



POLITECNICO DI MILANO

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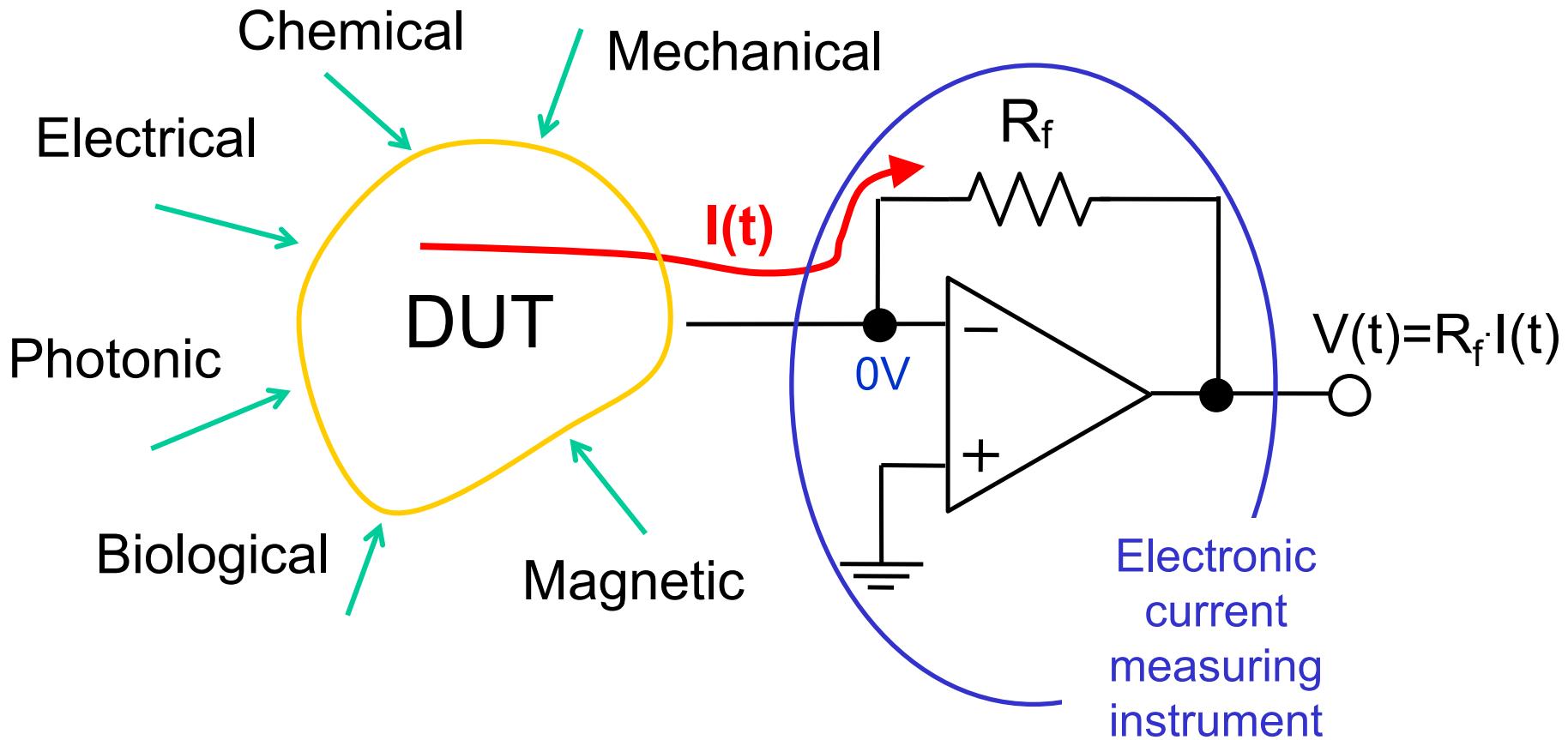
Advanced course on

HIGH RESOLUTION ELECTRONIC MEASUREMENTS IN NANO-BIO SCIENCE

MEASURING SMALL CURRENTS

Marco Sampietro

CURRENT MEASUREMENT



Down to very low levels

- Up to high frequencies

Problems/Error sources/Noise



Precision/Resolution

LESSON GUIDELINE

Instrument architectures

- Passive (shunt) ammeters 15 min
- Active current-to-voltage converter

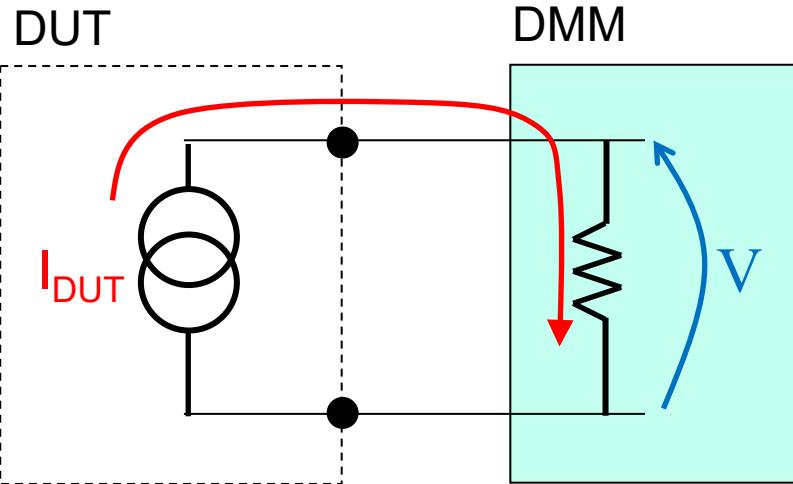
The TransImpedance Amplifier (TIA)

- Signal precision, Bandwidth 25 min
- Noise considerations

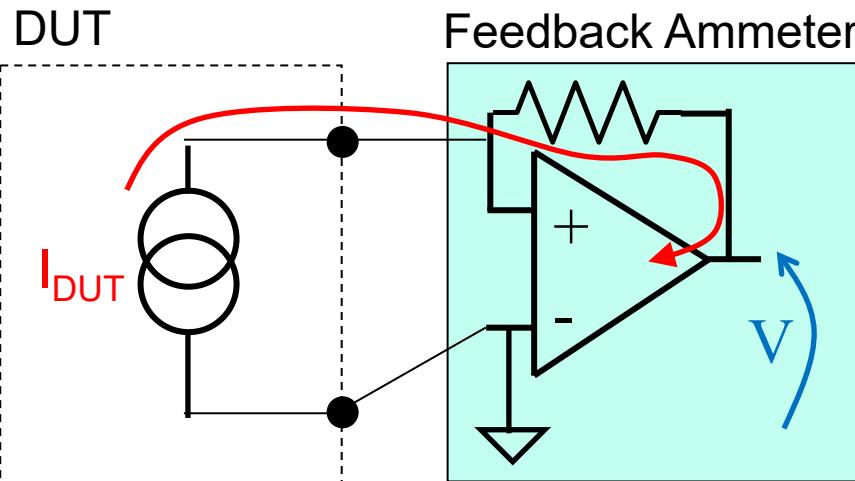
Tips and Tricks on the connections

- Coaxial and triaxial cables
- Guarded measurements 5 min

HOW to MEASURE SMALL CURRENTS



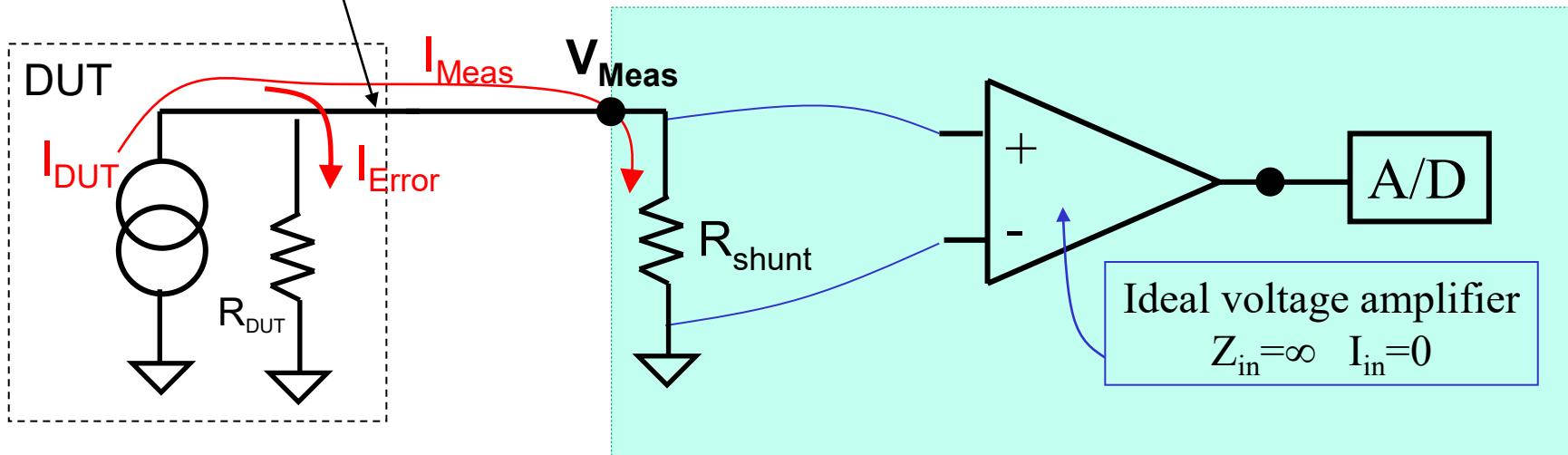
PASSIVE conversion of
CURRENT-into-VOLTAGE
(Shunt Ammeter, DMM)



ACTIVE conversion of
CURRENT-into-VOLTAGE
with feedback circuit
(Electrometers, SMU, Current
amplifiers, Integrated lab-on-
chips)

PASSIVE current-to-voltage converter (Ammeter)

Voltage across the DUT changes ($10\text{nA}, R_{shunt}=100\text{k}\Omega \rightarrow V_{meas}=1\text{mV}$)



Disadvantages :

To measure small I_{DUT} we need high value R_{shunt} but ...

Disturbs the experiment (*Voltage burden*)

Error in the measured current : $I_{Error}=V_{meas}/R_{DUT}$

↳ If $R_{DUT}/R_{shunt}=100$, measurement error due to the shunt is 1%

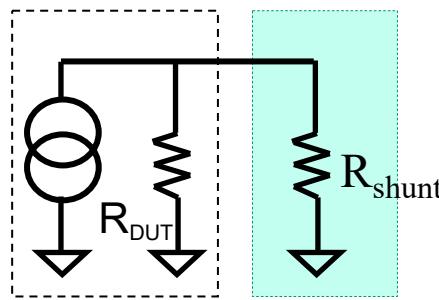


R_{shunt} the smallest as possible

Example of passive (shunt) Ammeters

Keithley 2001 7½-Digit High Performance Multimeter

Range	Full Scale	Resolution	Default Resolution	Maximum Burden Voltage ⁶
200 μ A	210.00000 μ A	10 pA	100 pA	0.25 V
2 mA	2.100000 mA	100 pA	1 nA	0.31 V
20 mA	21.000000 mA	1 nA	10 nA	0.4 V
200 mA	210.00000 mA	10 nA	100 nA	0.5 V
2 A	2.1000000 A	100 nA	1 μ A	1.5 V



$R_{\text{shunt}} \sim 1 \text{ k}\Omega$

If $R_{\text{DUT}} = 100 \text{ k}\Omega$
 $\text{error}_{\max} \sim 2 \mu\text{A}$
 $\gg \text{Resolution}$

\downarrow
 2.5Ω

Keithley 6485 Picoammeter



RANGE	5½ DIGIT DEFAULT RESOLUTION	ACCURACY (1YR) ¹	TYPICAL RMS NOISE ²	ANALOG RISE TIME ³ (10% to 90%)
		$\pm(\% \text{ RDG.} + \text{ OFFSET})$ $18^\circ\text{--}28^\circ\text{C}, 0\text{--}70\%$ RH		
2 nA	10 fA	0.4 % + 400 fA	20 fA	8 ms
20 nA	100 fA	0.4 % + 1 pA	100 fA	8 ms
200 nA	1 pA	0.2 % + 10 pA	1 pA	500 μ s
2 μ A	10 pA	0.15% + 100 pA	10 pA	500 μ s
20 μ A	100 pA	0.1 % + 1 nA	100 pA	500 μ s
200 μ A	1 nA	0.1 % + 10 nA	1 nA	500 μ s
2 mA	10 nA	0.1 % + 100 nA	10 nA	500 μ s
20 mA	100 nA	0.1 % + 1 μ A	100 nA	500 μ s

R_{shunt}

100 k Ω

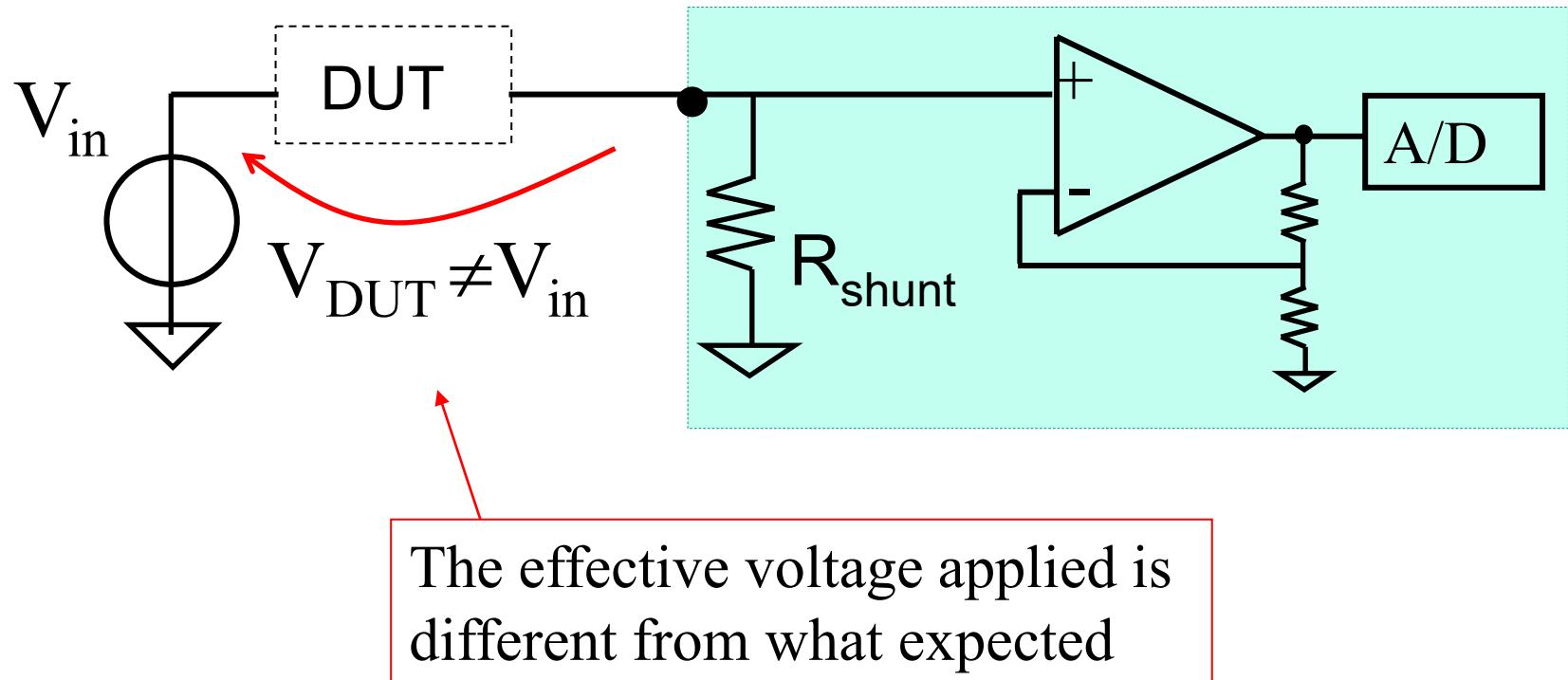
$R_{\text{DUT}} > 1 \text{ M}\Omega$

1 Ω

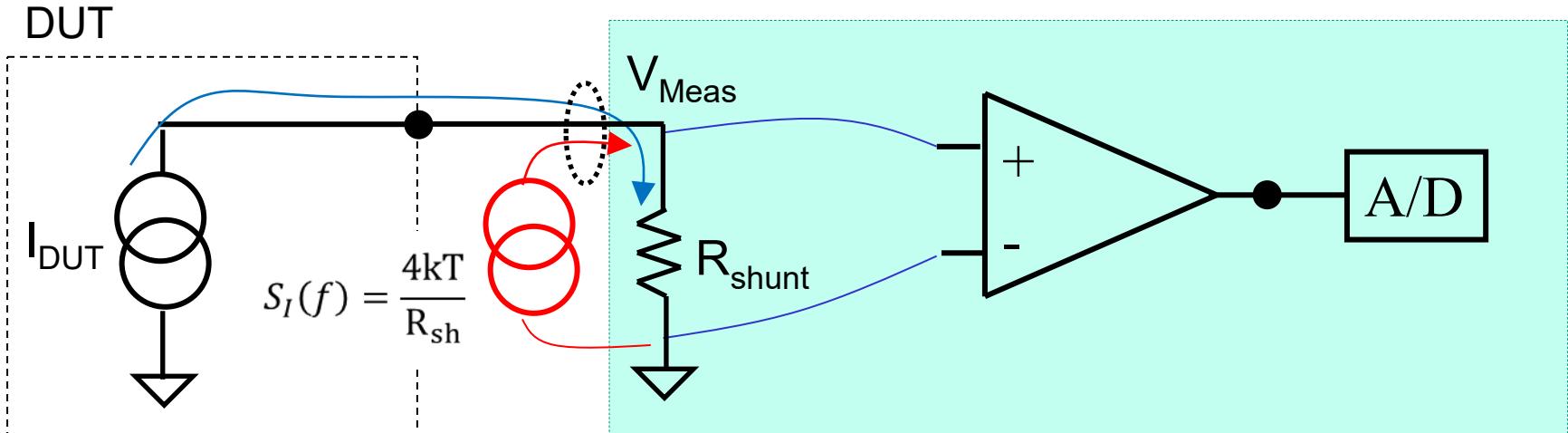
1000 times
better

INPUT VOLTAGE BURDEN: < 200 μ V on all ranges except < 1 mV on 20 mA range

Beware in your experiment of V_{burden}



NOISE in passive (shunt) Ammeters



R_{shunt} , Amplifier and ADC very stable over time and temperature

In commercial DMM R_{shunt} adds negligible noise (on 1Hz BW)

Range	Full Scale	Resolution	Default Resolution	Maximum Burden Voltage ⁶
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2 mA	2.1000000 mA	100 pA	1 nA	0.31 V
20 mA	21.000000 mA	1 nA	10 nA	0.4 V
200 mA	210.00000 mA	10 nA	100 nA	0.5 V
2 A	2.1000000 A	100 nA	1 μ A	1.5 V

$$\begin{aligned} R_{shunt} &\sim 1 \text{ k}\Omega \\ &\downarrow \\ &2.5 \Omega \end{aligned}$$

4 pA

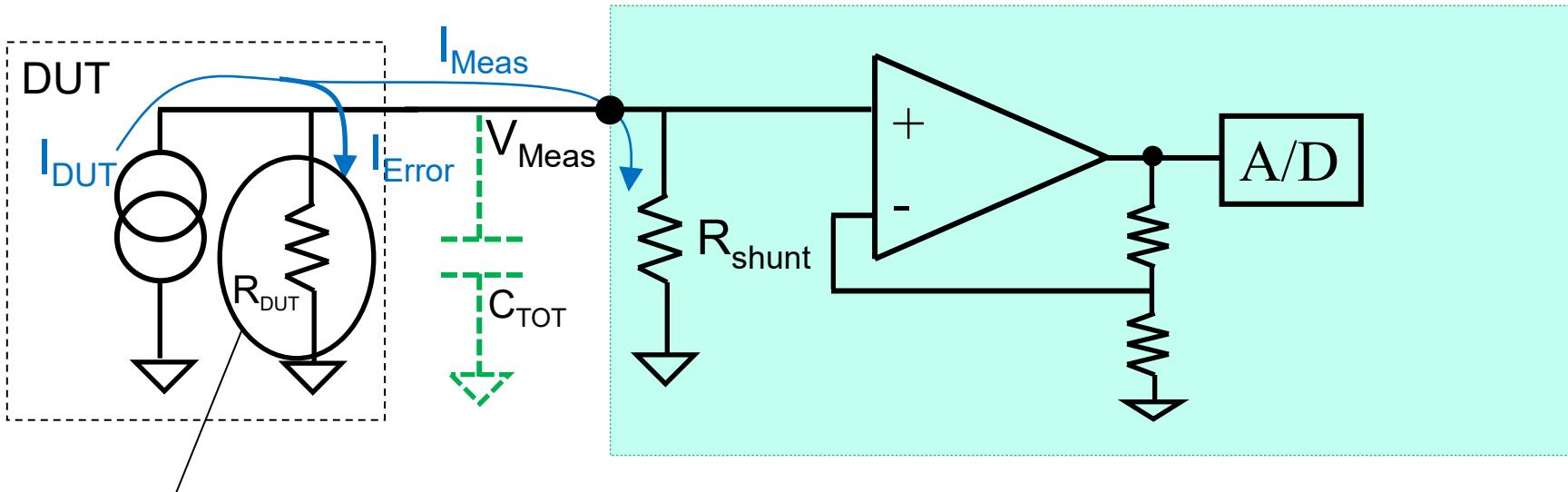
↓

80 pA

Larger R_{shunt} is beneficial to S/N : $\frac{S}{N} \propto \frac{I_{DUT}}{\sqrt{\frac{4kT}{R_{shunt}} \cdot BW}} \propto \sqrt{R_{shunt}}$

Bandwidth of PASSIVE I-to-V CONVERTER

Despite small R_{shunt} (that would permit high operating frequency), resolution is ensured only at very low BW



DUT with high output resistance

Range	Full Scale	Resolution	Default Resolution	Maximum Burden Voltage ⁶
200 μA	210.00000 μA	10 pA	100 pA	0.25 V
2 mA	2.100000 mA	100 pA	1 nA	0.31 V
20 mA	21.000000 mA	1 nA	10 nA	0.4 V
200 mA	210.00000 mA	10 nA	100 nA	0.5 V
2 A	2.1000000 A	100 nA	1 μA	1.5 V

$$R_{\text{shunt}} \rightarrow \text{BW} = 6.25 \text{ Hz}$$

\downarrow

$$2.5 \Omega$$

LESSON GUIDELINE

Instrument architectures

- Passive (shunt) ammeters 15 min
- Active current-to-voltage converter

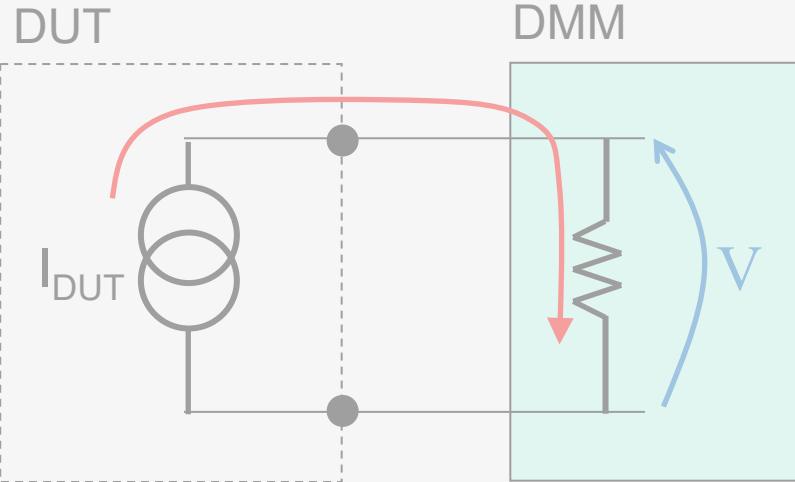
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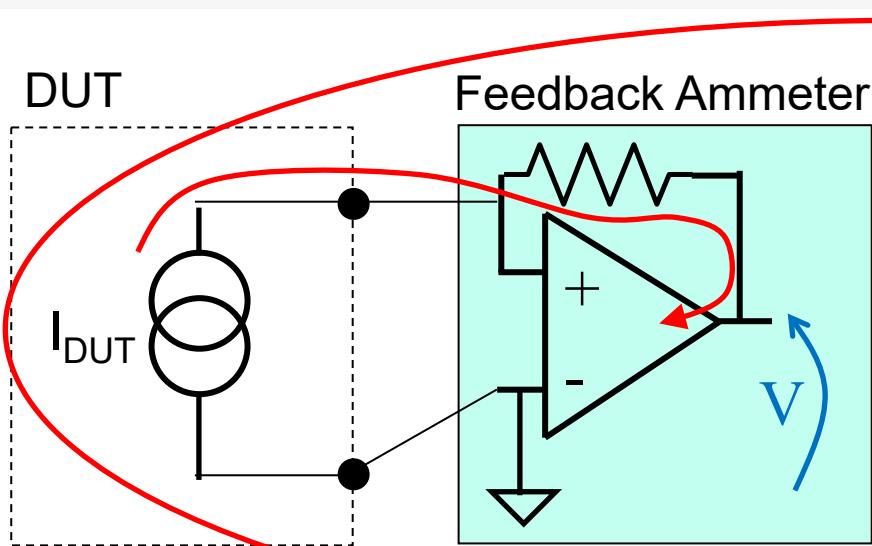
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HOW to MEASURE SMALL CURRENTS

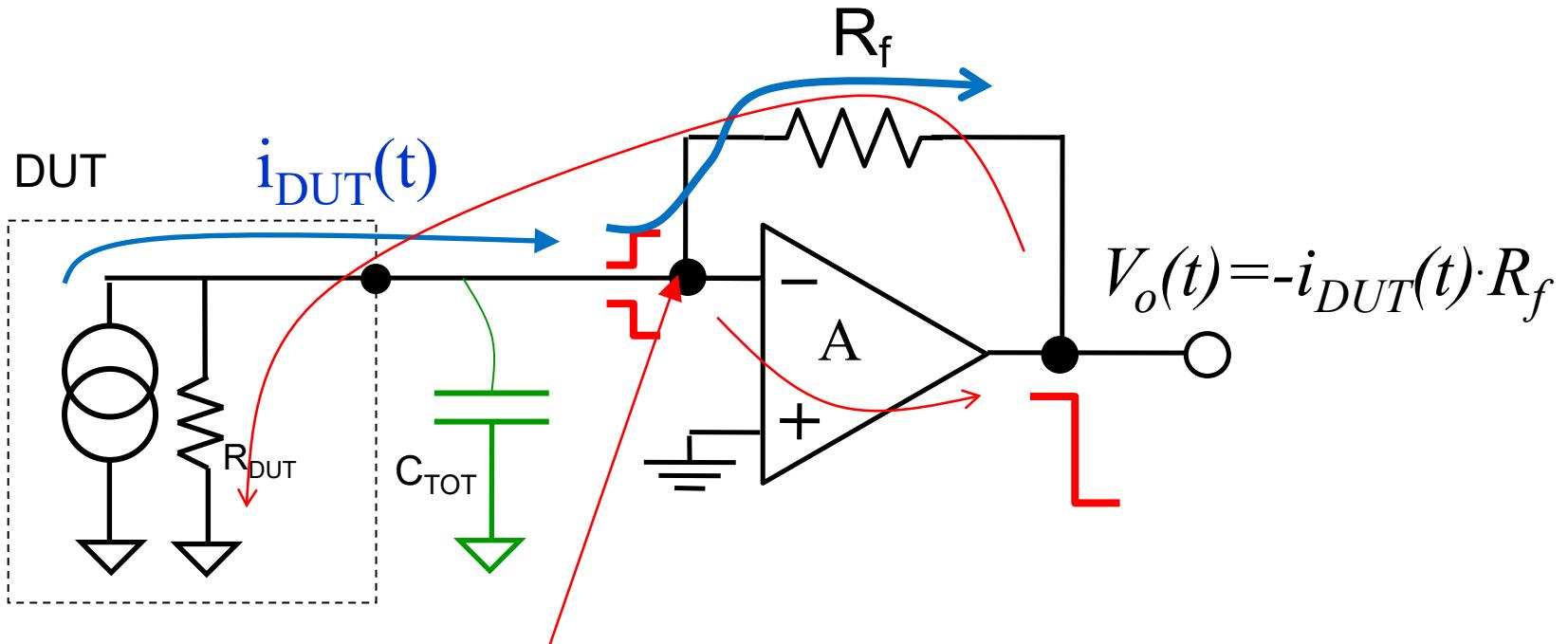


PASSIVE conversion of
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ACTIVE conversion of
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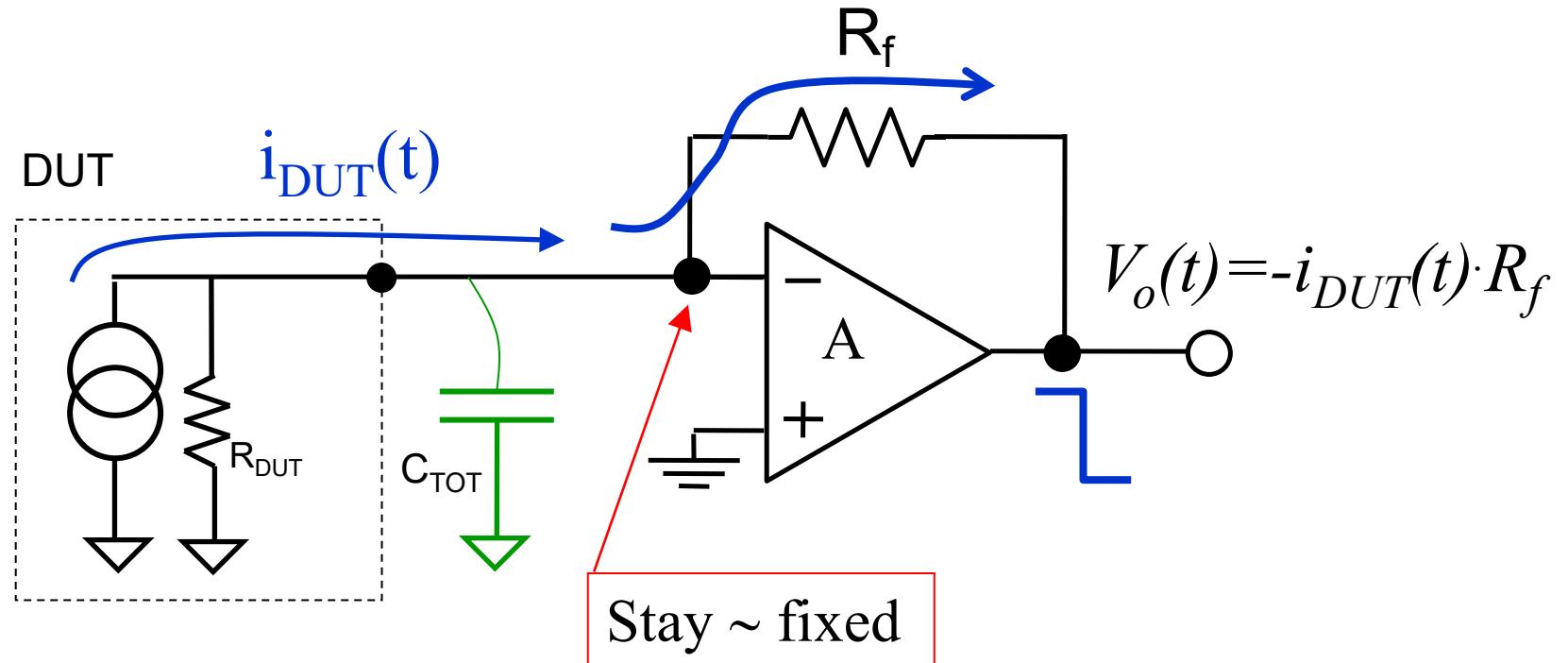
The ideal TRANSIMPEDANCE AMPLIFIER



Practically does NOT move (ideal) : NO voltage Burden

Very low input impedance, ideal for absorbing currents
(i.e. ideal for practical sources with low R_{DUT} !)

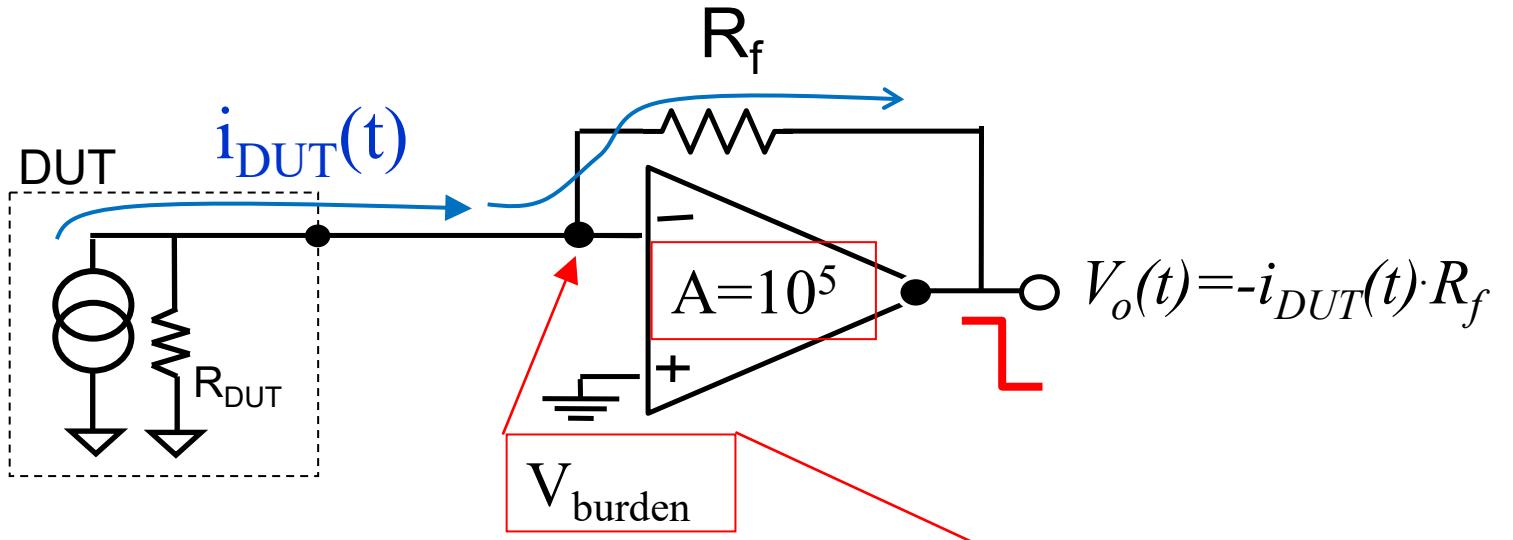
CURRENT SENSING with a TRANSIMPEDANCE AMPLIFIER



sensitivity \Rightarrow large R_f precision \Rightarrow stable R_f

... for a large range of R_{DUT} and C_{TOT}

CURRENT SENSING with a TRANSIMPEDANCE AMPLIFIER



Ex. : $i_{DUT} 2\text{nA} \rightarrow R_f = 100\text{k}\Omega \rightarrow V_o = 200\mu\text{V} \rightarrow V_{DUT} = 2\text{nV}$ (Burden)

To be compared with previous:

RANGE	5½ DIGIT DEFAULT RESOLUTION	ACCURACY (1YR) ¹	TYPICAL RMS NOISE ²	ANALOG RISE TIME ³ (10% to 90%)	R_{shunt}
		$\pm(\% RDG. + OFFSET)$ $18^\circ\text{--}28^\circ\text{C}, 0\text{--}70\% RH$			
2 nA	10 fA	0.4 % + 400 fA	20 fA	8 ms	100 kΩ $V_{BURDEN} < 200\mu\text{V}$

Higher «amplification»

Less noise of following stages

Ex. : $i_{DUT} 2\text{nA} \rightarrow R_f = 100\text{M}\Omega \rightarrow V_o = 200\text{mV} \rightarrow V_{DUT} = 2\mu\text{V}$ (Burden)

FRONT-END of most quality INSTRUMENTS

Picoammeter



SMU



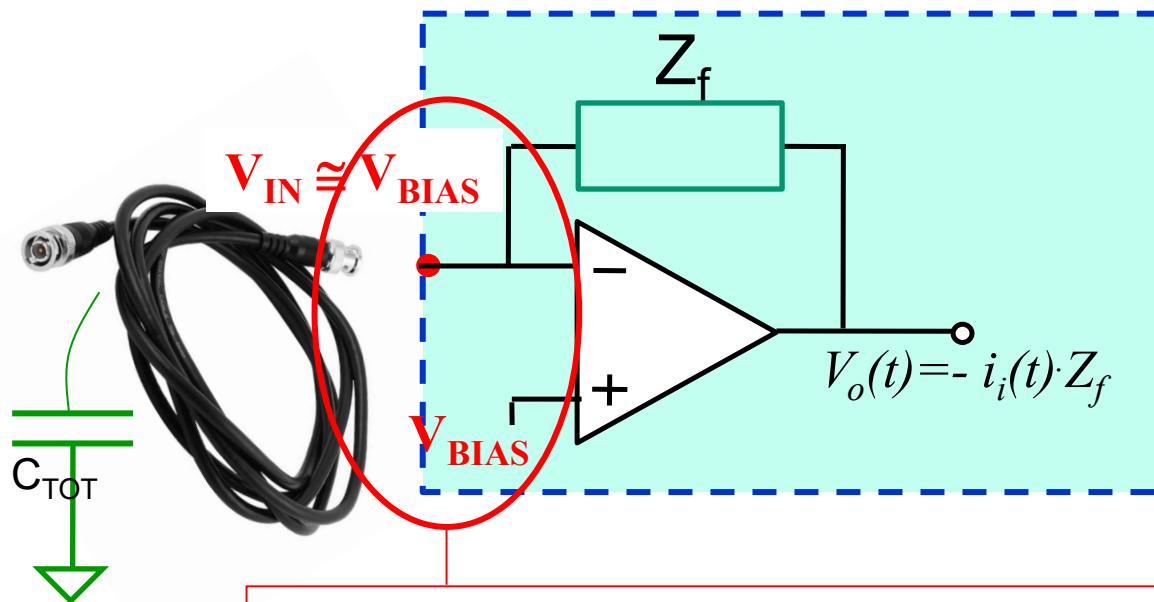
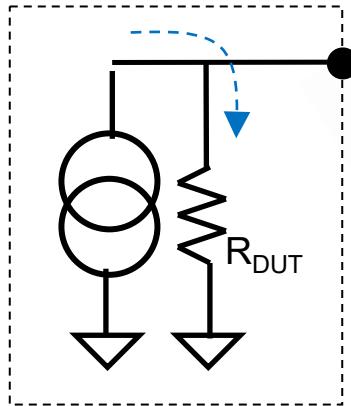
Potentiostat



LCR meter

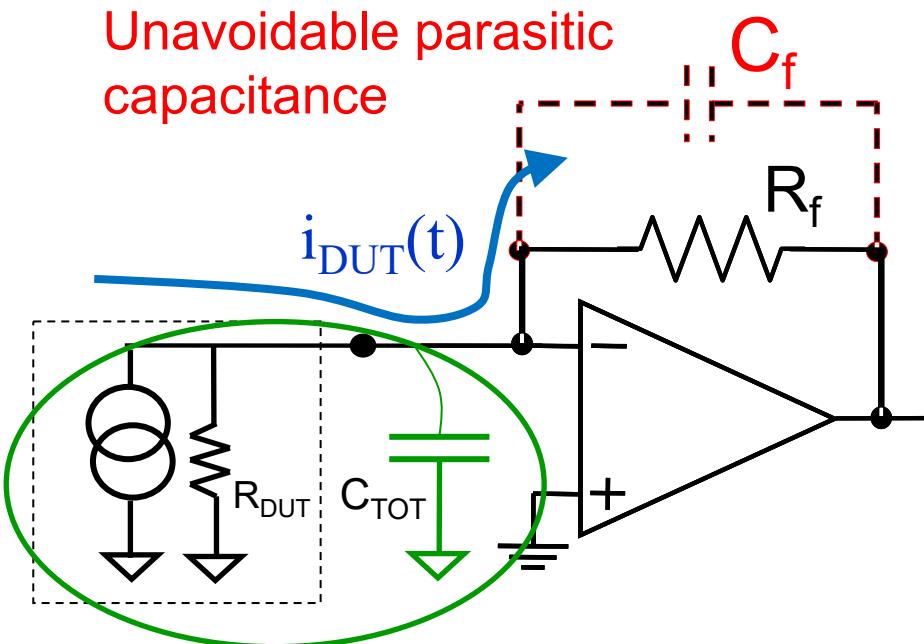


DUT

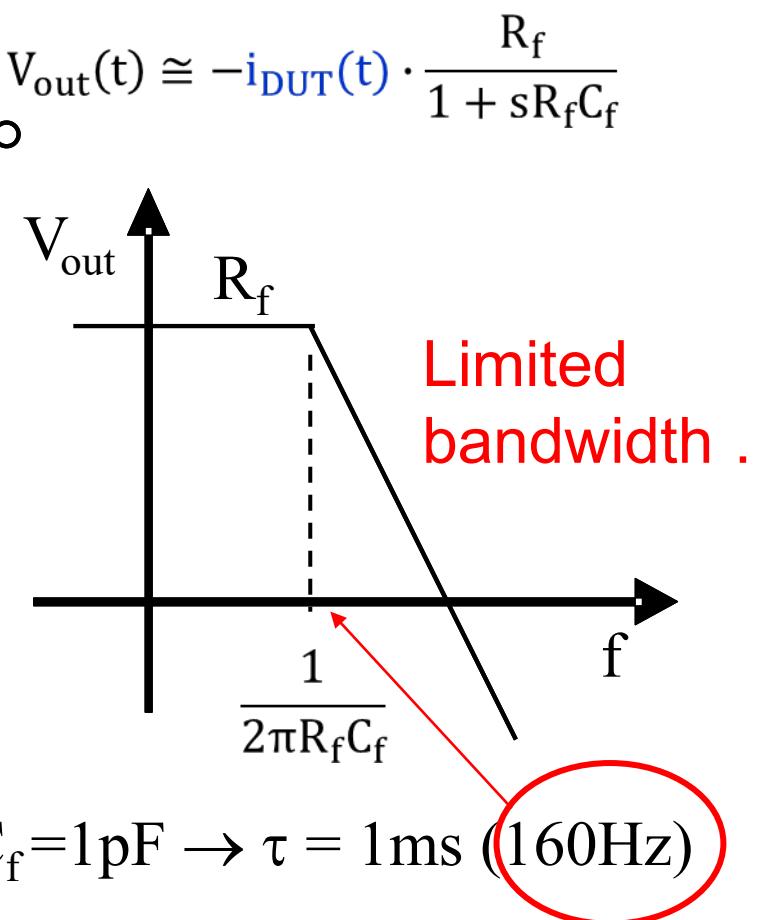


DC input voltage can be set at your will

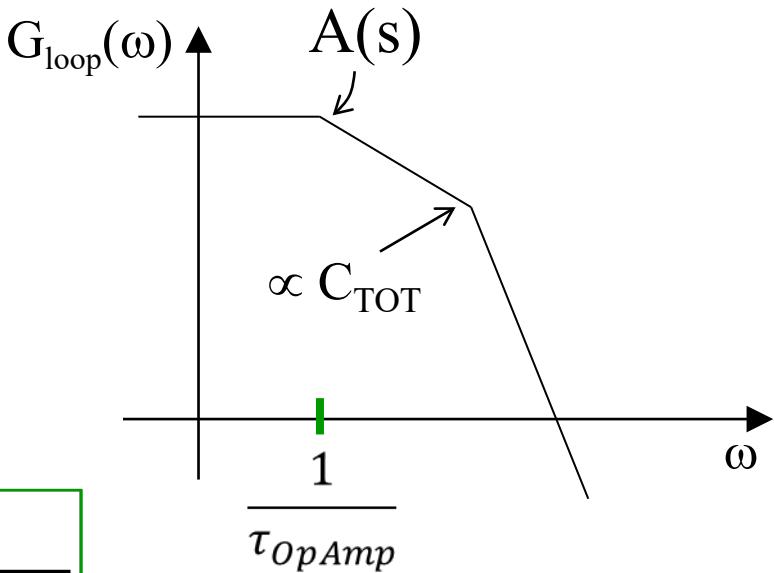
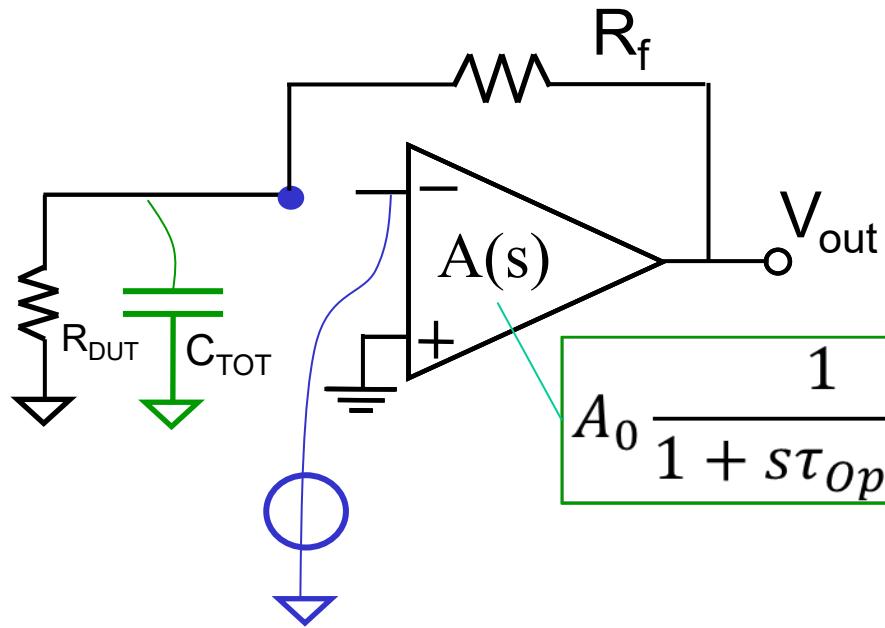
FREQUENCY RESPONSE : ideal case



... but ~ independent of setup

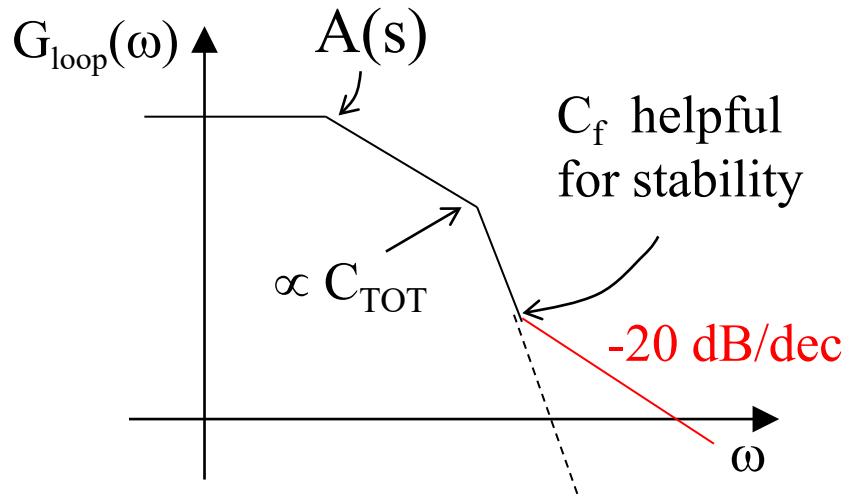
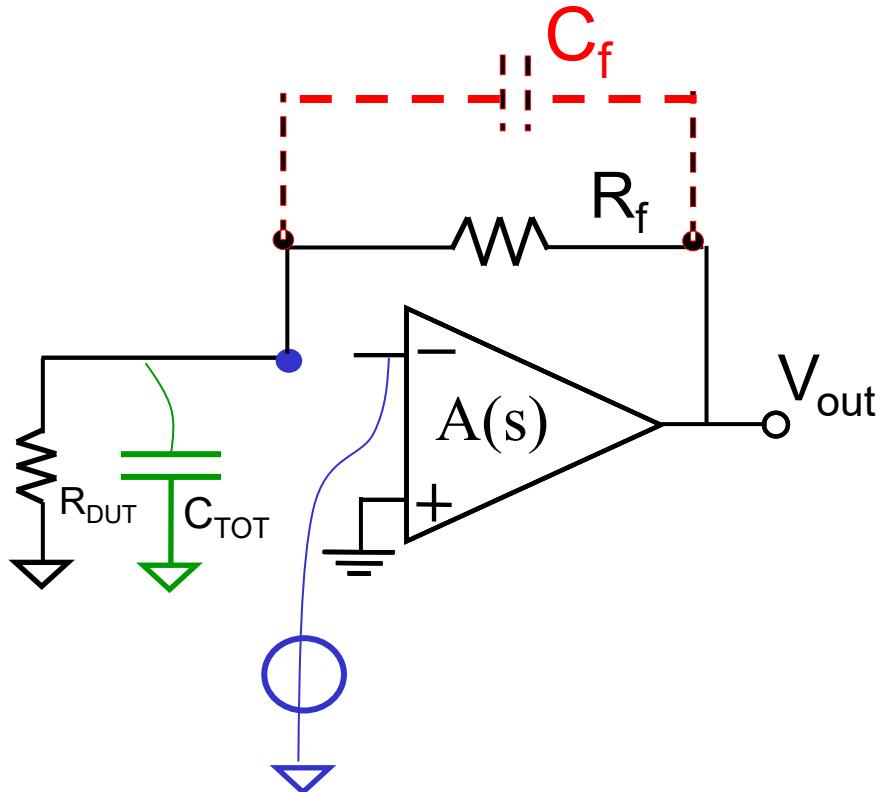


STABILITY CONSIDERATIONS



$$G_{\text{loop}}(s) = \frac{A_0 R_{DUT}}{R_{DUT} + R_f} \cdot \frac{1}{1 + s\tau_{OpAmp}} \cdot \frac{1}{1 + sC_{TOT} \frac{R_{DUT}R_f}{R_{DUT} + R_f}}$$

STABILITY CONSIDERATIONS

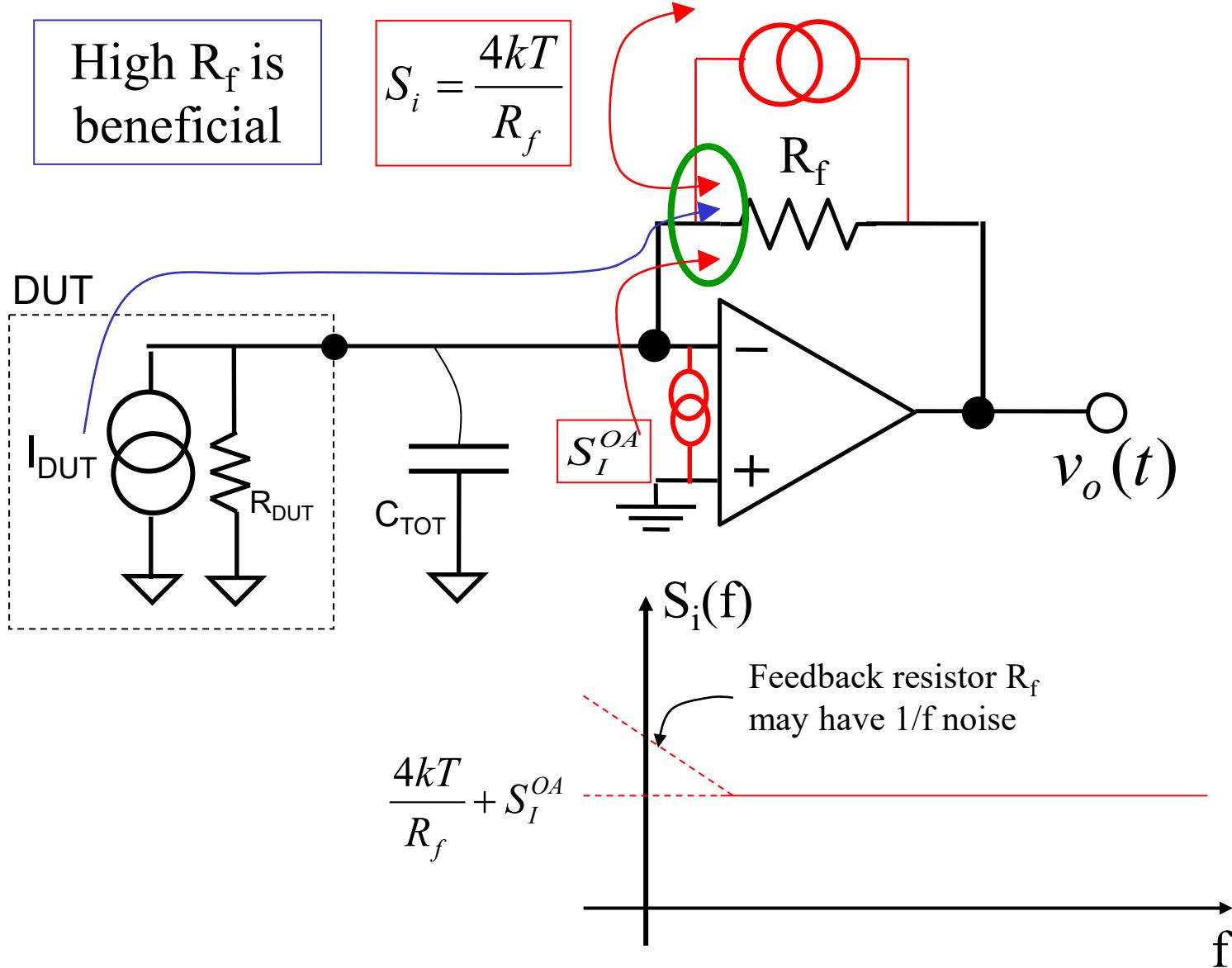


$$G_{\text{loop}}(s) = \frac{A_0 R_{\text{DUT}}}{R_{\text{DUT}} + R_f} \cdot \frac{1}{1 + s\tau_{\text{opamp}}} \cdot \frac{1 + sC_f R_f}{1 + s(C_f + C_{\text{TOT}}) \frac{R_{\text{DUT}} R_f}{R_{\text{DUT}} + R_f}}$$

NOISE ANALYSIS - PARALLEL NOISE

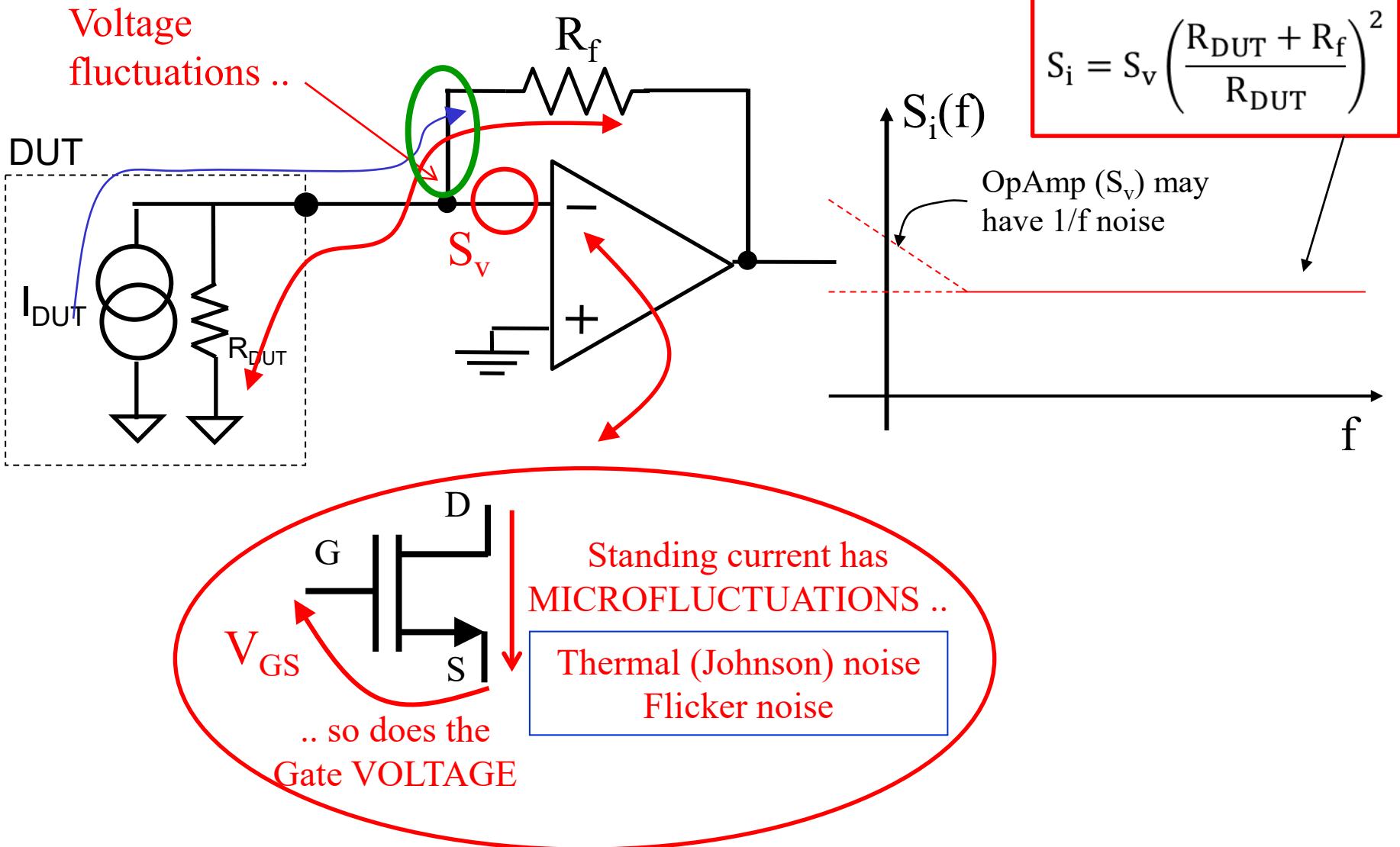
High R_f is beneficial

$$S_i = \frac{4kT}{R_f}$$



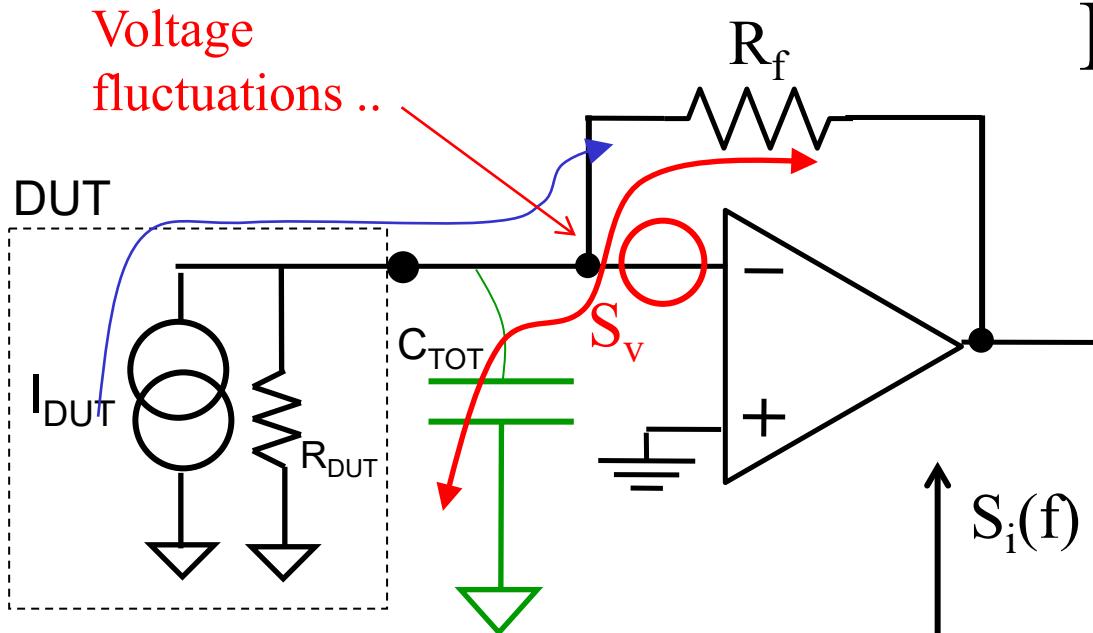
NOISE ANALYSIS - SERIES NOISE

.. produce an additional fluctuating current that mixes with signal



NOISE ANALYSIS - SERIES NOISE : Effect of CAPACITANCE

.. produce an additional fluctuating current that mixes with signal



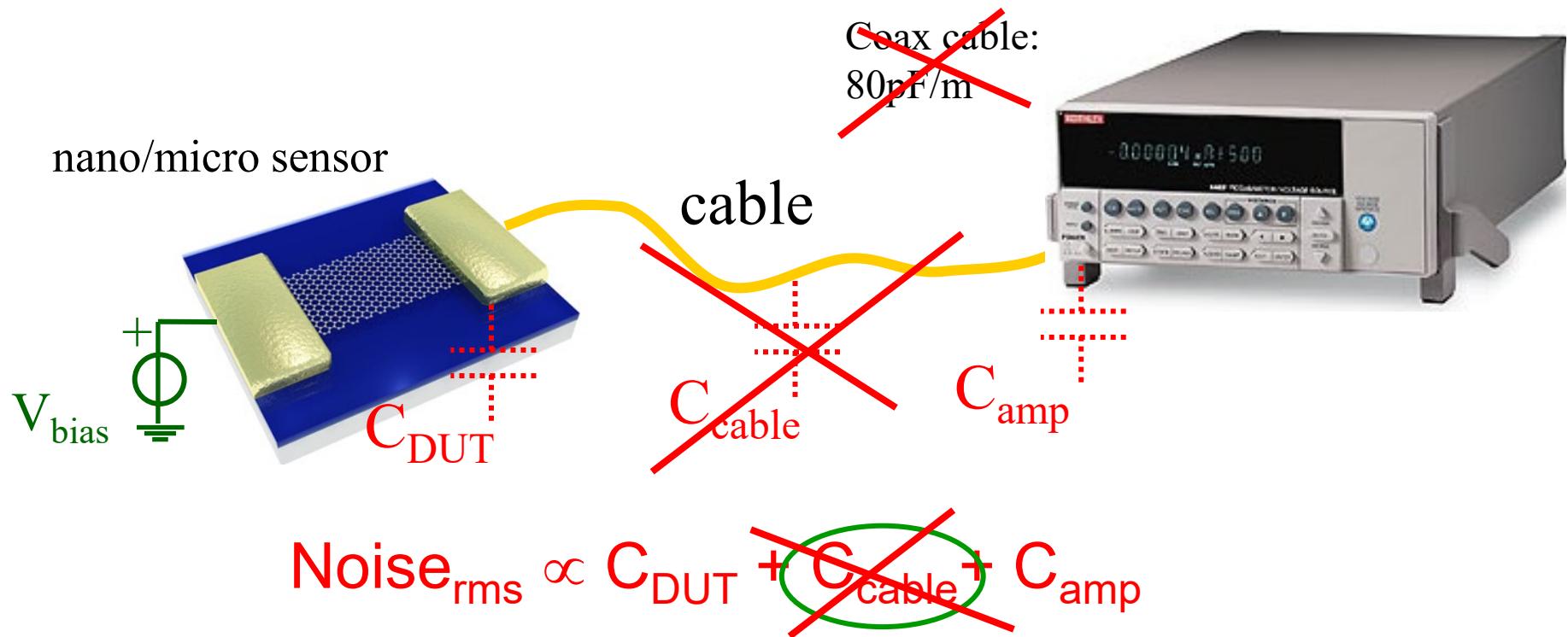
$$I_{noise} = C \cdot \frac{dV_G}{dt}$$

Keep ALL capacitances small !

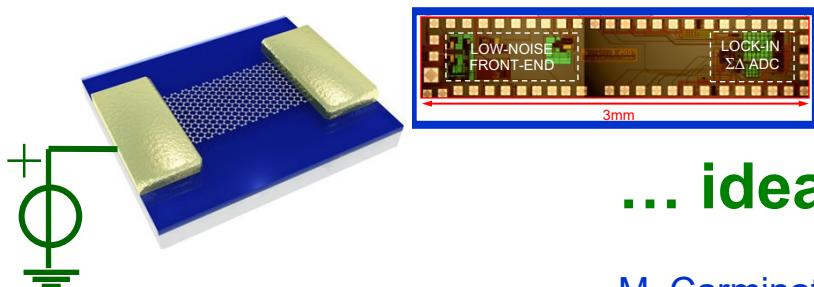
Noise increases with CAPACITANCE



Design RULE in nano-bio-sensor experiments

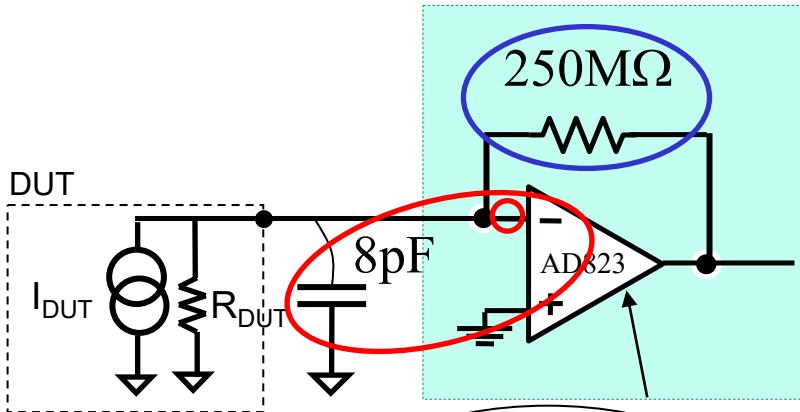


Parasitic should go nano...so ELECTRONICS should go nano



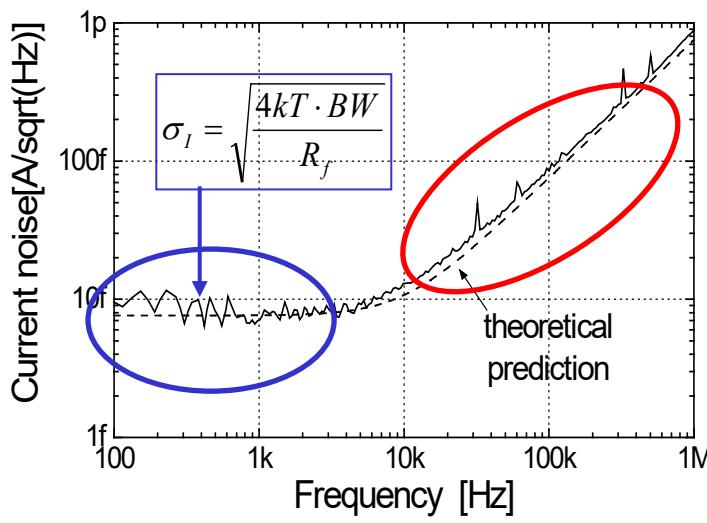
... ideally merging into the sensor

Effect of INPUT CAPACITANCE on NOISE



$$S_V = (12\text{nV})^2/\text{Hz}$$

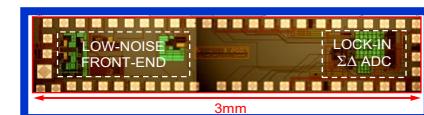
$$S_I = (3\text{fA})^2/\text{Hz}$$



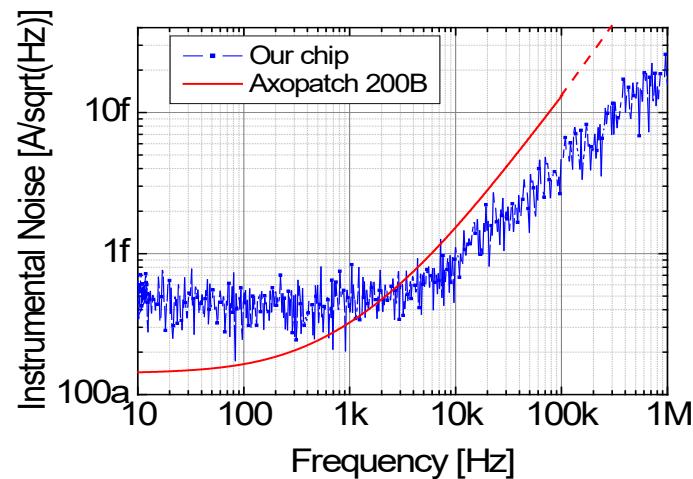
Instrumental noise can be very low
(if no DUT nor cable connected)
irrespective of being a chip or bulky



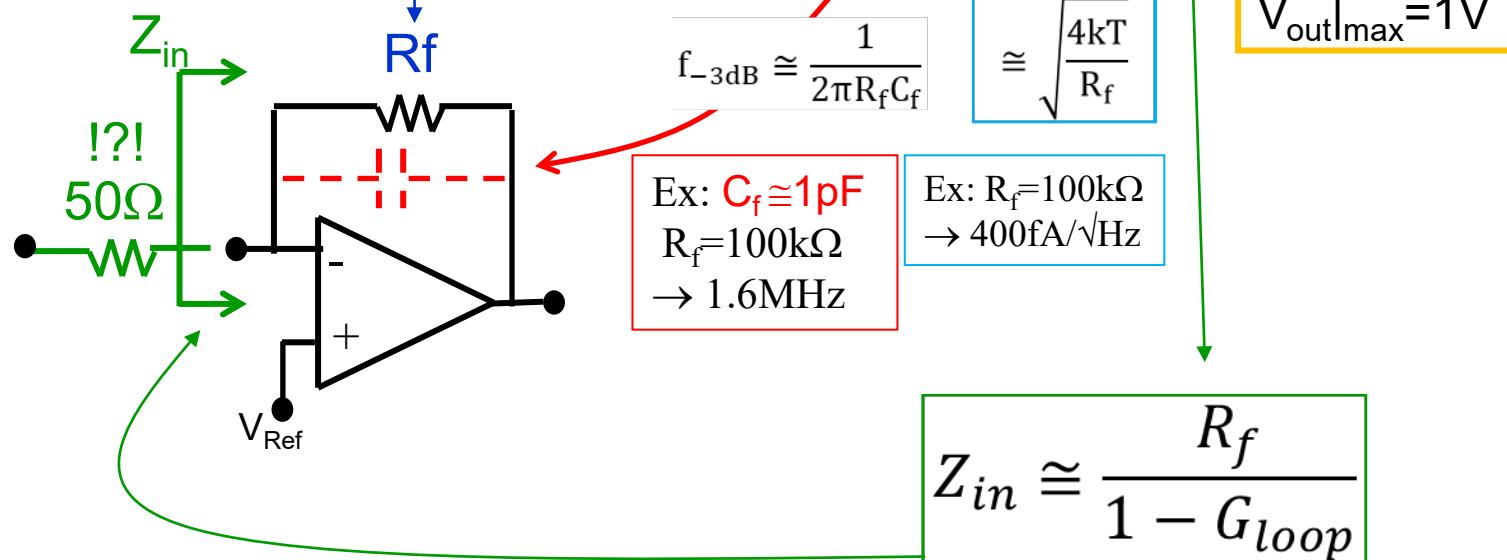
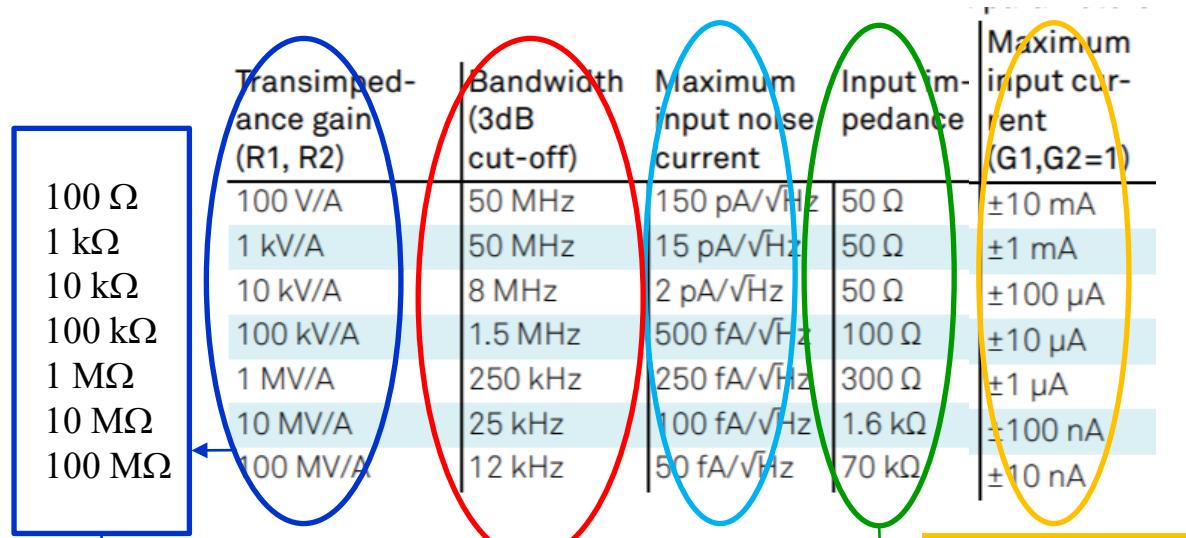
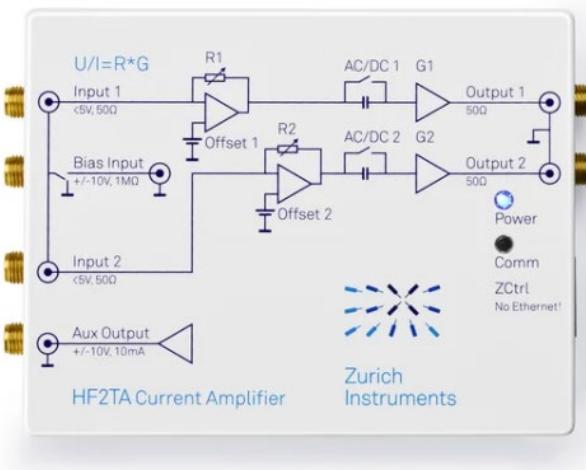
Axopatch 200B



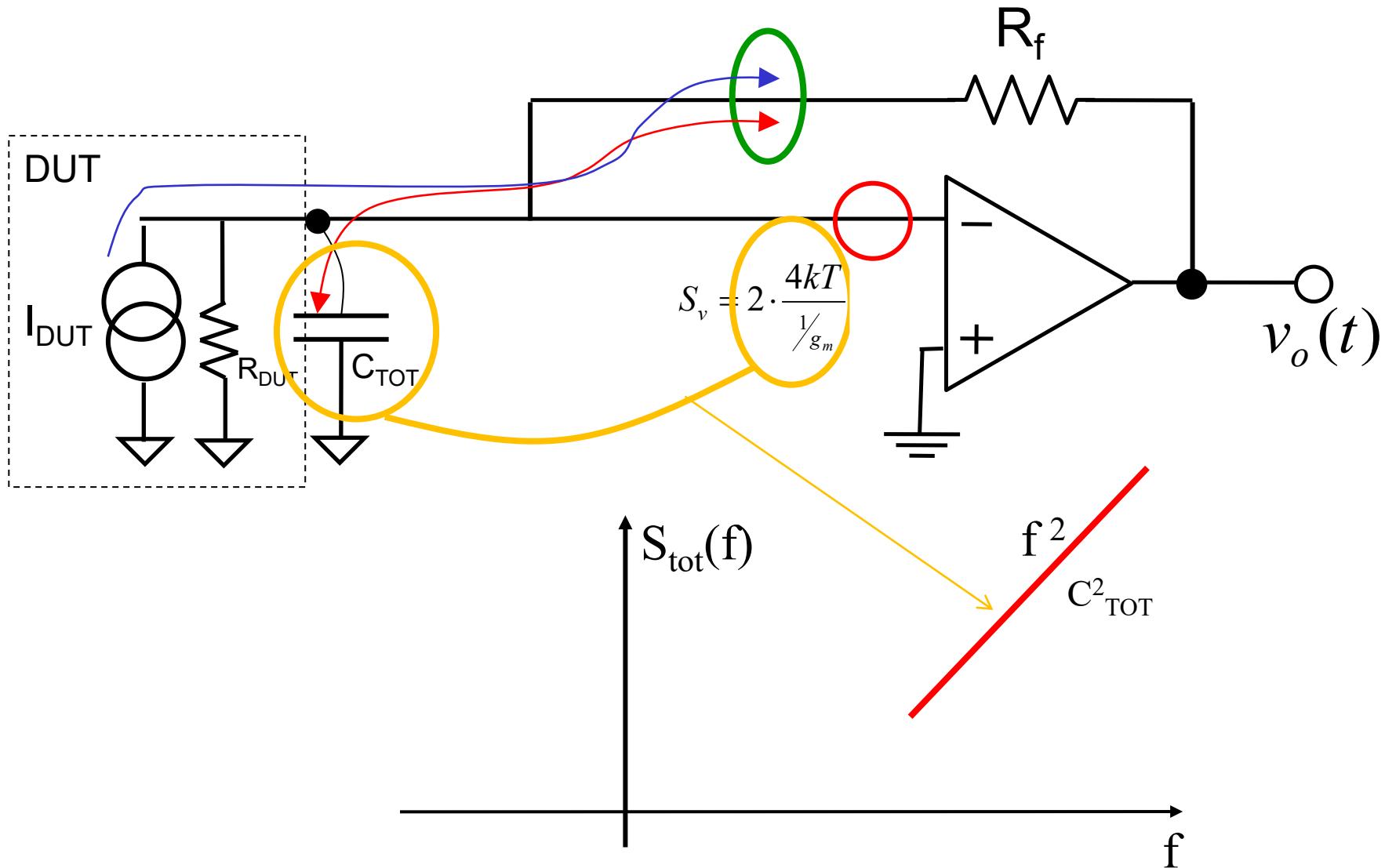
POLIMI Pe7



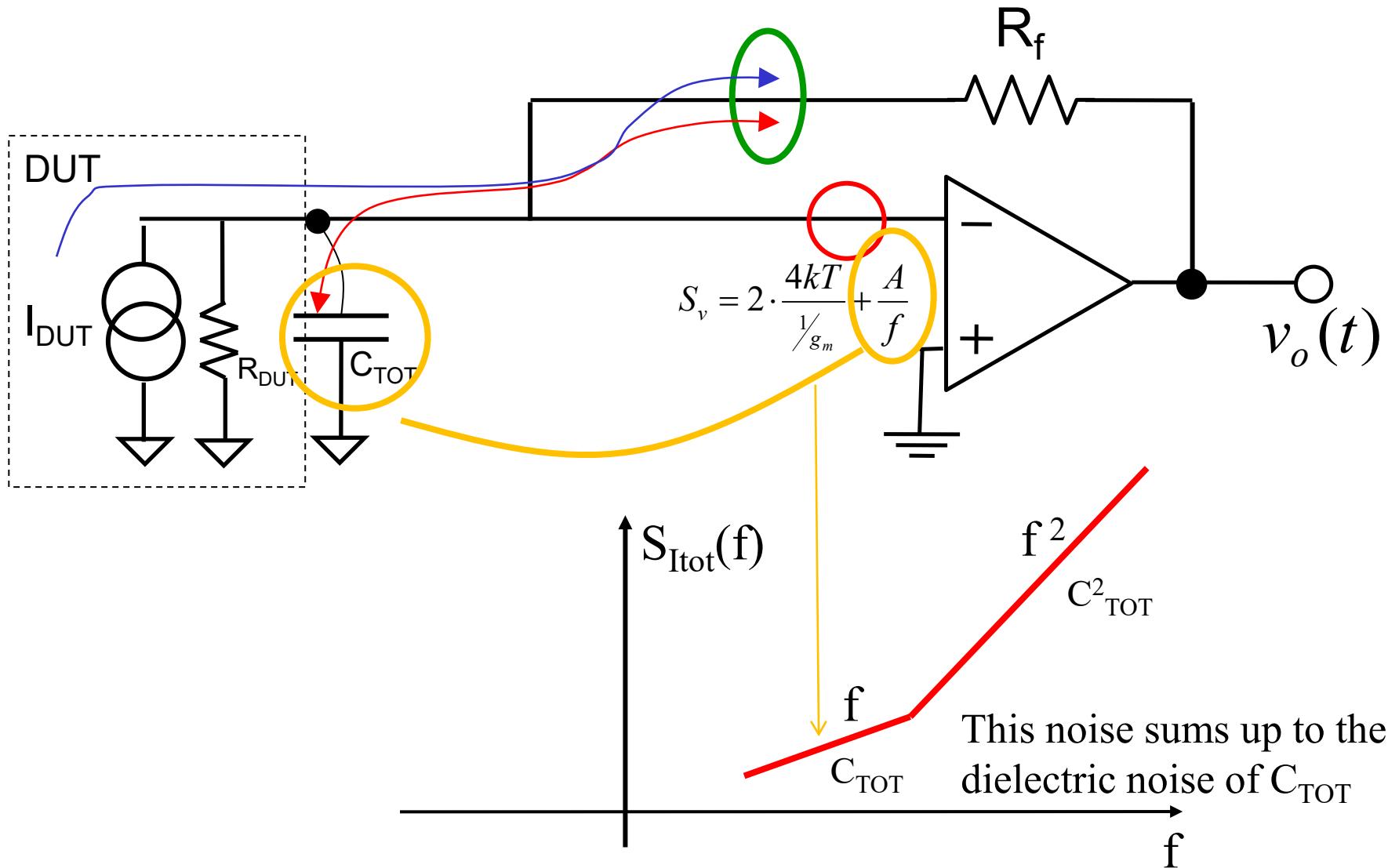
Reading specs of a commercial TIA



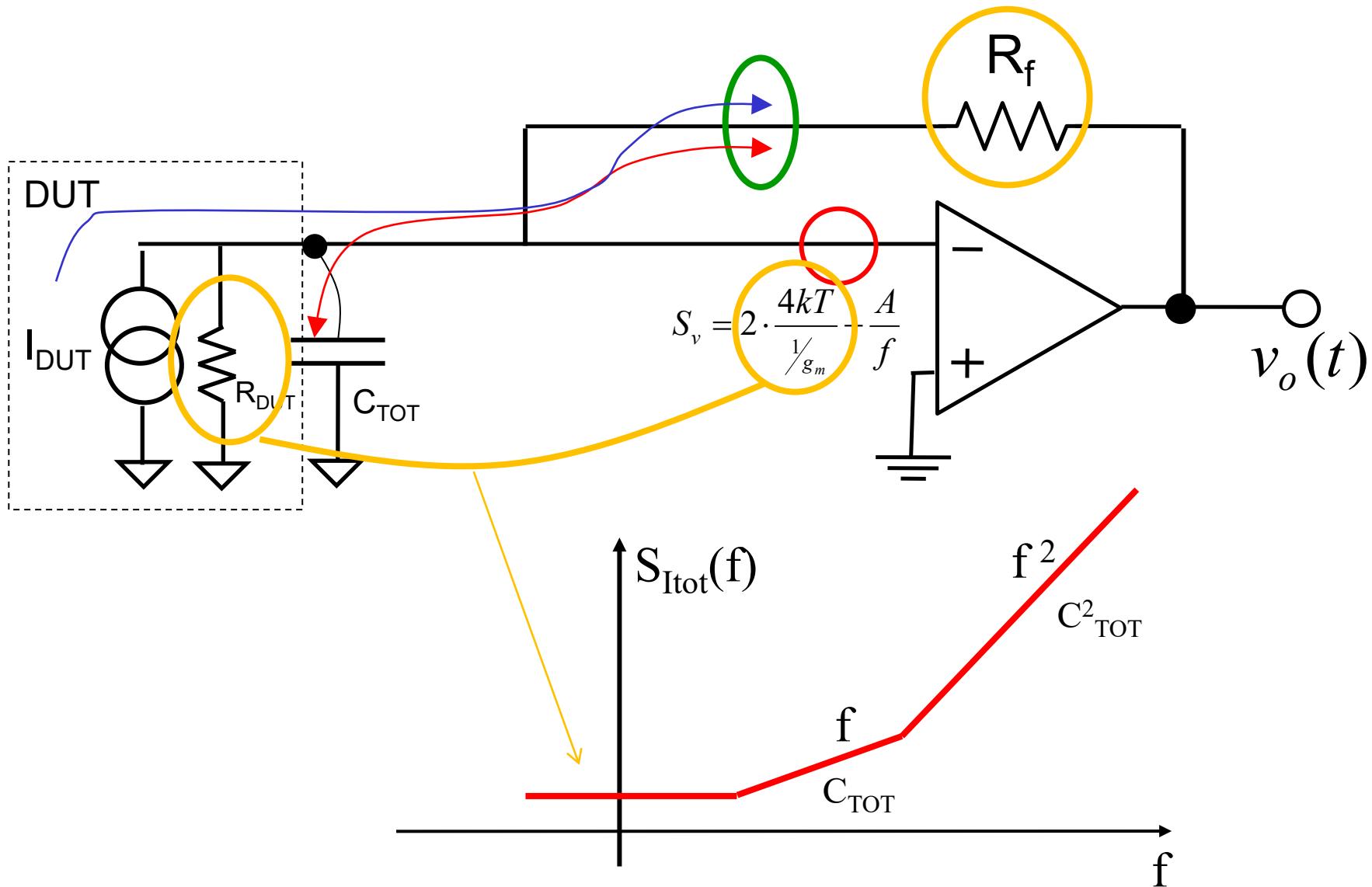
SUMMARY : spectrum of produced current noise



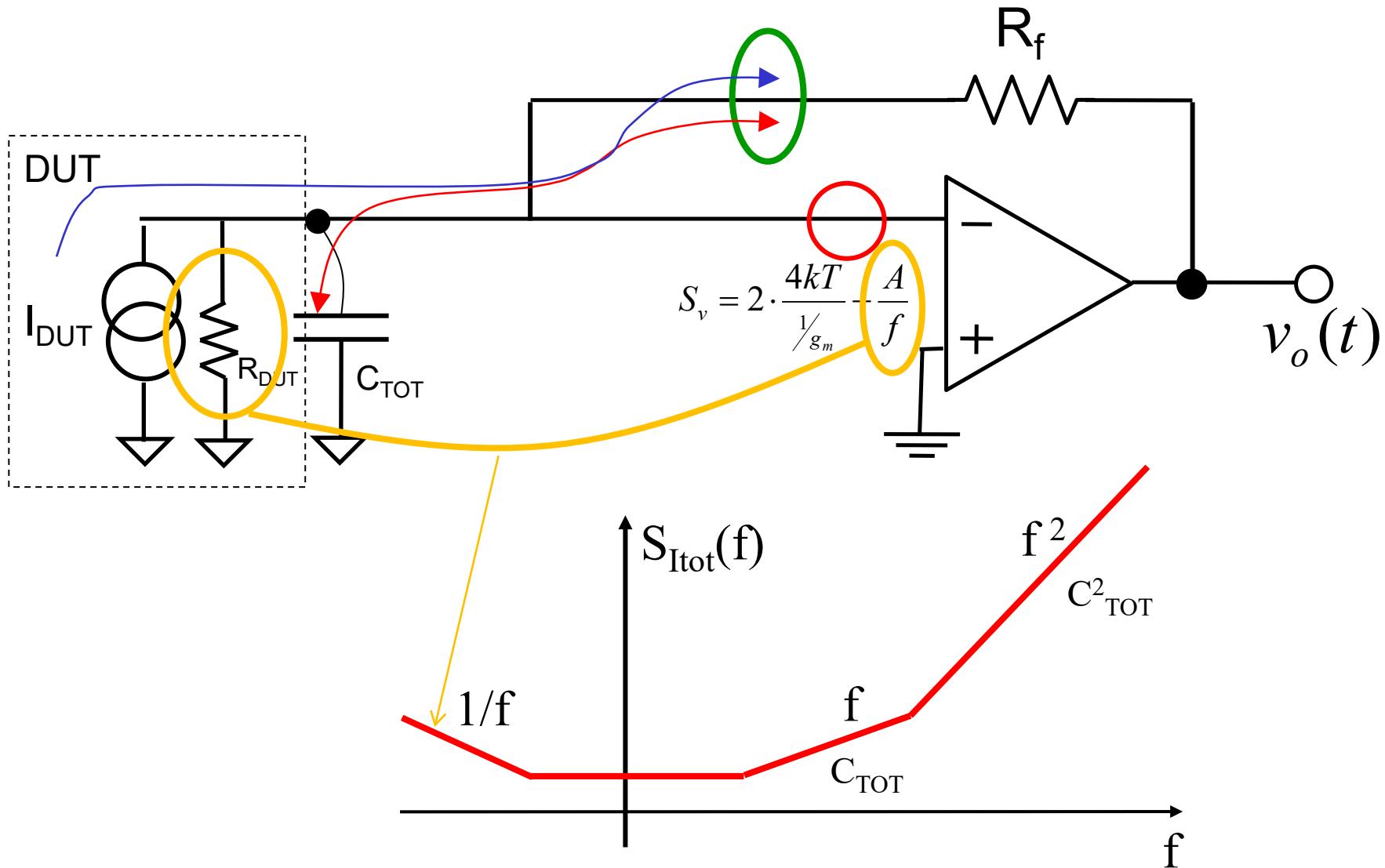
SUMMARY : spectrum of produced current noise



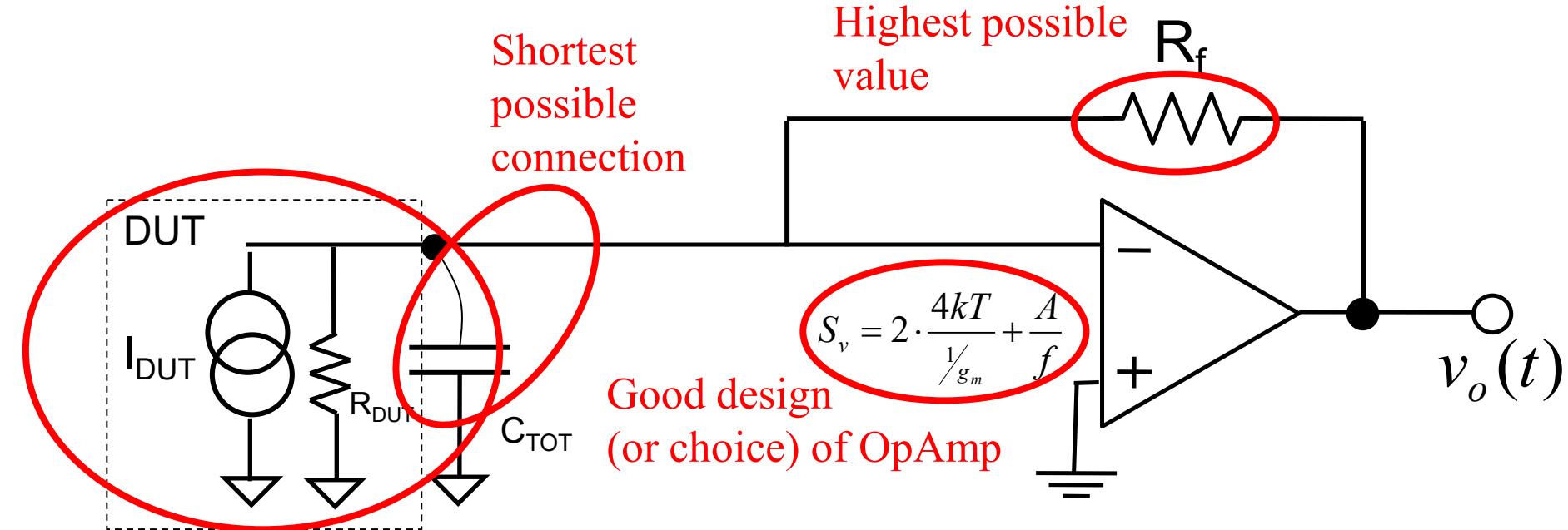
SUMMARY : spectrum of produced current noise



SUMMARY : spectrum of produced series noise

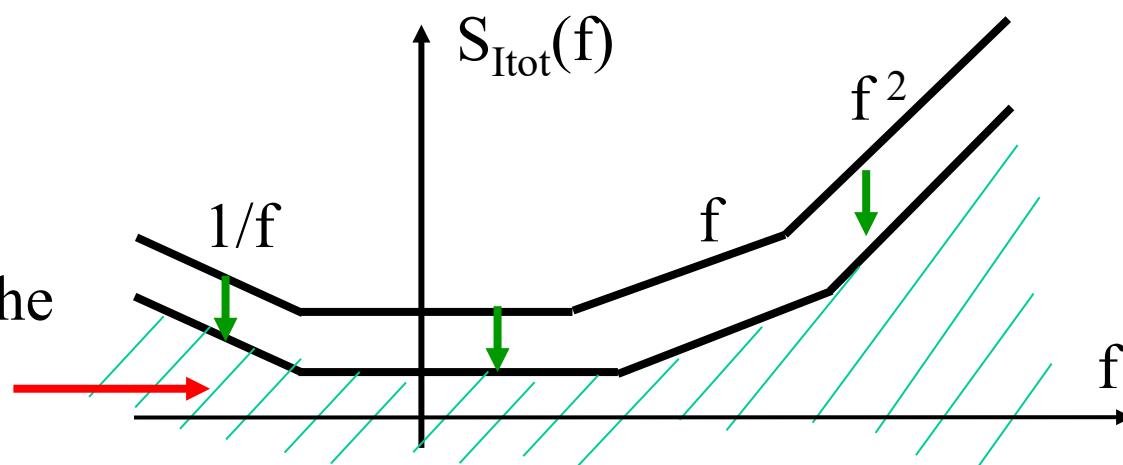


HOW TO MINIMIZE NOISE

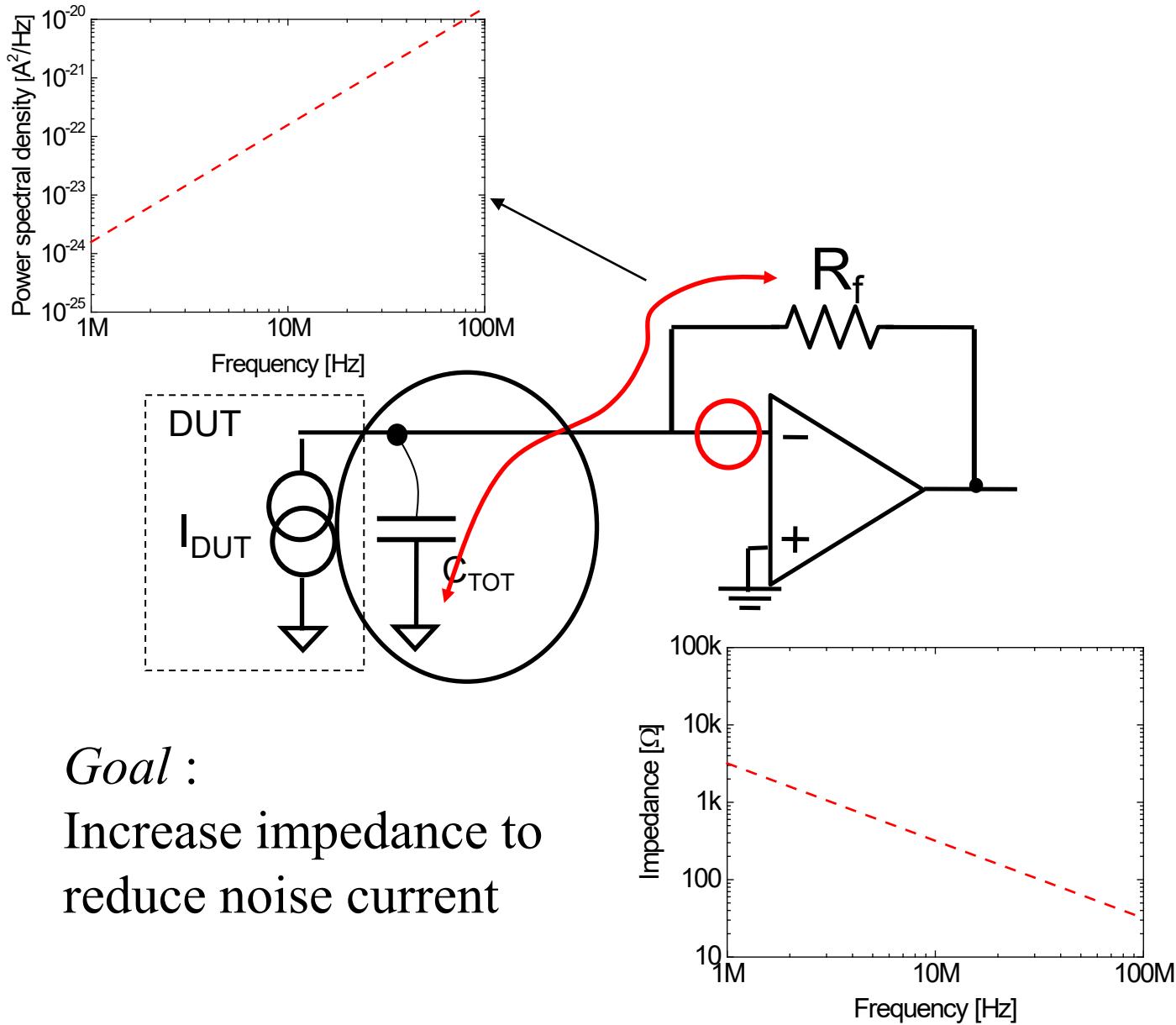


Carefully designed sensor

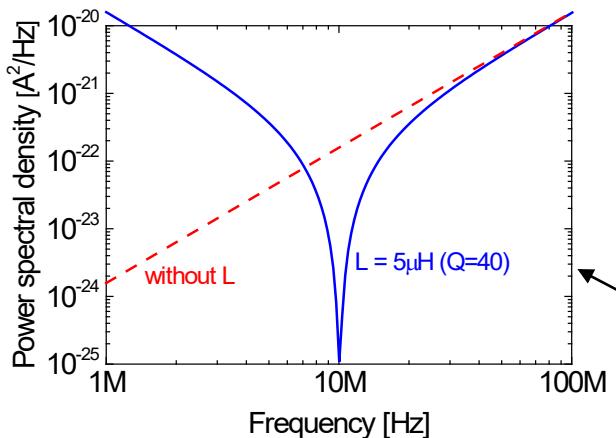
Goal : reduce the area (noise) !



RESONANT NOISE-CANCELLING option

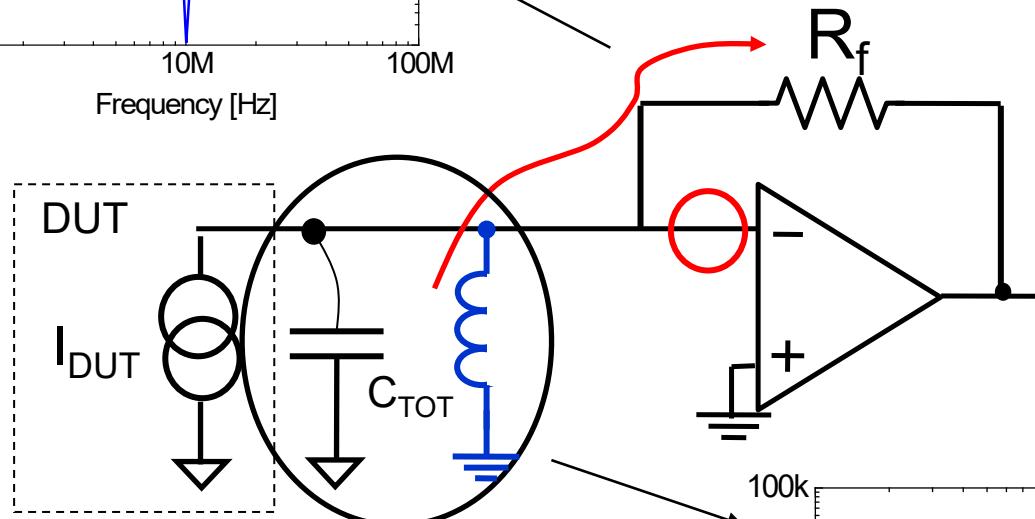


RESONANT NOISE-CANCELLING option



It works only at resonance :

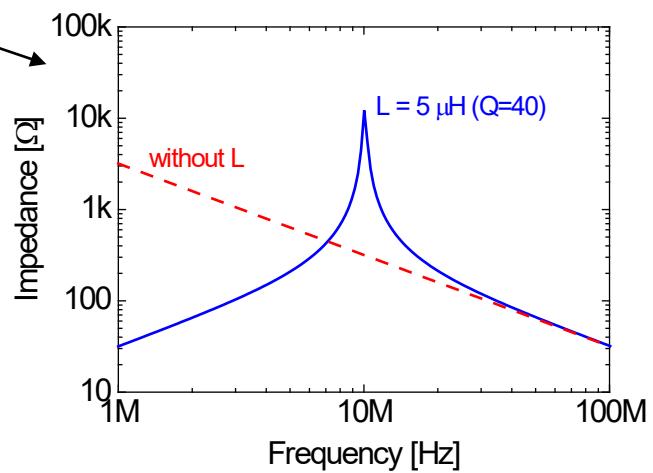
$$f_{res} = \frac{1}{2\pi\sqrt{(C_{in} + C_F)L}}$$



In real (Q) systems :

$$S_i(f_{res}) \approx e_n^2 \frac{[2\pi f(C_{in} + C_F)]^2}{Q^2} + 4kT \sqrt{\frac{C_{in} + C_F}{LQ^2}}$$

Thermal noise given by energy loss



LESSON GUIDELINE

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- Active current-to-voltage converter

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Tips and Tricks on the connections

- Coaxial and triaxial cables
- Guarded measurements 5 min

Source-Measure Unit (SMU)

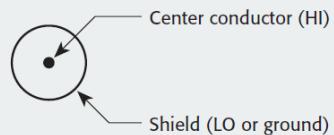
Coaxial cable

a. Configuration

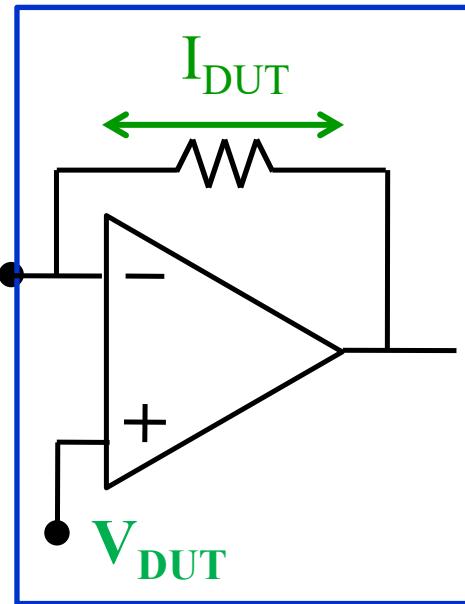
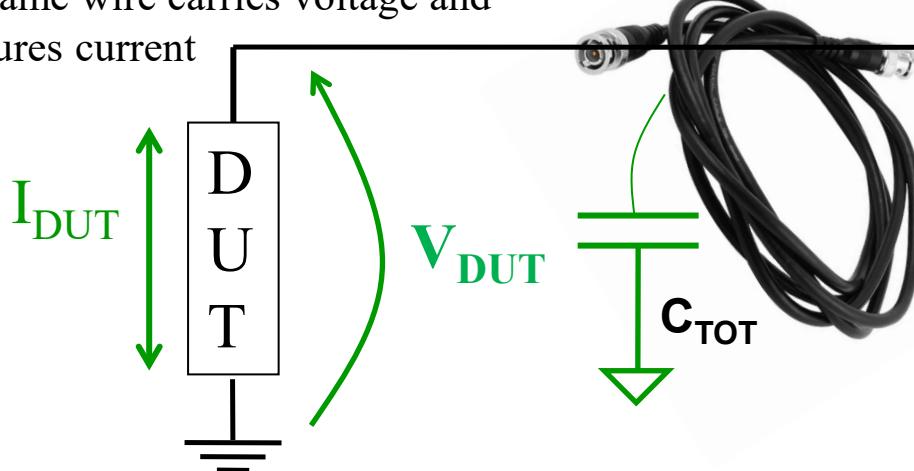
Shield
Center conductor



b. Connections

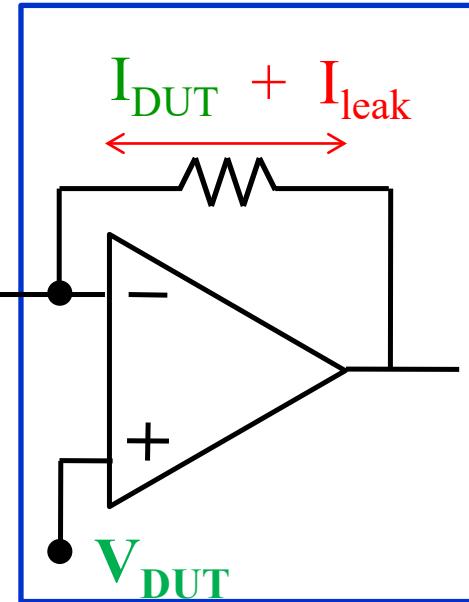
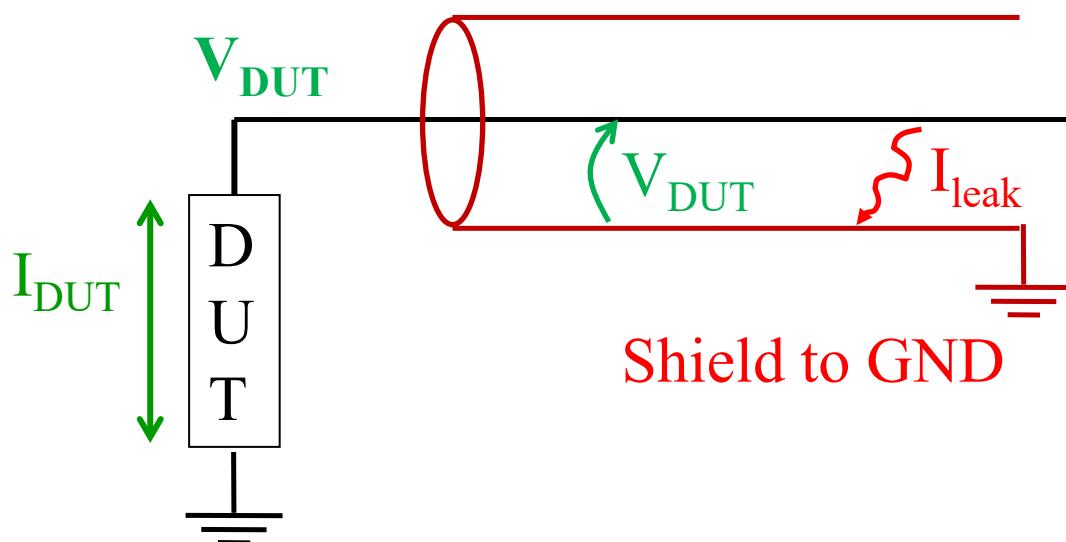


The same wire carries voltage and measures current



Force V_{DUT}
Measure I_{DUT}

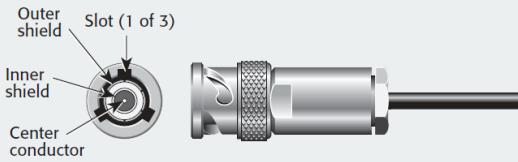
Leakage currents with COAX cable



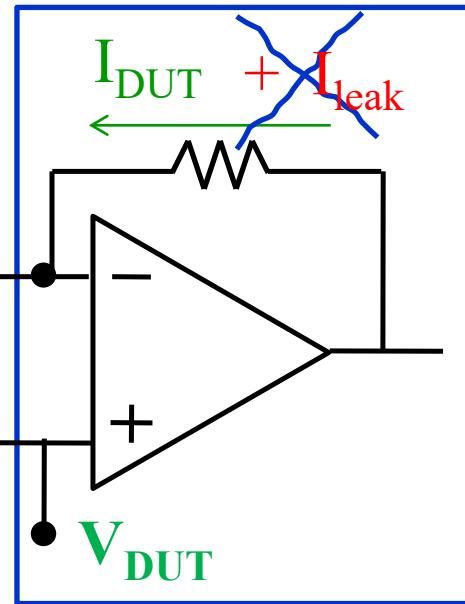
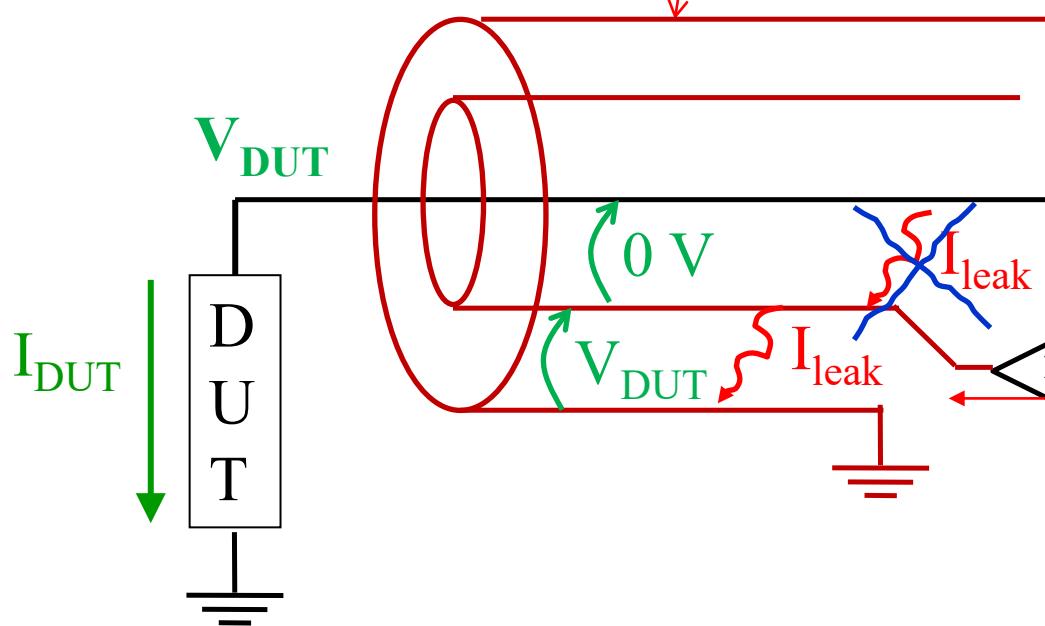
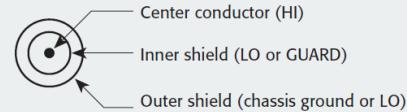
Advantage in using a TRIAX cable

Triaxial cable

a. Configuration



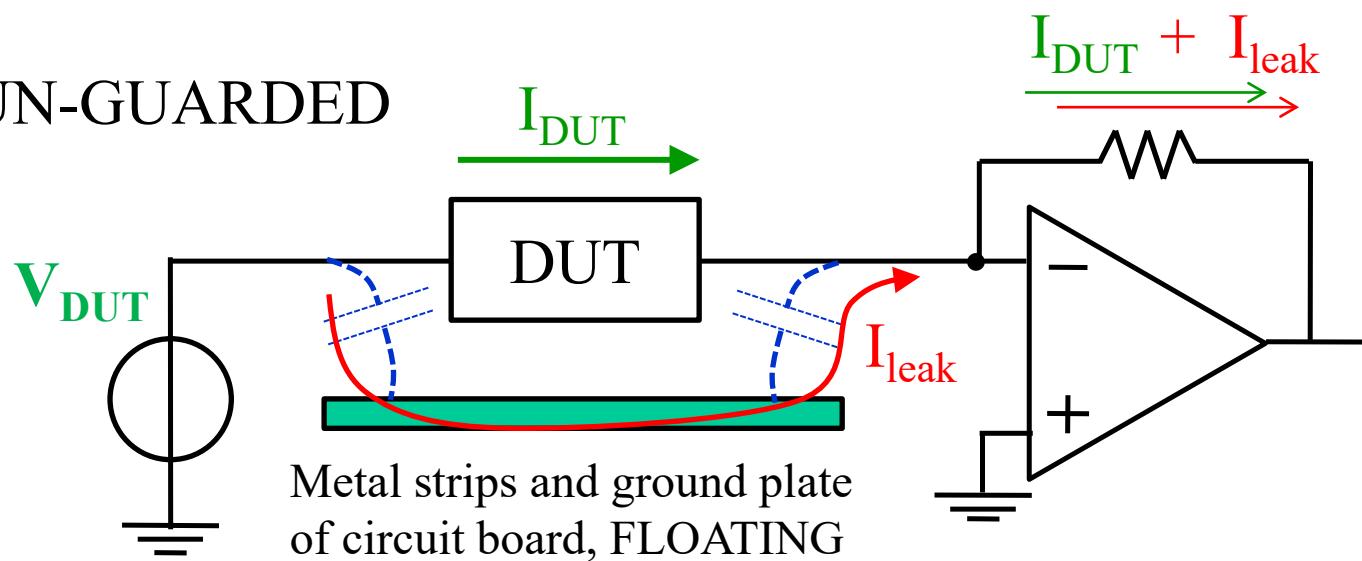
b. Connections



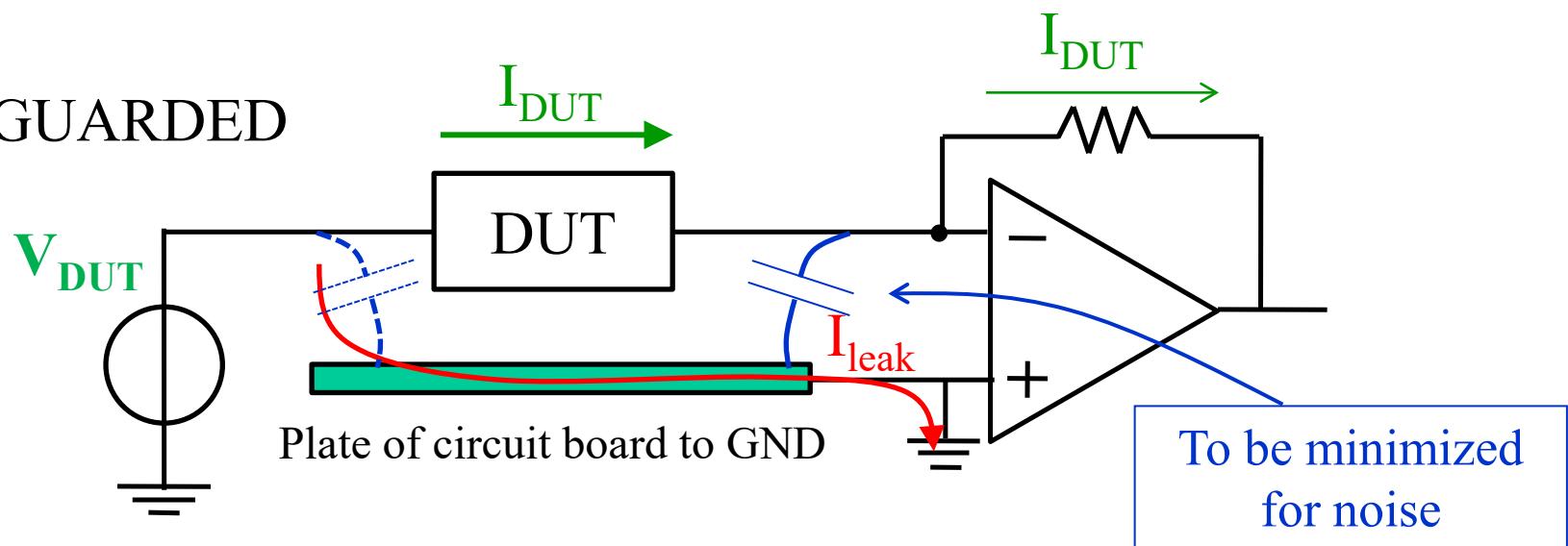
Force V_{DUT}
Measure I_{DUT}

GUARDS and NOISE

UN-GUARDED

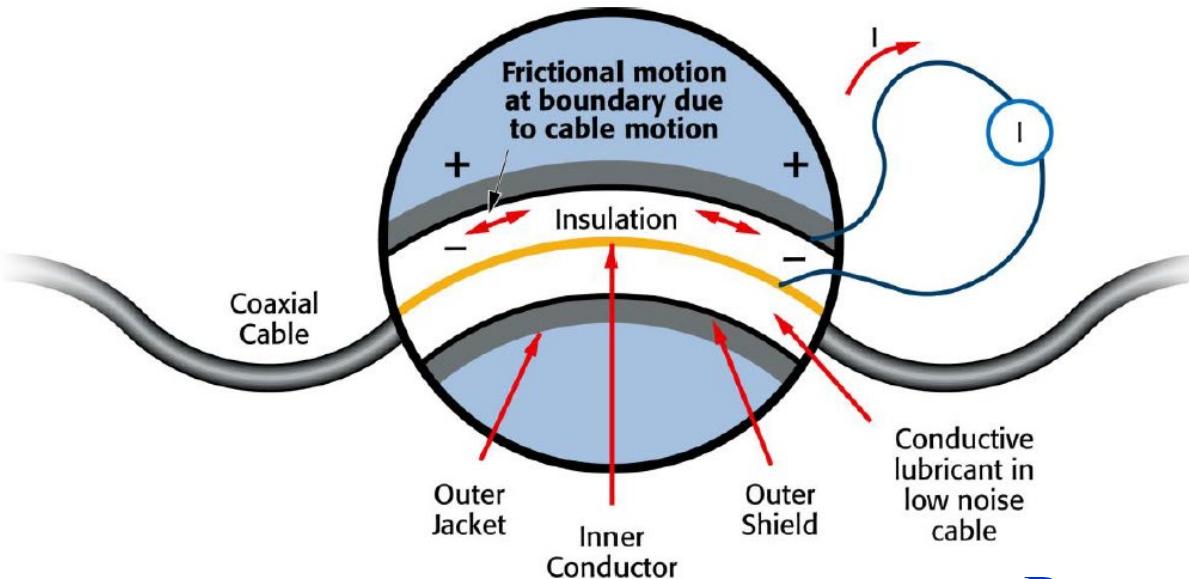


GUARDED



Do not forget dielectric noise of the board (see 1st lesson)

Noise sources : Triboelectric effect



Reported effect up to nA

How to reduce :

- Isolate measurement from vibration;
- Tape cables to a stable surface;
- Minimize cable length;
- Use low noise cable.

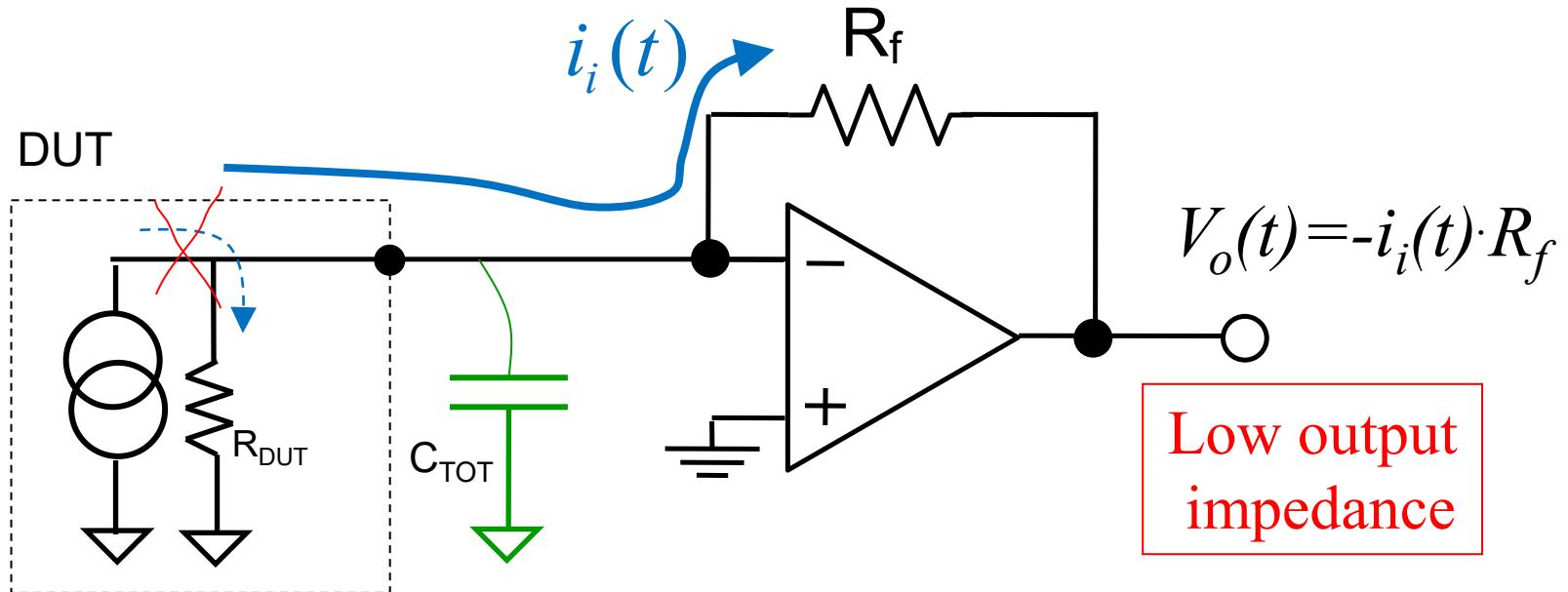
Source :

KEITHLEY
A Tektronix Company

In conclusion . . .

Things to remember (1)

Read currents with a
TRANSIMPEDANCE AMPLIFIER



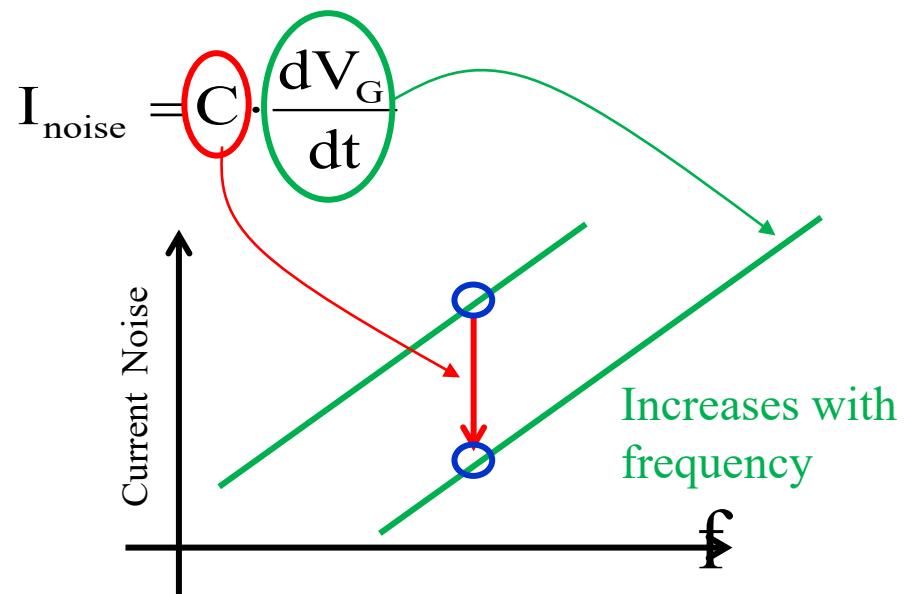
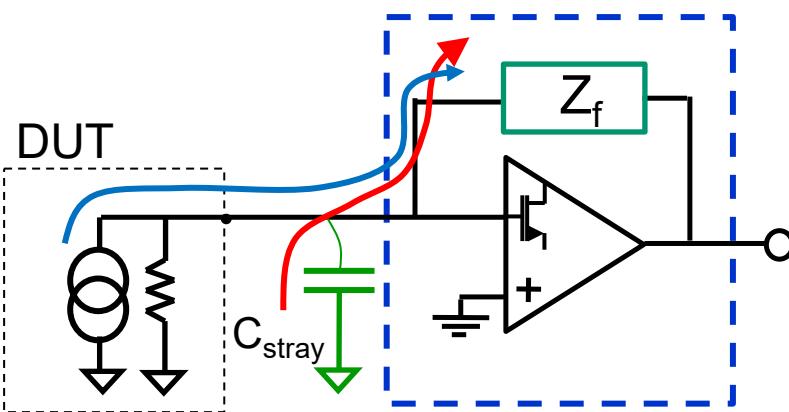
sensitivity \Rightarrow large R_f

precision \Rightarrow stable R_f

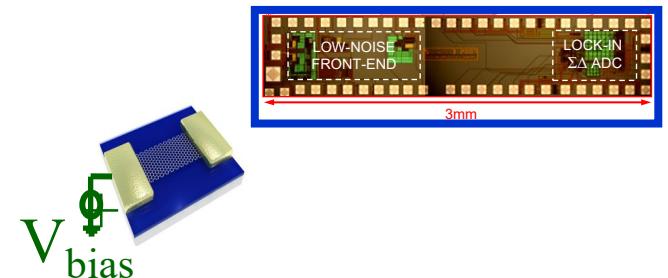
gain independent of C_{TOT}

Things to remember (2)

Be aware of input capacitance : KEEP C_{stray} SMALL for lower noise

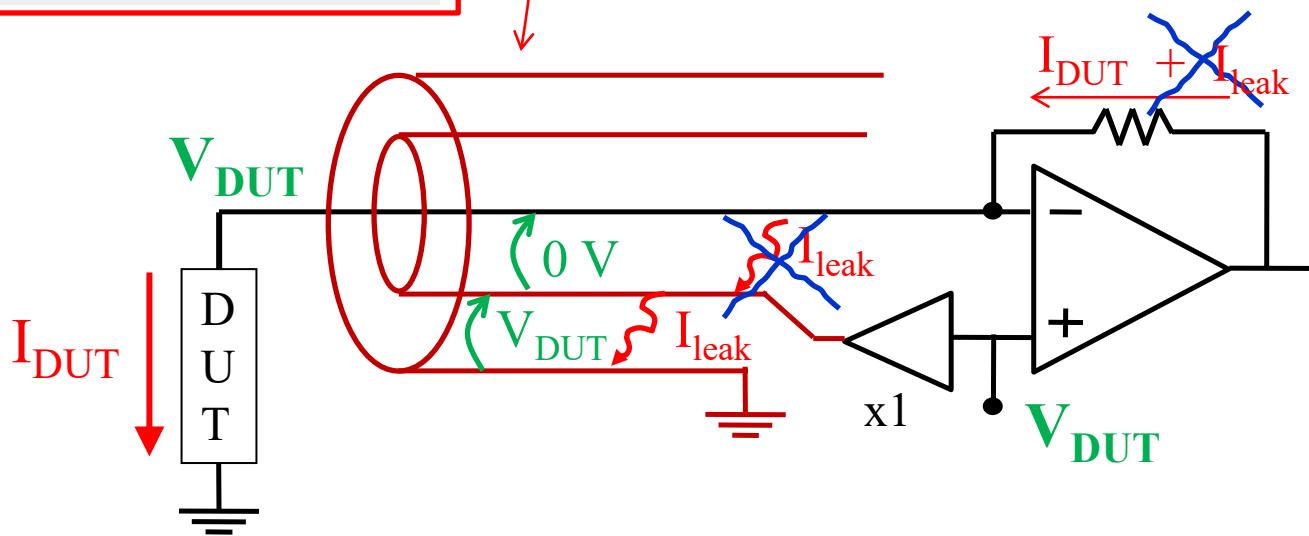
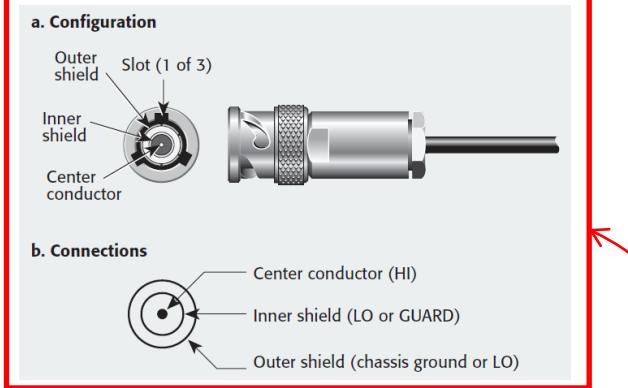


If possible design your own IC-TIA



Things to remember (3)

Triaxial cable



Use TRIAX for ultra-low current measurements when single wire carries V and measures I