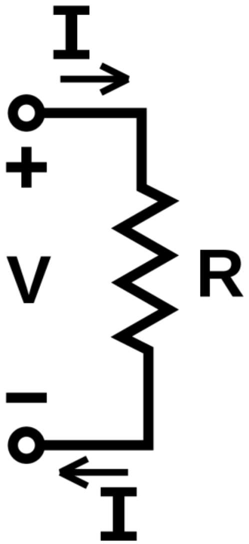
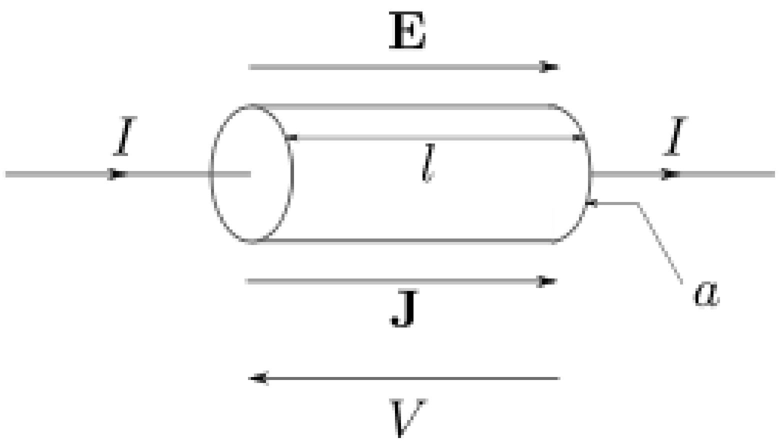
measurement of current flow, voltage and resistance

Kalenyuk O.A.

Ohm's law 1826



$$I = \frac{V}{R}$$



$$\mathbf{J} = \sigma \mathbf{E}$$

resistance

Перше дослідження напівпровідників 1833 р. Майкл Фарадей від’ємний температурний коефіцієнт опору у сульфіду срібла.

Магніторезистивний ефект
1856 р. Уильямом Томсоном

$$\vec{j} = qn\vec{v}_{cp.}$$

$$\vec{v}_{cp.} = \mu\vec{E}$$

μ Рухливість

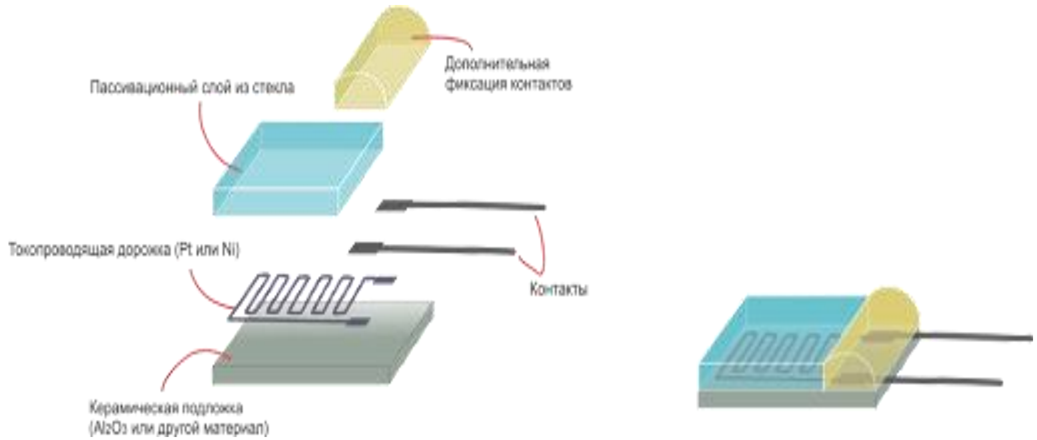
Закон Відемана - Франца

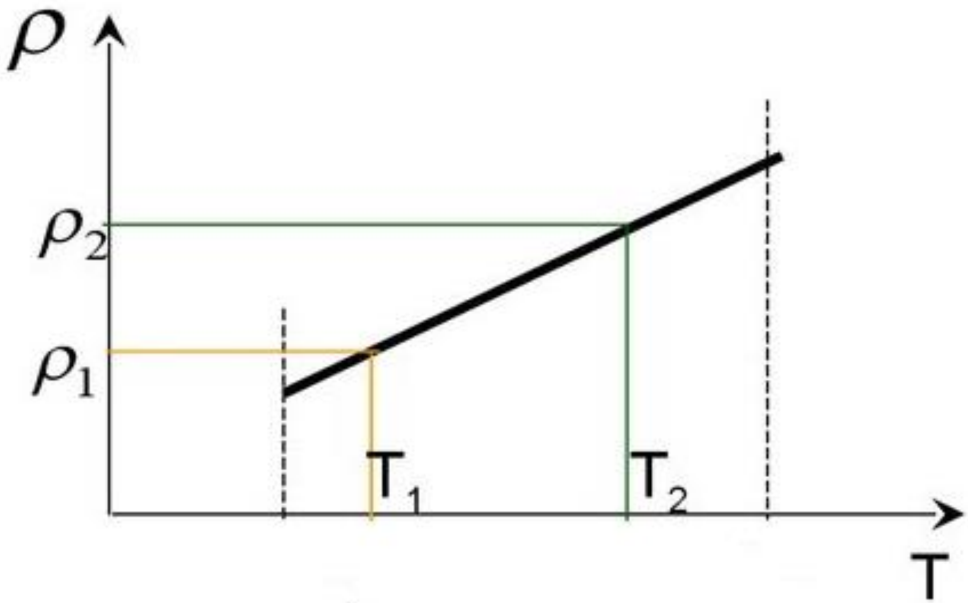
$$\frac{K}{\sigma} = LT$$

L – число Лоренца

$$L = \frac{3}{2}\left(\frac{k}{e}\right)^2 \approx 1{,}11 \times 10^{-8}\ \mathrm{W\Omega K^{-2}}$$

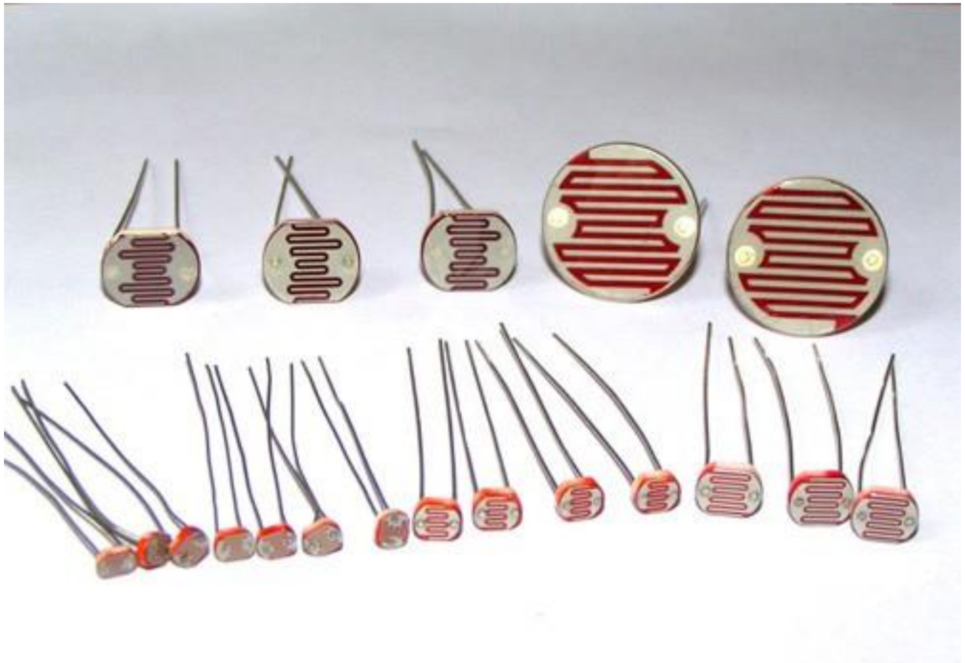
thermal resistor

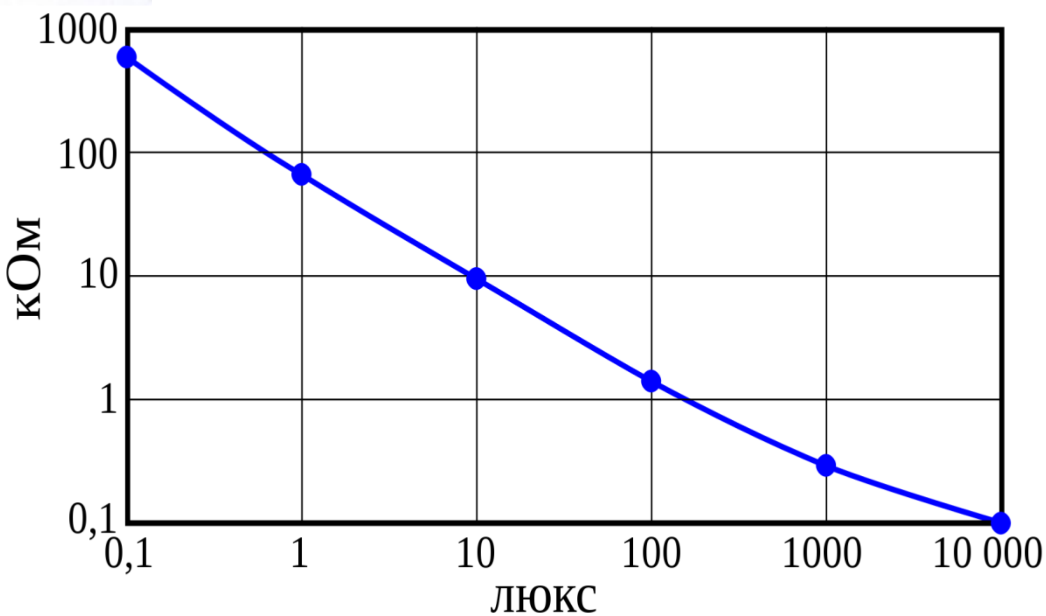




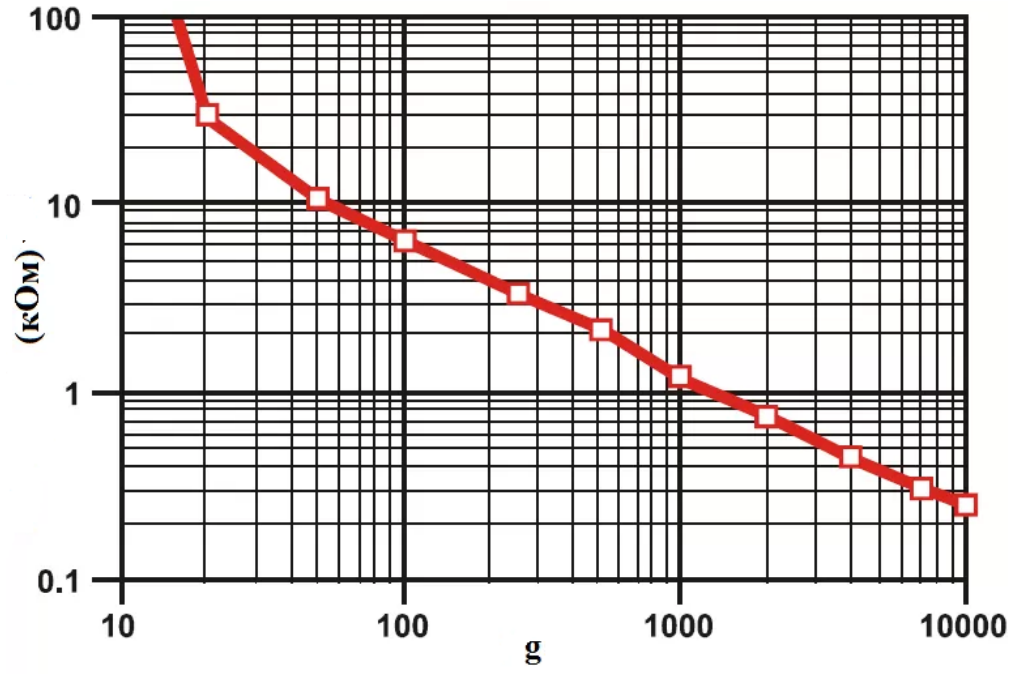
humidity resistor

photo resistor

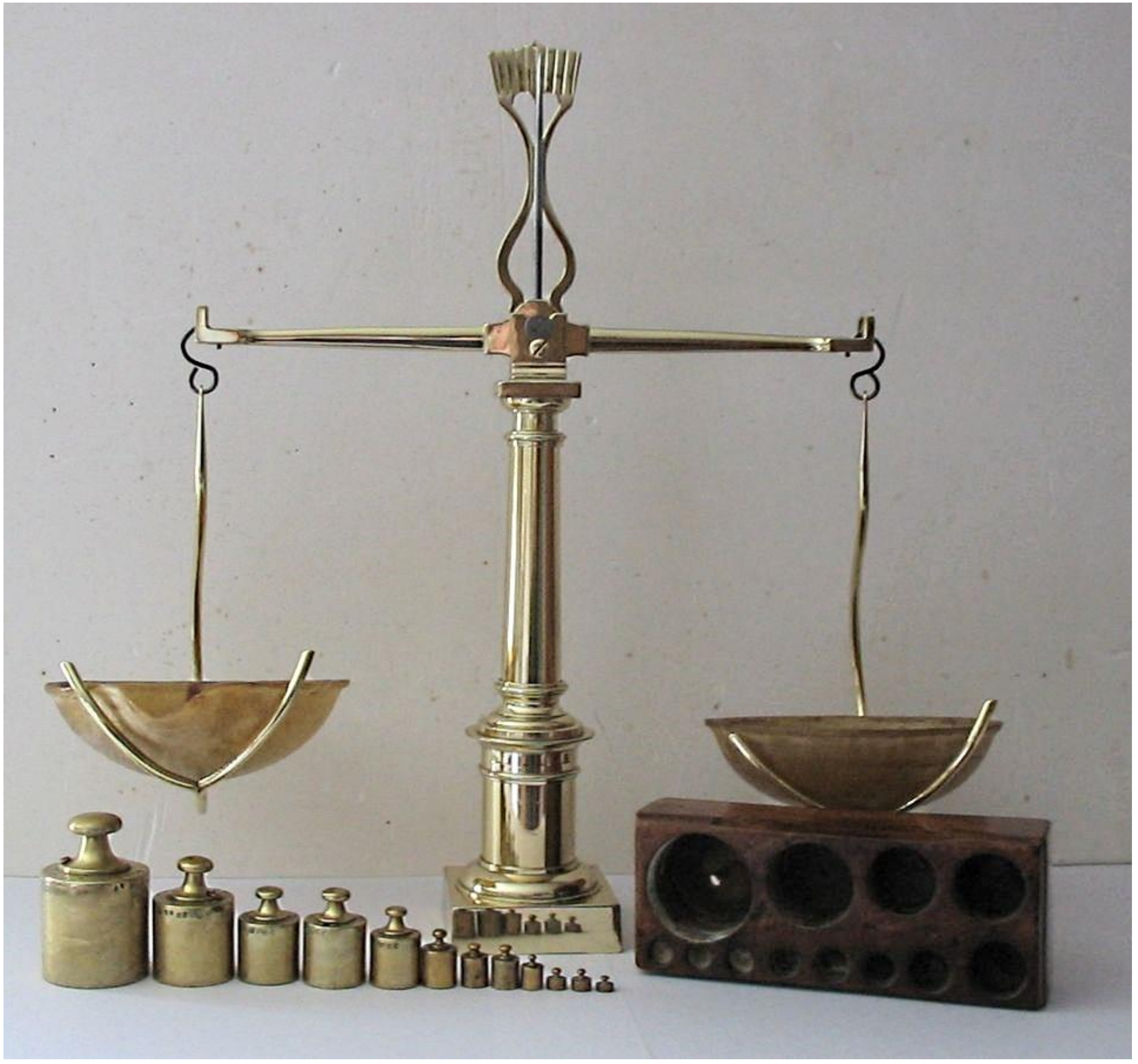




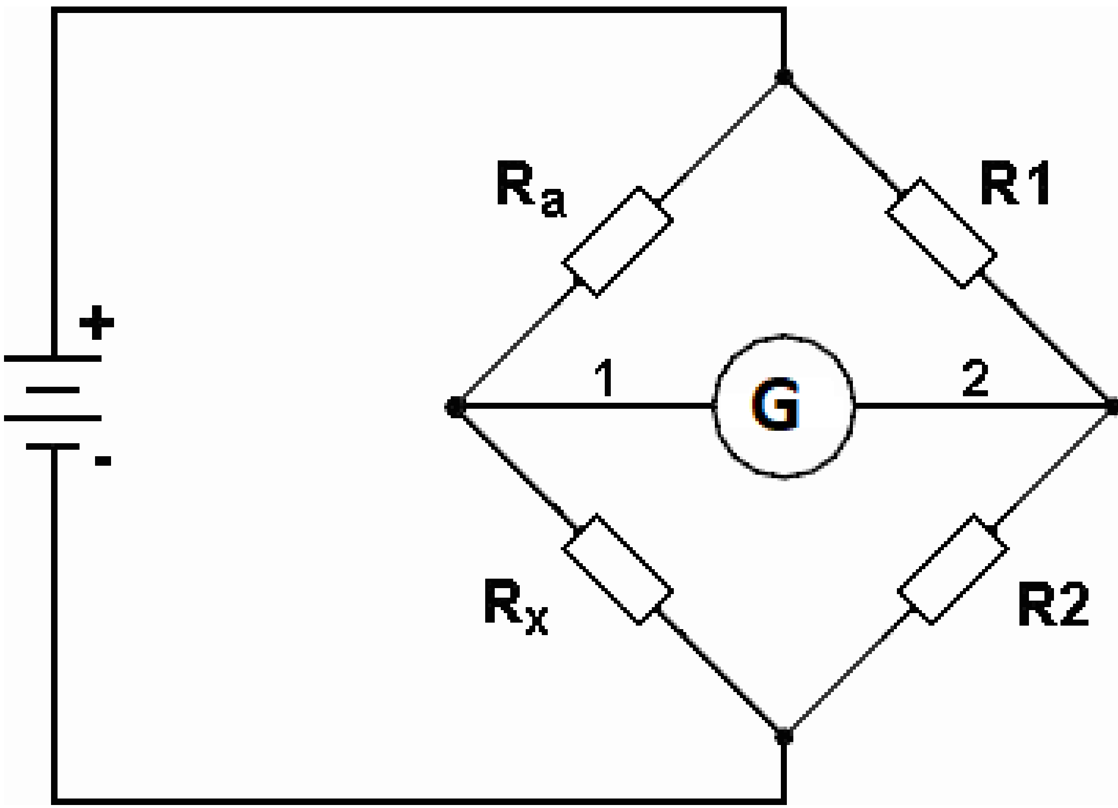
pressure resistor



scales



Wheatstone bridge

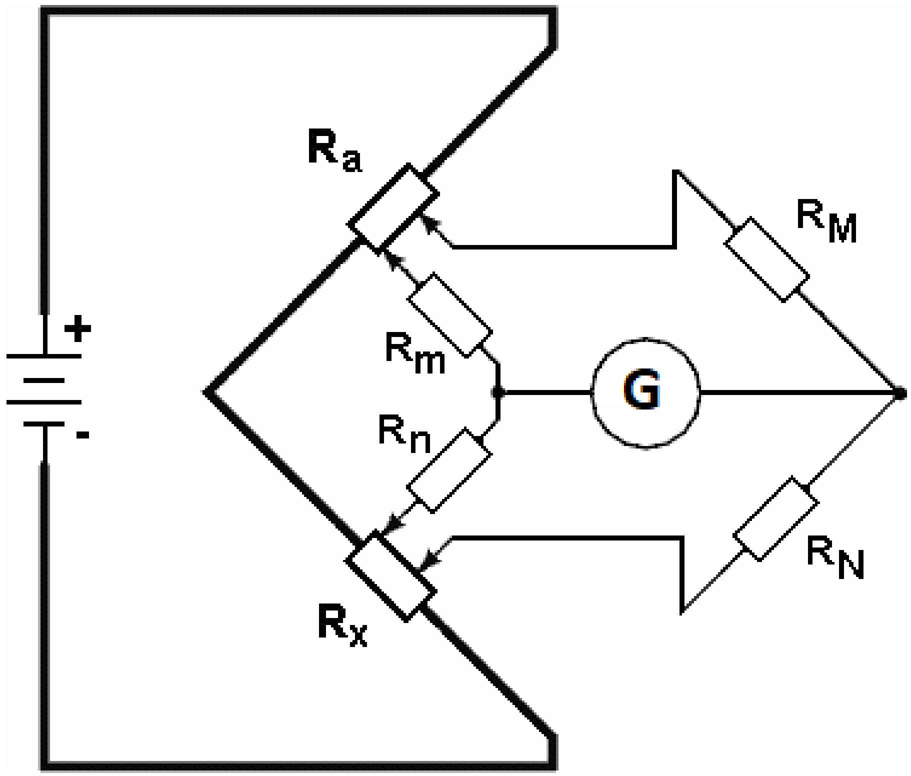


$$\frac{R_a}{R_x} = \frac{R1}{R2}$$

R (0.1 Ohm – 100MOhm)

Запропоновано у 1833 году Самуелєм Хантером Кристі (англ. Samuel Hunter Christie) та в 1843 удосканалено Чарльзом Уітстоном.

Kelvin Double Bridge

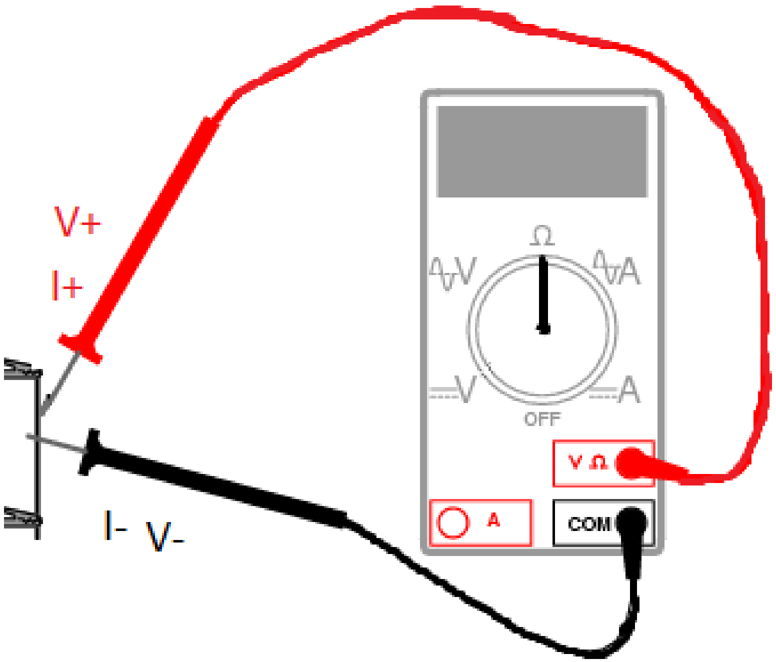


$$\frac{R_x}{R_a} = \frac{R_N}{R_M} + \frac{R_{wire}}{R_a}\left(\frac{R_m}{R_m + R_n + R_{wire}}\right)\left(\frac{R_N}{R_M} - \frac{R_n}{R_m}\right)$$

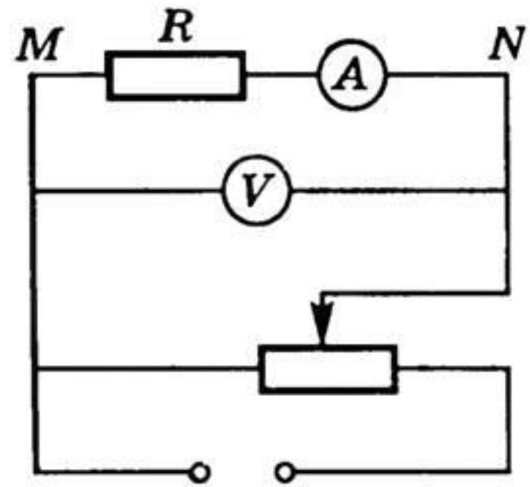
$R_a/R_x = R_M/R_N$

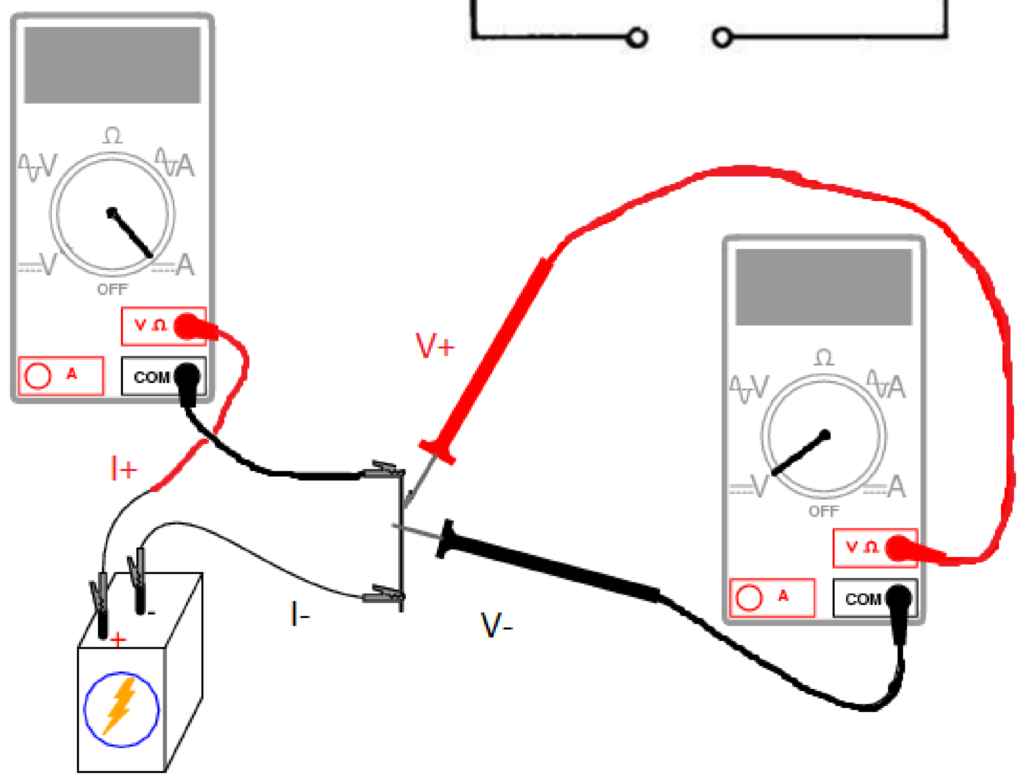
$$R_x = R_a \frac{R_N}{R_M}$$

2-Points and 4-Points measurements

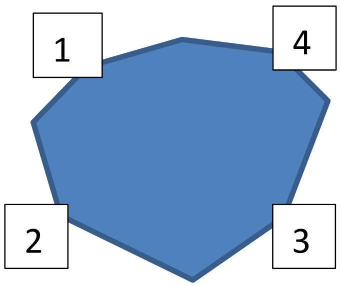


$$R = \frac{U}{I}$$





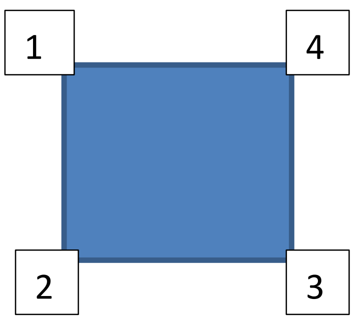
The van der Pau method (1958)



$$R_{12,34} = \frac{U_{34}}{I_{12}}$$

$$e^{-\pi R_{12,34}/\rho_s} + e^{-\pi R_{23,41}/\rho_s} = 1$$

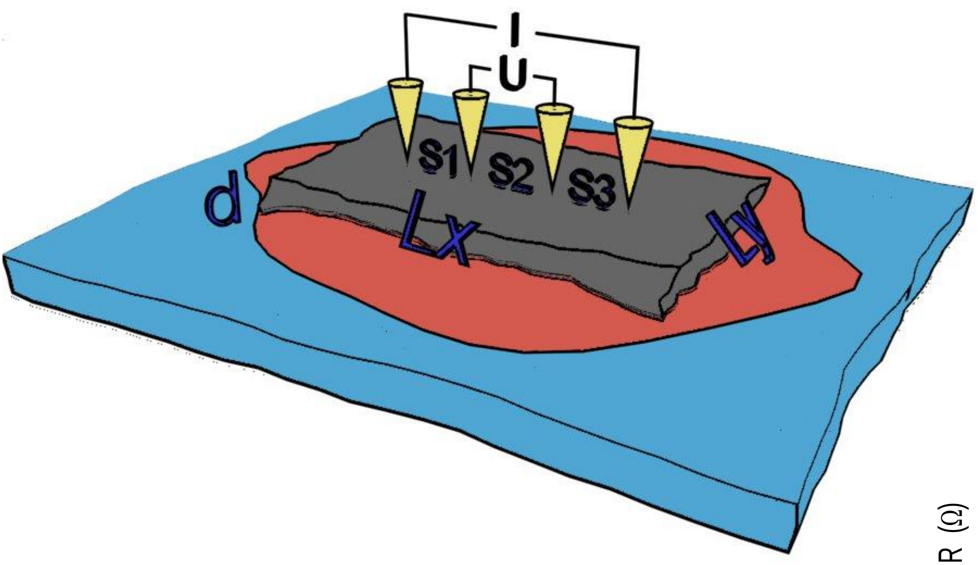
d=const<<L



$$\rho_s = \frac{\pi R}{\ln{(2)}}$$

$$\rho = \rho_s d$$

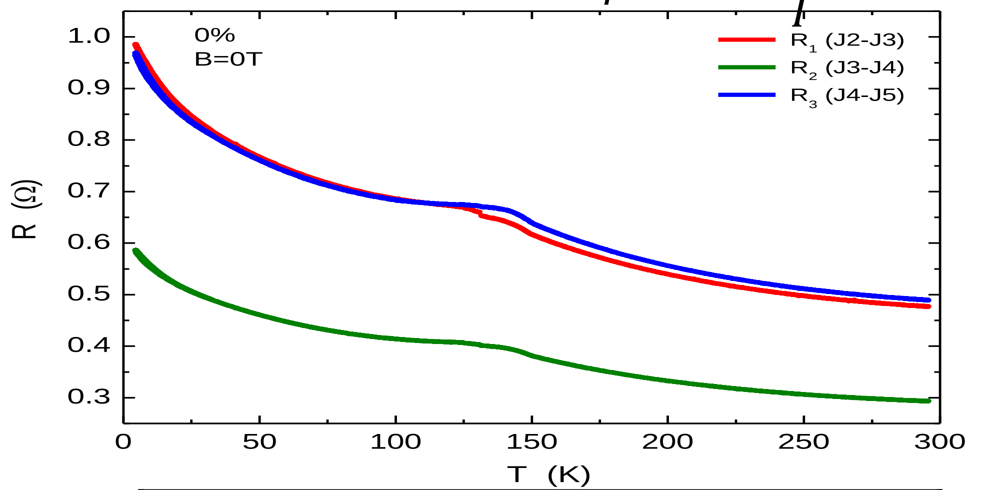
4-Points Line



$$\rho = \frac{2\pi}{\left(\frac{1}{S1} - \frac{1}{S2+S3} - \frac{1}{S1+S2} + \frac{1}{S3}\right)} \frac{U}{I}$$

$$S1, S2, S3 \ll Lx, Ly, d$$

$$S1 = S2 = S3 \Rightarrow \rho = 2\pi S \frac{U}{I}$$

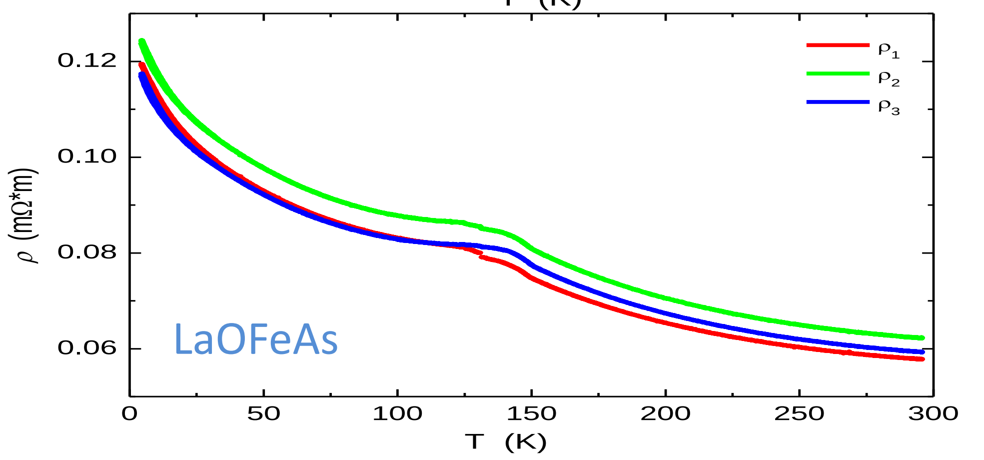


our case with six probes

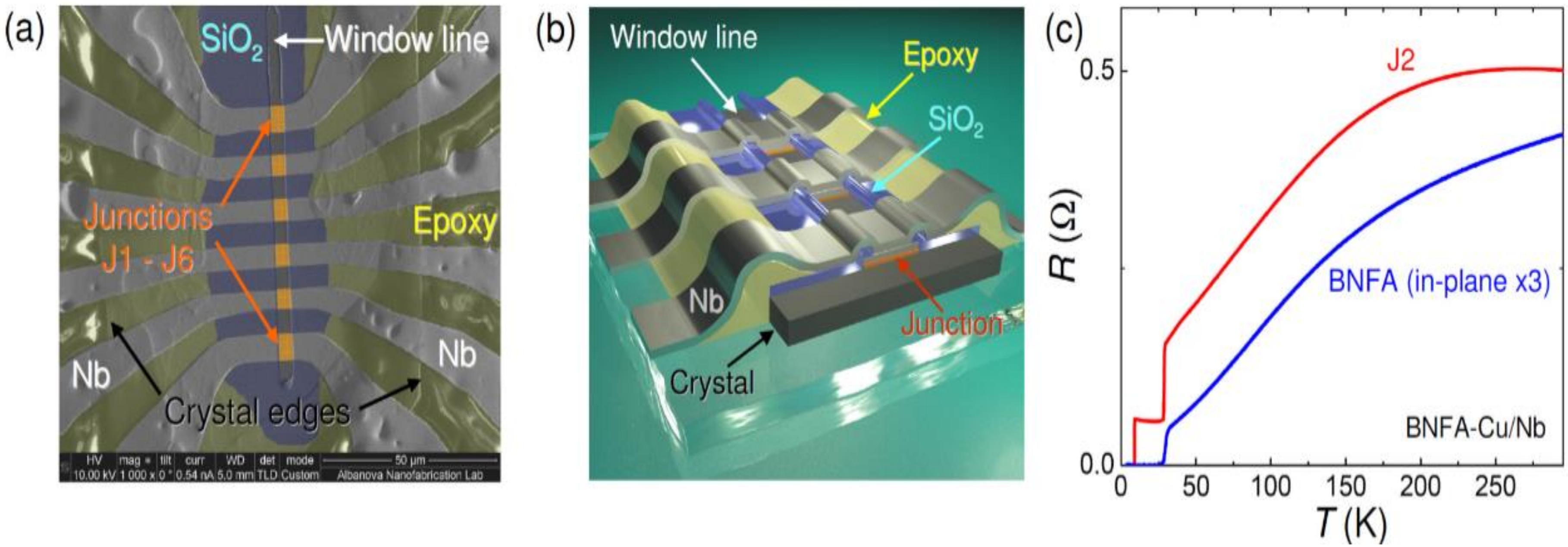
$$\rho 1(\rho 3) = \frac{24}{7}\pi S R1(R3)$$

$$\rho 2 = 6\pi S R2$$

$$\rho 1 = \rho 2 = \rho 3 \Rightarrow \frac{R1(R3)}{R2} = \frac{7}{4}$$



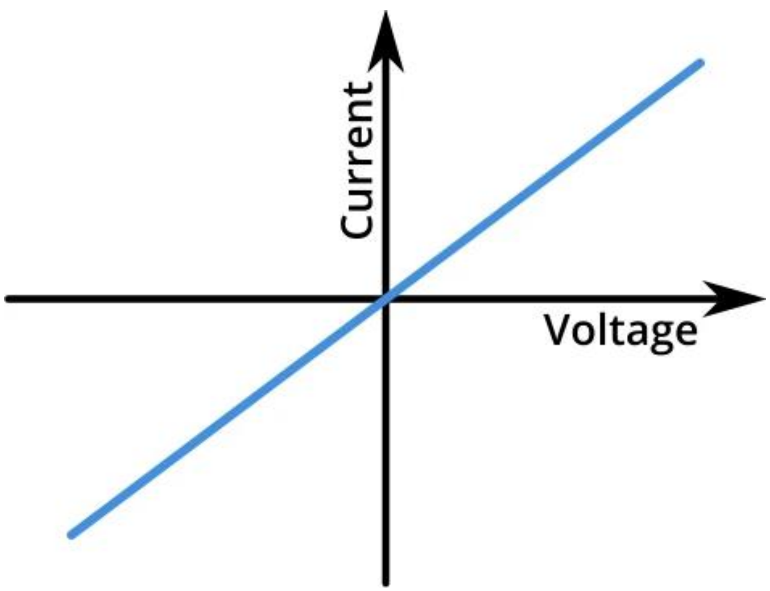
R vs temperature

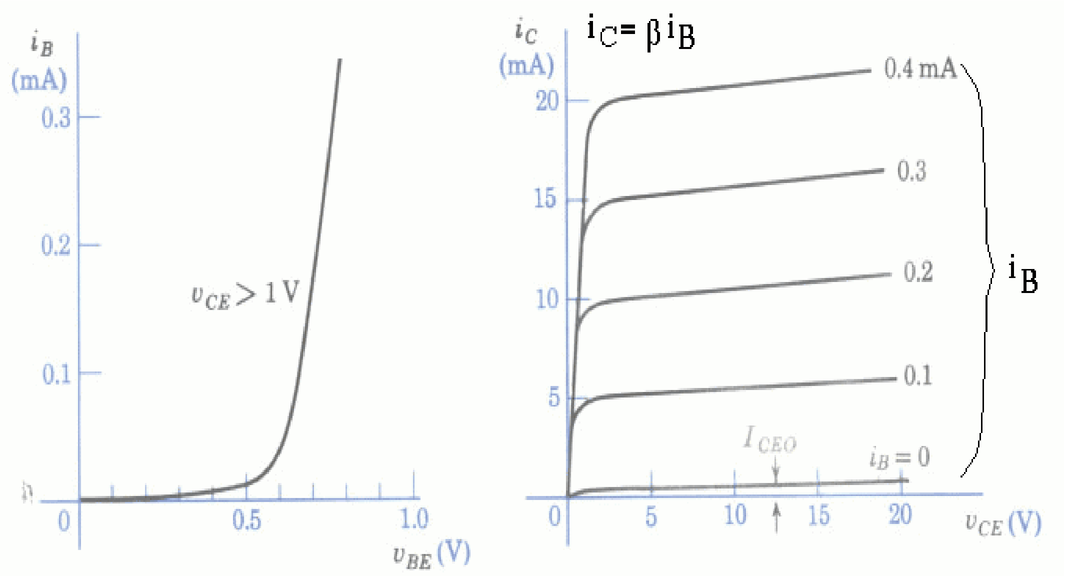


PHYSICAL REVIEW B103, 214507 (2021)

Resistor and bipolar transistor iv

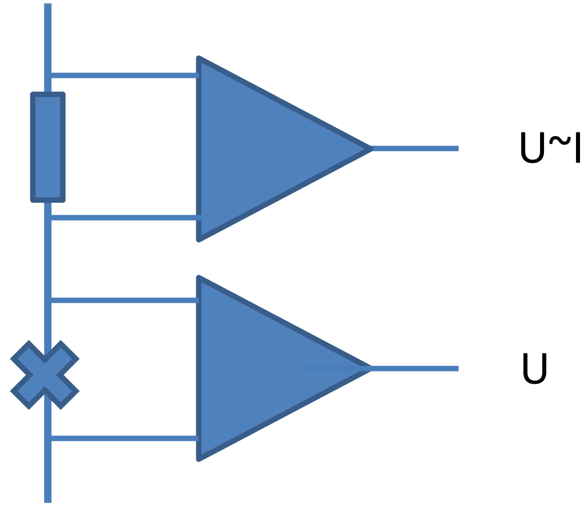
$$I = \frac{V}{R}$$



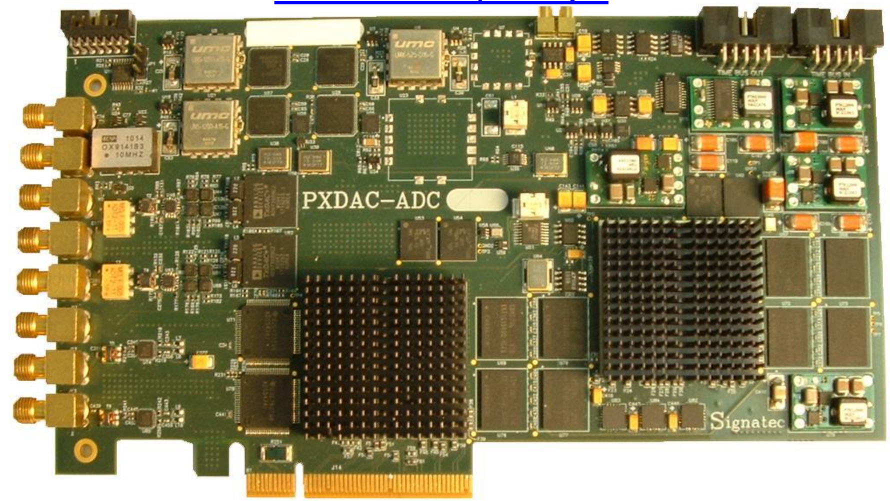


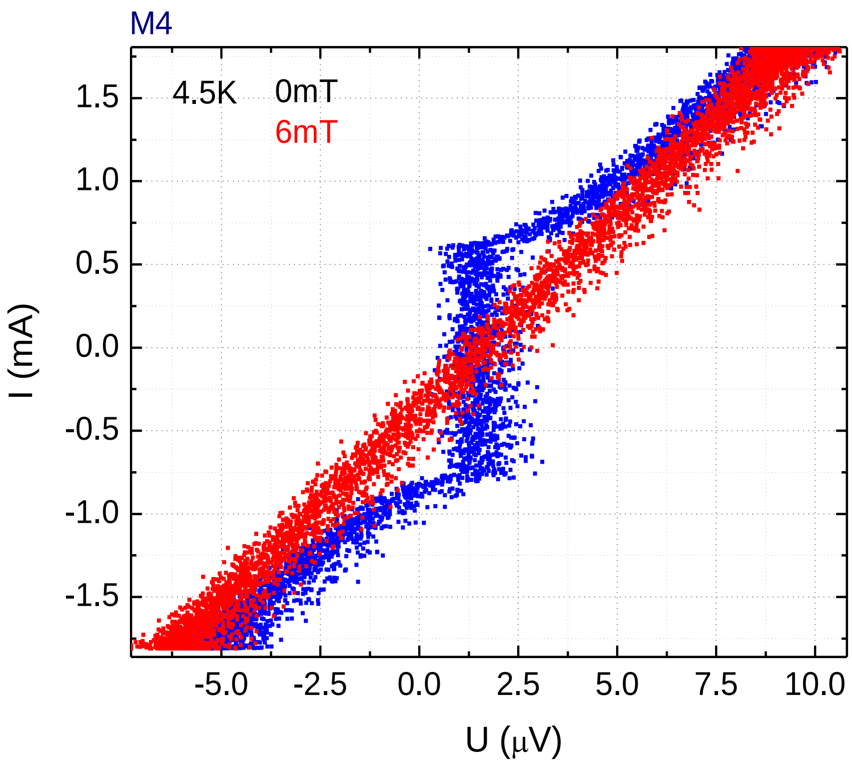
(a) Base characteristics

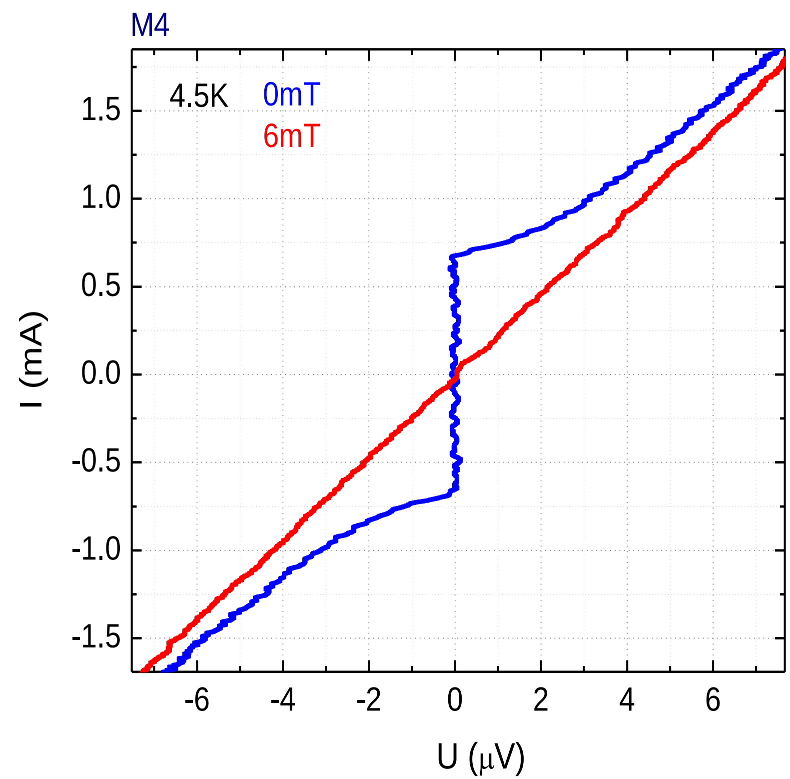
(b) Collector characteristics



14 bit 2x1,2GS/s







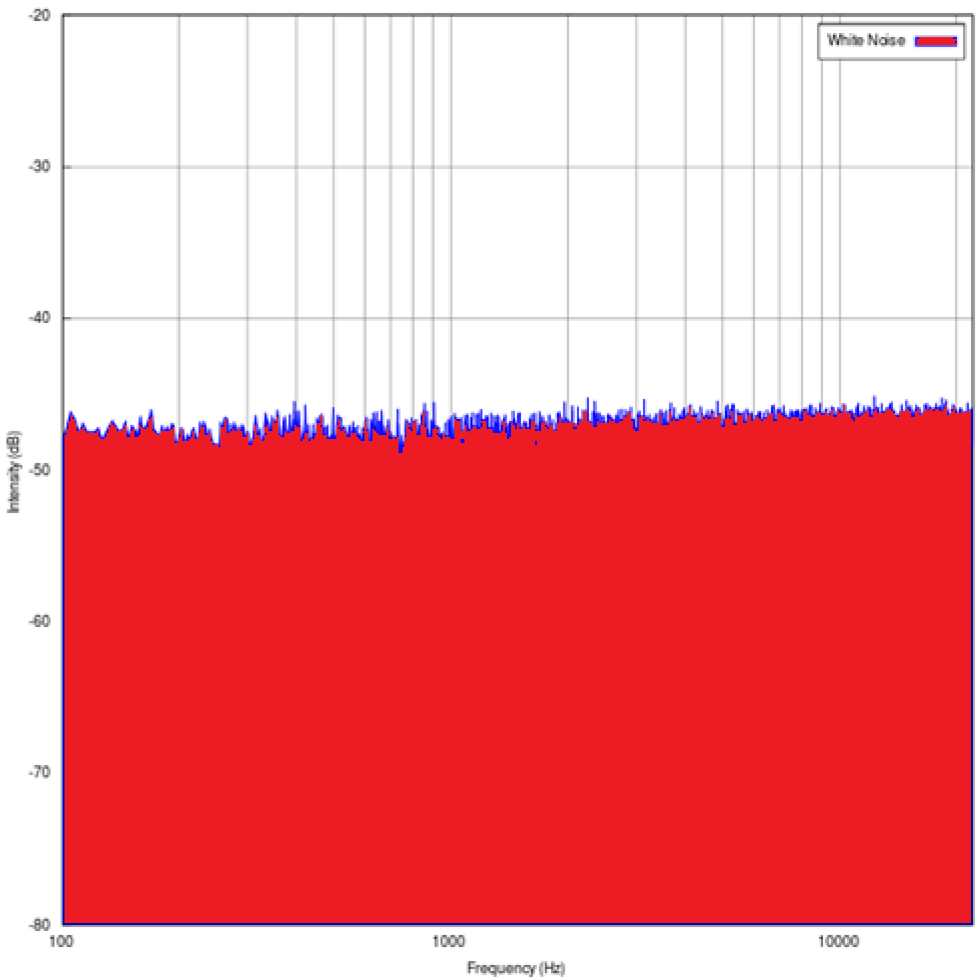
Noise

Acoustic noise is any sound in the acoustic domain, either deliberate (e.g., music or speech) or unintended. In contrast, noise in electronics may not be audible to the human ear and may require instruments for detection.

In electronics, noise is an unwanted disturbance in an electrical signal. Noise generated by electronic devices varies greatly as it is produced by several different effects.

Johnson-Nyquist (white) noise

f independent power spectral density



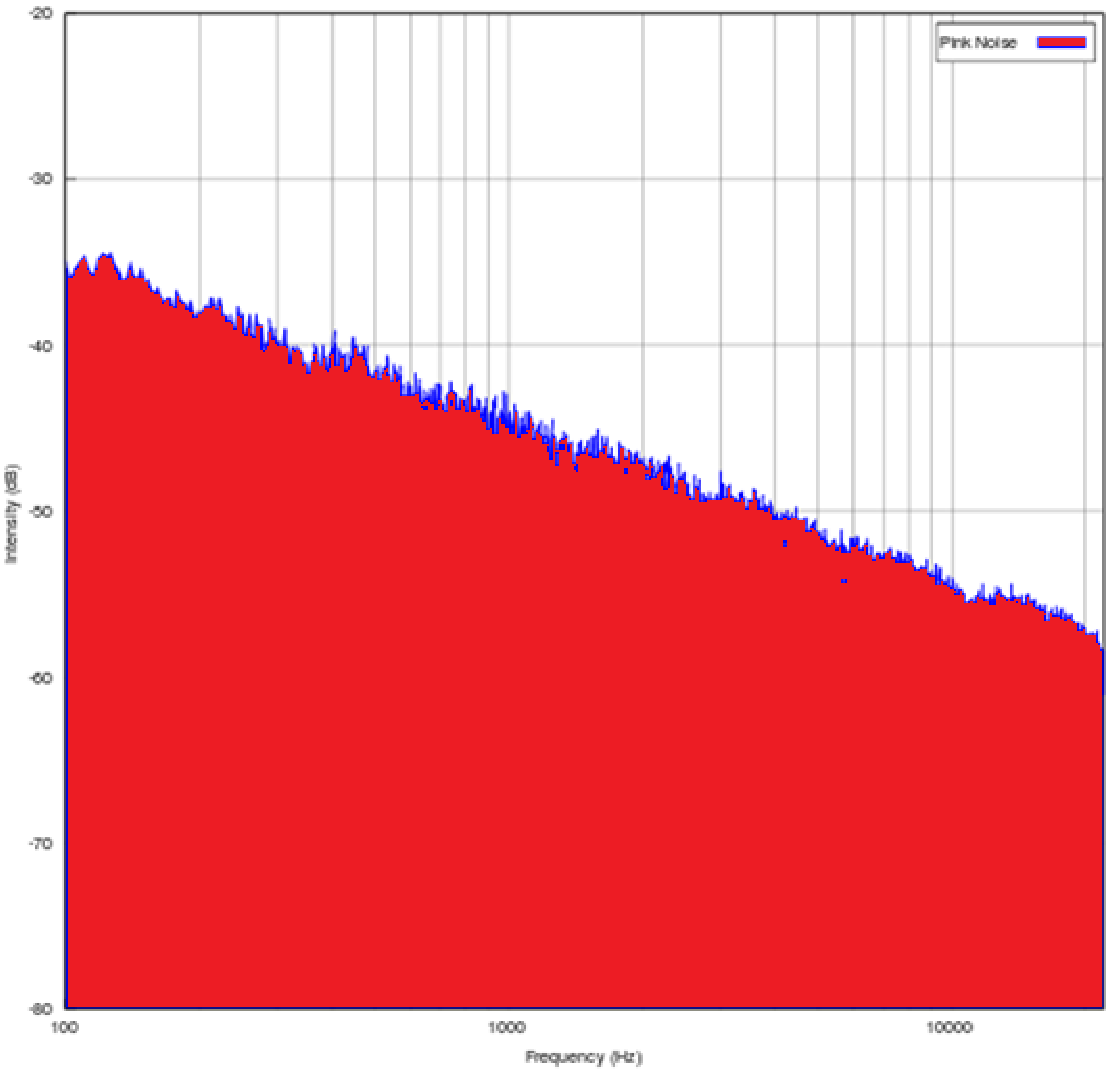
$$S_f = \frac{\overline{e_t^2}}{\triangle f} = 4kTR$$

$$f_m \approx kT/h$$

$$f_m \approx 6 \cdot 10^{12}$$ Гц

Flicker (pink) noise

1/*f* power spectral density

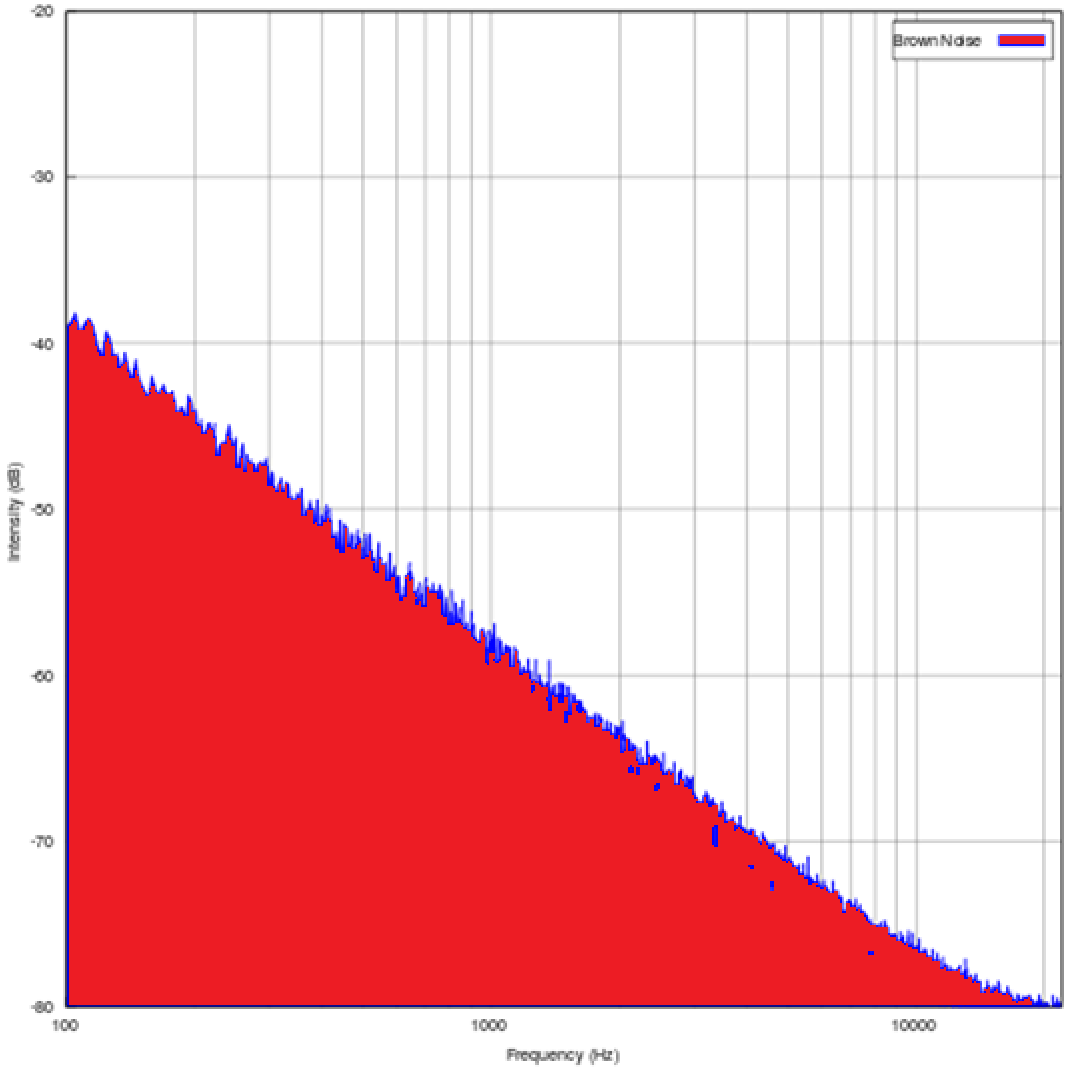


Pink noise is one of the most common signals in biological systems

- Electronic devices
- In gravitational wave astronomy
- Climate change
- Diffusion processes

Brownian (brown) noise

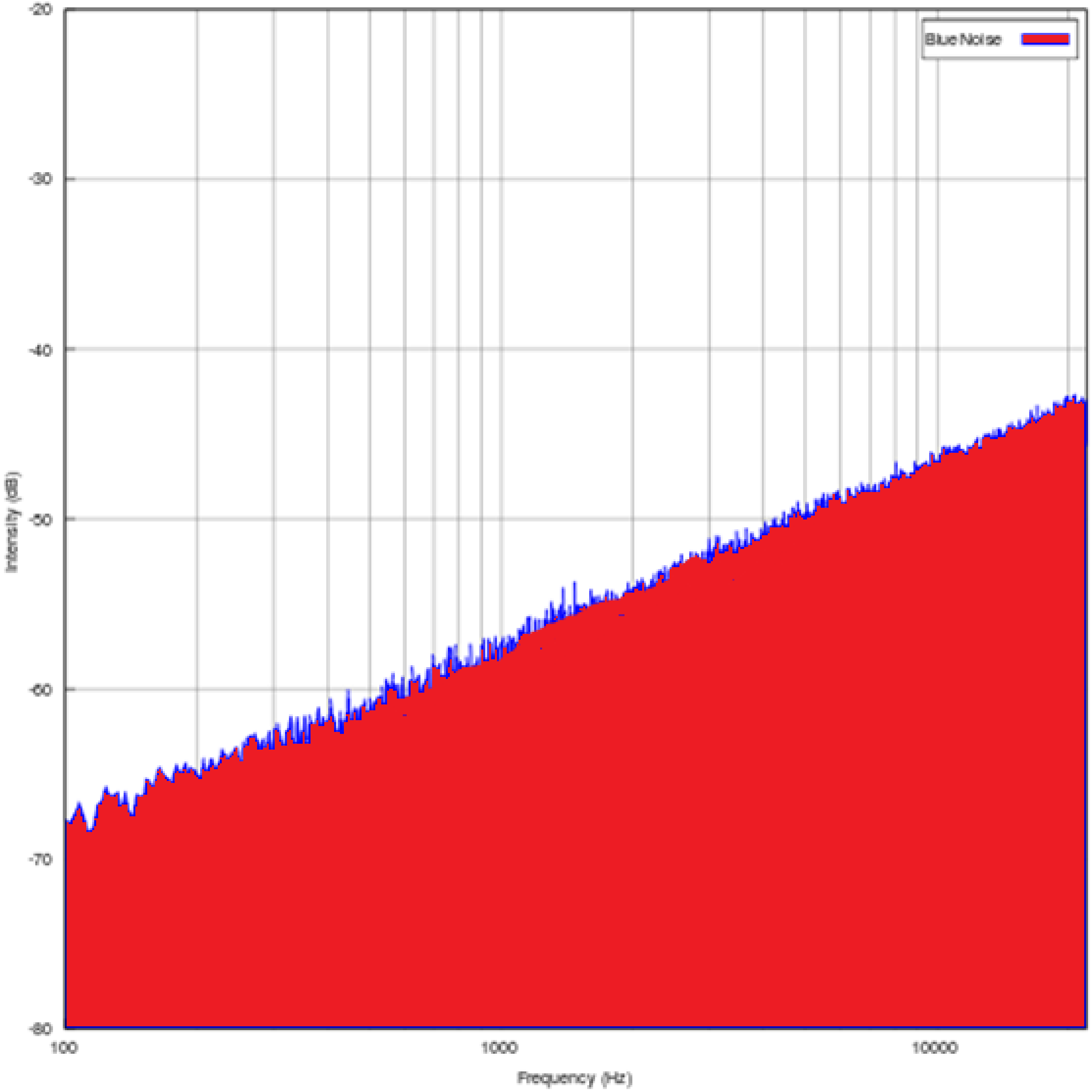
frequency density proportional to $1/f^2$



name derives from Brownian motion. Also known as "random walk" or "drunkard's walk". "Red noise"

Blue noise

density proportional to *f*



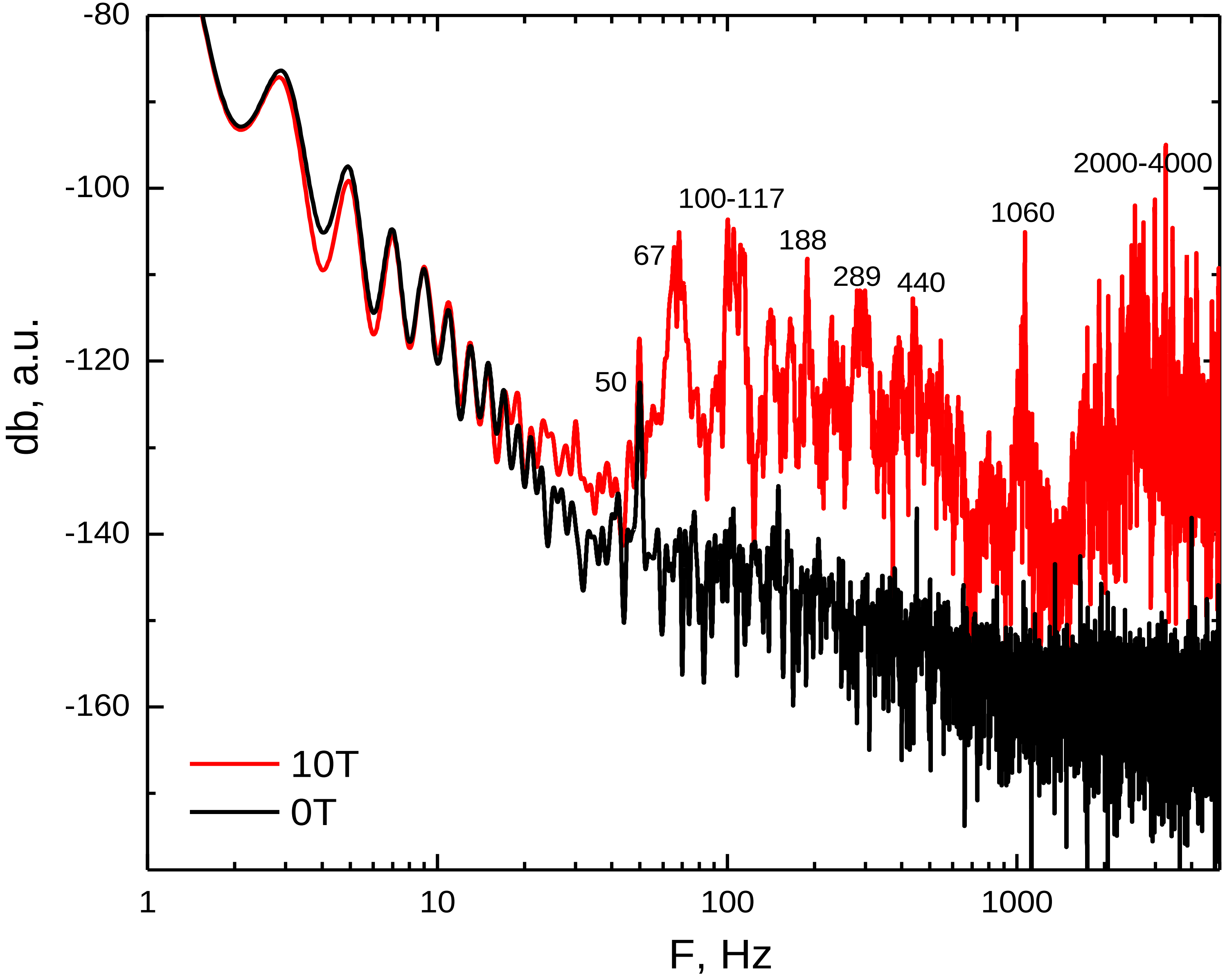
Cherenkov radiation is a naturally occurring example of almost perfect blue noise

Spectrum Analyzer

R&S®FSU Spectrum Analyzer
20 Hz to 50 GHz

Rigol RSA3030E-TG
up to 3 GHz
€3,343.00

Noise in the real system



What is a lock-in amplifier?

- to detect and measure very small AC signals (up to a few nanovolts)
- accurate measurements may be made even when the small signal is obscured by noise sources many thousands of times larger

Why use a lock-in?

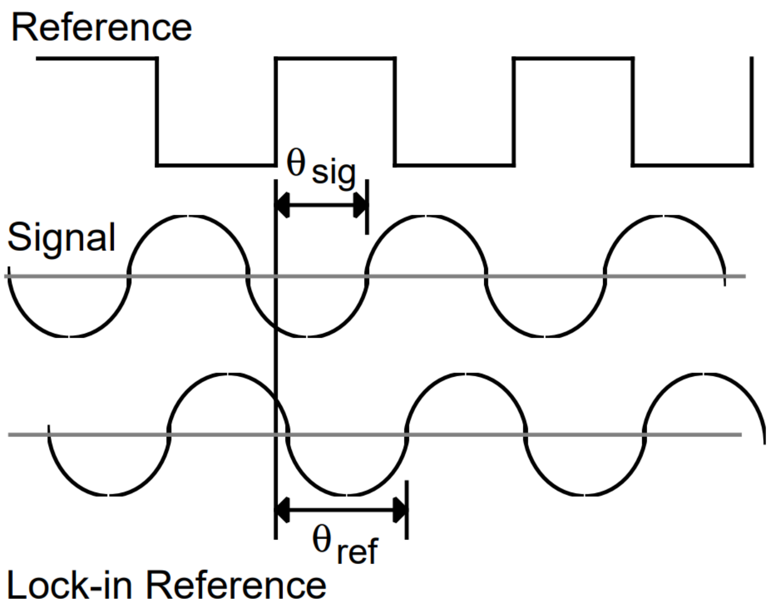
- signal is a 10 nV sine wave at 10 kHz
- a low noise amplifier 5 nV/√Hz of input noise.
- amplifier bandwidth is 100 kHz
- amplifier's gain is 1000
- 10 μV of signal (10 nV x 1000)
- 1.6 mV of noise (5 nV/√Hz x √100 kHz x 1000)

- Using band pass filter with a Q=100 bandwidth will be 10 kHz/Q, the noise will be 50 μV (5 nV/√Hz x √100 Hz x 1000)

- Using a phasesensitive detector (PSD). The PSD can detect the signal at 10 kHz with a bandwidth as narrow as 0.01 Hz. The noise will be 0.5 μV (5 nV/√Hz x √.01 Hz x 1000)

- https://research.ece.cmu.edu/~mems/resources/HH1212/SR830m.pdf

AC detection



$V_{sig}\sin(\omega_r t + \theta_{sig})$

$V_L\sin(\omega_L t + \theta_{ref})$

$$V_{psd} = V_{sig}V_L\sin(\omega_r t + \theta_{sig})\sin(\omega_L t + \theta_{ref})$$

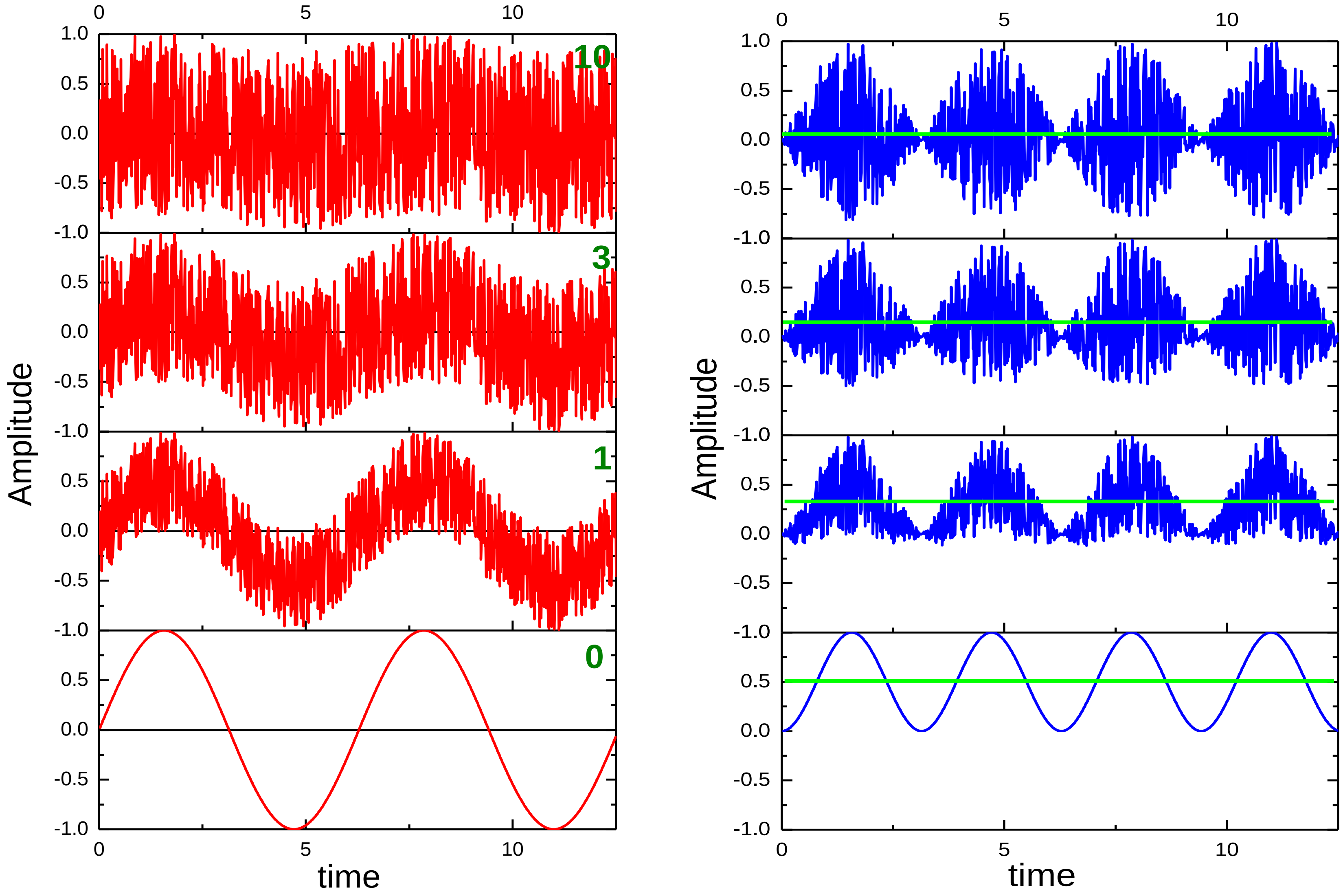
$$= 1/2\, V_{sig}V_L\cos([\omega_r - \omega_L]t + \theta_{sig} - \theta_{ref}) - 1/2\, V_{sig}V_L\cos([\omega_r + \omega_L]t + \theta_{sig} + \theta_{ref})$$

$\omega_r = \omega_L$

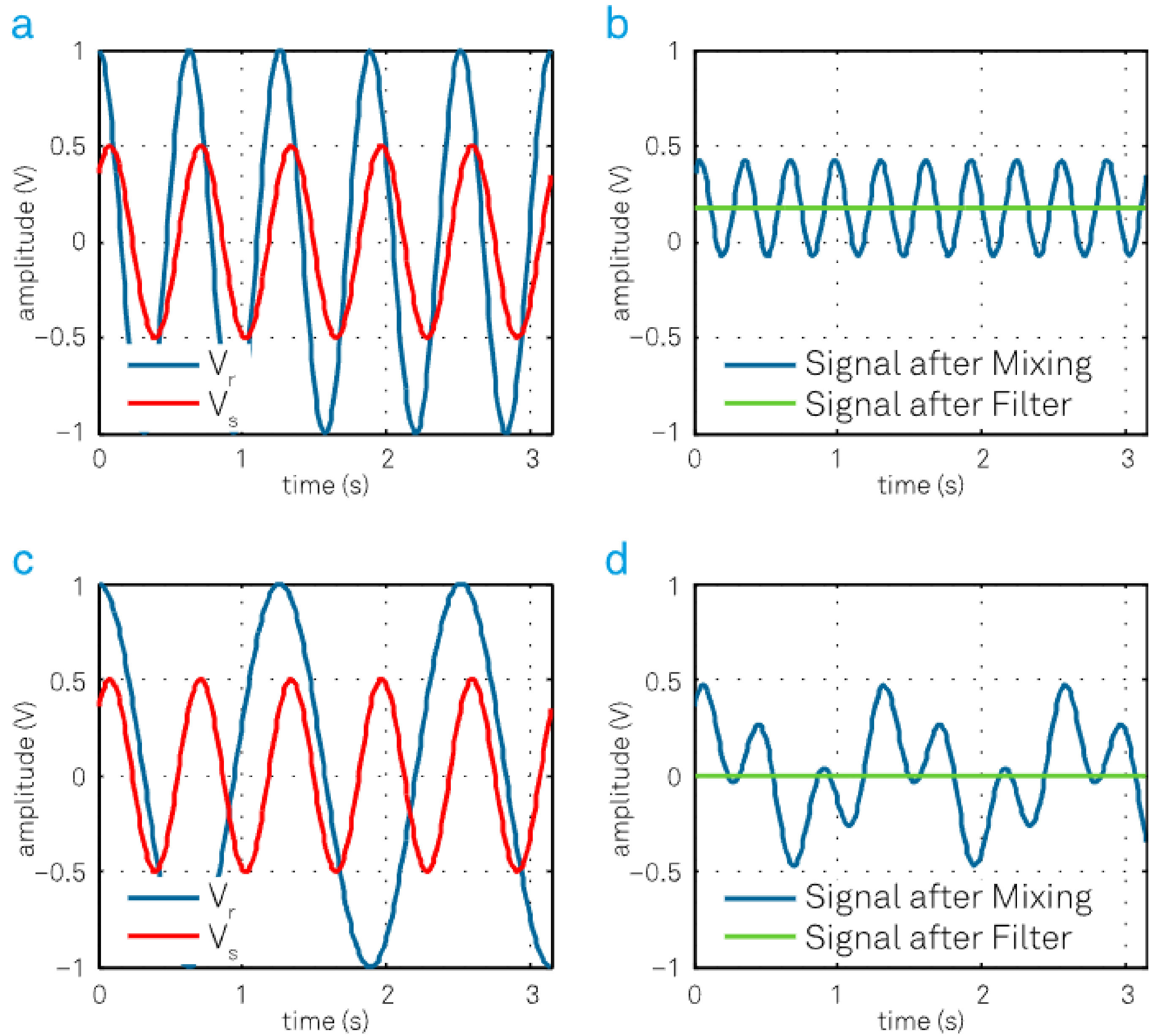
$$V_{psd} = 1/2\, V_{sig}V_L\cos(\theta_{sig} - \theta_{ref})$$

https://research.ece.cmu.edu/~mems/resources/HH1212/SR830m.pdf

Signal processing



Signal processing



https://www.zhinst.com/others/en/resources/principles-of-lock-in-detection

Phase sensitive detector (PSD)

$V_L \sin(\omega_L t + \theta_{ref})$

$$V_{psd} = 1/2\ V_{sig} V_L \cos(\theta_{sig} - \theta_{ref})$$

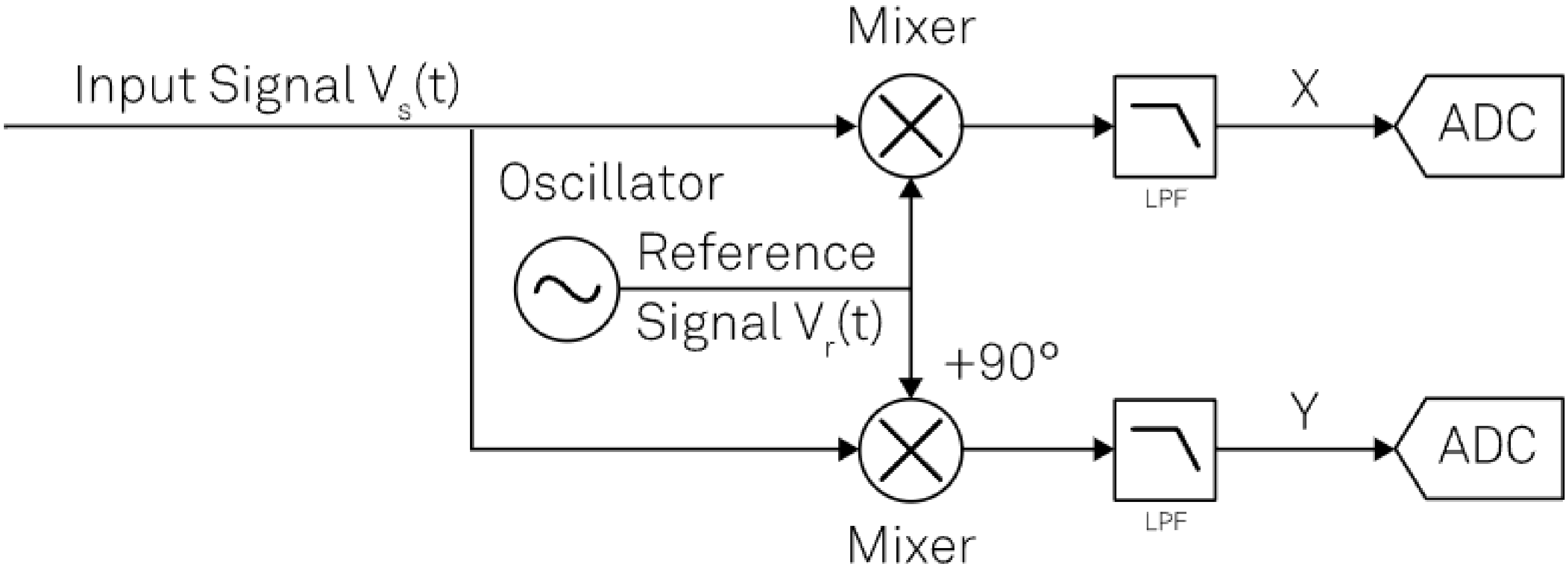
$V_L \sin(\omega_L t + \theta_{ref} + 90°)$

$$V_{psd2} = 1/2\ V_{sig} V_L \sin(\theta_{sig} - \theta_{ref})$$

$X = V_{sig} \cos\theta$ $\qquad$ $Y = V_{sig} \sin\theta$

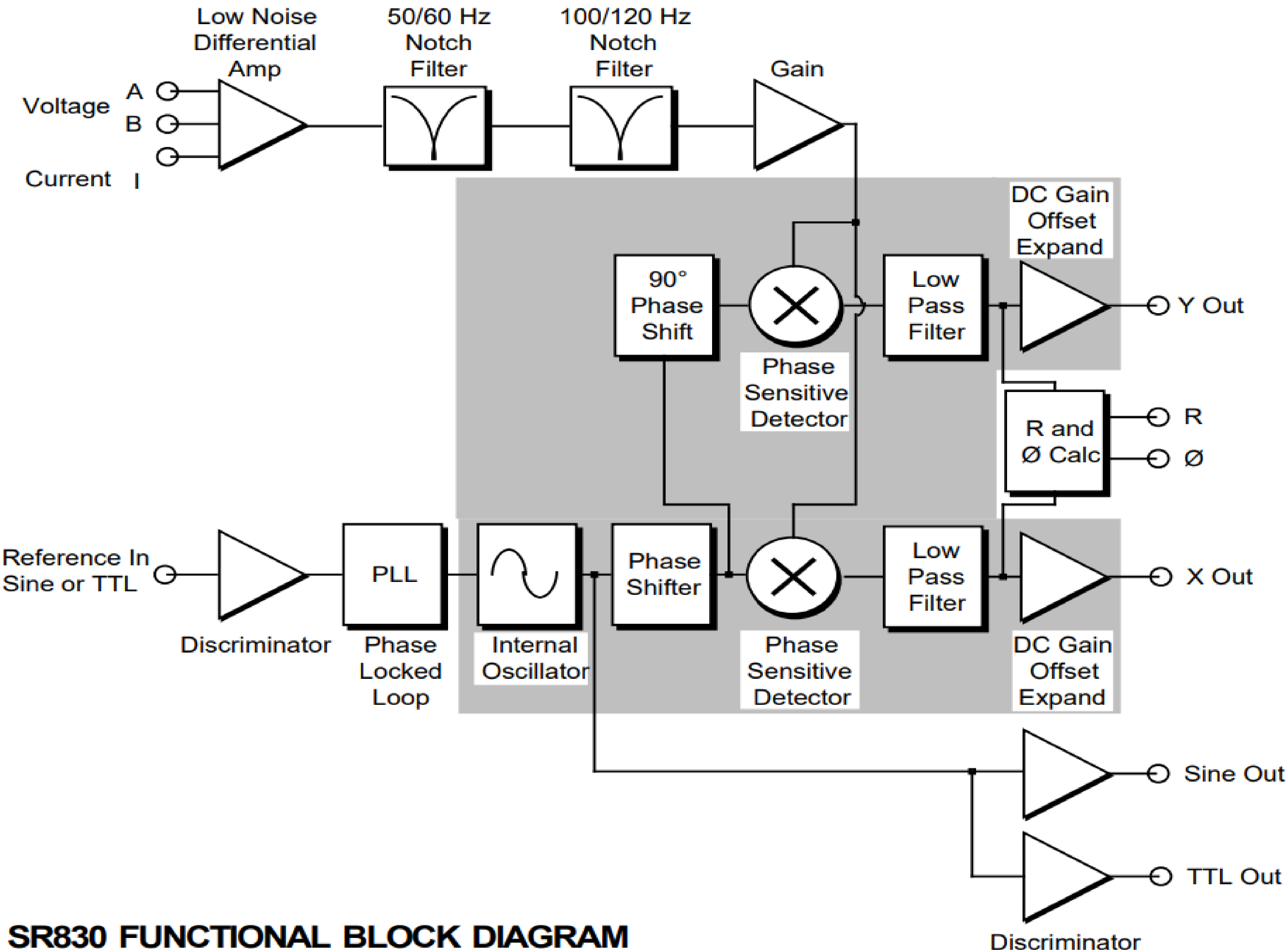
$R = (X^2 + Y^2)^{1/2} = V_{sig}$

PSD block diagram



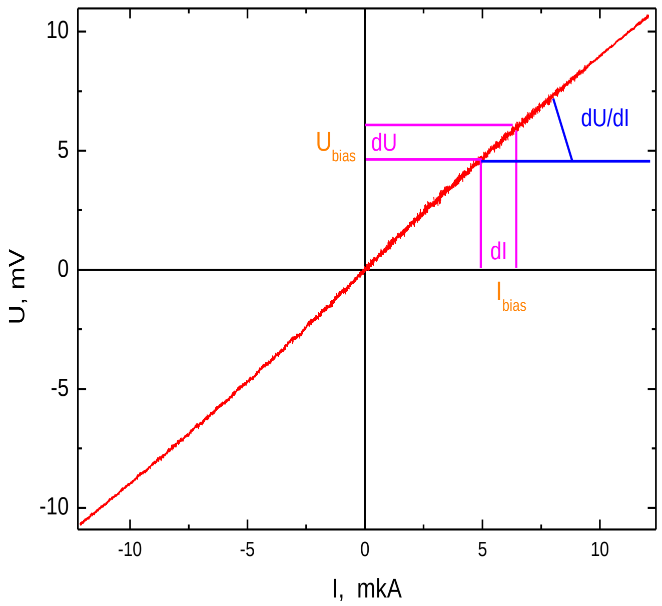
SR830 DSP Lock-in Amplifier

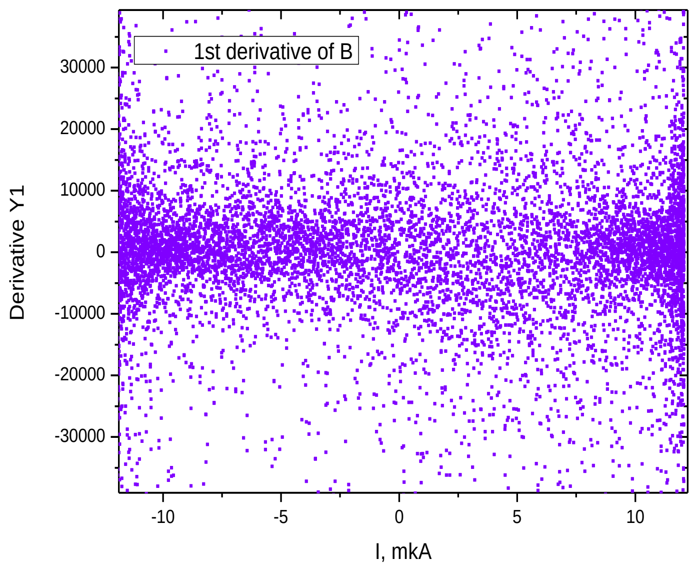
SR830 functional block diagram

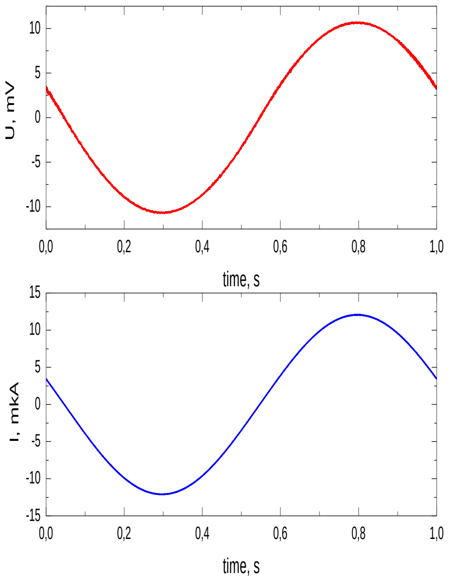


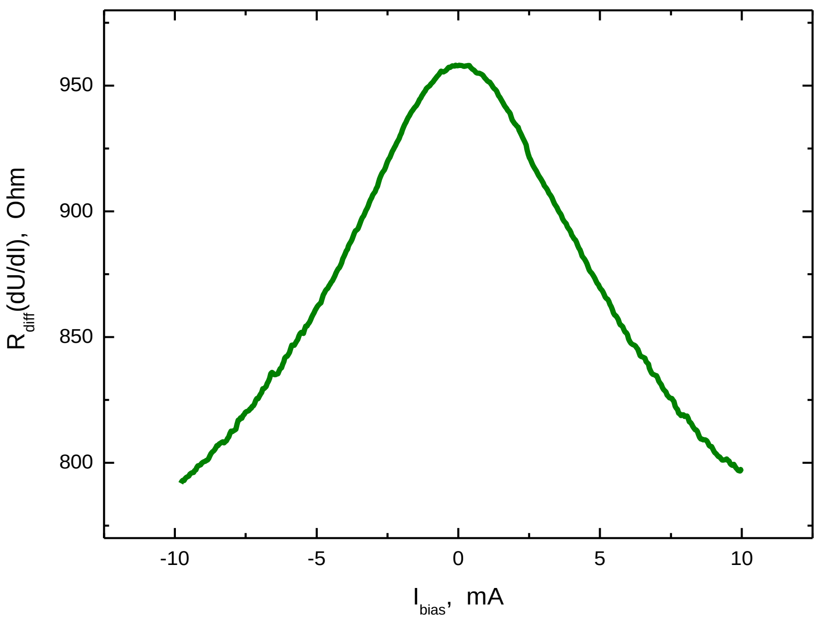
SR830 FUNCTIONAL BLOCK DIAGRAM

differential i-v characteristic

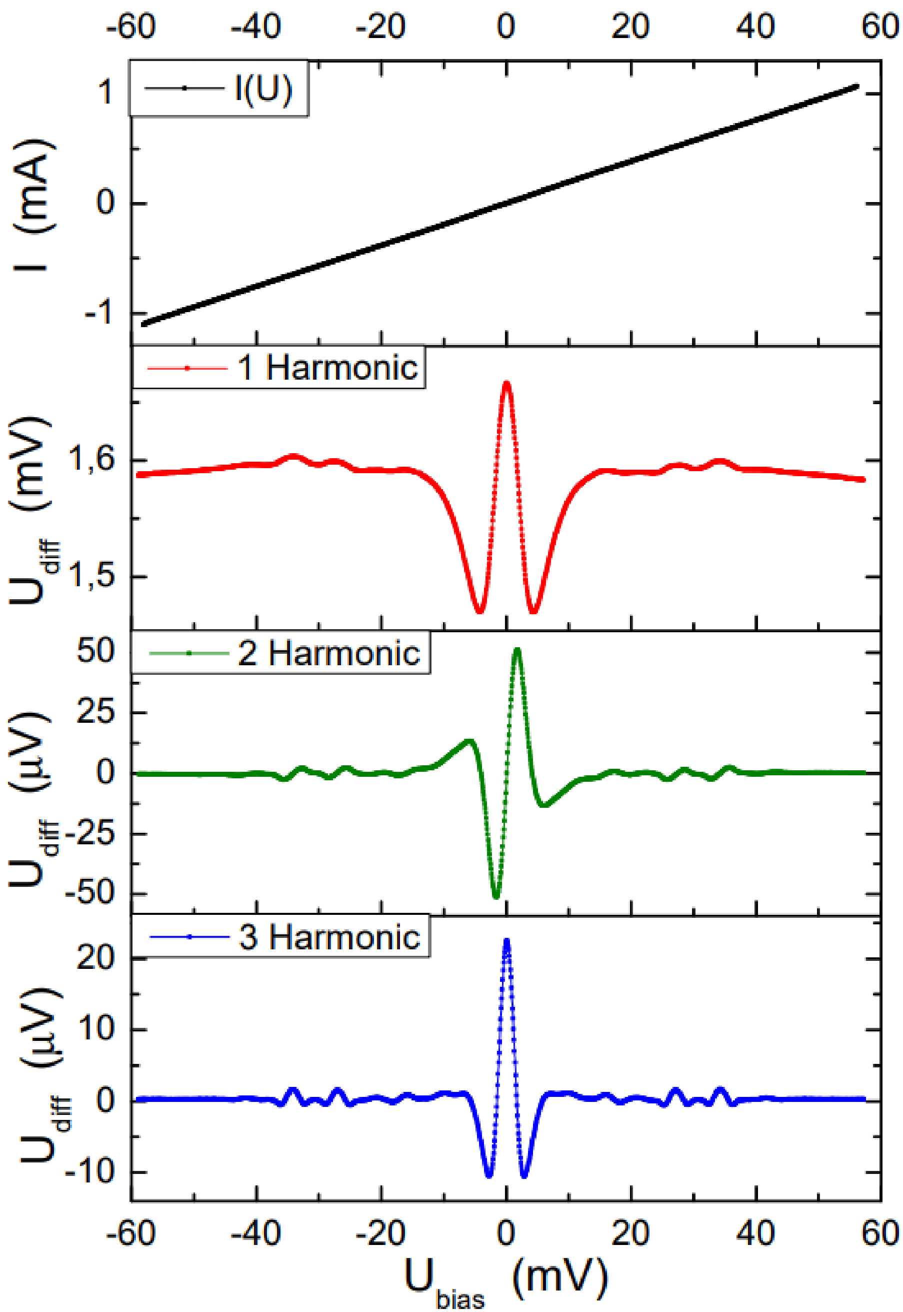




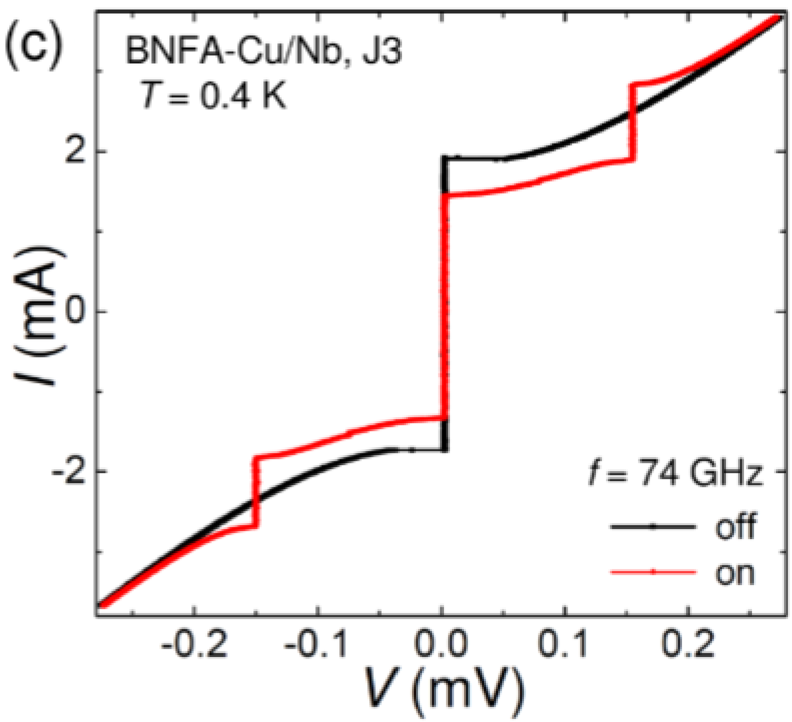


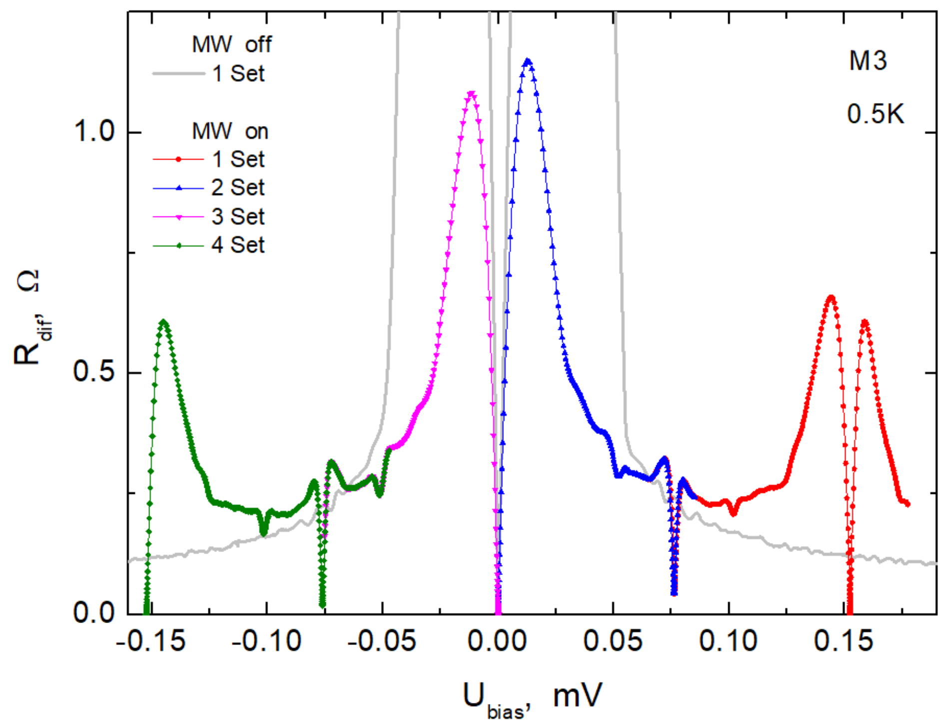


MoRe-AgOx-Ag I-V characteristic



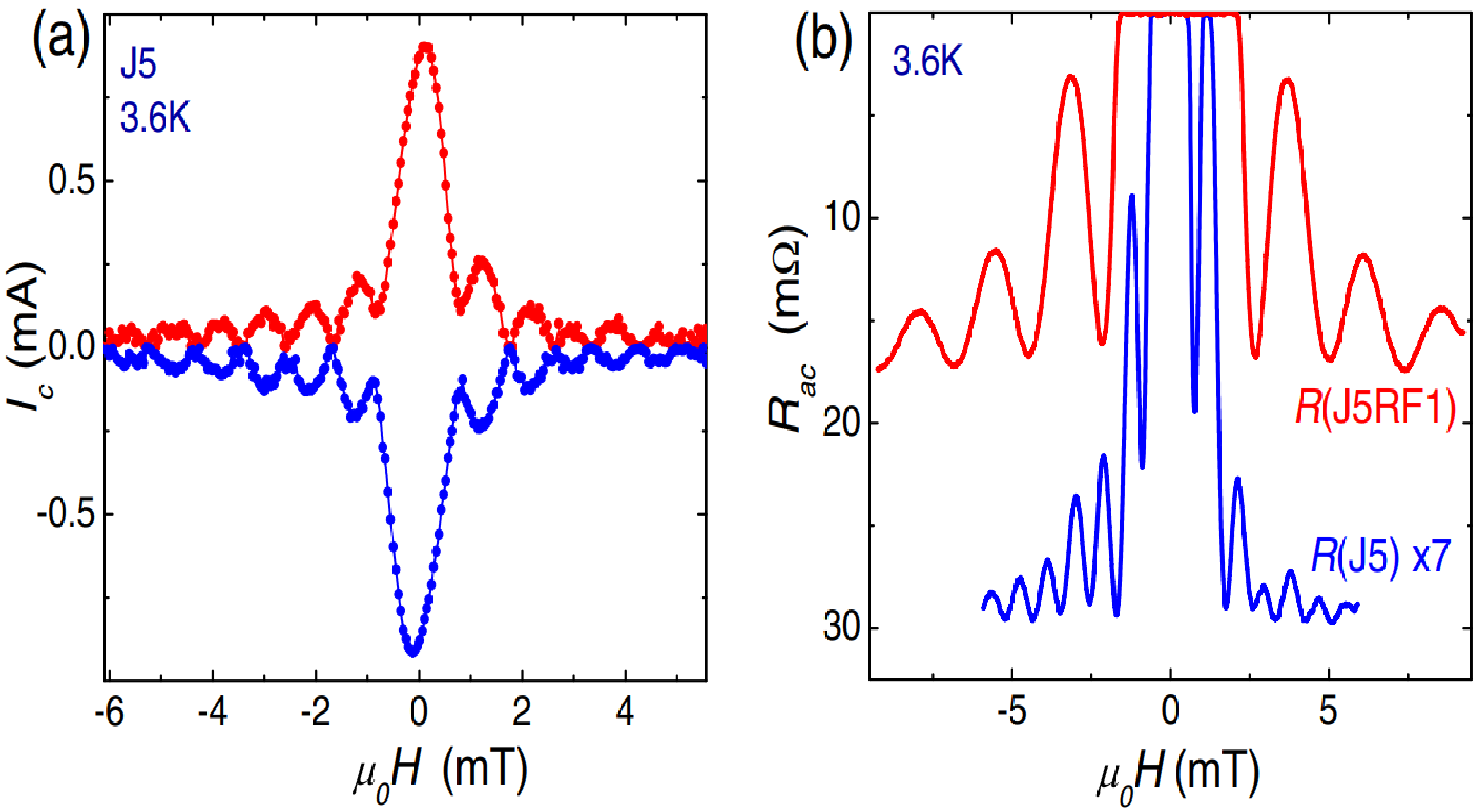
Shapiro steps





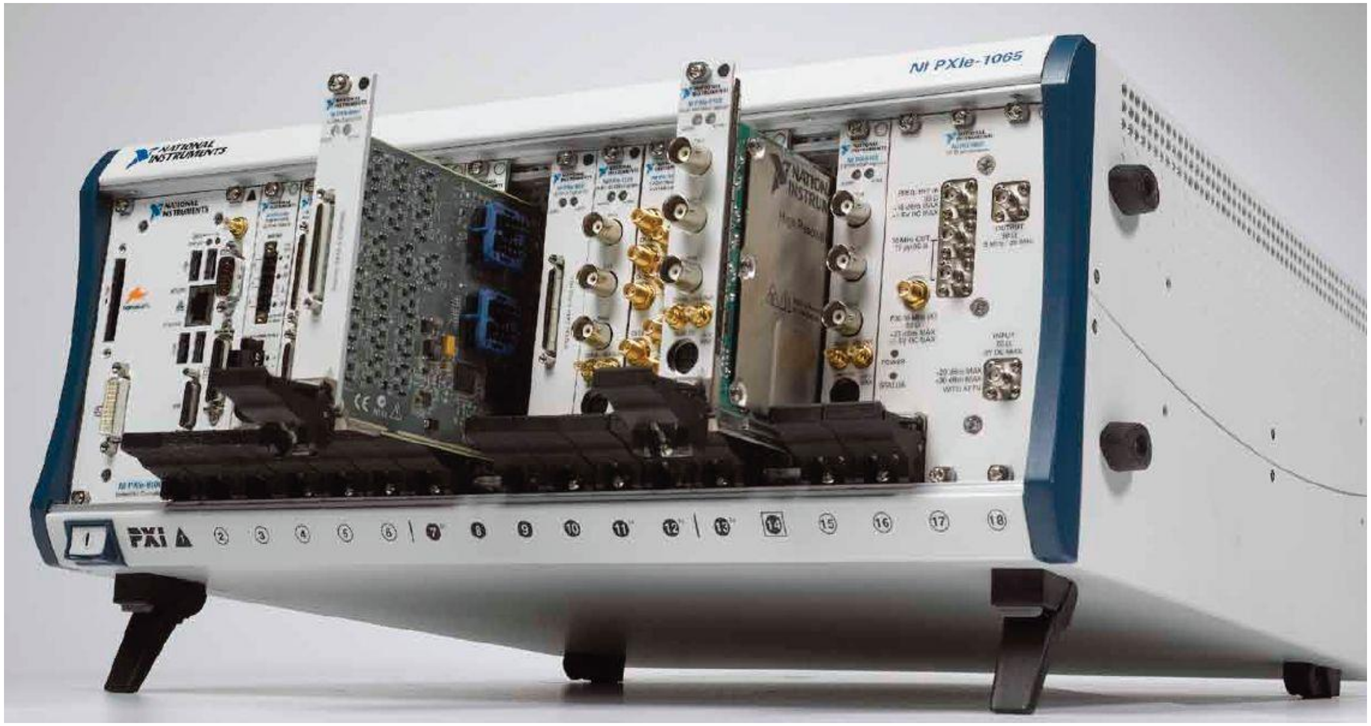
PHYSICAL REVIEW B103, 214507 (2021)

Fraunhofer modulation Ic(H)



PHYSICAL REVIEW LETTERS 120, 067001 (2018)

PXI Platform



thanks for attention