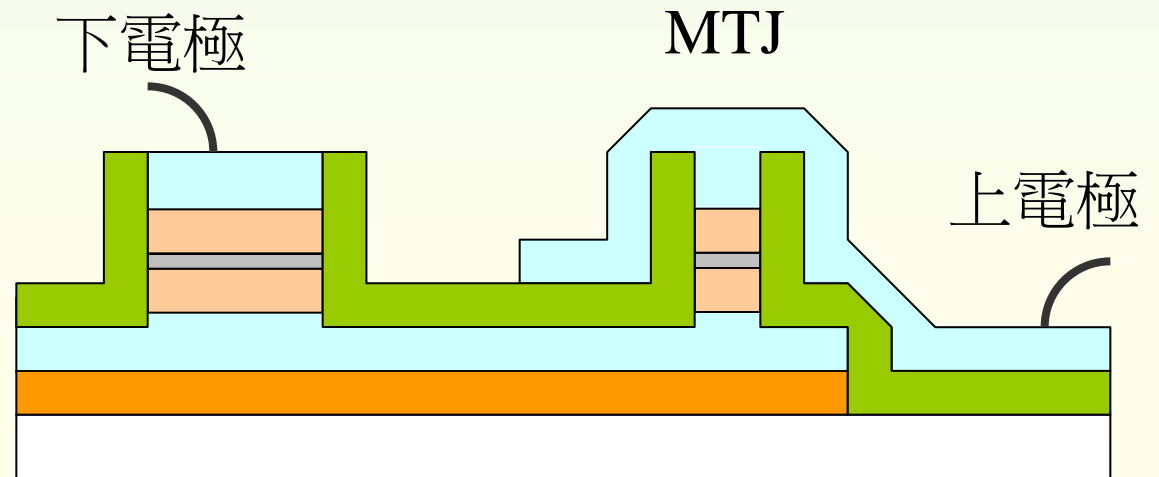
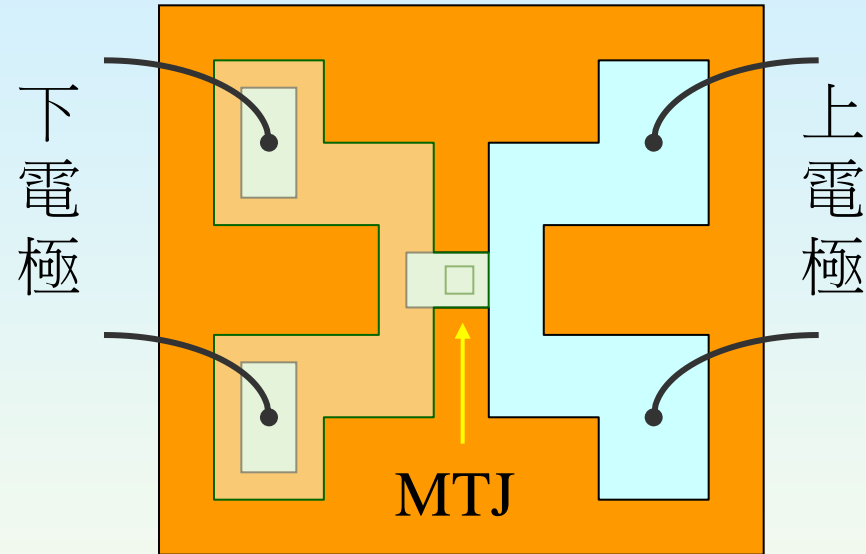
Co-Fe

AlO_x

Ni-Fe

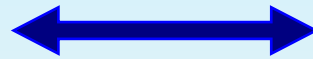
Ti (seed layer)

Si substrate

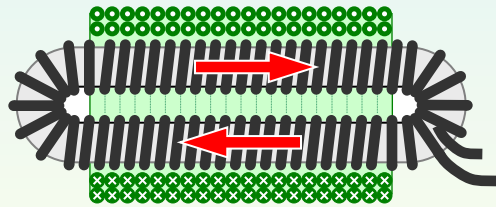


通量閘(fluxgate)

感測方向

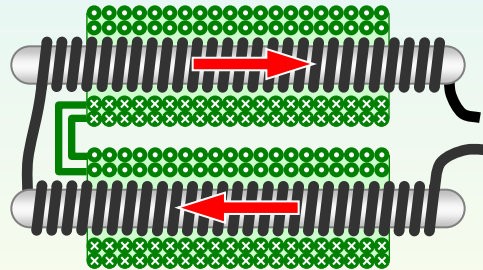


sensing direction



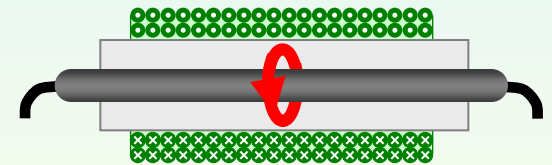
Parallel
(racetrack)

環型(跑道型)



Parallel
(rod core)

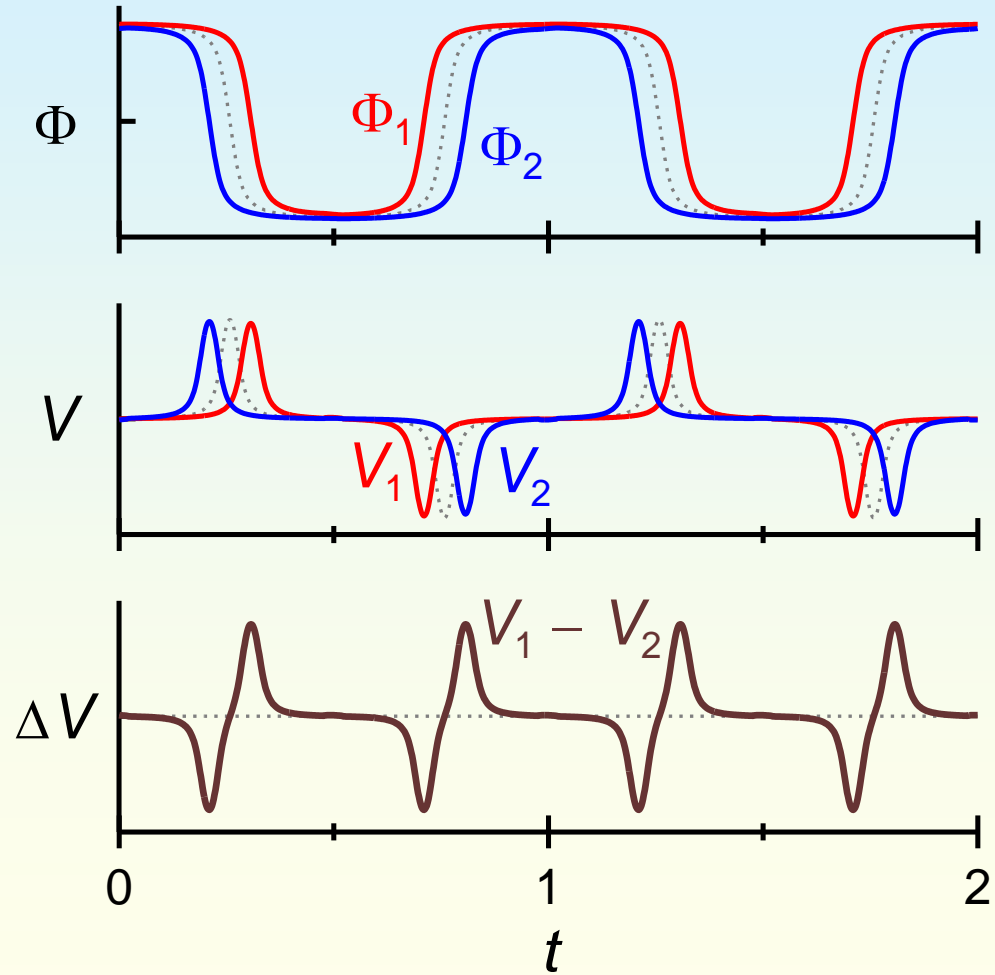
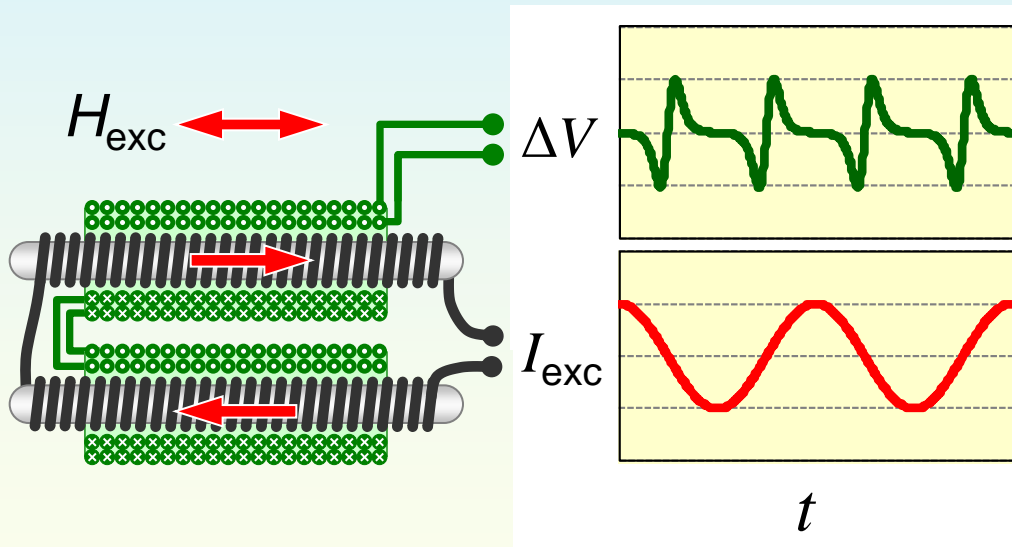
棒型



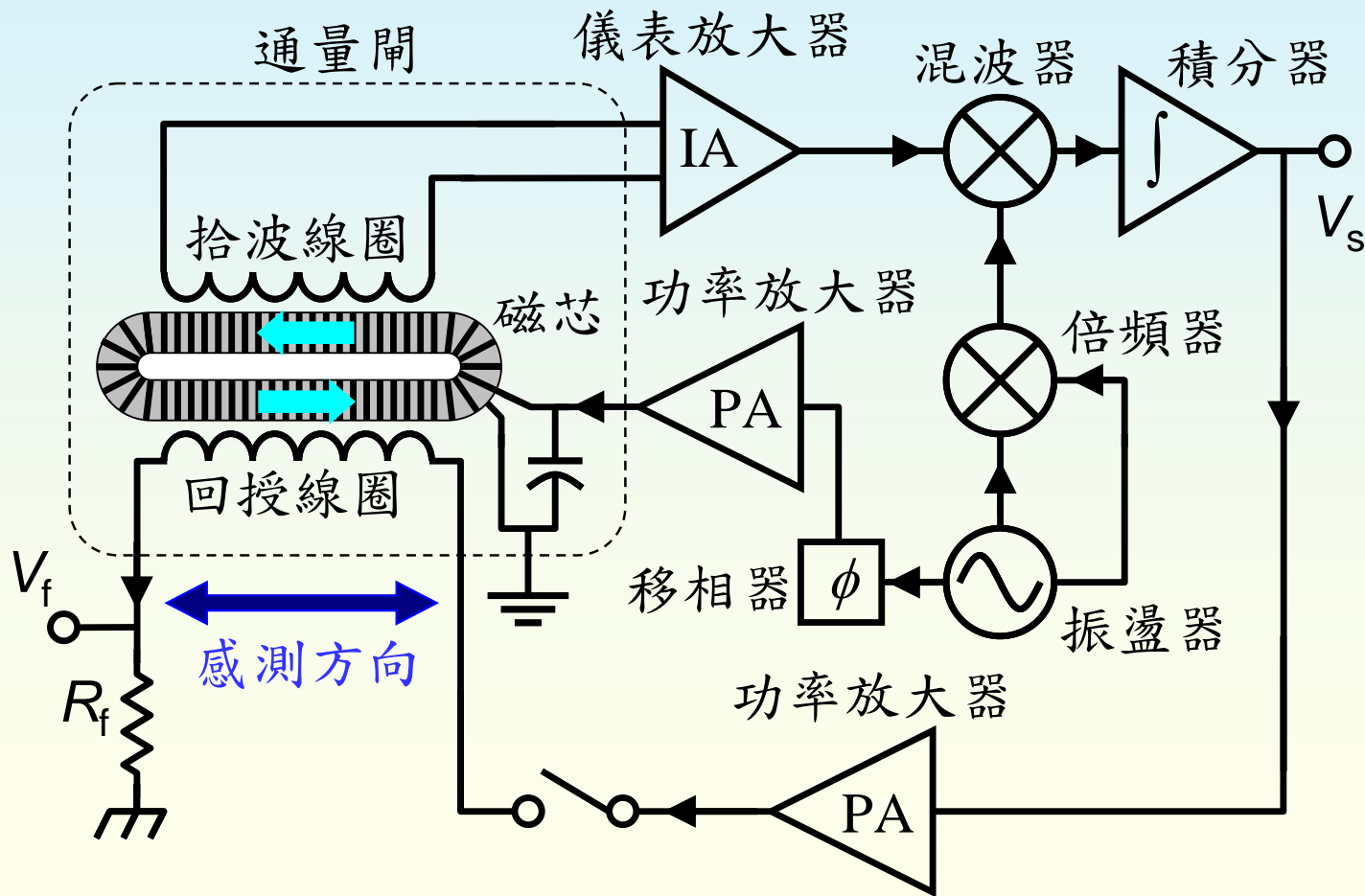
Orthogonal
(wire core)

正交型

通量閘(fluxgate)原理



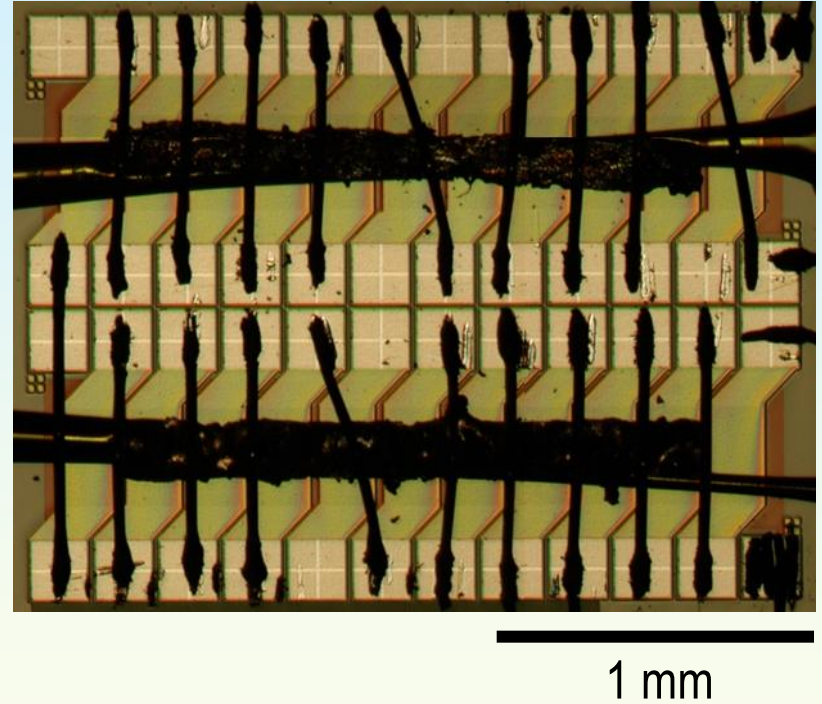
通量閘驅動電路：二次諧波偵測



微通量閘 (microfluxgates)



繞線型微通量閘^[1]



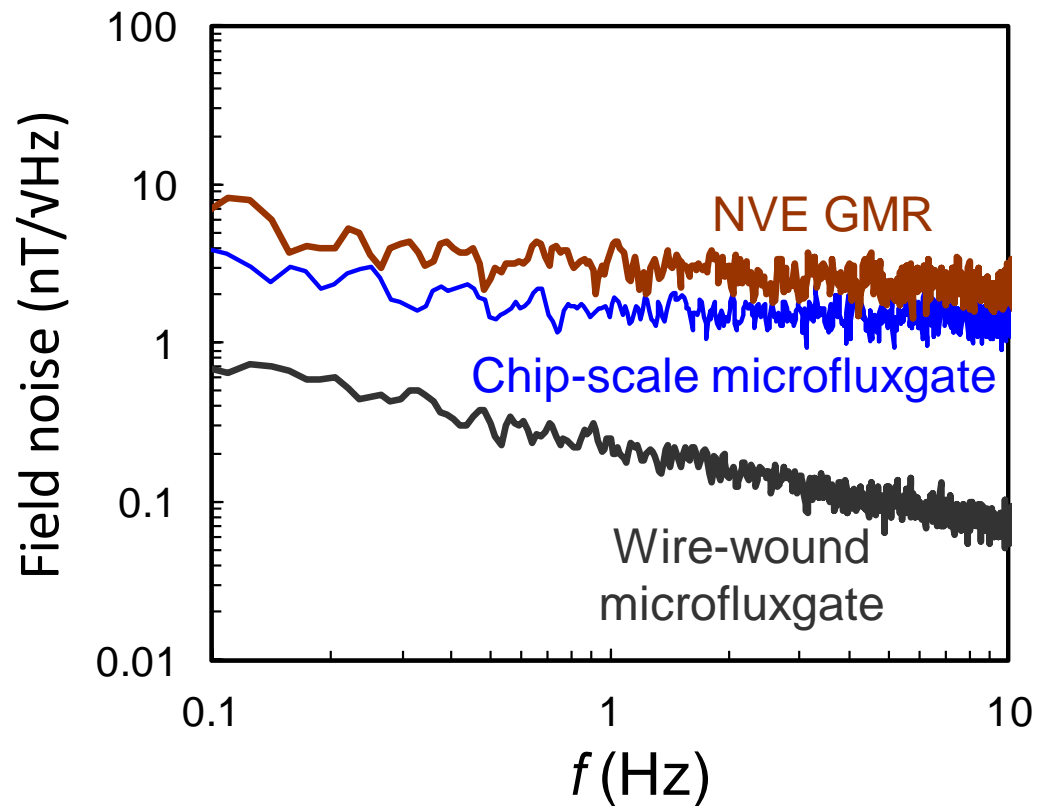
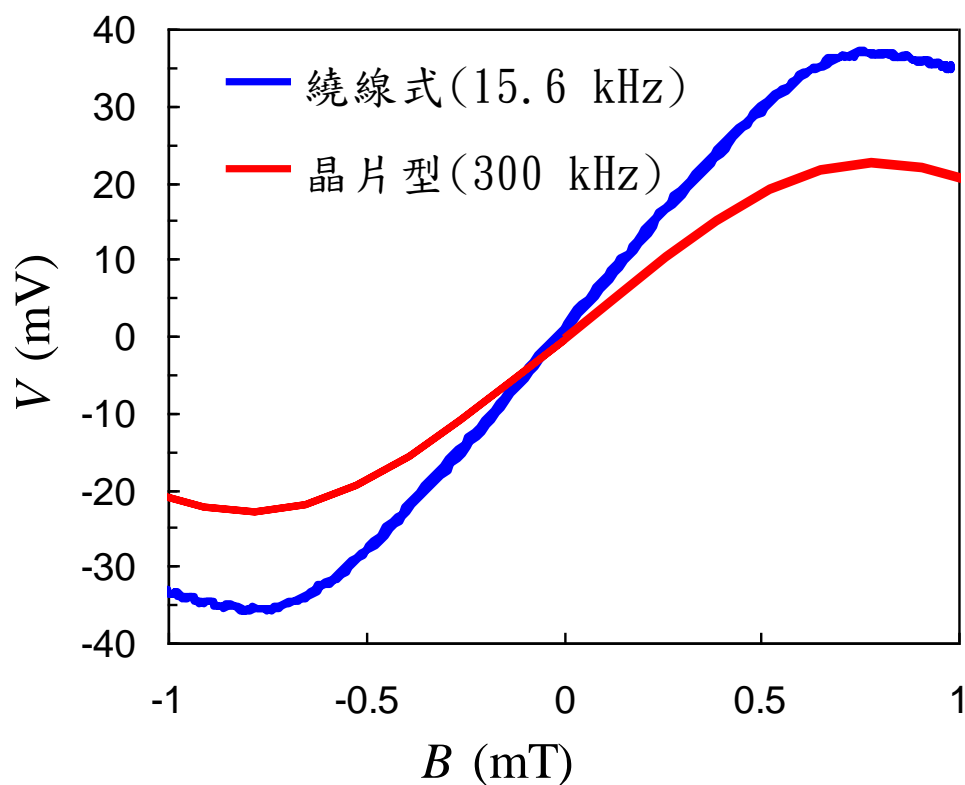
晶片型微通量閘^[2]

(TSMC CMOS-MEMS 0.35 μ m)

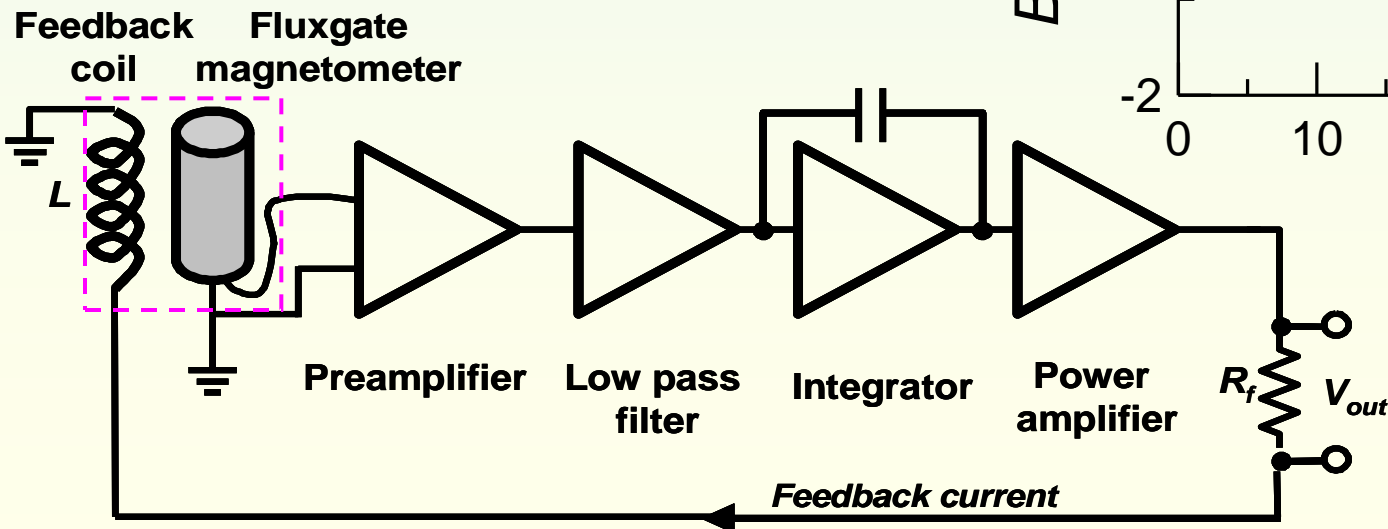
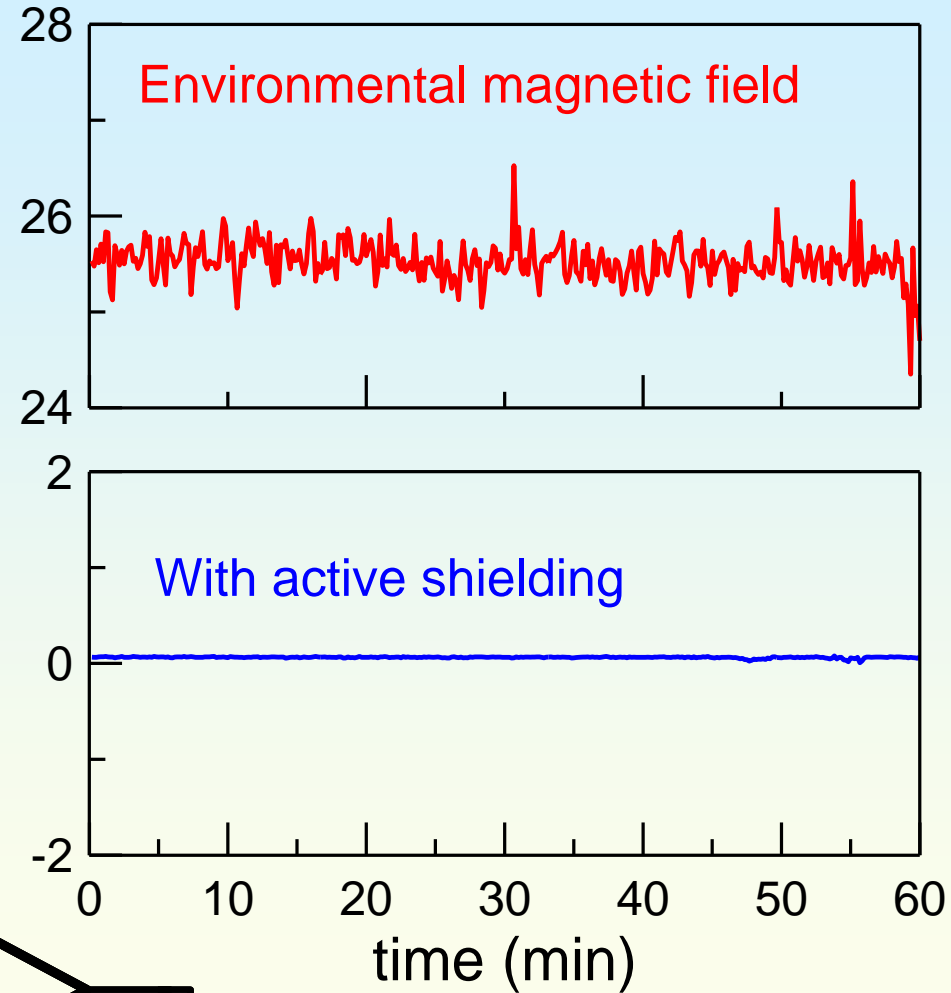
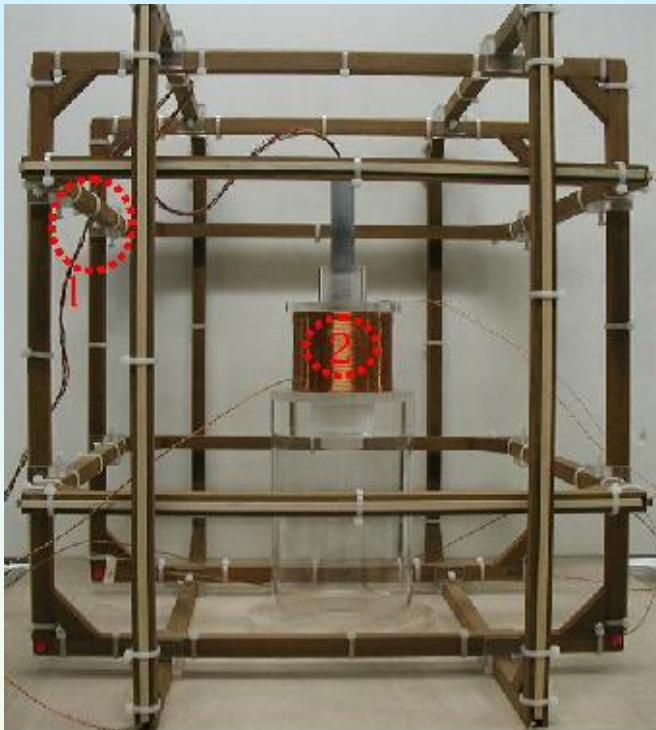
[1] J.T. Jeng, J.H. Chen, and C.C. Lu, IEEE Transactions on Magnetics. 48, pp.3696-3699 (2012)

[2] C.C. Lu, Y.T. Liu, F.Y. Jhao, and J.T. Jeng, Sensors and Actuators A 179, pp. 39-43 (2012).

微通量閘特性(characteristics of microfluxgates)



通量閘應用：主動式磁屏蔽 (Active Magnetic Shielding)



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◆磁感測器應用

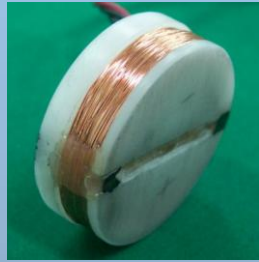
- 心臟磁場量測：SQUID
- 磁場圖掃描、磁源電流逆算：GMR
- 硬幣辨識：高頻渦電流偵測器

◆結語

利用「低頻」渦電流探頭偵測裂隙深度



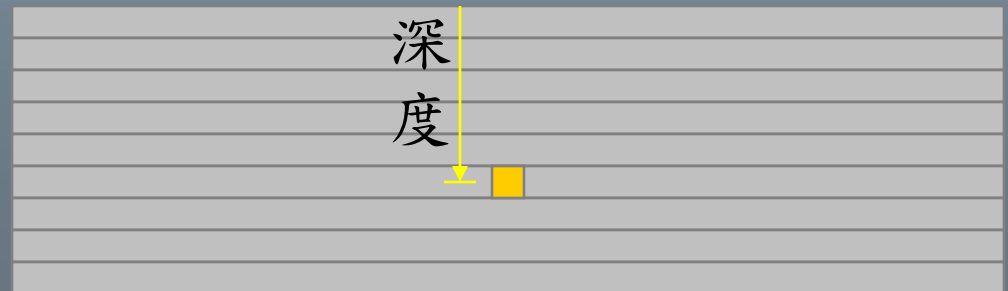
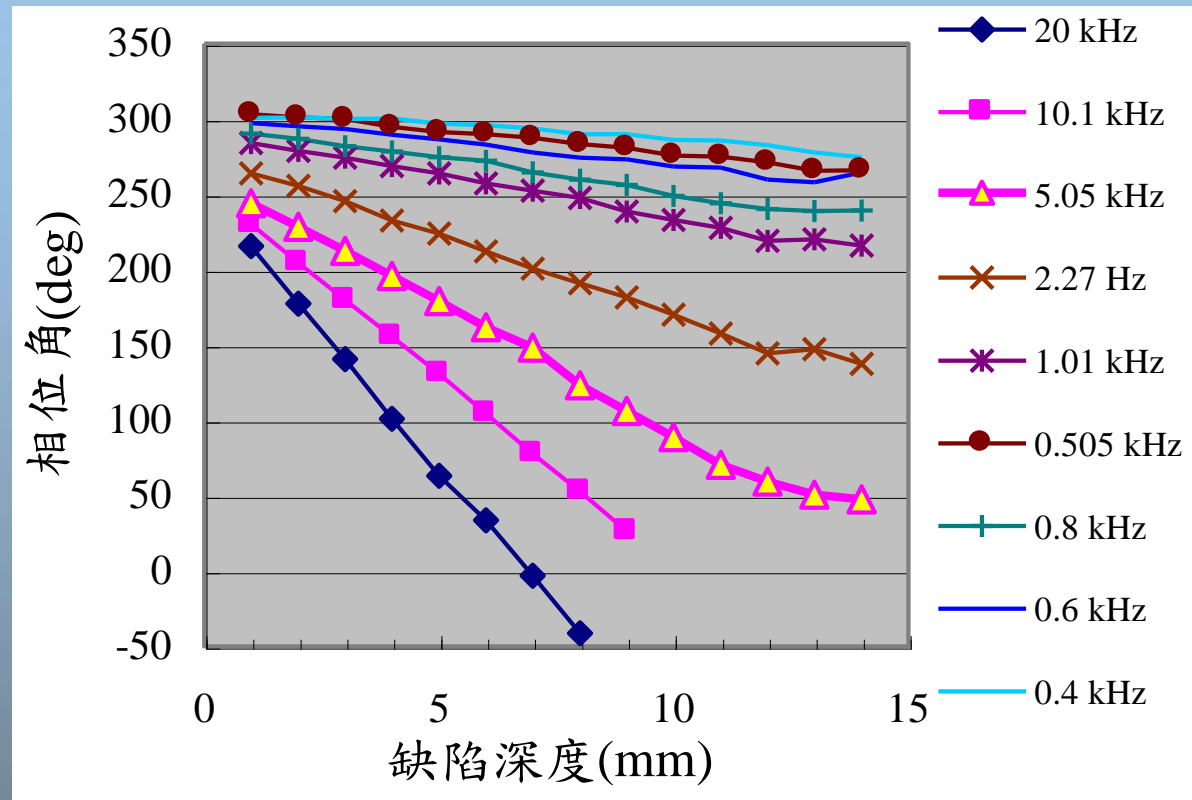
GMR



Induction coil

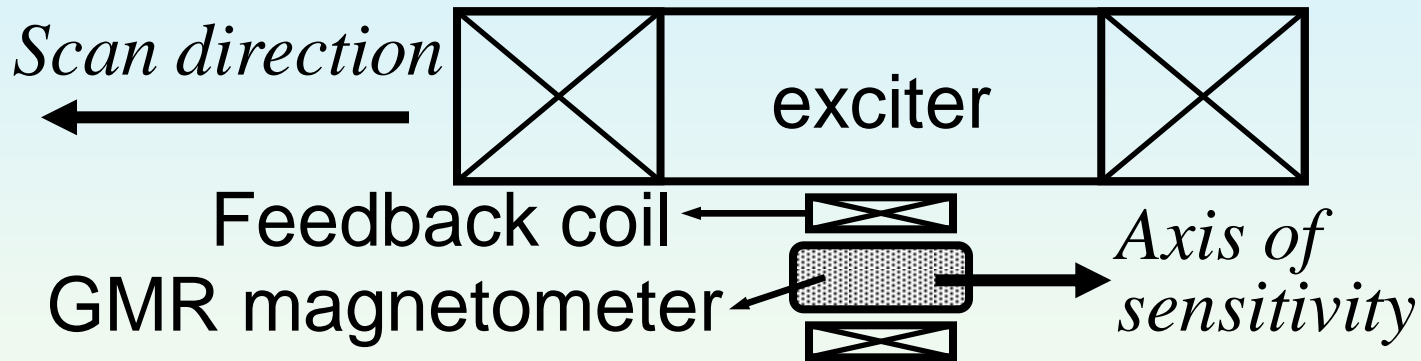


LF EC NDE system



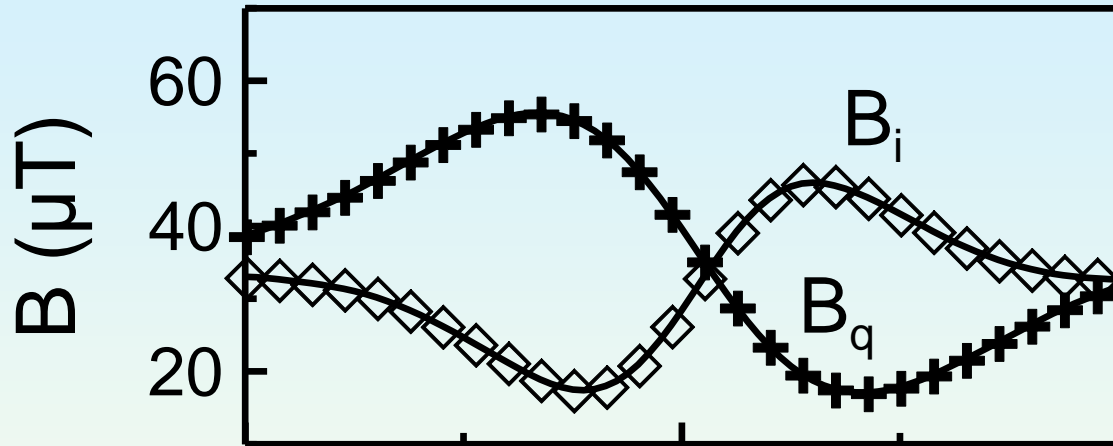
Laminated stainless steel 304

GMR-based Eddy-Current Probe



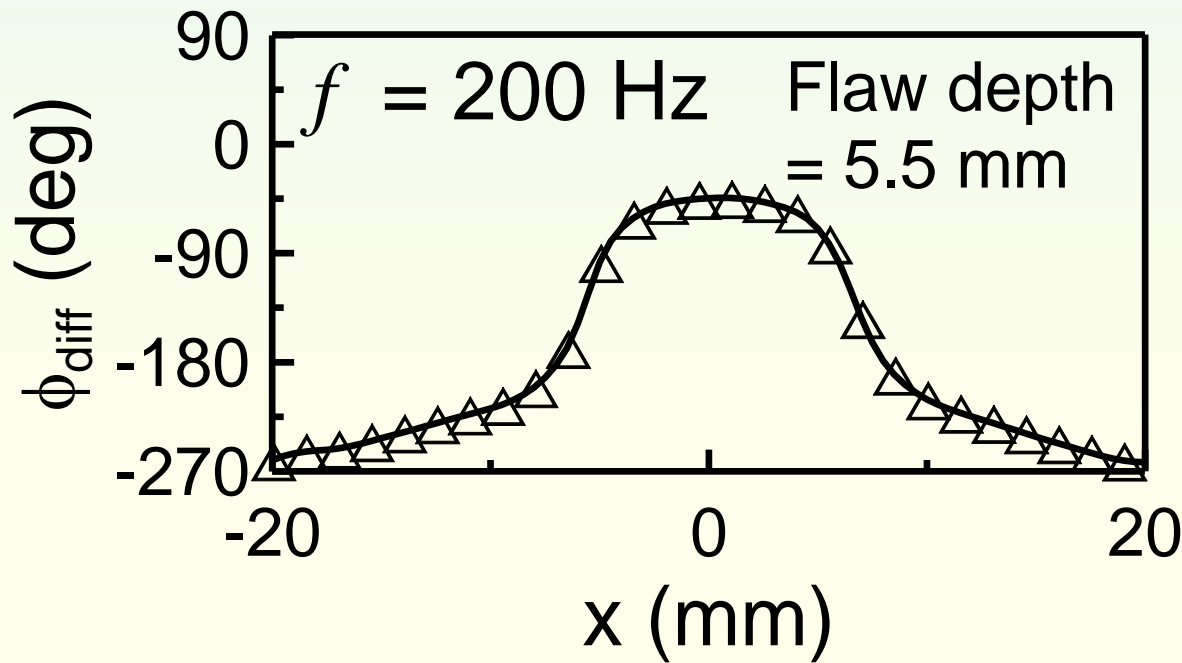
Aluminum sheets

Defect signal of a hidden crack in layered aluminum sheets



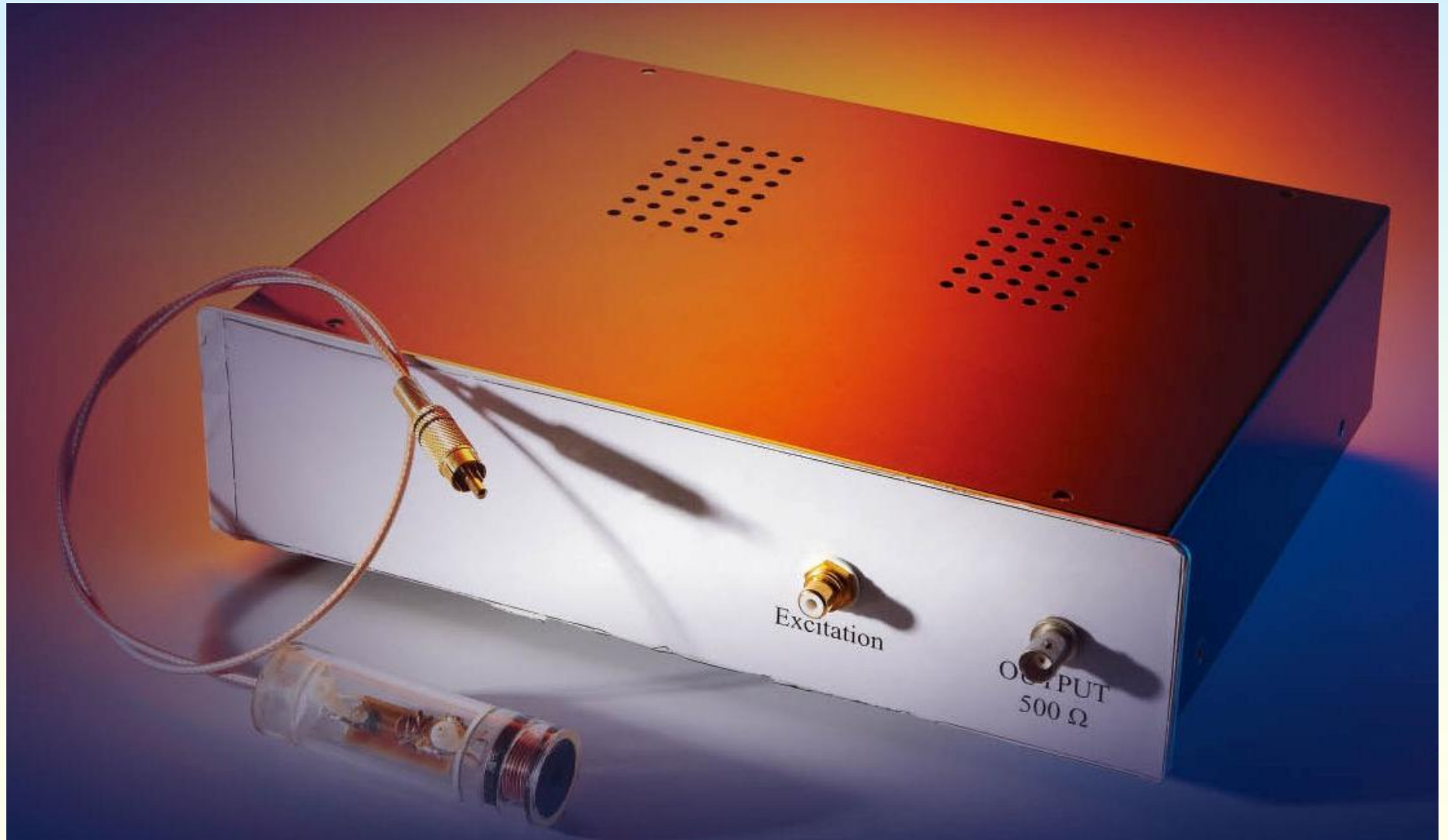
Signal-to-noise ratio:
>104 dB at 200 Hz

→ comparable to
HTS-SQUID-based
eddy-current probe



Spatial resolution
limited by the size of
magnetometer
(IC package and
feedback coil)

渦電流位移感測器



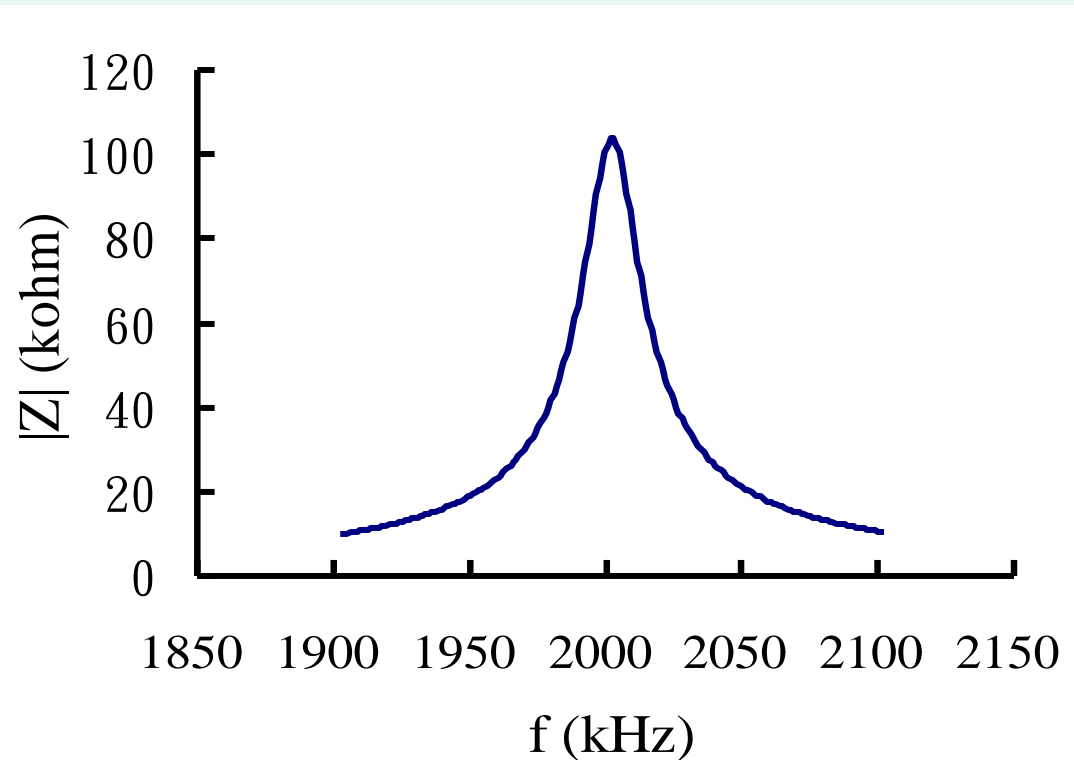
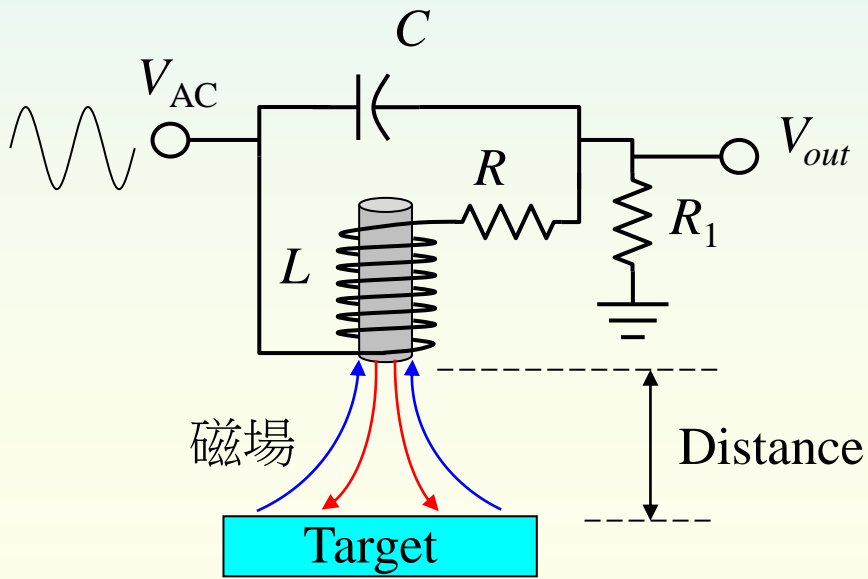
「高頻」渦電流偵測器

共振角頻率

$$\omega_c = \frac{1}{\sqrt{LC}}$$

總阻抗

$$|Z| = \frac{R \sqrt{1 + \omega^2 [RC - (\frac{L}{R})(1 - \omega^2 LC)]^2}}{(1 - \omega^2 LC)^2 + (\omega RC)^2}$$

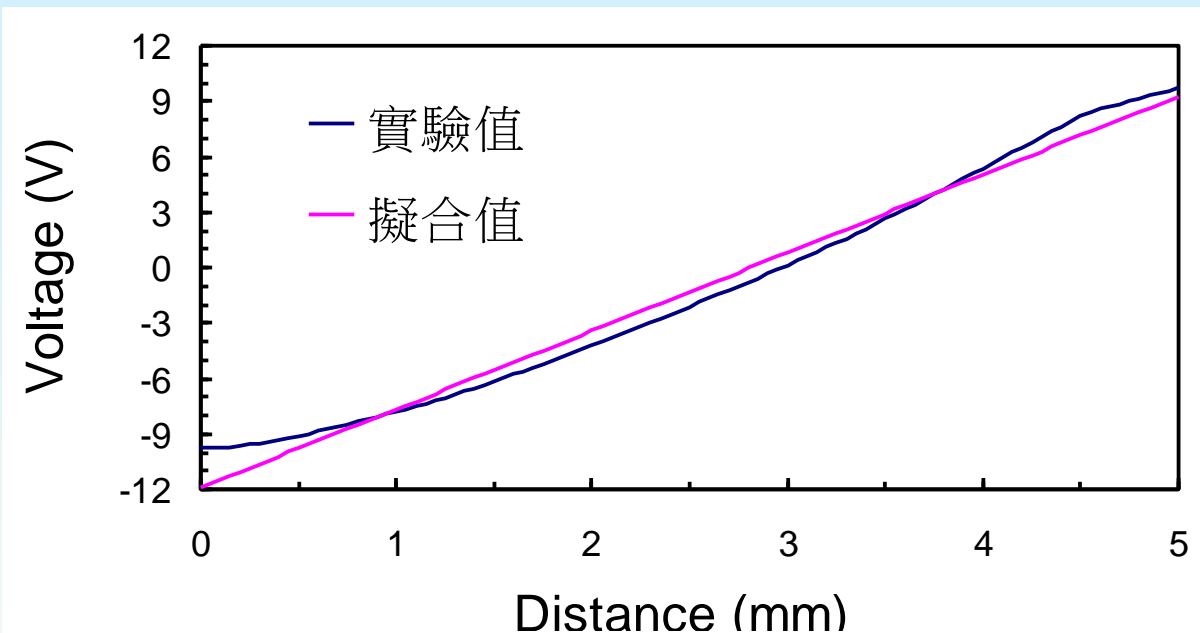


渦電流位移偵測器(目標物: SS304 $\phi 100$ mm \times 19 mm)

目標物距離 0~5 mm

非線性度 = 10.8%

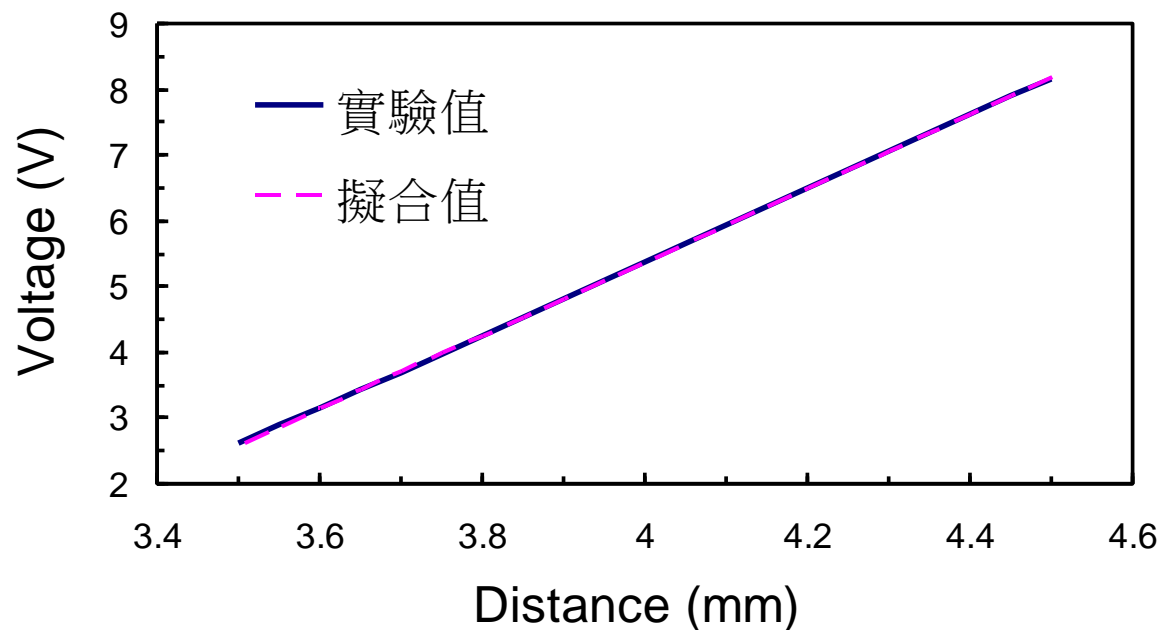
平均靈敏度 = 4.23 V/mm



目標物距離 3.5~4.5 mm

非線性度 = 0.71 %

平均靈敏度 = 5.59 V/mm



微磁技術實驗室-研究主題

◆磁強計 (magnetometers)

- 超導量子干涉元件 (Superconducting Quantum Interference Devices, SQUID)
- 巨磁阻 (giant magnetoresistance, GMR)
- 通量閘 (fluxgate)

◆渦電流偵測器 (eddy-current detectors)

- 低頻(10 Hz~10 kHz)：渦電流缺陷偵測器
- 高頻(10 kHz~10 MHz)：非接觸式距離偵測器

◆磁感測器應用

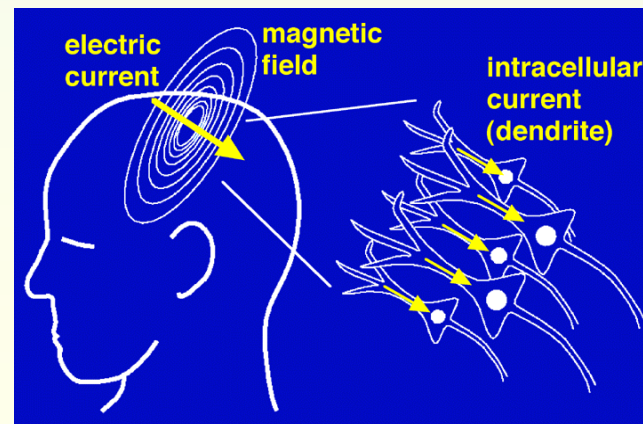
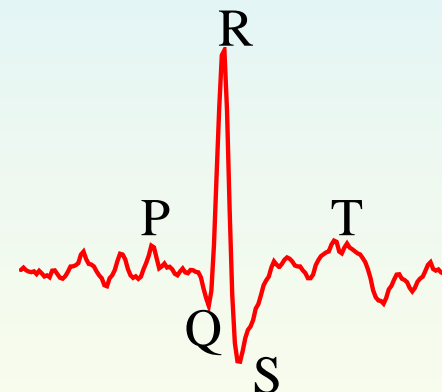
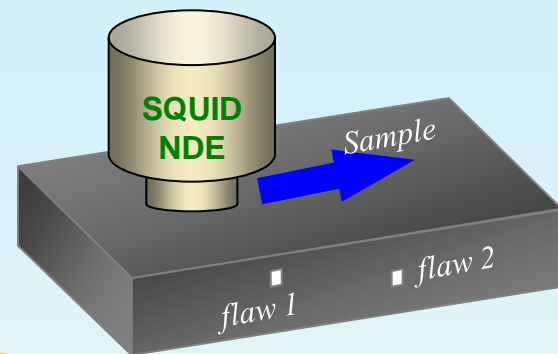
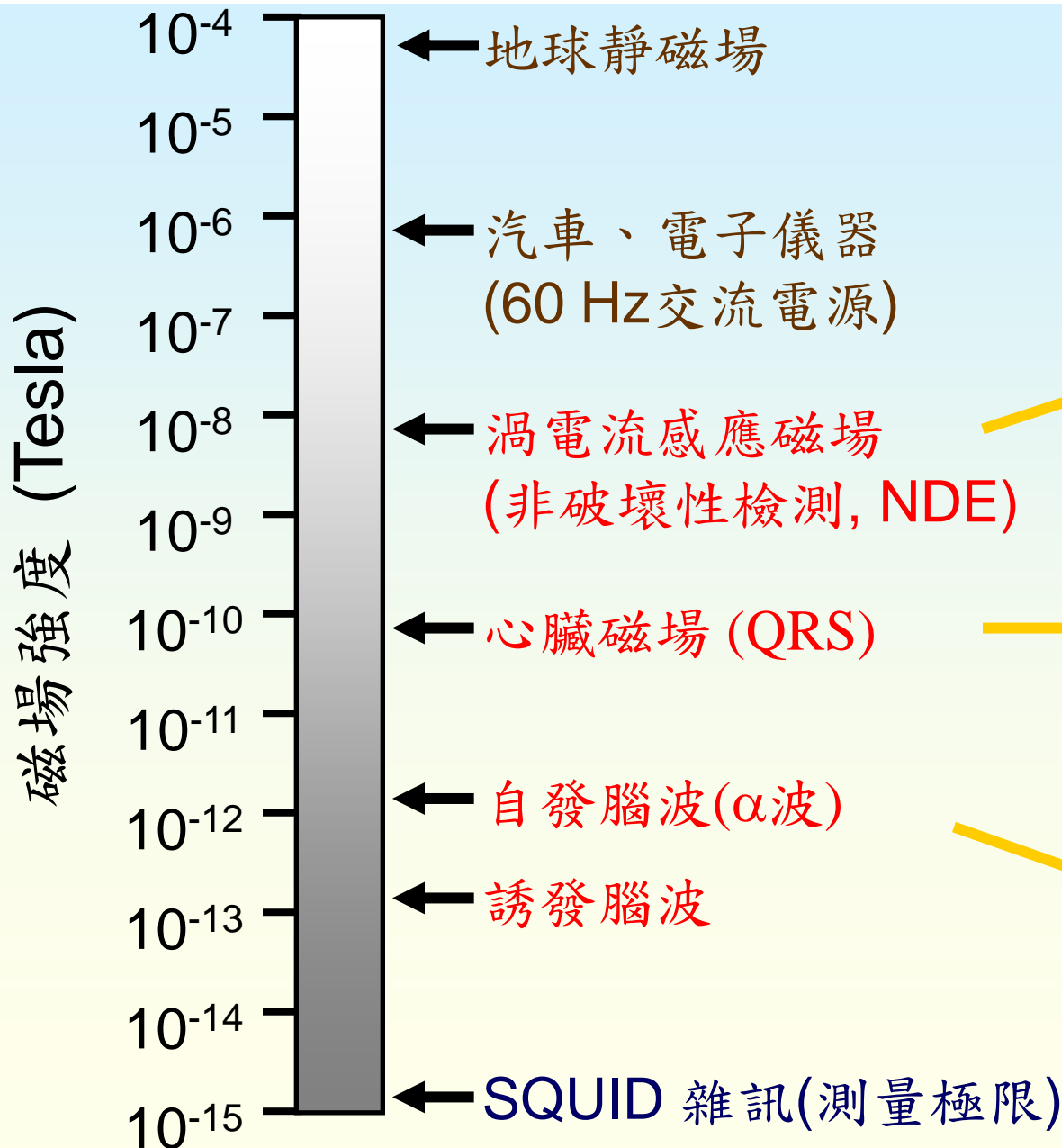
- 心臟磁場量測：SQUID
- 磁場圖掃描、磁源電流逆算：GMR
- 硬幣辨識：高頻渦電流偵測器

◆結語

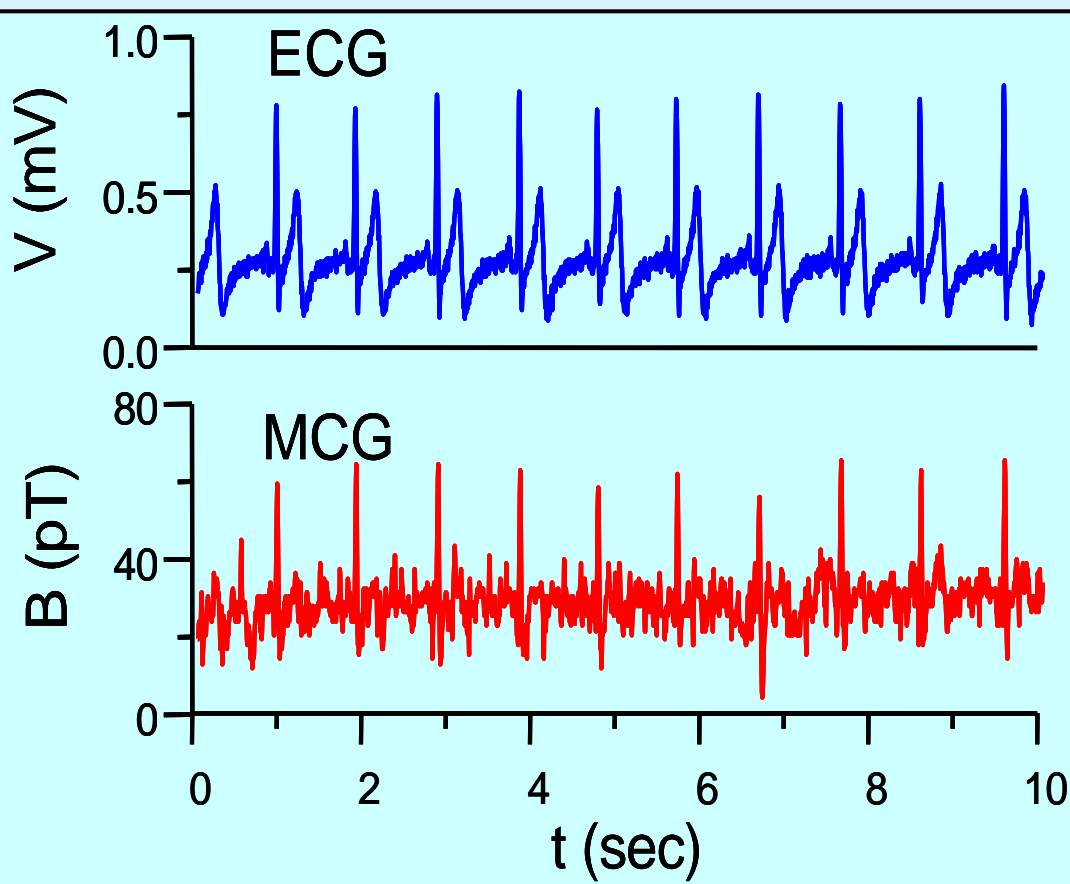
磁感測器的應用範圍

- ◆ Motion tracking (fluxgate)
- ◆ Aviation navigation (fluxgate)
- ◆ Electronic compass (fluxgate)
- ◆ Current sensing (Hall, GMR)
- ◆ Rotation sensing (Hall, GMR)
- ◆ Vehicle detection (AMR, GMR, fluxgate)
- ◆ Audio sensor (GMR)
- ◆ Eddy-current probe (GMR, fluxgate, SQUID)
- ◆ Micro-magnetic imaging (Hall, GMR, SQUID)
- ◆ Geophysical applications (fluxgate, SQUID)
- ◆ Active Magnetic Shielding (fluxgate, SQUID)
- ◆ Active biomagnetic fields (SQUID):
 - MagnetoCardioGram (MCG, 心磁圖)
 - MagnetoEncephaloGram (MEG, 腦磁圖)
- ◆ Low-field magnetic resonance imaging (SQUID)

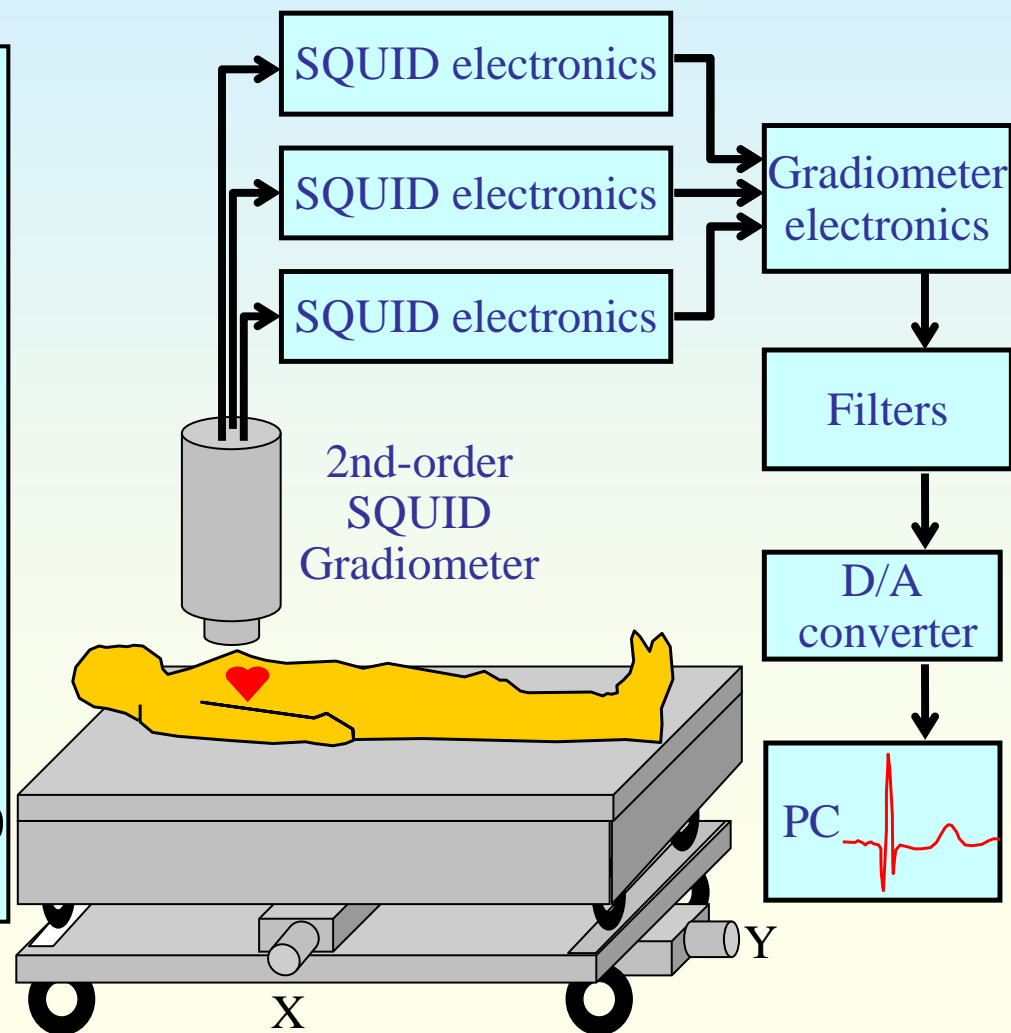
微小磁場強度表



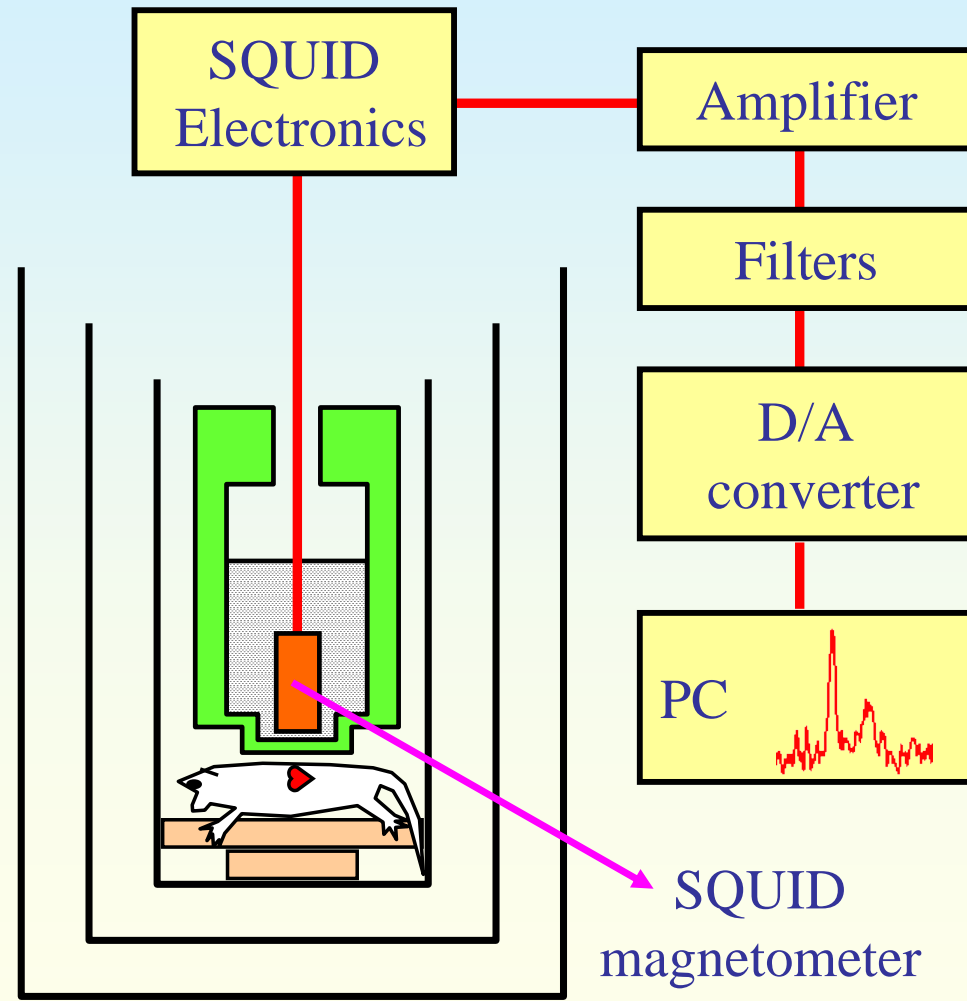
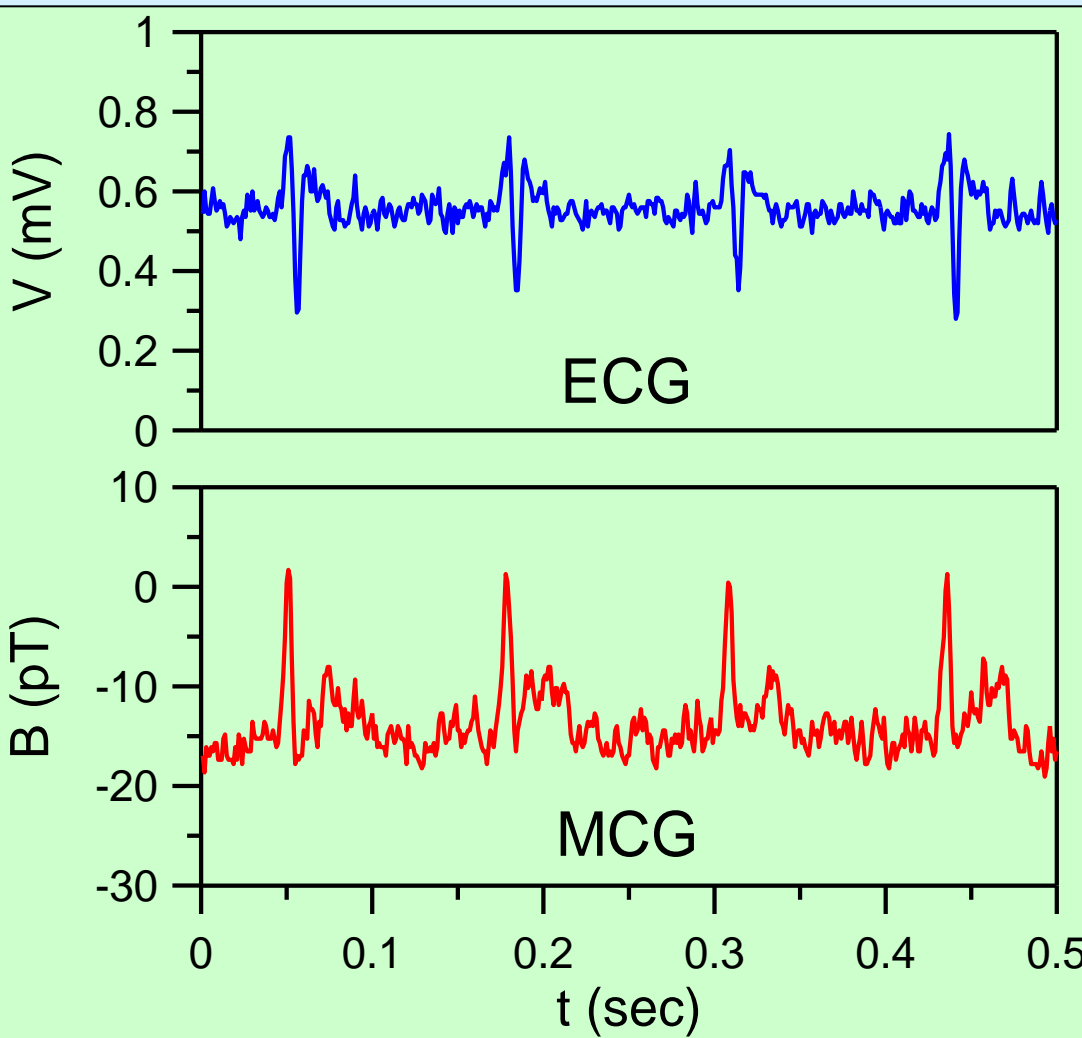
Magnetocardiogram (MCG, 心磁圖) in an unshielded environment



IEEE Tran. Appl. Supercond. 13, 360 (2003)

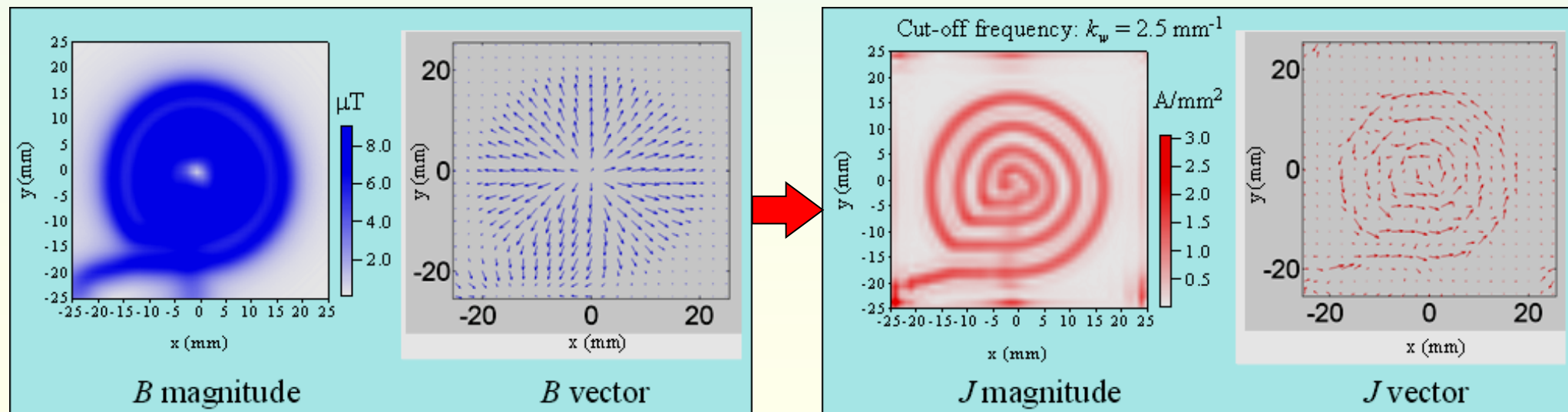
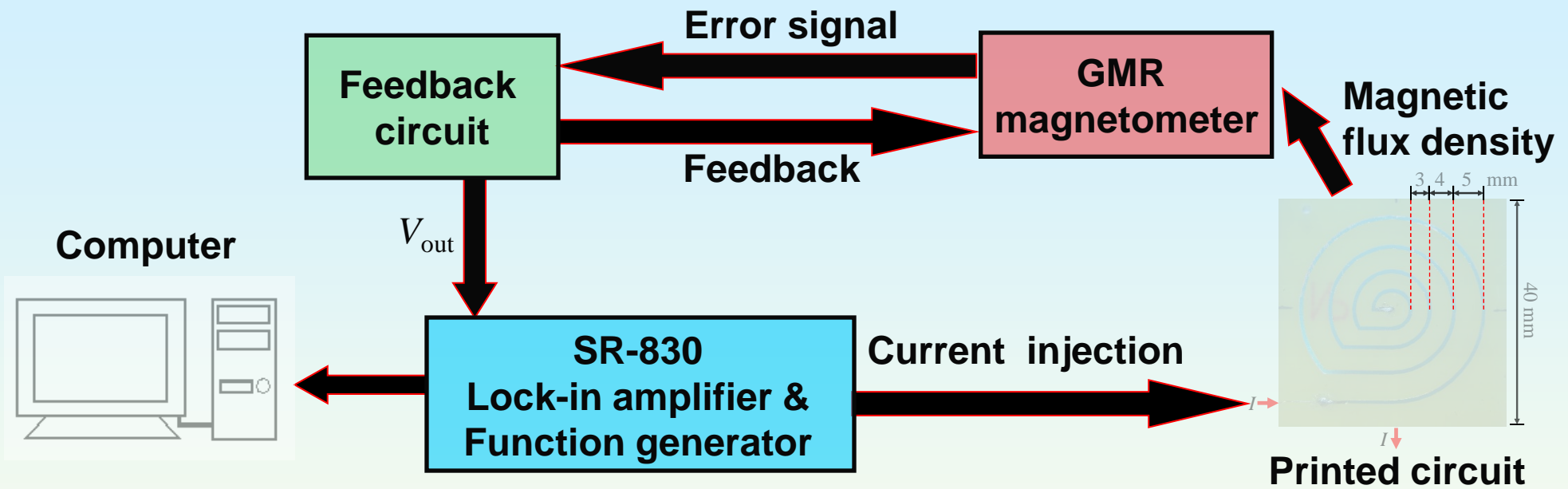


MCG & ECG of a rat's heart (in a shielded environment)

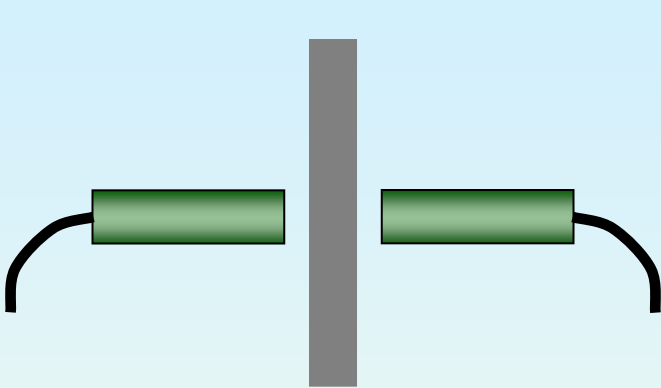


IEEE Tran. Appl. Supercond. 13, 381 (2003)

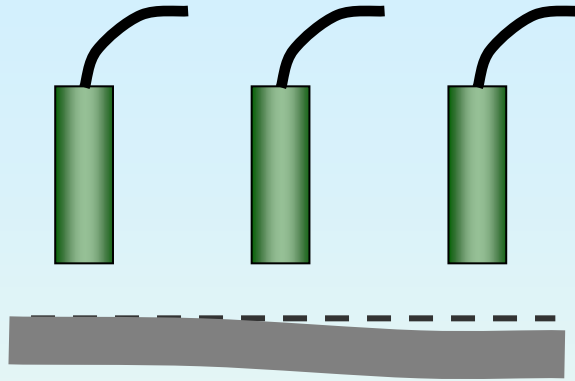
磁場圖掃描、磁源電流逆算 (GMR, fluxgate, & SQUID)



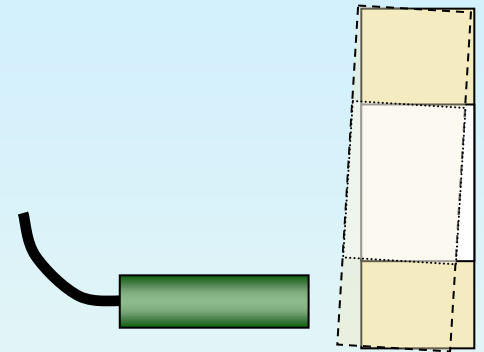
渦電流偵測器的應用



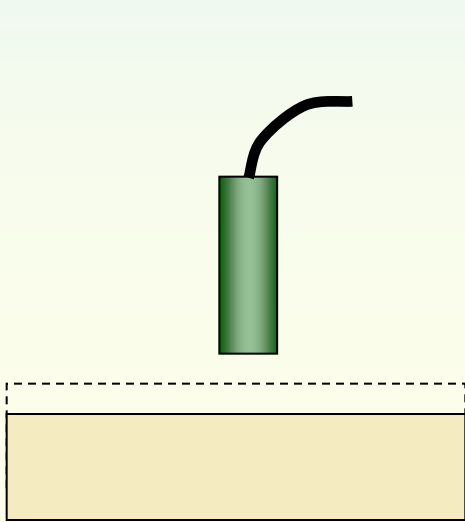
厚度量測



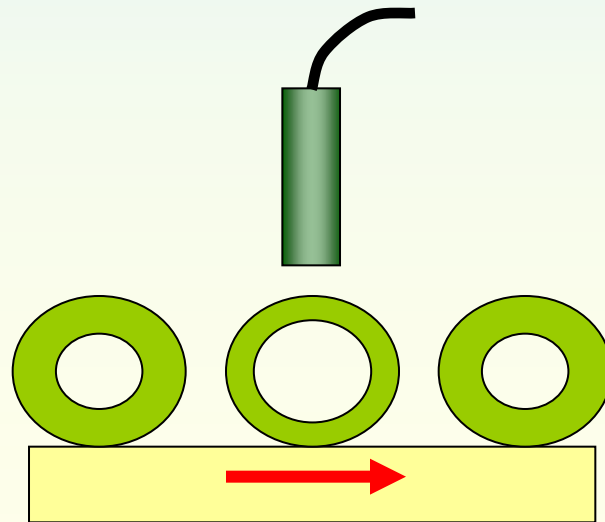
形變檢測



振動、偏心率



動態位移



工件品質檢測



硬幣辨識

結語

◆三種磁強計比較

- ➔ 靈敏度：SQUID > fluxgate > GMR
- ➔ 頻寬：SQUID > GMR > fluxgate
- ➔ 功率消耗：fluxgate > GMR > SQUID

◆研究領域特性：

- ➔ 基礎研究(論文發表)：SQUID, fluxgate, GMR, MTJ
- ➔ 應用研究(產學合作)：eddy-current, coin validation

◆未來有無限的可能性，唯一的限制在於想像力