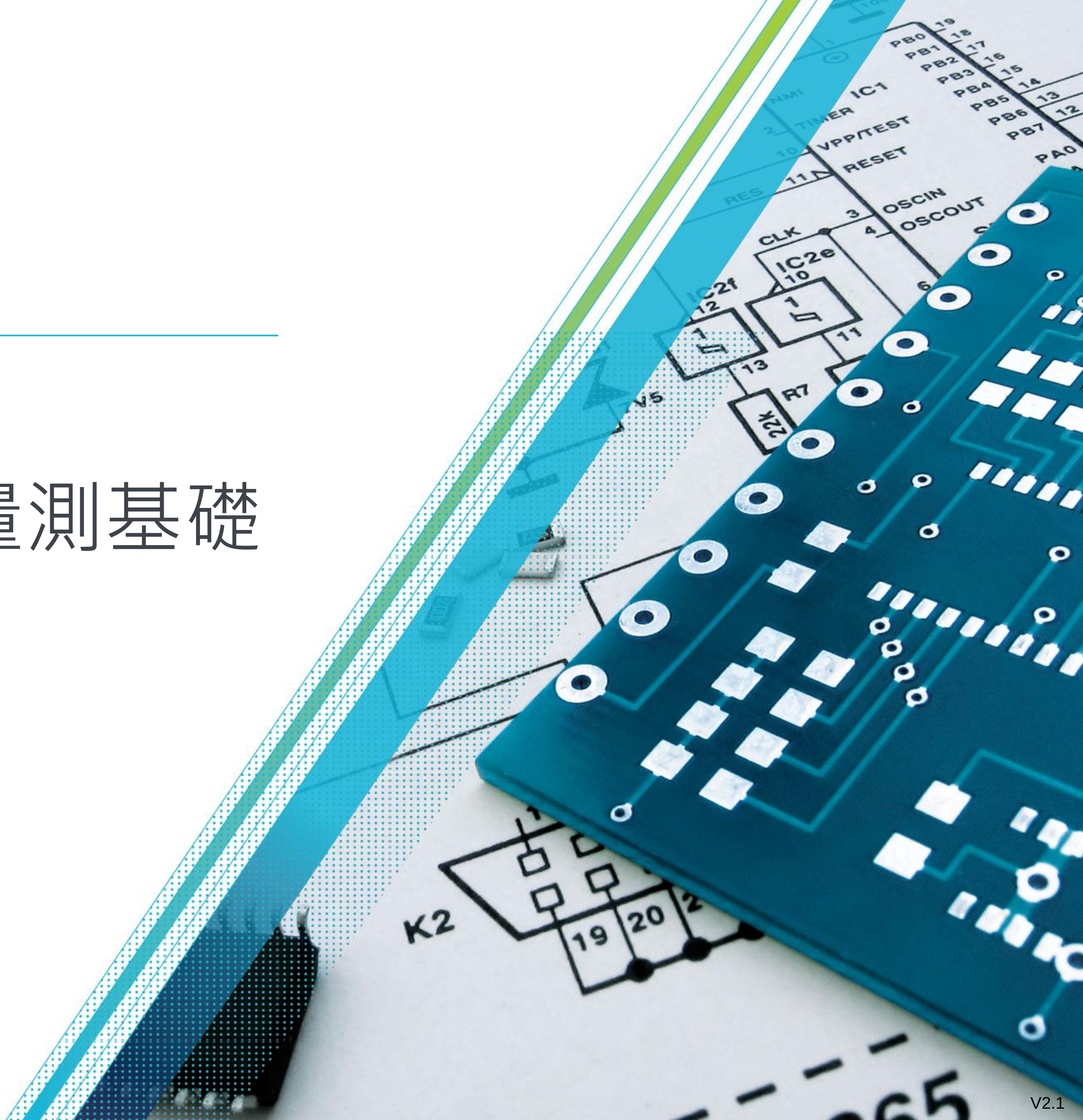
2016 Keithley熱門應用技術論壇

Tektronix

精密電性量測基礎

張志豪



V2.1

大綱

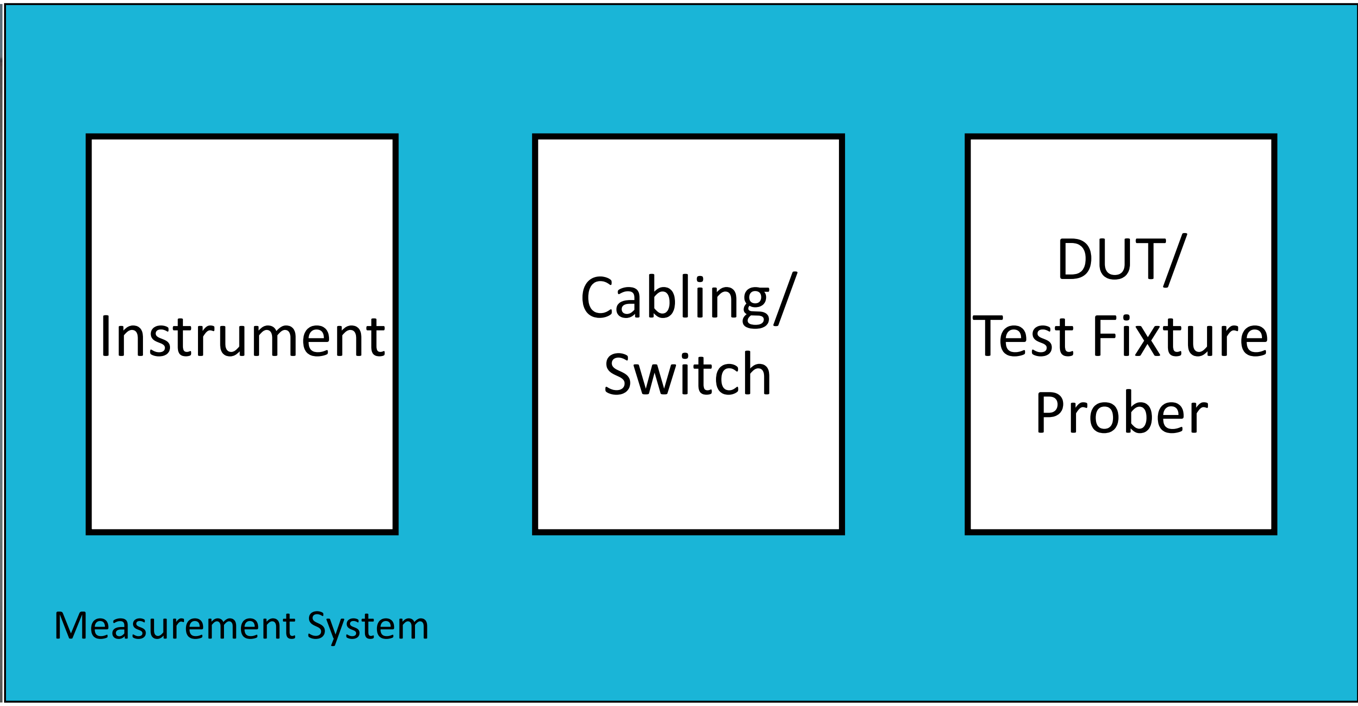
1.使用技術規格書選擇合適設備的基本原則。

2.如何測試您的系統以確保其符合要求。

3.找出系統誤差源。

4.降低量測誤差的技術。

Measurement System



What will limit your results?

- *The material or device under test [DUT] itself?*
- *The connections between the DUT and instruments [including cables, fixtures, switching, etc.]?*
- *The measuring instrument?*

4-Step Measurement Process

1. **Define required measurement quality**

   Accuracy, Repeatability, Timing, …

2. **Design measurement system**

   Select equipment and fixtures

3. **Build and verify performance**

   Techniques to improve measurements

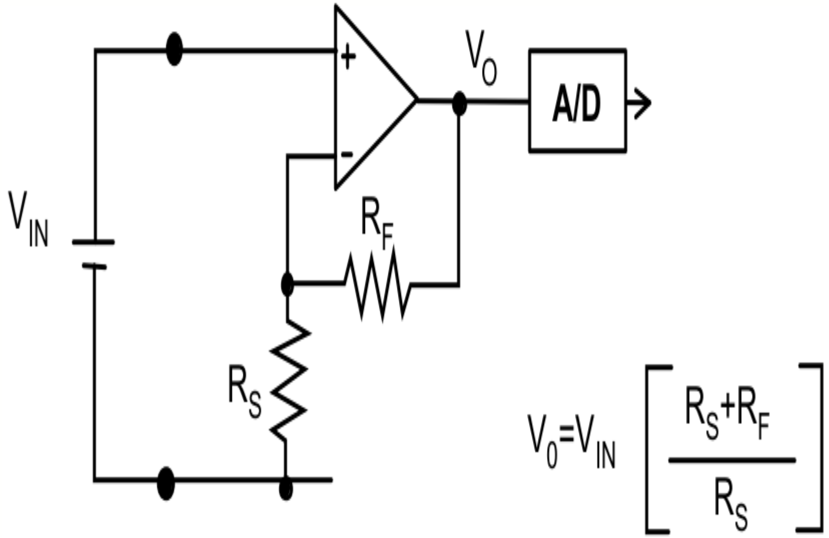
4. **Use system to gather desired information**

Resolution

Sensitivity

Accuracy

Repeatability



Resolution

- **The smallest portion of the signal that can be observed**

- **12-bit resolution = 1 part in 4096**
- **4-1/2 digits = 1 part in 20000 counts (00000 to 19999)**
- **7-1/2 digits = 1 part in 20,000,000 counts (00000000 to 19999999)**

Resolution – Bits and Counts

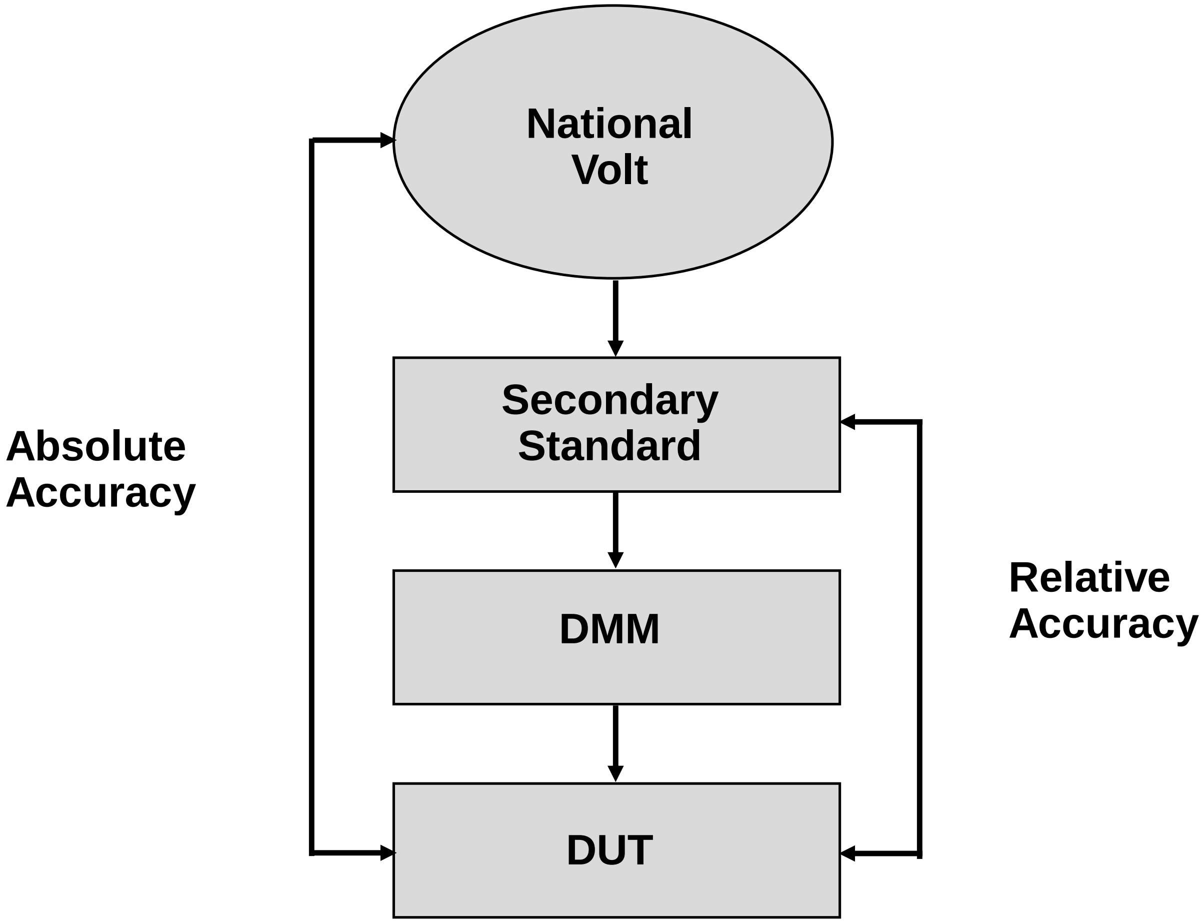
- **12 bit A/D – 4096 counts – approx 3.5 digits**
- **16 bit A/D – 65,536 counts – approx 4.5 digits**
- **18 bit A/D - 262,144 counts – approx 5.5 digits**
- **22 bit A/D – 4,194,304 counts – approx 6.5 digits**
- **25 bit A/D – 33,554,304 counts – approx 7.5 digits**
- **28 bit A/D – 268,435,456 counts – approx 8.5 digits**

Sensitivity

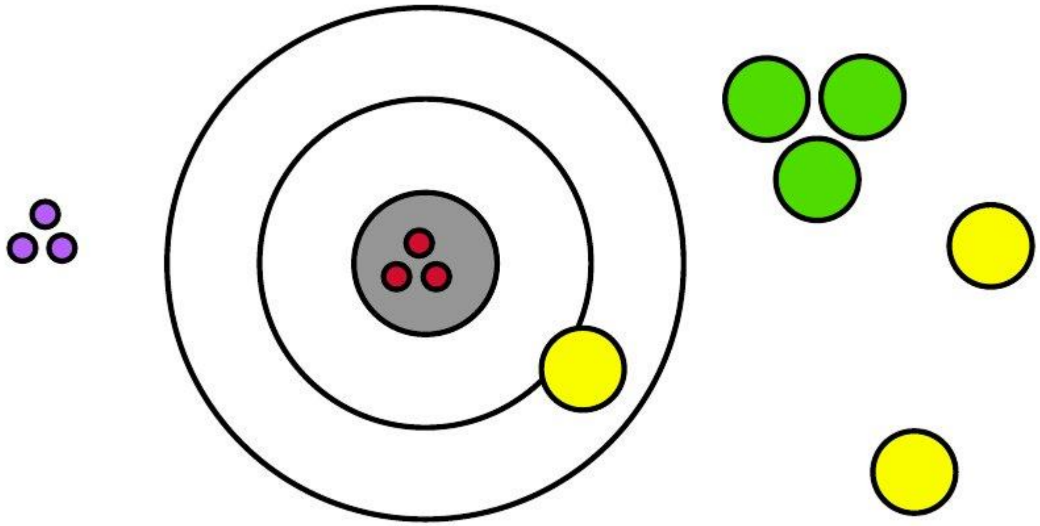
- **The smallest *change* that can be detected**
- **Specified in units of the measured value**
  – Volts, ohms, degrees
- **Examples:**
  – 3-1/2 digits (2000) on 2V range = 1mV
  – 4-1/2 digits (20000) on 2W range = 100mW
  – 16-bit (65536) A/D on 2V range = 30mV
  – 8-1/2 digits on 200 mV range = 1nV

Accuracy

- **Absolute accuracy**
  - A measure of the closeness of agreement between a measured value and that of a primary standard value
- **Relative accuracy**
  - A measure of the closeness of agreement between a measured value and that of a locally established reference value


National
Volt
Secondary
Standard
DMM
DUT
Absolute
Accuracy
Relative
Accuracy

Resolution, Accuracy, Repeatability

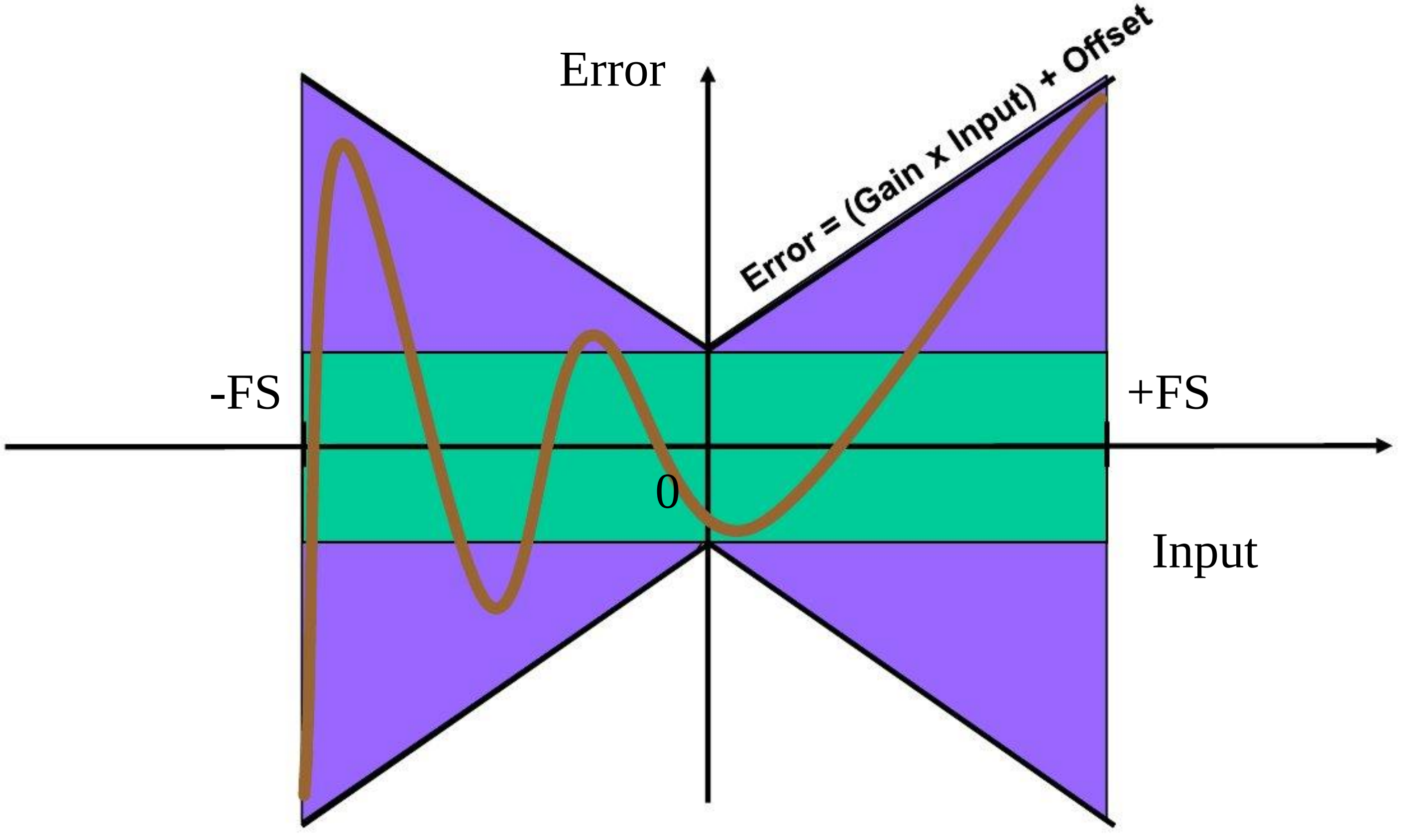


Resolution	Accuracy	Repeatability
High	High	High
High	Low	High
Low	Low	High
Low	Low	Low

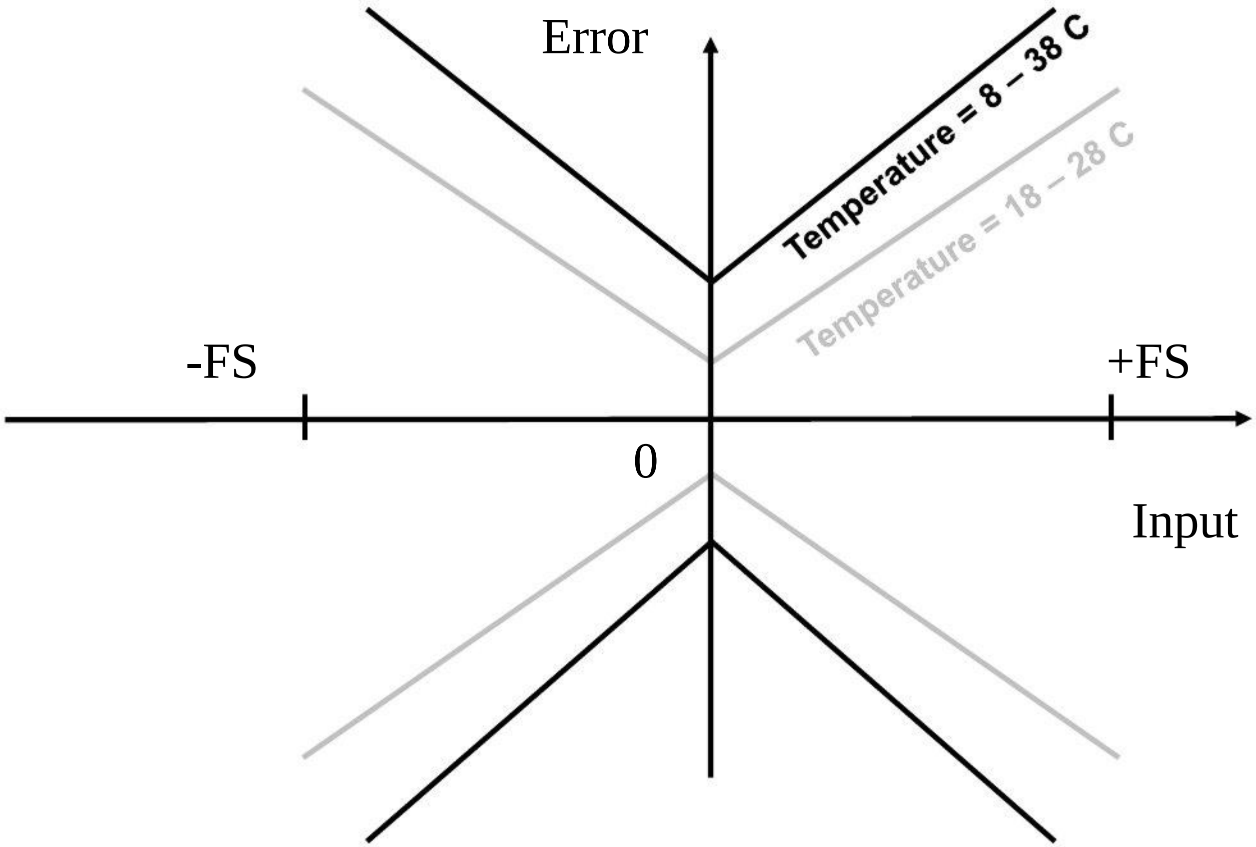
How to read instrument specs

- **Accuracy**
  - Offset error vs. Gain error
  - Temperature coefficient
- **Sensitivity**
  - Noise vs. resolution
- **Timing**
  - Settling Time vs. Rise Time

Accuracy



Temperature Coefficient



Instrumentation Error

- **Accuracy** = ± (% reading + % range)

  = ± (gain error + offset error)
- **For example, DMM 2V range:**

  Accuracy = ± (0.03% of reading + 0.01% range)
- **For a 0.5V input:**

  Uncertainty = ± (0.03% x .5V + .01% x 2.0V)

  = ± (.00015V + .00020V)

  = ± **350** mV
- **Reading** = .49965 to .50035

Instrumentation Error - DMM Example

- **DMM, 6 1/2 digit, 2V range (2.000000)**
  Accuracy
  = ± (0.003% reading + 0.001% range)
  = ± (30 ppm readings + 10 ppm range)
  = ± (0.003% reading + 20 counts)
  Uncertainty @ .5V
  = ± (.000015 + .000020)
  = ± .000035V
  = ± 35 mV

Instrumentation Error – Data Acquisition Board Example

- **Analog input board, 12 bit, 2V range**

Accuracy

$$= \pm\,(0.01\%\ \text{reading} + 1\ \text{LSB})$$

$$= \pm\,(100\text{ppm} + 1\ \text{bit})$$

Uncertainty @ .5V

$$= \pm\,\left(.000050 + \frac{2.0}{4096}\right)$$

$$= \pm\,(.000050 + .000488)$$

$$= \pm\,.000538$$

$$= \pm\,538\ \mu\text{V}$$

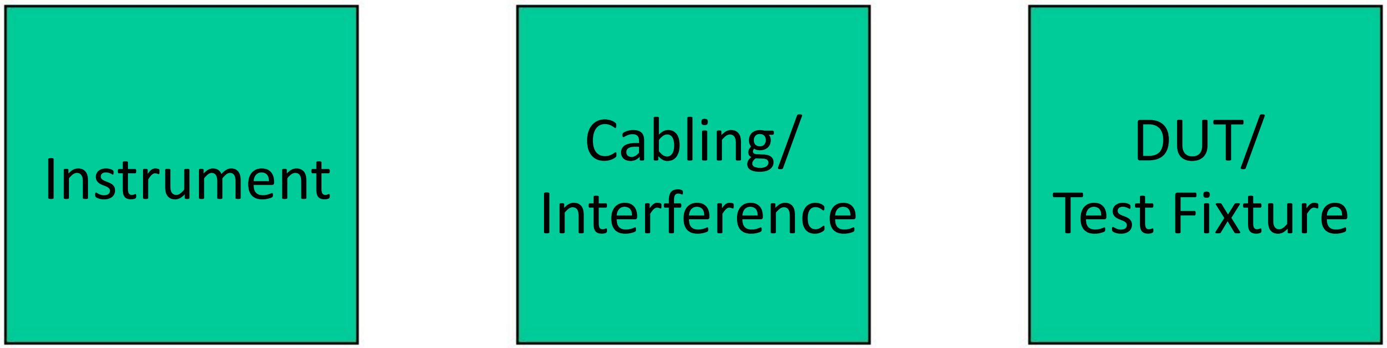
Sensitivity

- **The smallest observable change may be limited either by noise or by digital resolution**
- **Instrument Noise is often specified**
  - Peak-to-peak, RMS, in some bandwidth
- **If not specified, could be measured:**
  - Voltmeters/Ohmeters: Shorted Input
  - Ammeters: Open (Shielded) Input

Timing

- **Rise Time:**
  - 10% – 90%
  - 2.2 time constants (2.2 X RC)
- **Settling Time:**
  - Specified as time for measurement circuitry to settle to within 1% (or .1%) of final value

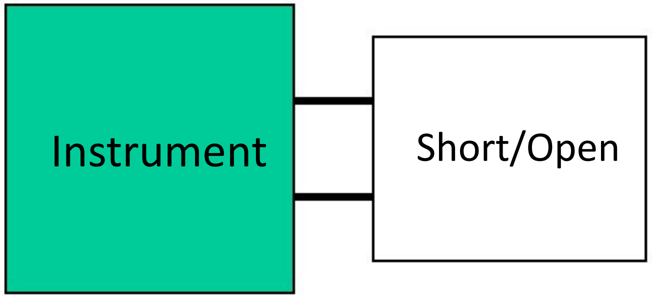
Measurement System



- **We have picked appropriate equipment, cables, and fixtures**
- **We know the specs of the equipment**
- **Verify performance one step at a time**

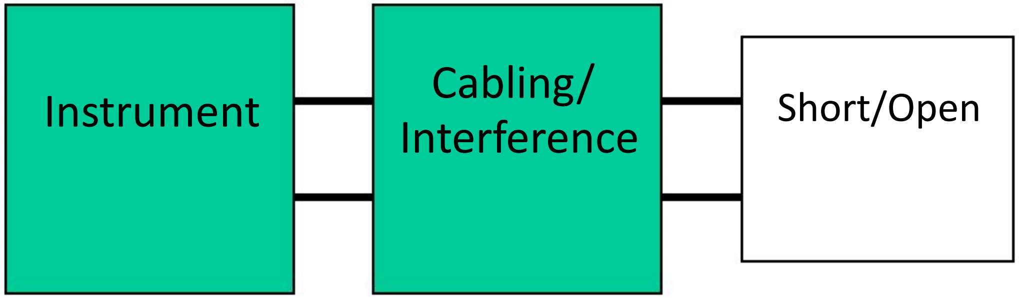
Assemble system one piece at a time

- **Start with the instrument, verify noise and error:**
  - Voltage measurements: Short circuit input
  - Ammeter: Open circuit input



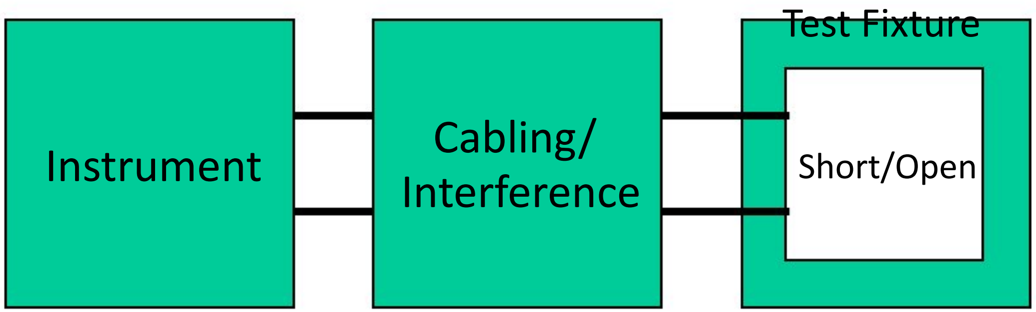
Assemble system one piece at a time

- **Start with the instrument, verify noise and error:**
  - Voltage measurements: Short circuit input
  - Ammeter: Open circuit input
- **… Then include Cabling**



Assemble system one piece at a time

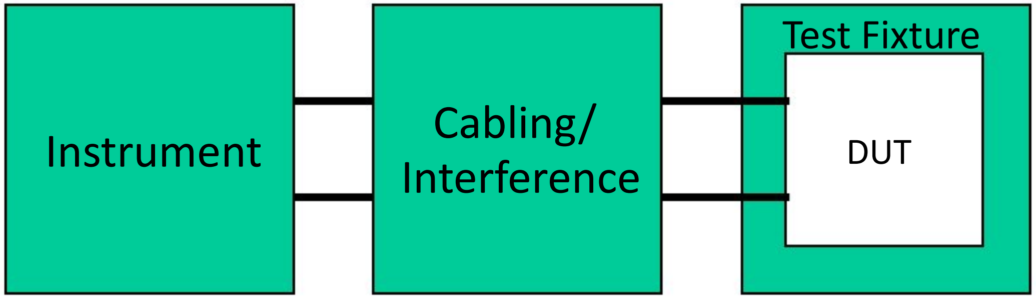
- **Start with the instrument, verify noise and error:**
  – Voltage measurements: Short circuit input
  – Ammeter: Open circuit input
- **Include Cabling**
  …..Then include Test Fixture



Assemble system one piece at a time

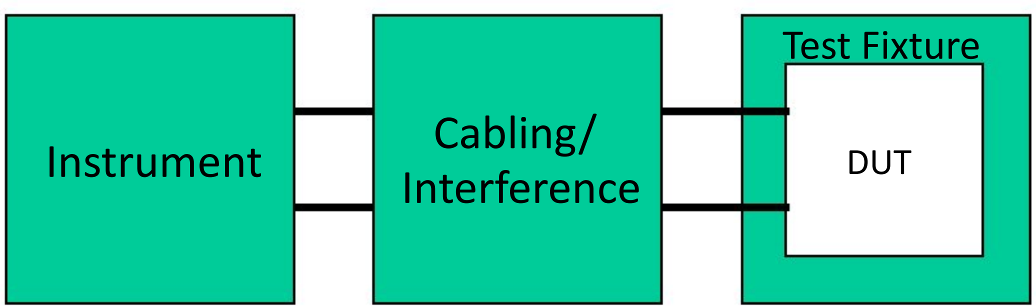
- **Start with the instrument, verify noise and error:**
  - Voltage measurements: Short circuit input
  - Ammeter: Open circuit input
- **Include Cabling**
- **Include Test Fixture**

  .... Then include DUT



Assemble system one piece at a time

- **Start with the instrument, verify noise and error:**
  - Voltage measurements: Short circuit input
  - Ammeter: Open circuit input
- **Include cabling**
- **Include test fixture**
- **Include DUT**
- **Check timing, reassess measurement speed goal**



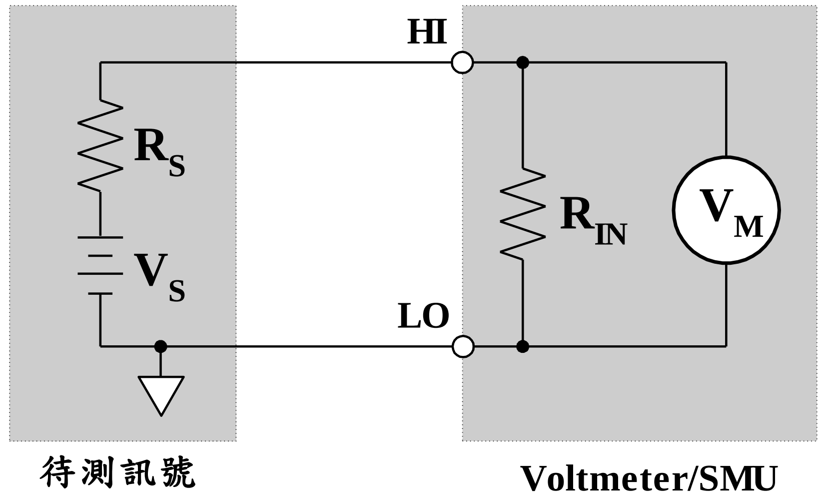
降低量測誤差的技術

- 儀器
  - 輸入阻抗 ,負載效應
  - 接地 , 隔離 (Grounding, Shielding)
- 小電流量測
  - 影響量測品質之因素
  - Guard
  - Settling Time
- 小電壓量測

- **低電阻量測**
  - Kelvin
- **高電阻量測**
- **改善措施/注意事項**
- **常見雜訊消除方法**
  - Low Pass Filter (低通濾波器)
  - Integration (積分)
  - Average (平均)

輸入阻抗，負載效應

- 輸入阻抗 影響量測準確性

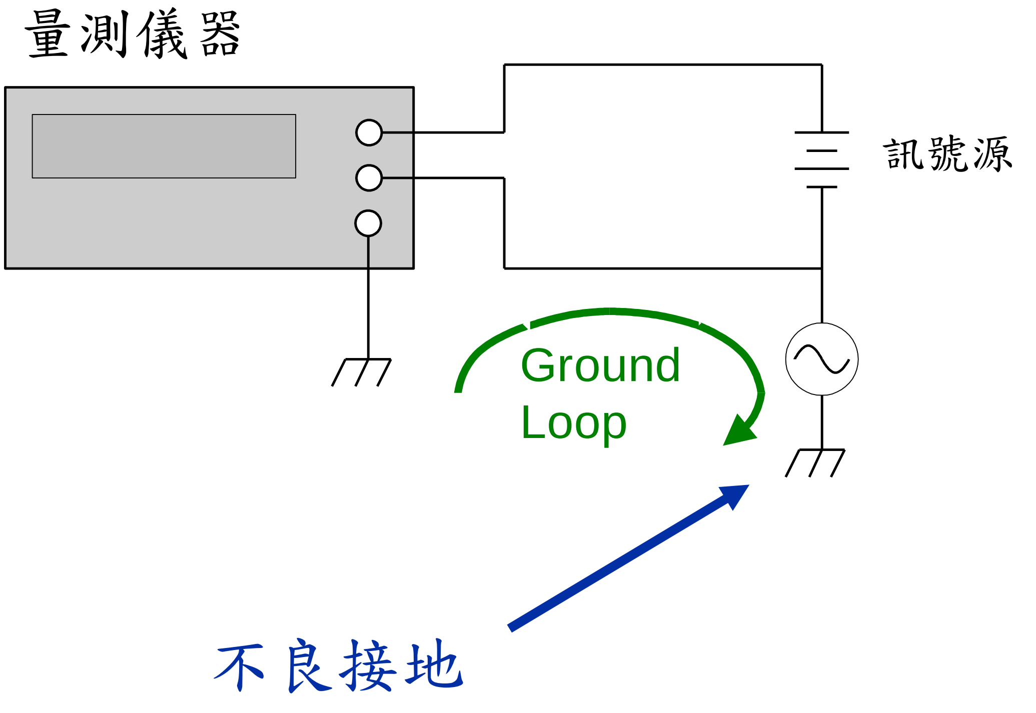


$$\text{量得電壓 } V_M = V_S\left(\frac{R_{IN}}{R_S + R_{IN}}\right)$$

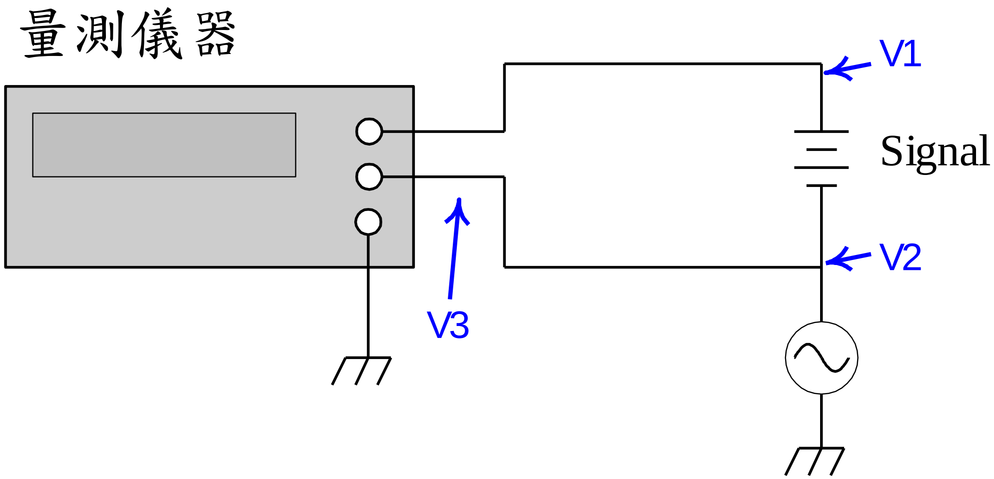
Typical: 10MΩ ~ 10G Ω

接地，隔離 (Grounding, Shielding)

- 避免儀器各自接地，造成 Ground Loop



接地，隔離 (Grounding, Shielding)

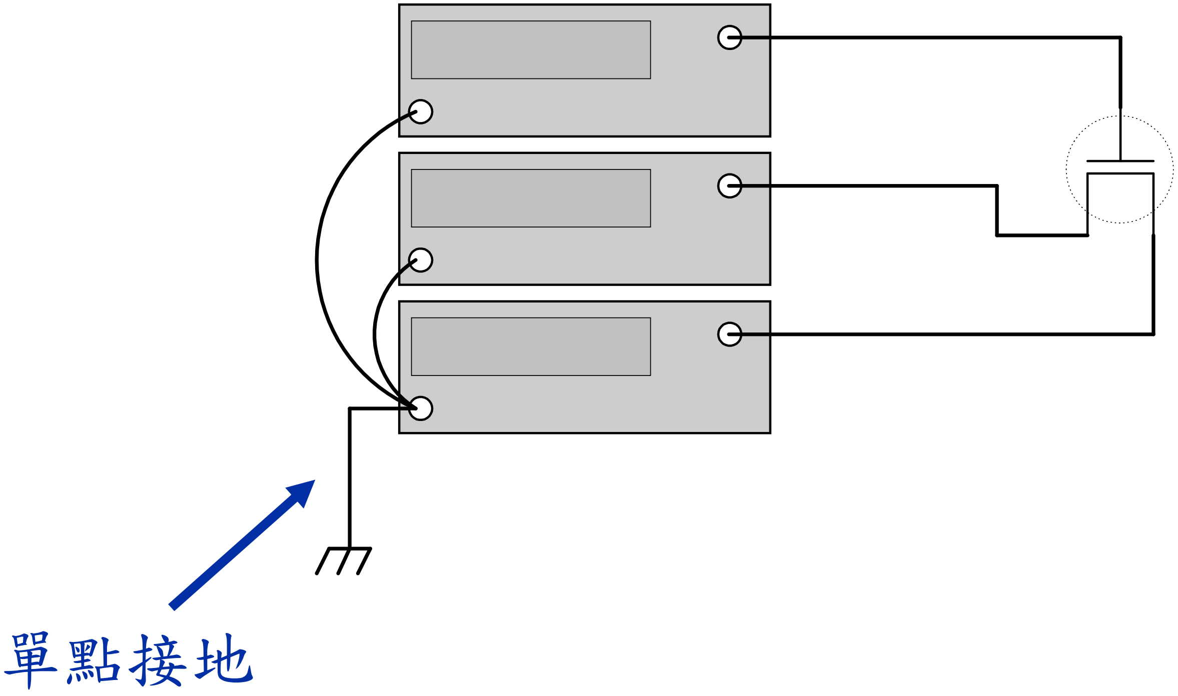


Ideal Result = V1 - V2

Actual Result = V1 - V3

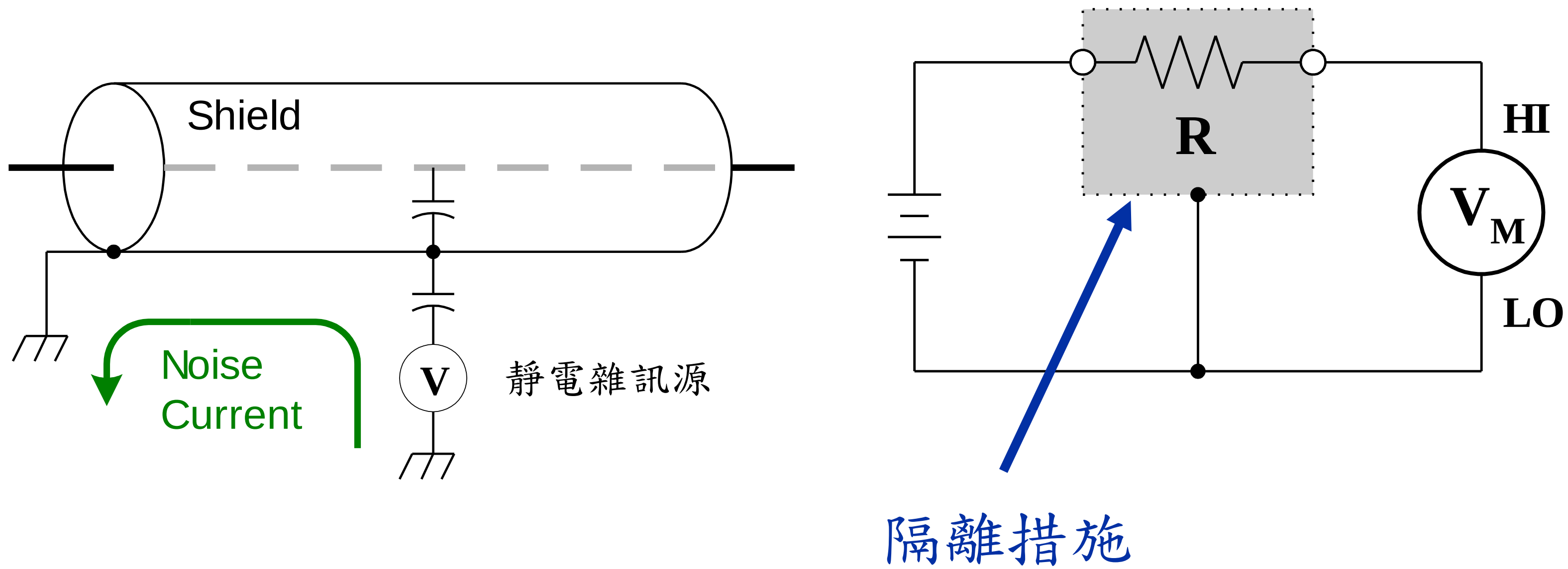
接地，隔離 (Grounding, Shielding)

- 理想接地方式



接地，隔離 (Grounding, Shielding)

- 適當的隔離可避免雜訊

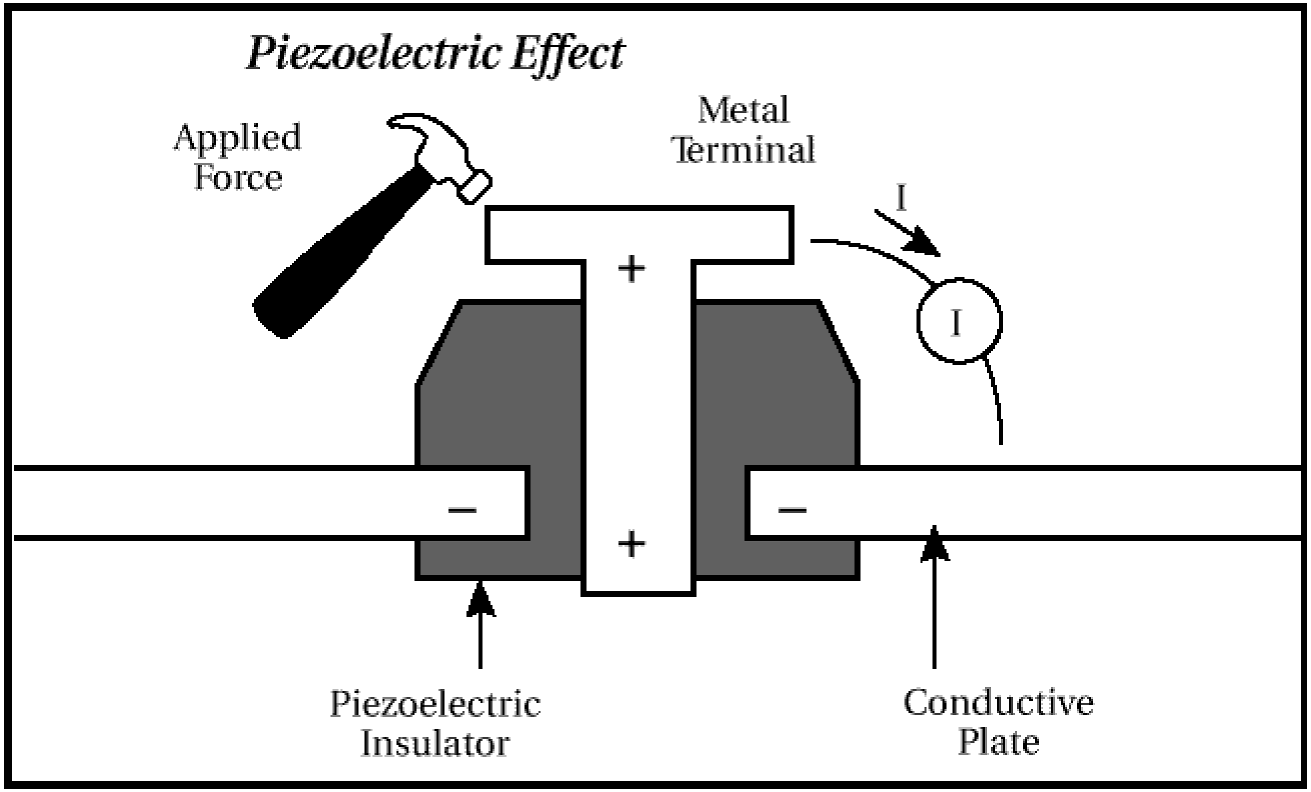


小電流量測

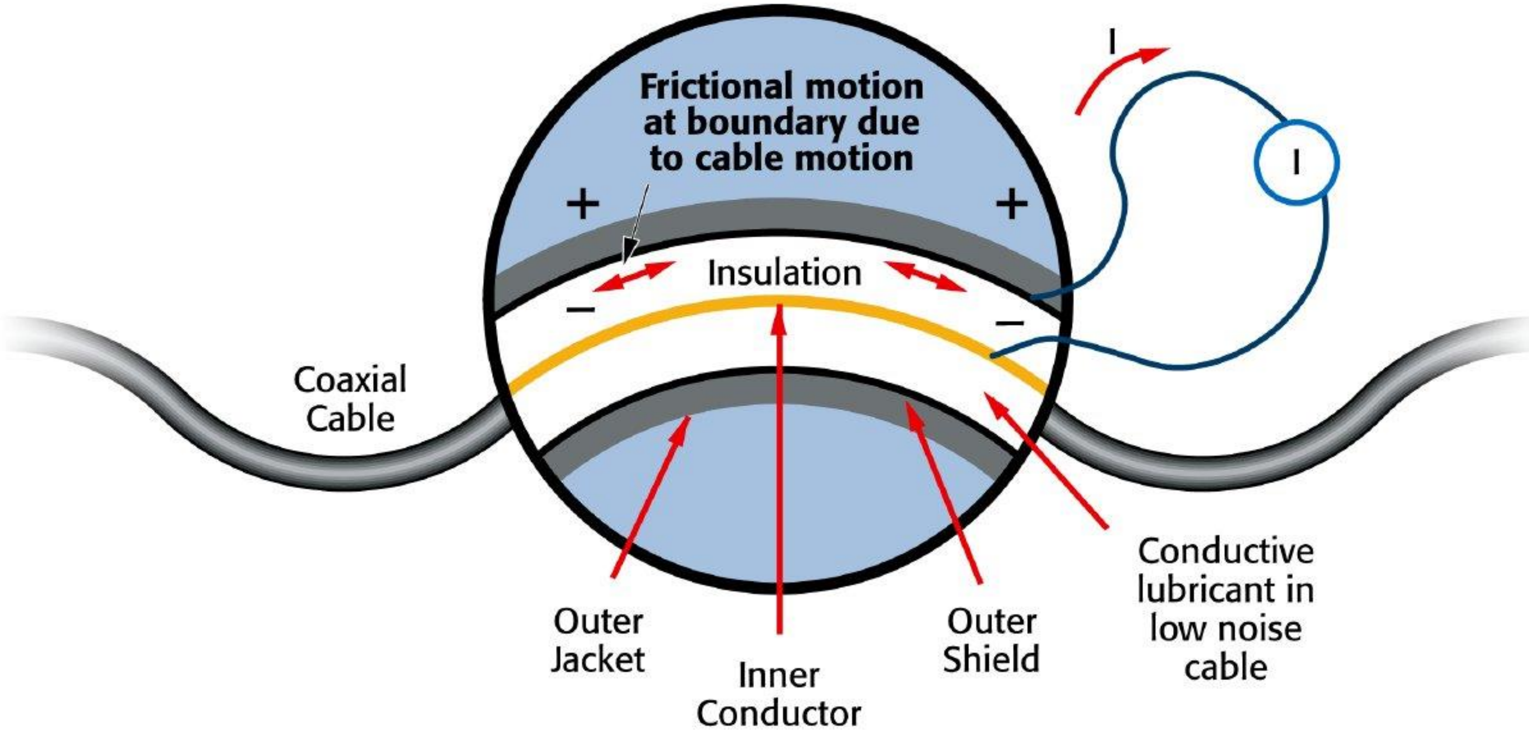
- 影響量測品質之因素
  - 壓電效應 (Piezoelectric Effect)
  - 摩擦生電 (Triboelectric Effect)
  - 溫溼度
  - 材料絕緣度
  - Guard
  - 寄生電容

壓電效應 (Piezoelectric Effect)

材料可能



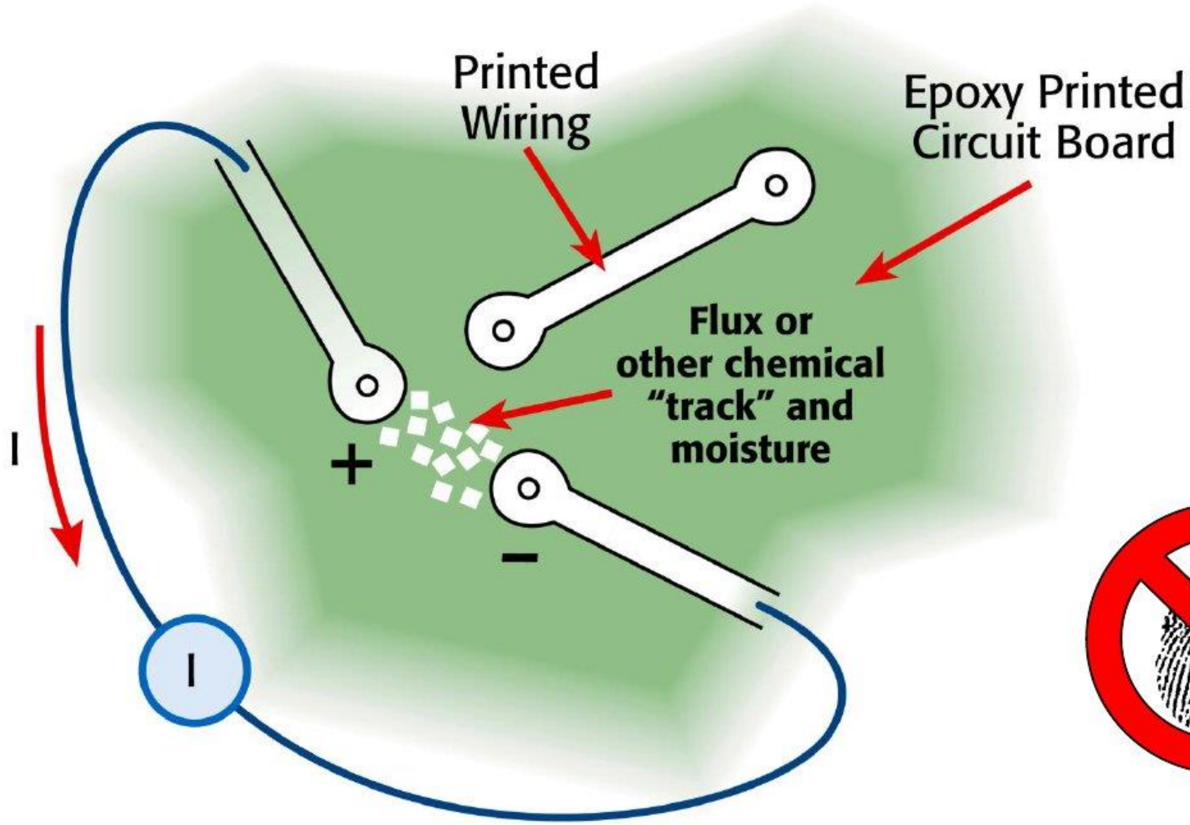
摩擦生電 (Triboelectric Effect)



扭動訊號線可能會產生微弱電流(~ nA)

A GREATER MEASURE OF CONFIDENCE

Contamination Effect

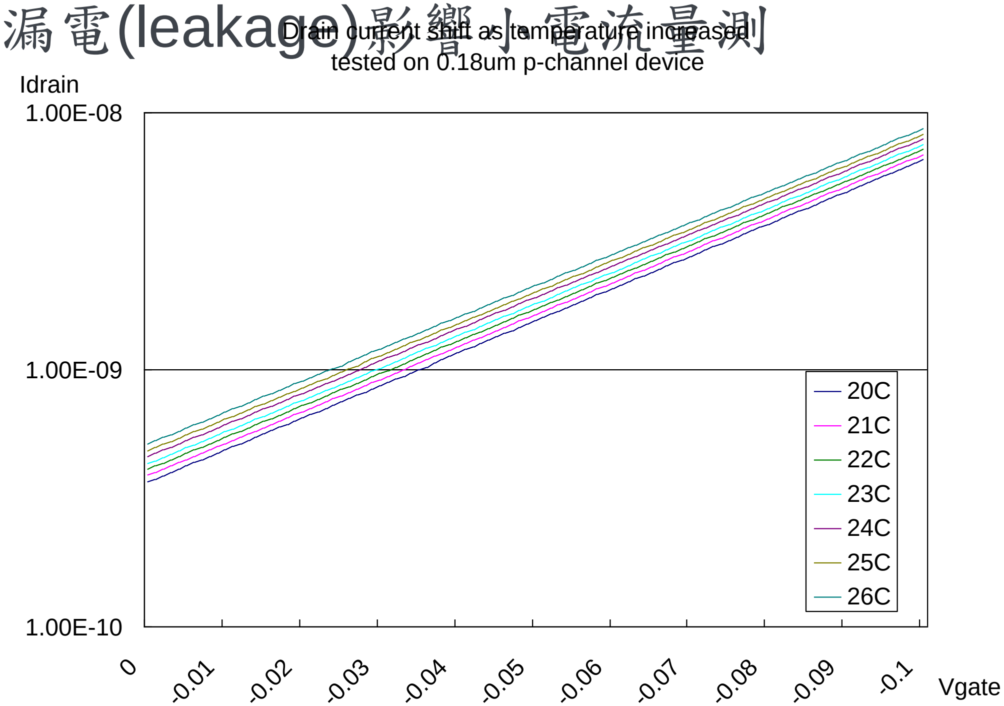


Noise current can be tens of nA

溫溼度

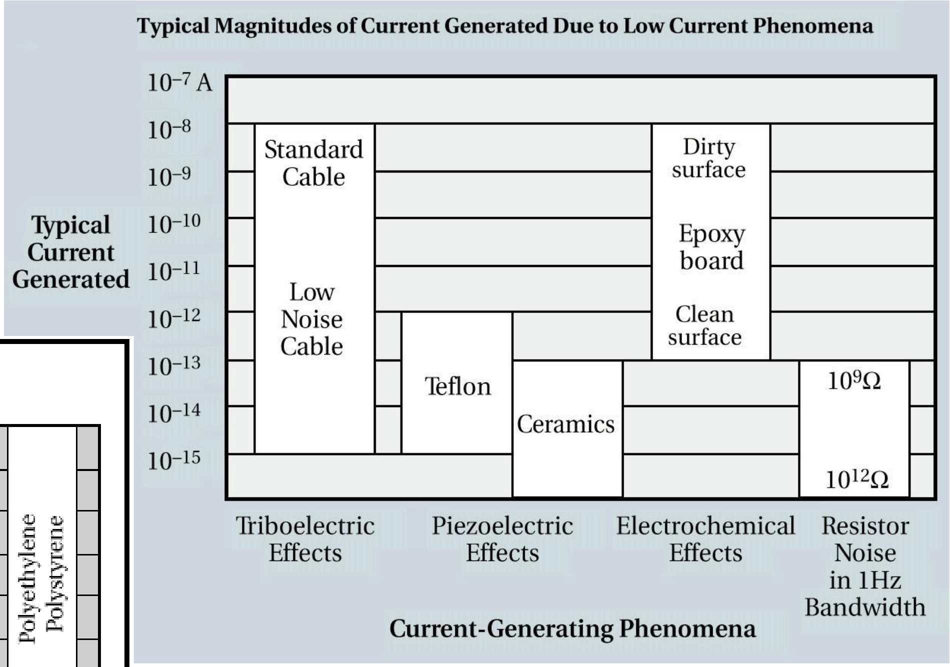
- 環境溫度應維持於 23°C　容許變動範圍視儀器規格而定
- 環境溼度一般應維持於 30 ~ 50 RH
- 潮濕環境容易產生漏電(leakage)影響小電流量測

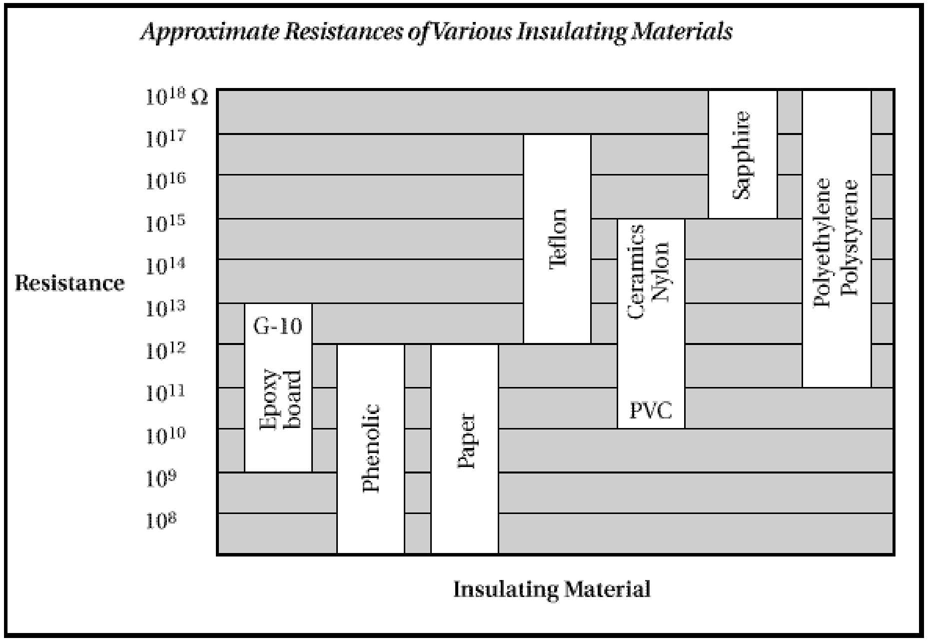
  (fA ~ pA level)



小電流量測 – 材料絕緣度

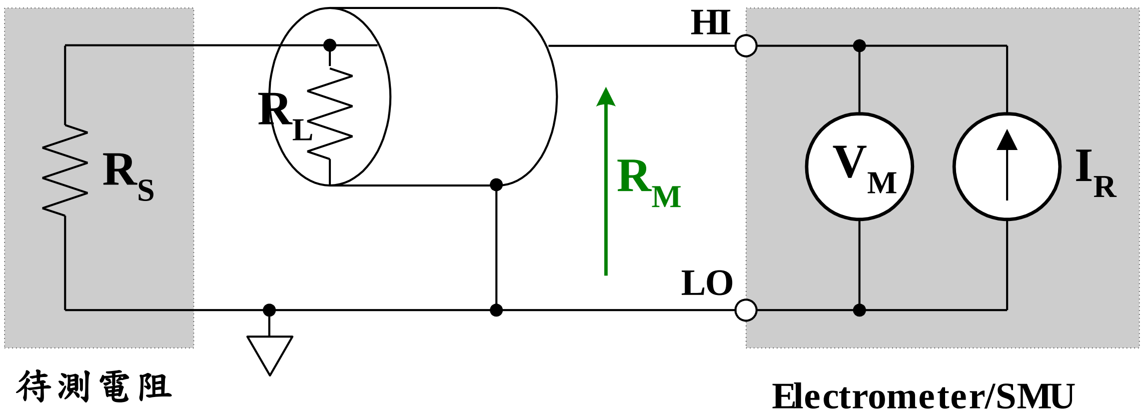
- 材料絕緣度





小電流量測 – Guard

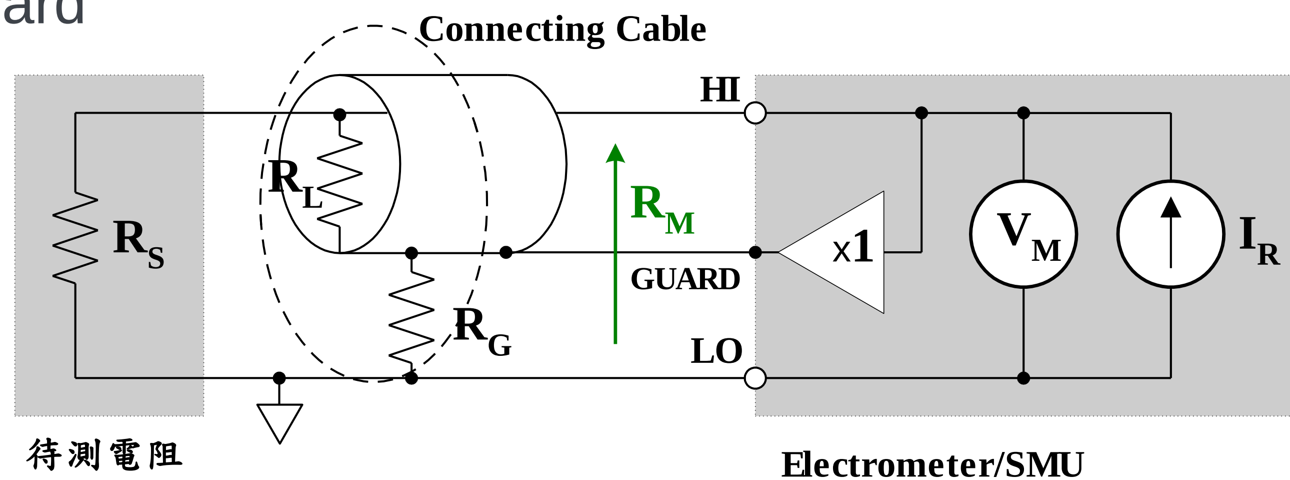
- 未使用 Guard

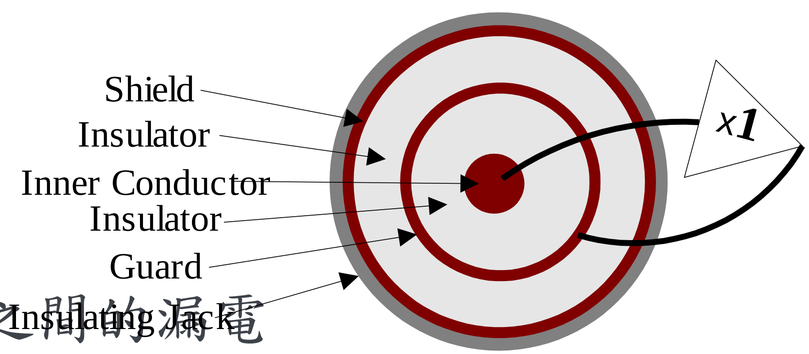


$$\text{量得電阻} = R_M = R_S \left(\frac{R_L}{R_S + R_L} \right)$$

小電流量測 – Guard

- Guard

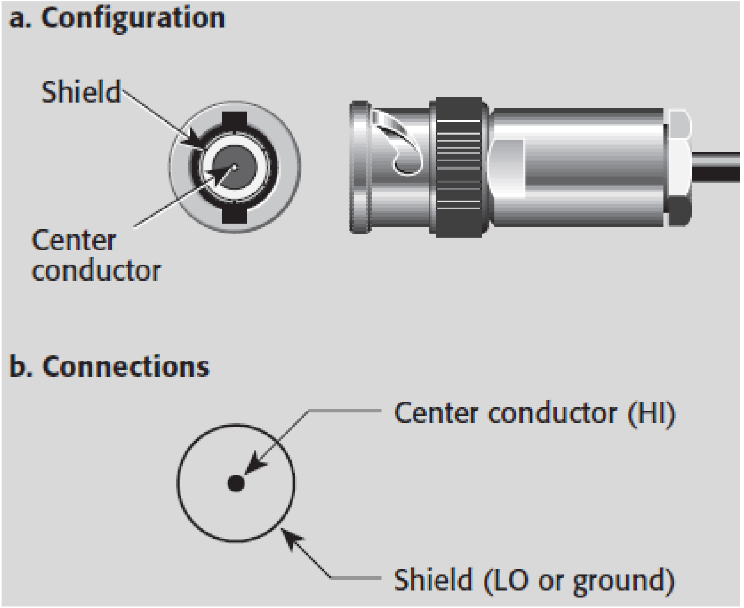


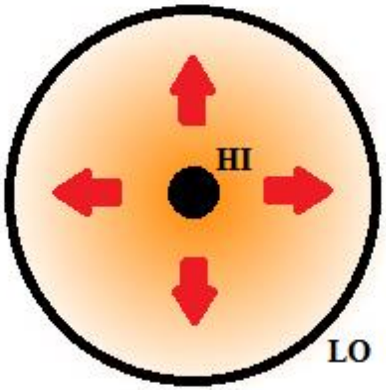


- Guard 減輕訊號和隔離層之間的漏電

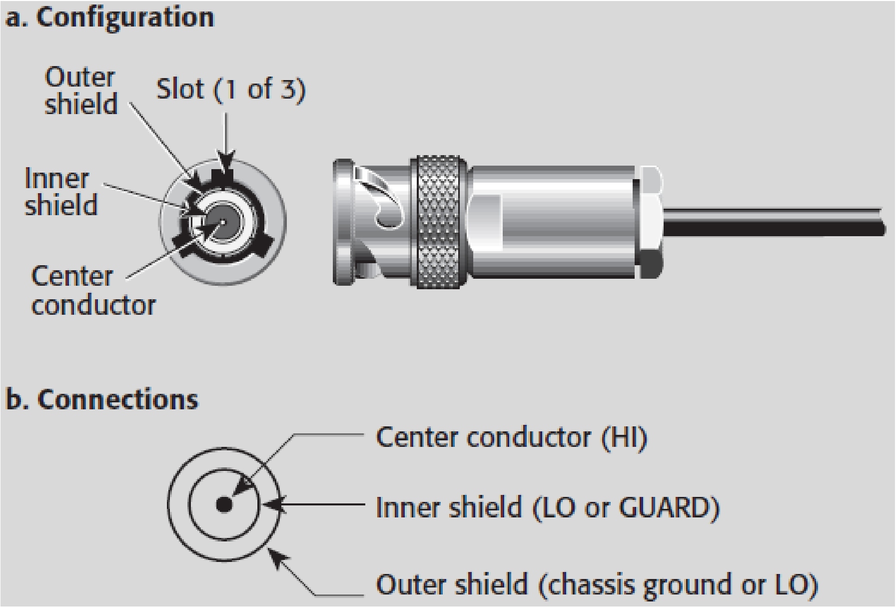
Cables

Co-axial (BNC)



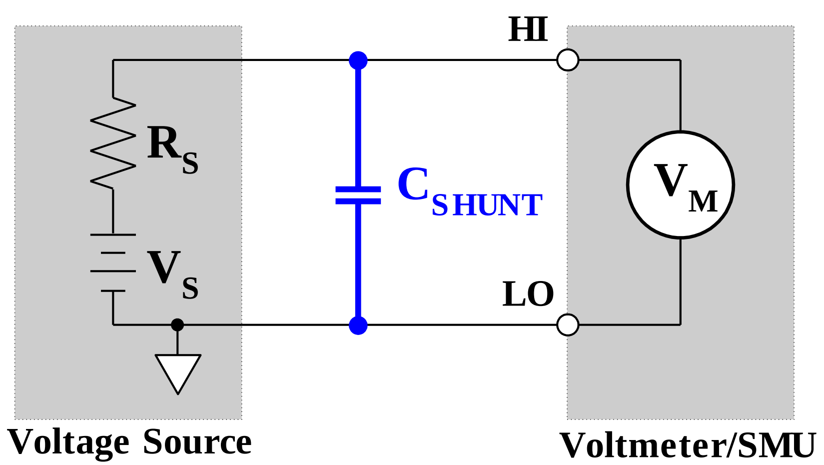


Tri-axial (Triax)



小電流量測 – Settling Time

- 寄生電容影響量測速度



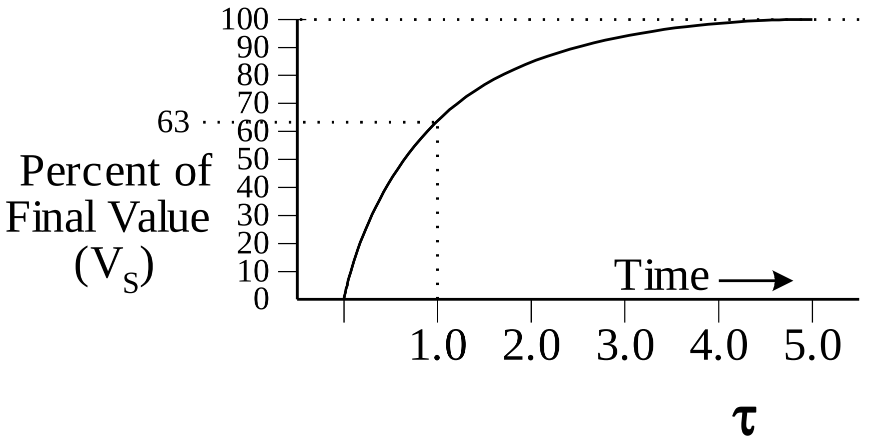
量得電壓 $= V_S(1 - e^{-t/R_S C_{SHUNT}})$

Time Constant $\tau = R_S C_{SHUNT}$

小電流量測 – Settling Time

- 時間常數 $\tau = R_S C_{SHUNT}$

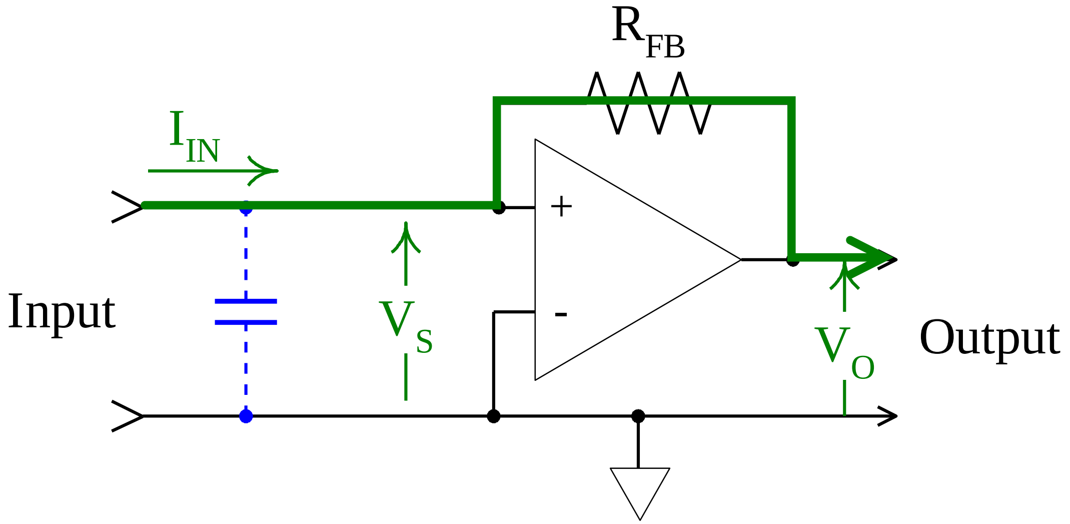
  待測物之阻抗及寄生電容皆對量測速度產生影響
  - $R_S = 100G\Omega$, $C_{SHUNT} = 10pF$ $\tau = 1sec$



τ	Percent of Final Value
1	63%
2	86%
3	95%
4	98%
5	99.3%

小電流量測 - 電流表

- 典型的 SMU電流量測模式
  - 回授示電流計
  - 低電壓負荷



小電流量測

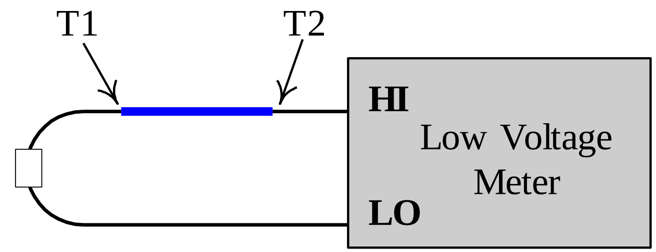
- 對nA以下訊號量測應注意以下措施
  - 控制環境溫濕度
  - 選用正確訊號線
  - 訊號線應固定好
  - 配合有Guard功能的儀器
  - 訊號線越短越好
  - 根據訊號等級給予足夠穩定時間

小電壓量測

- 影響量測品質之因素
  - 熱電偶 (Thermal EMF)
  - 磁場

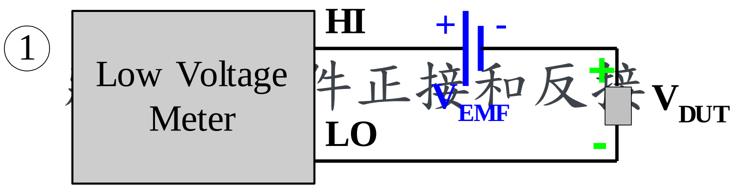
小電壓量測 -熱電偶

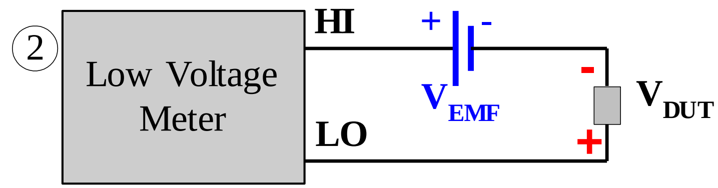
- 熱電偶 (Thermal EMF)
  - Cu - Cu ~0.2µV/°C
  - Cu - Ag 0.3µV/°C
  - Cu - Au 0.3µV/°C
  - Cu - Cu Oxide 1400µV/°C



- 消除熱電偶

件正接和反接

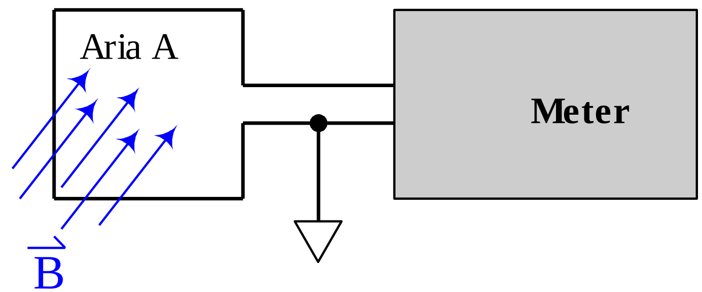




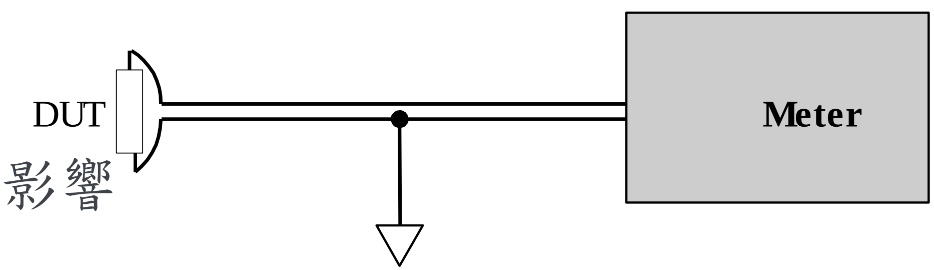
$$\frac{\text{Reading\#1 - Reading\#2}}{2} = \frac{(V_{DUT} + V_{EMF}) - (-V_{DUT} + V_{EMF})}{2} = V_{DUT}$$

小電壓量測 -磁場

- 磁場



$$E_B = \int_A \frac{\partial \vec{B}}{\partial \vec{t}}\, dA$$



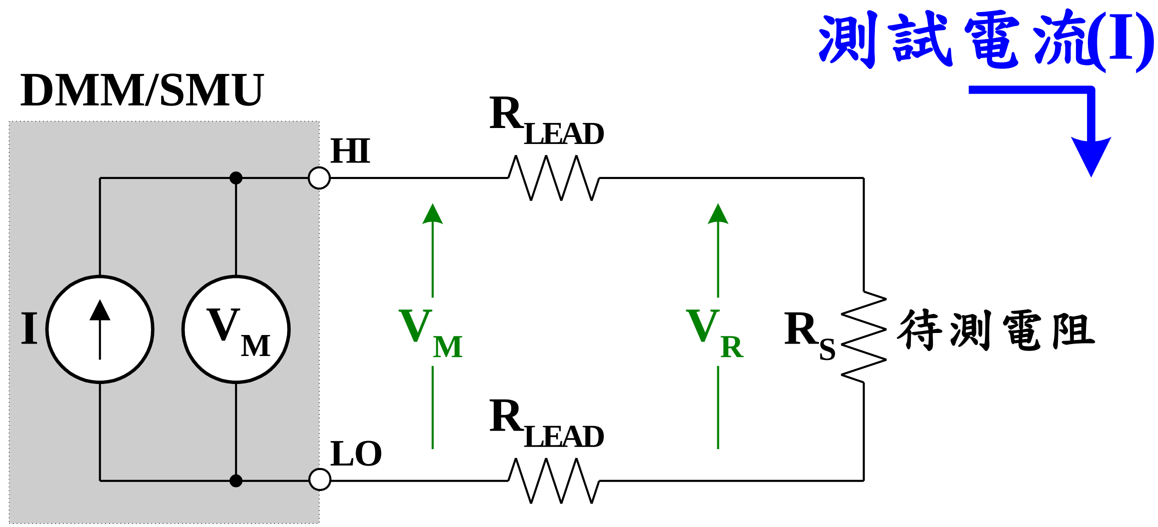
- 消除磁場的影響

小電壓量測

- 對μV以下訊號量測應注意以下措施
  - 控制環境溫濕度
  - 選用正確訊號線
  - 訊號線應固定好或是絞在一起
  - 考慮正反極性皆進行量測再將誤差源抵消

低電阻量測

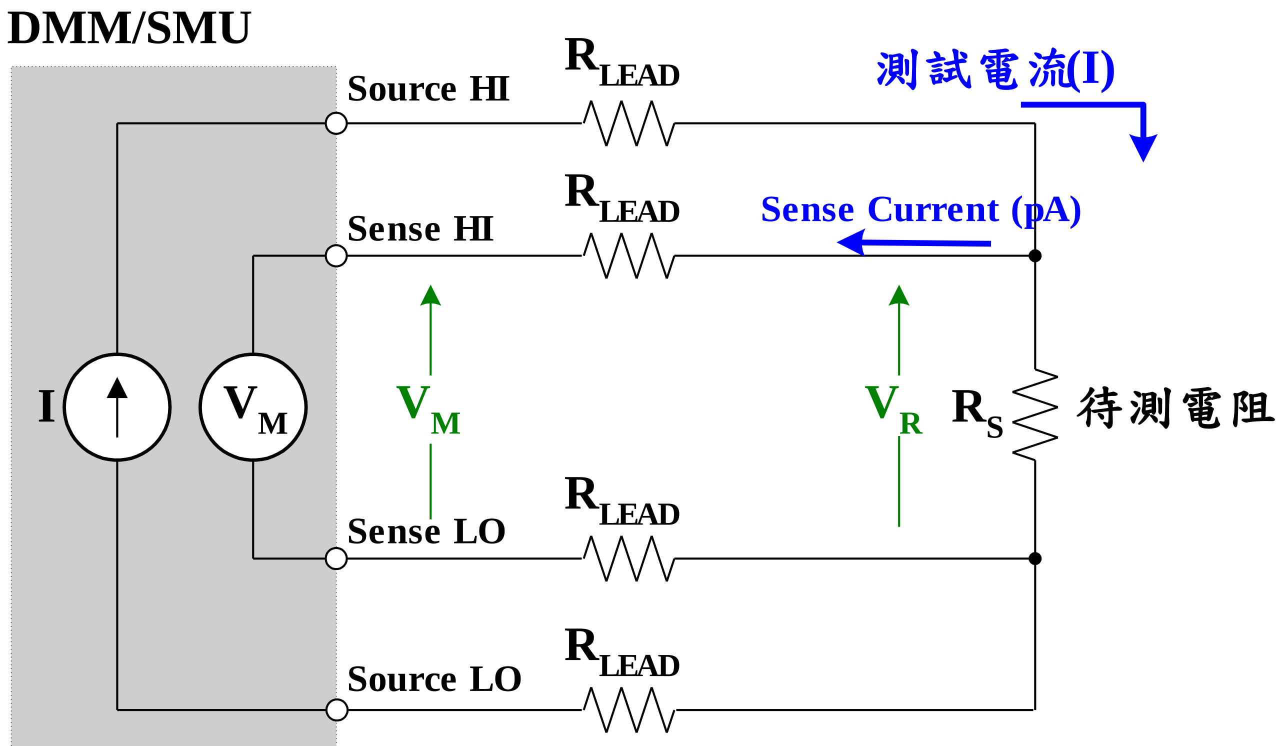
以二線式量得之電阻值包含了導線電阻



$$量得電阻 = \frac{V_M}{I} = R_S + (2 \times R_{LEAD})$$

低電阻量測

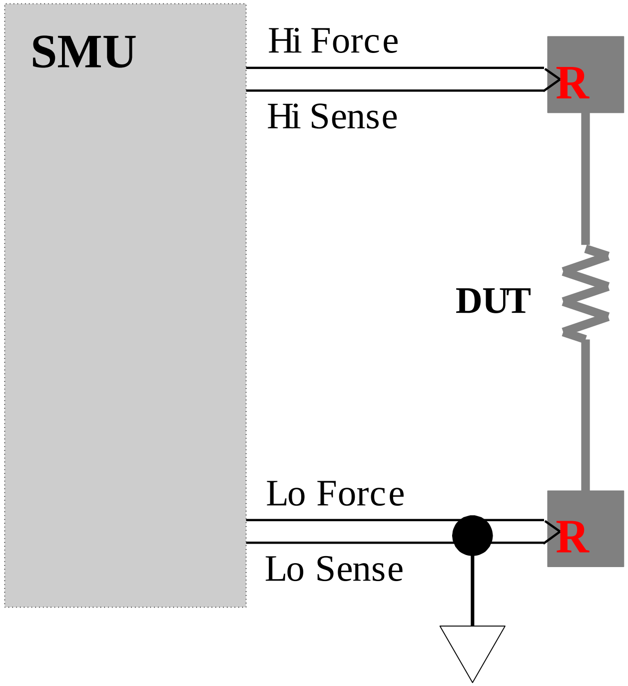
以四線式量測 (Kelvin) 可避免導線電阻造成之誤差



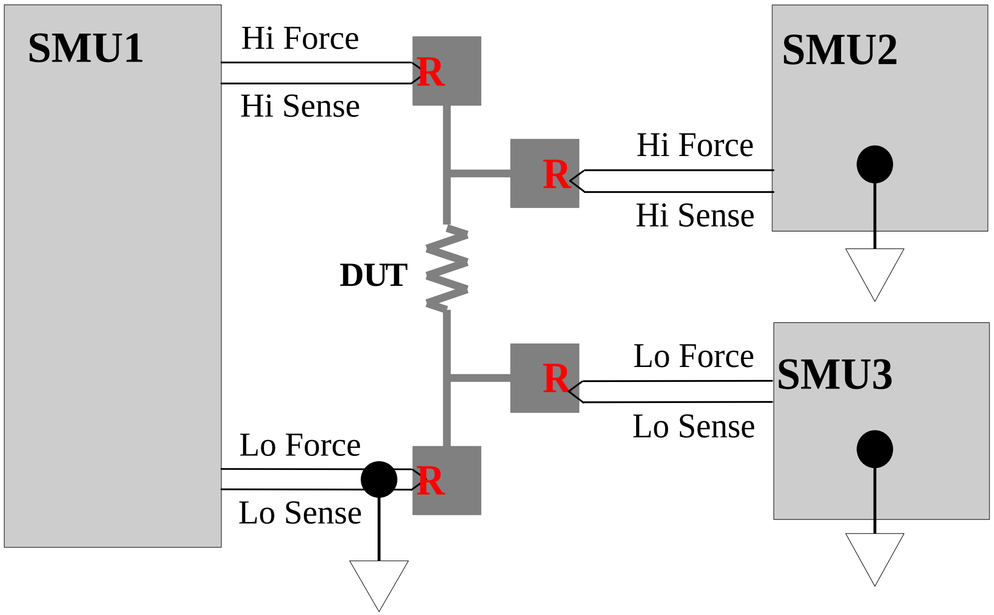
$$\text{量得電阻} = \frac{V_M}{I} = \frac{V_R}{I}$$

Wafer上的低電阻量測

- Measure on two pads structure



- Measure on Kelvin (four pads) structure



低電阻量測

- 小電阻量測(<100Ω)應採用方法
  - 選用四線式量測儀器或是自行組織多台儀錶以定電流源方式測量
  - 以定電流源方式測量時應考量電流源等級

- 對小電阻量測(<100Ω)應注意以下誤差來源
  - 控制環境溫濕度
  - 選用正確訊號線
  - 訊號線應固定好

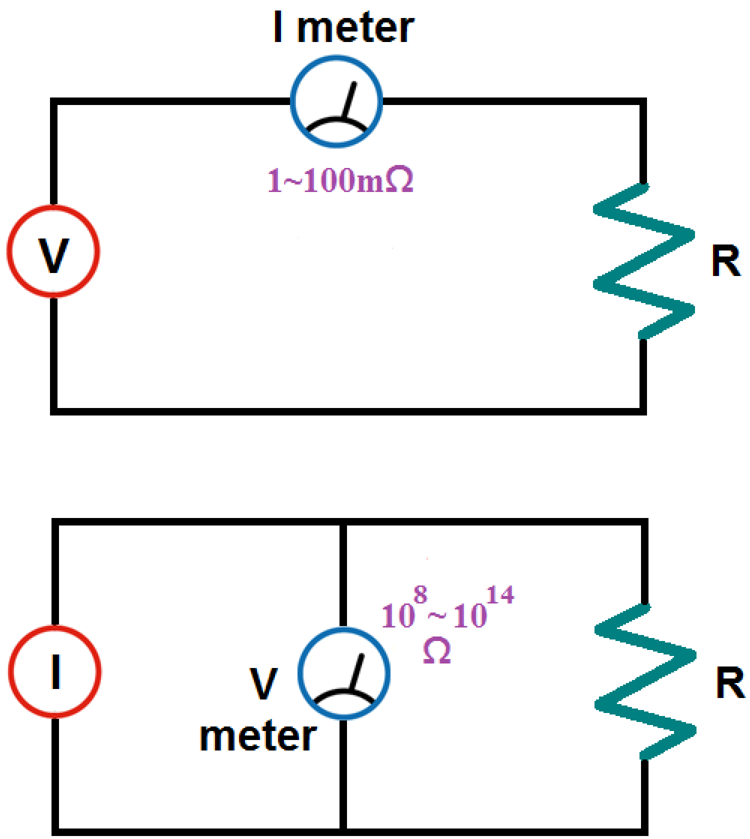
高電阻量測

- 量測電阻的方法:
  - force I measure V (FIMV)
  - force V measure I (FVMI)

- FIMV
  - 電流不能太小
  - I x R 受限於儀器能接受的電壓及待測物的耐壓
  - 此法多應用於 100MΩ以下之量測

- 高電阻量測使用FVMI
  - 運用儀器 low current量測能力
  - 需治具(test fixture) 隔離雜訊之干擾

FVMI / FIMV



高電阻量測

- 材料(絕緣)阻抗與操作電壓有正向比例關係，一般會以指定的高電壓測量，儀器需選用有穩定的高電壓輸出能力

- 應注意事項同低電流量測
- 注意高電壓操作安全

一般改善措施/注意事項

- 電源
  - 電源相位(Line, Neutral, Ground)應安裝正確
  - 注意Neutral與Ground之間的電壓
  - 避免使用延長線串接
- 接地 (Grounding)
  - 良好的接地才能使隔離措施發揮效用
  - 電源線的接地不可拔除
  - 單點接地避免Ground Loop
- 訊號線
  - 訊號線應固定好, 避免晃動
  - 使用正確的訊號線(Coaxial, Triaxial)

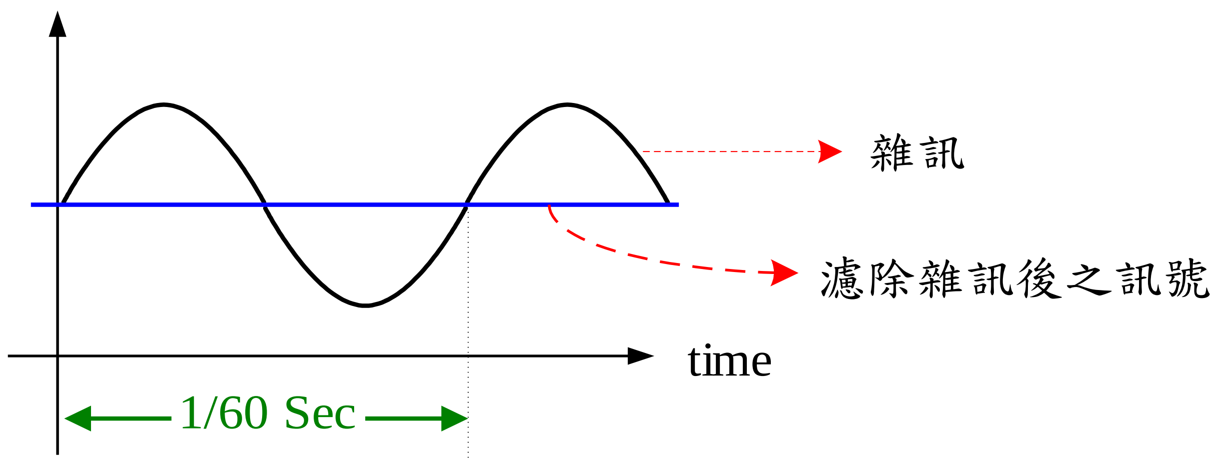
Coaxial vs. Triaxial

- Coaxial Cable (BNC 同軸電纜)
  - RG-58 (一般BNC cable)
  - Keithley 4801 (Low Noise BNC cable)
    多一層特殊絕緣層防止扭動訊號線產生之電流
  - 一般應用BNC cable於nA以上電流之量測

- Triaxial Cable
  - 於nA(含)以下電流之量測會應用Triaxial cable

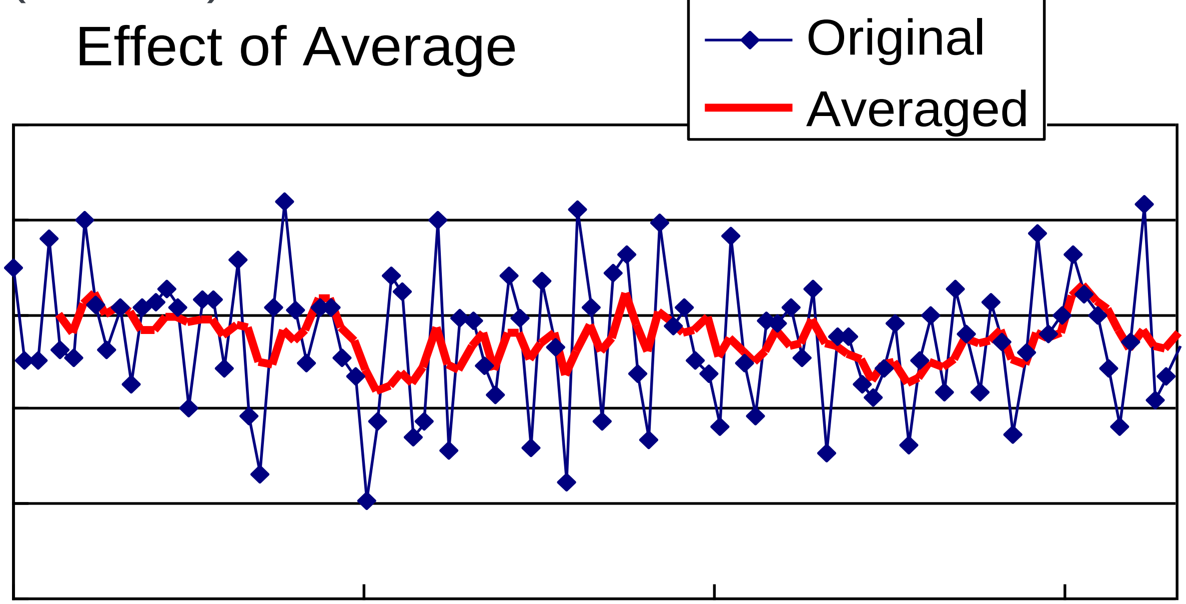
常見雜訊消除方法

- 硬體方式
  - Low Pass Filter (低通濾波器)
    有些儀器內建有濾波器
  - Integration (積分)
    Integration 適用於電源及其諧波之類(週期性)的雜訊
    積分時間須為電源週期 (16.67m sec = 1PLC) 之倍數



常見雜訊消除方法

- 數位方式
  - Average (平均) --- digital filter
  - 適用於隨機(random)的雜訊



排除量測誤差

如何避免常見的量測誤差

1 量測類型及應用		2 誤差現象	3 可能原因	4 改善方式
低電壓	標準電池比對 約瑟夫森接面電壓陣列 溫度測量 熱電動勢 繼電器/連接器之接觸電壓 磁電動勢	偏置電壓	熱電動勢	保持所有接點在相同溫度，使用銅-銅接點
		讀值不穩定	熱電動勢	保持所有接點在相同溫度，使用銅-銅接點
			磁場干擾	改採雙絞線連結，排除或屏蔽磁場。
			接地不佳，形成迴路	單點接地，避免地線迴路
低電流	離子/電子流 穿遂電流 元件漏電流 光電偵測器電流 絕緣層漏電流/崩潰電壓 MOS Charge Pumpiing 電流 準靜態電容 摩擦/壓電感應電流	偏置電流	絕緣層漏電	清潔/選擇高品質的絕緣體，採用防護技術
			儀錶本身電流	選用微電流錶/高阻計(Electrometer)
			偵測器暗電流	使用儀錶之REL功能
		讀值不穩定	靜電感應	屏蔽，避免移動並移除附近高壓源
			振動/變形 輸入電容過大 偏置電流漂移	排除振動/使用低雜訊電纜 使用分流電流錶或增加串連電阻 保持恆溫
		低電壓之增益誤差	儀器內阻之壓降	使用反饋式電流錶，使用較高檔位
低電阻	超導電阻 金屬 材料斷裂/疲勞 搭接電阻 繼電器/連接器電阻	偏置電阻	探棒電阻	四線式量測(Kelvin四線接法)
		讀數漂移	熱電動勢	採用脈衝訊號 (Delta模式/偏置補償)
		讀值不穩定	磁場干擾	改採雙絞線連結，屏蔽或遠離磁場。
高電阻	絕緣電阻 表面絕緣 (PCB, 電路板, 封裝) 材料電阻率 聚合物導電性 體電阻/面電阻 四點探針量測 擴散電阻	讀值過低	夾具電阻與DUT並聯	採用更高絕緣電阻的夾具及電纜，使用Guard電路
			電壓錶壓輸入阻抗過低	使用送電壓量電流方式
			偏置電流	使用儀錶之REL功能， 使用正反向測試電壓再平均
		讀值不穩定	靜電感應	屏蔽，避免移動或靠近波動電壓源
			共模電流	單點接地，避免地線迴路，使用濾波功能
電壓量測 (含高阻源)	pH或離子選擇電極 介電吸收 場效電晶體閘級電壓 霍爾效應	讀值過低 (負載誤差)	並聯電阻	採用更高絕緣電阻的夾具及電纜， 使用Guard電路
			偏置電流	使用高阻計(Electrometer)
		讀值不穩定	靜電感應	屏蔽，避免移動或靠近波動電壓源
			儀器產生之波動電流	使用高阻計(Electrometer)