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Tutorial 4

Low-Noise Impedance Sensing: Circuits and Micro-Technological Applications

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IEEE
ITALY SECTION

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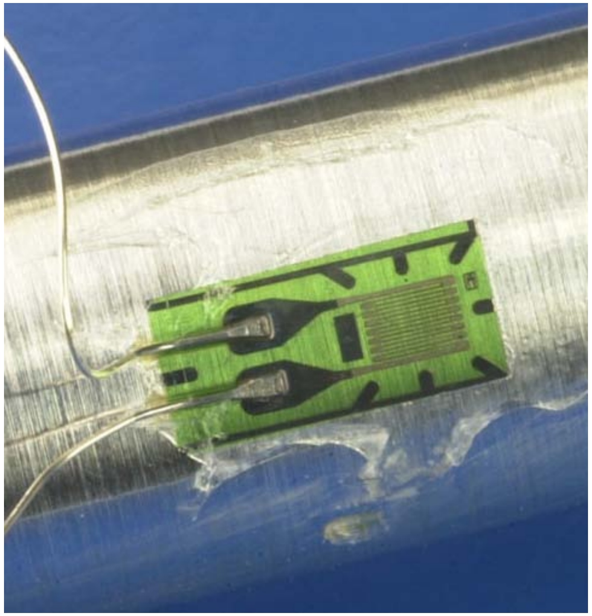
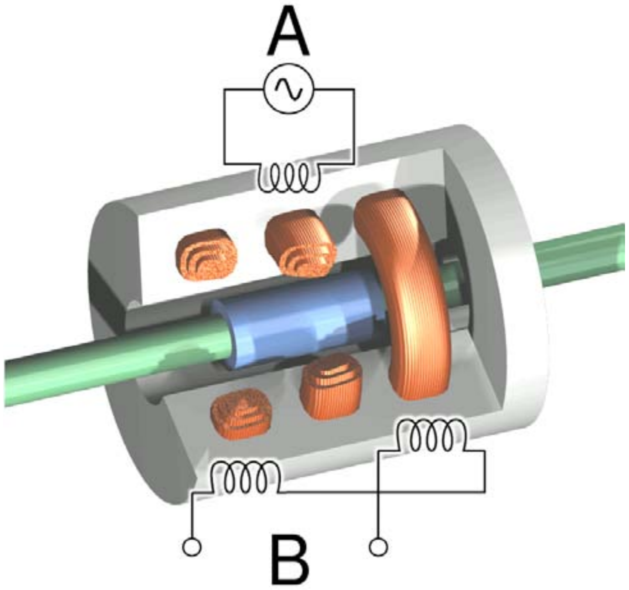
Motivation: Impedance is Everywhere

Thanks to its versatility, impedance is traditionally leveraged in **several industrial sensing applications**

Strain/Pressure	Level	Displacement
Resistance	*Capacitance*	*Inductance*



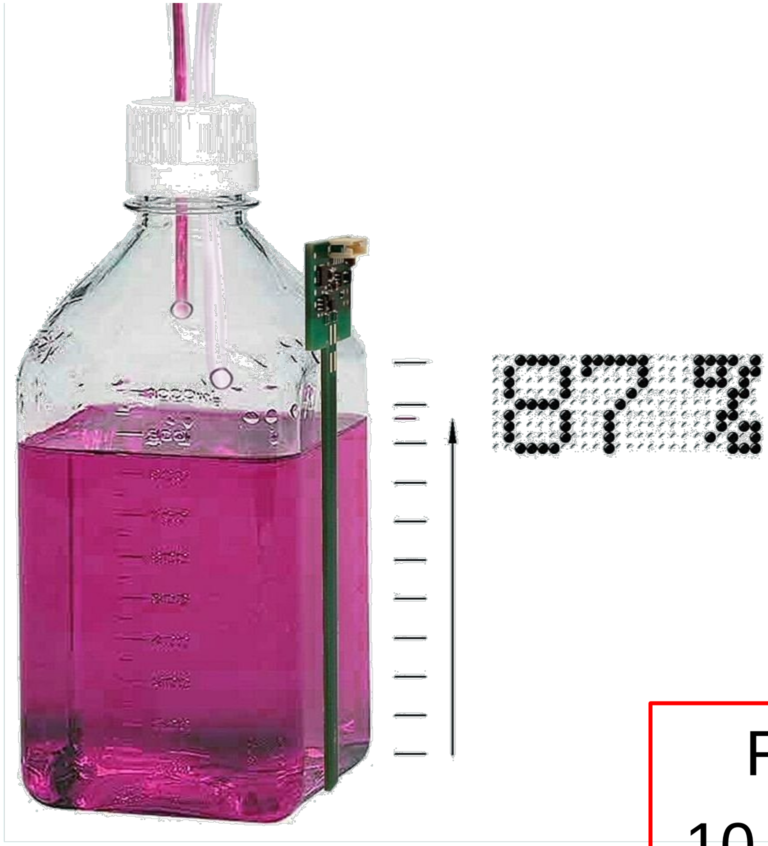


Introduction

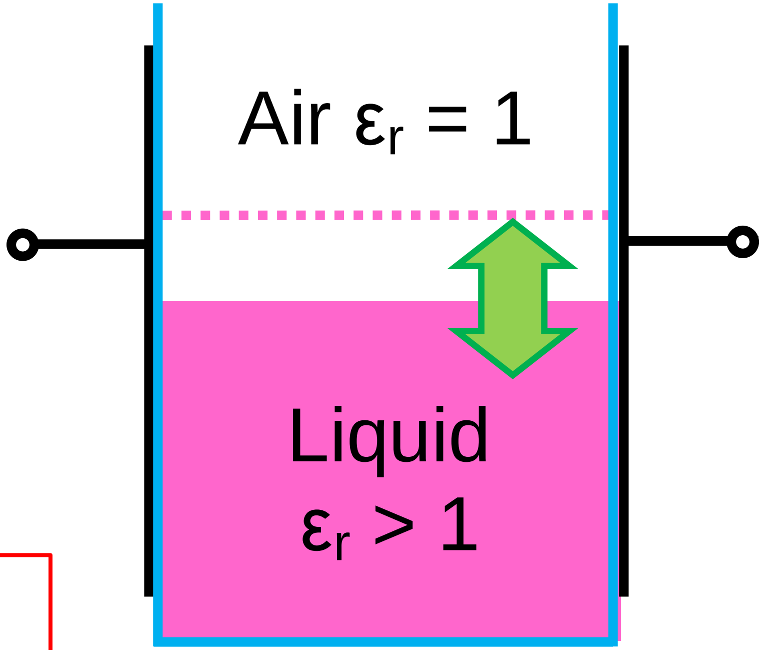
Focusing on the example of *contactless capacitive sensing*, let's see the scaling trend **from macro to micro** size applications

Macro: Contactless Liquid Sensing

Electrodes are protected from the liquid,
the capacitance increases linearly with the tank level

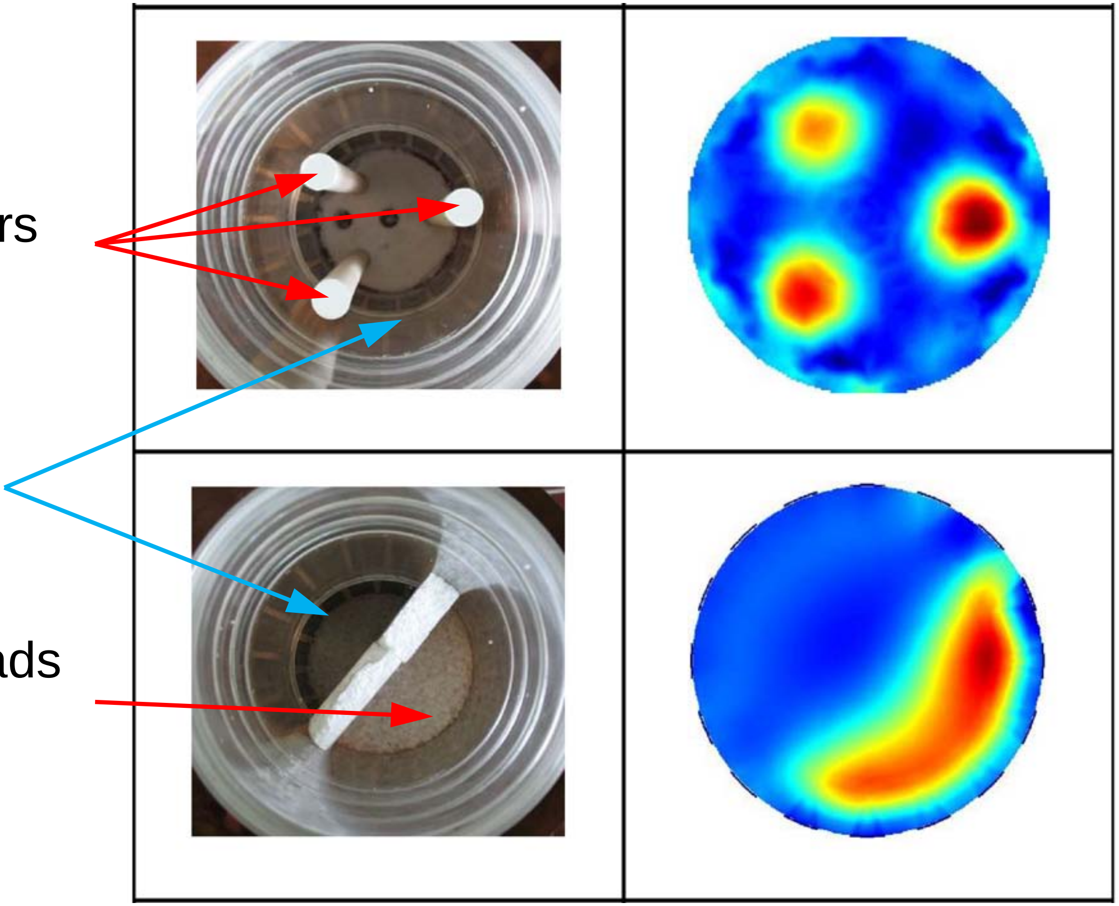


Range
10-1000pF



Macro: Contactless Capacitance Tomography

Impurities inside pipes (or droplets in microfluidic channels) can be detected with several electrodes properly arranged

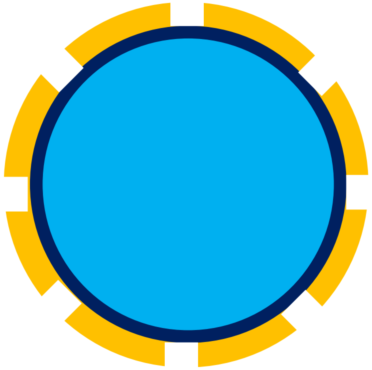


Plastic bars
$\varepsilon_r = 3$

Air
$\varepsilon_r = 1$

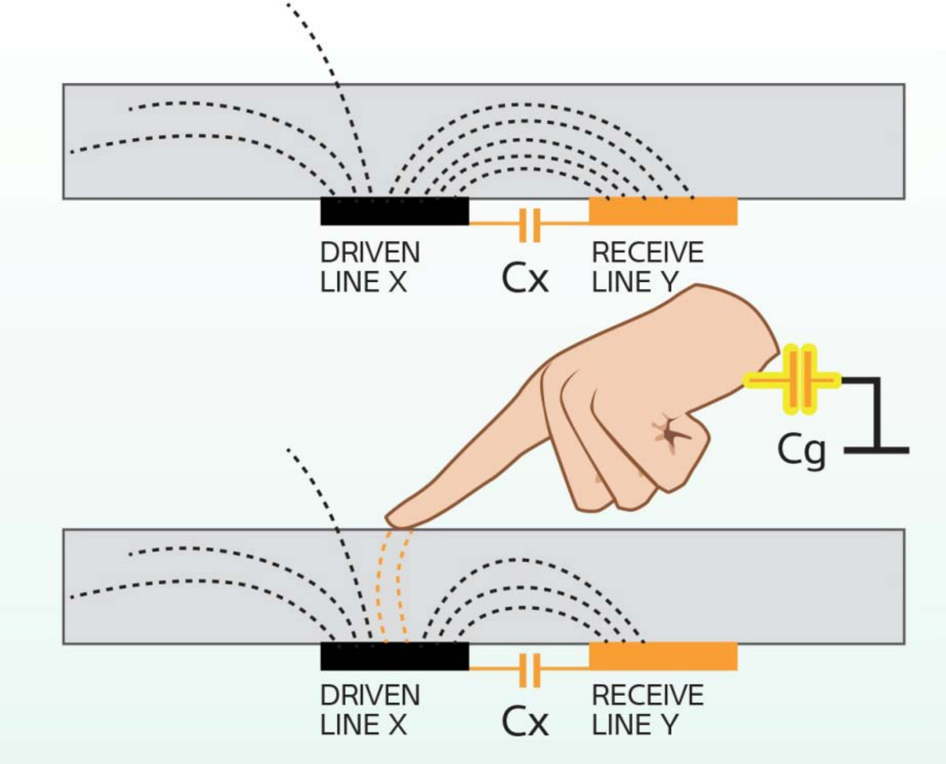
Plastic beads
$\varepsilon_r = 3$

Pipe cross-section



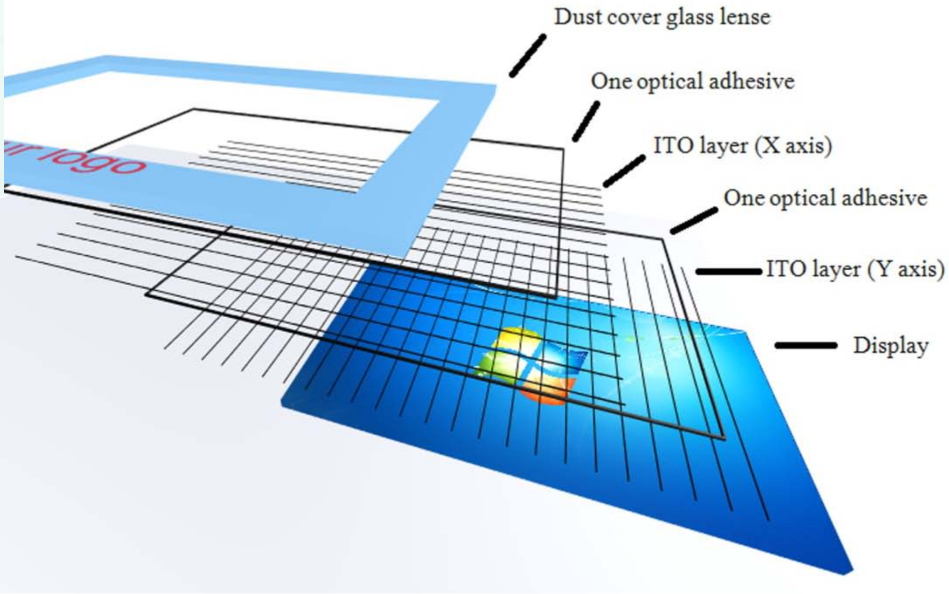
Range
10-100pF

Mini: Capacitive Touchscreen

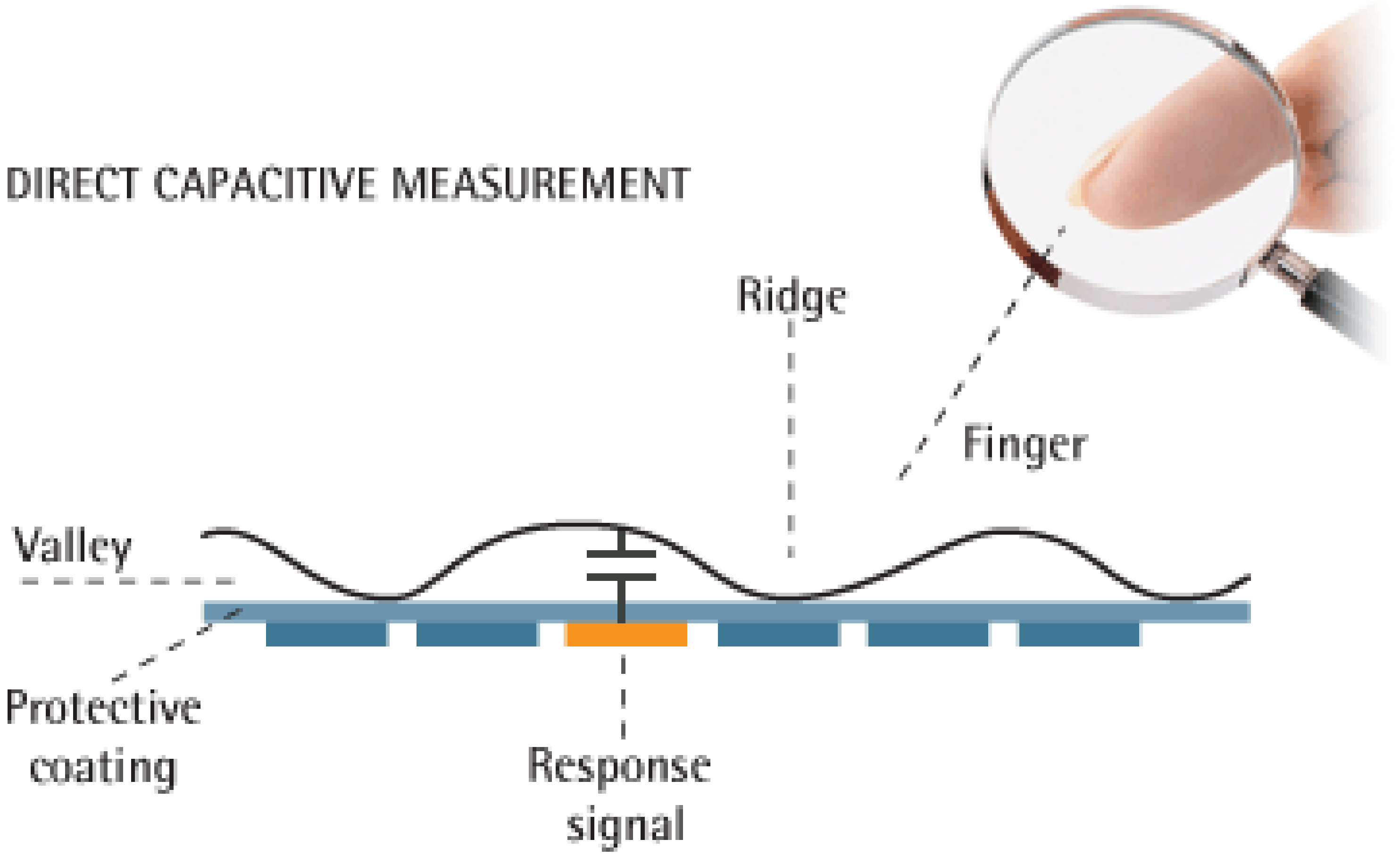


Range

10-100fF



Milli: Capacitive Fingerprint Scanner

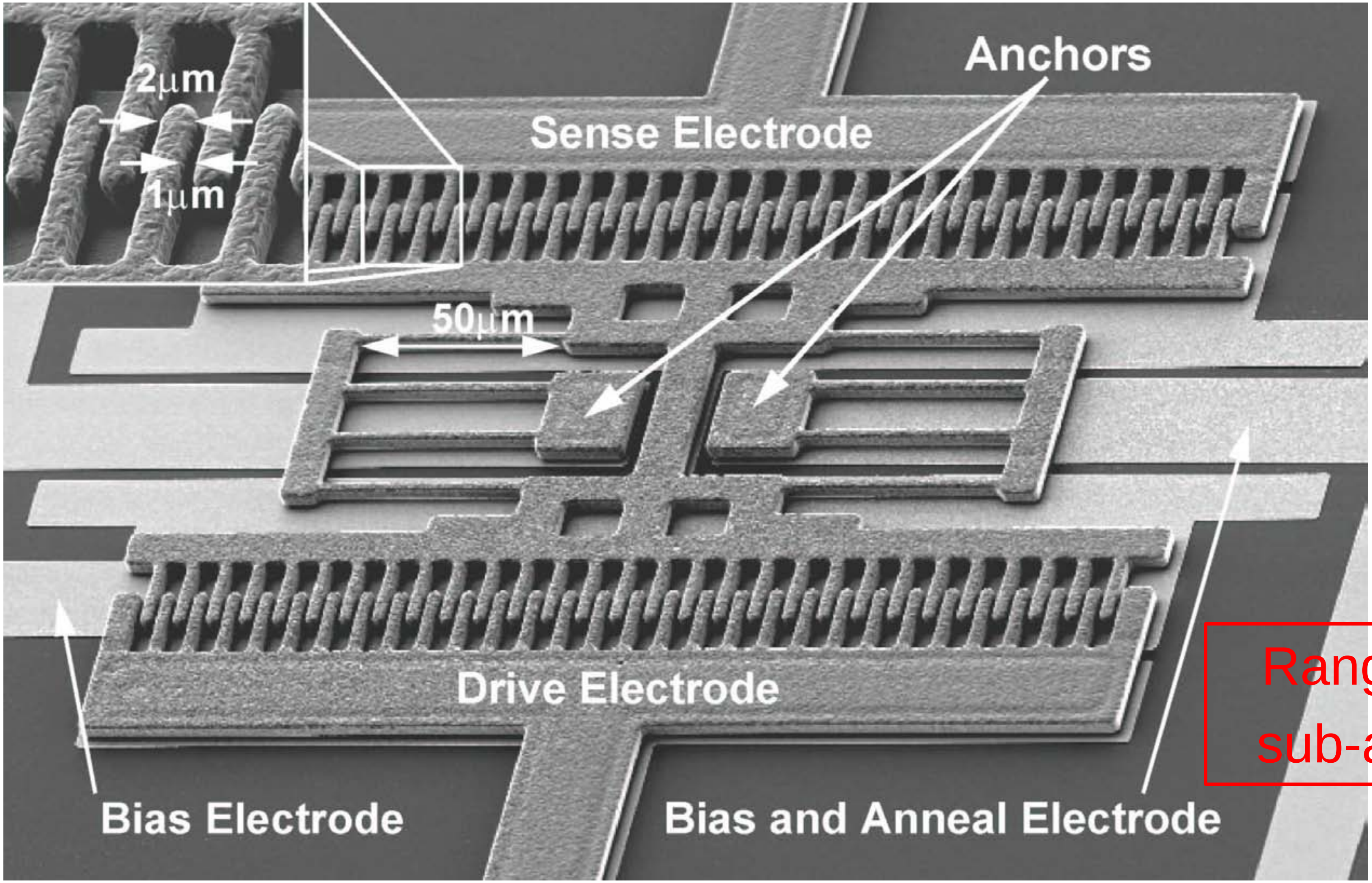


Range

5-50fF

Micro: Inertial MEMS

Capacitive sensing of displacement of micro proof masses



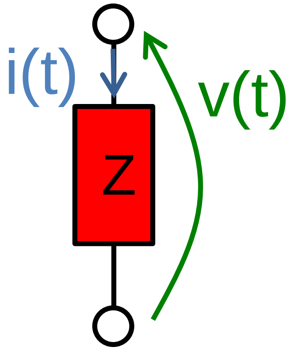
Range
sub-aF

Tutorial Outline

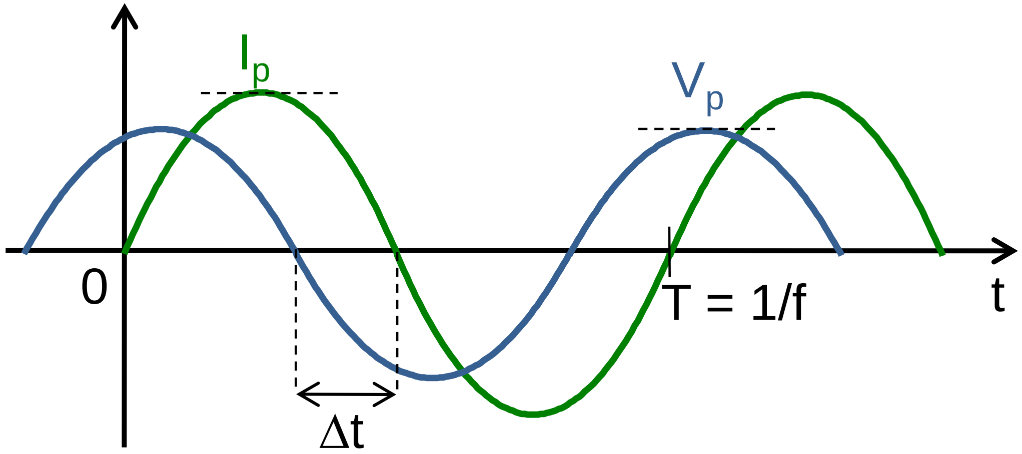
- Definitions and spectra diagrams
- Microscale impedance measurement
- Introduction to electronic noise
- Low-noise current sensing
- Transimpedanace amplifier and lock-in
- Role of the input (stray) capacitance: cables and substrates
- Advanced circuit topologies
- **Example of applications:**
  - Biological cell counting
  - Particulate matter detection
  - Non-invasive light power metering

Definitions

Impedance is a complex quantity changing with frequency f:



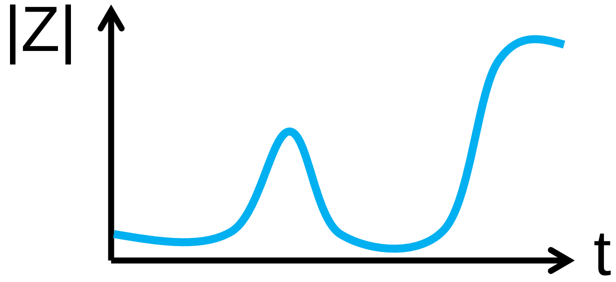
$$Z(f) = \frac{V_p}{I_p} e^{j2\pi\Delta tf}$$



Re{Z}: energy dissipation, Im{Z}: energy storage

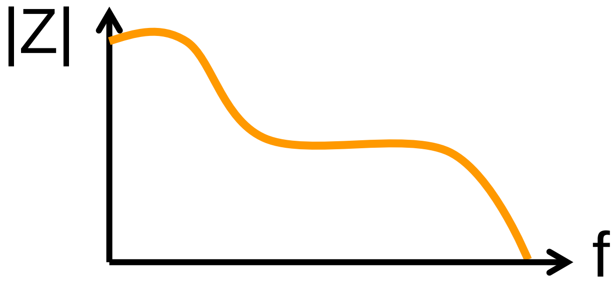
Impedance can be measured:

Time tracking



fixed f

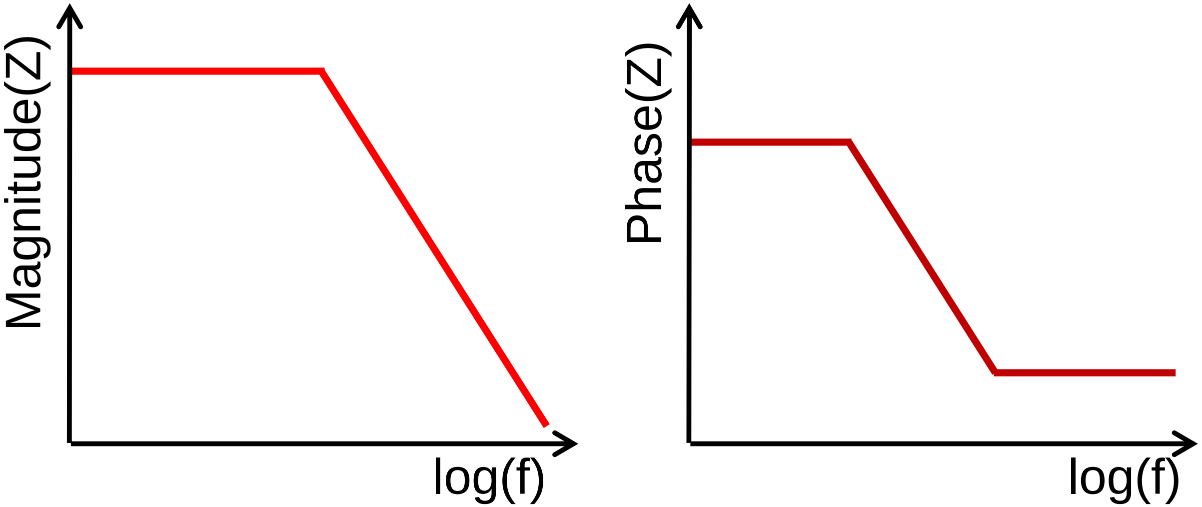
Spectroscopy



Plotting Impedance Spectra

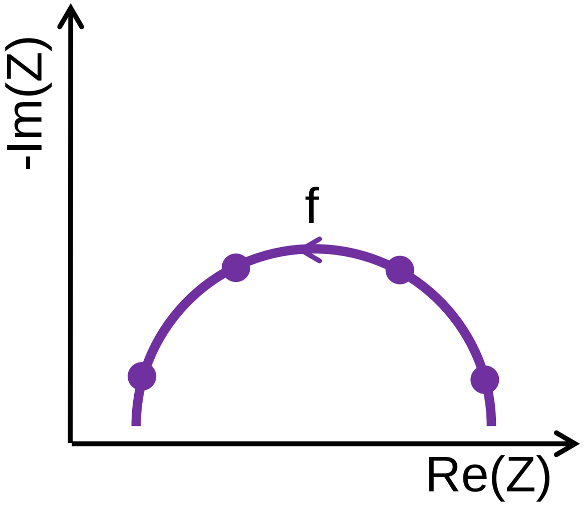
Two alternative ways to present impedance spectra:

Bode Plots



Electronic engineering and automation/control science

Cole-Cole Plot

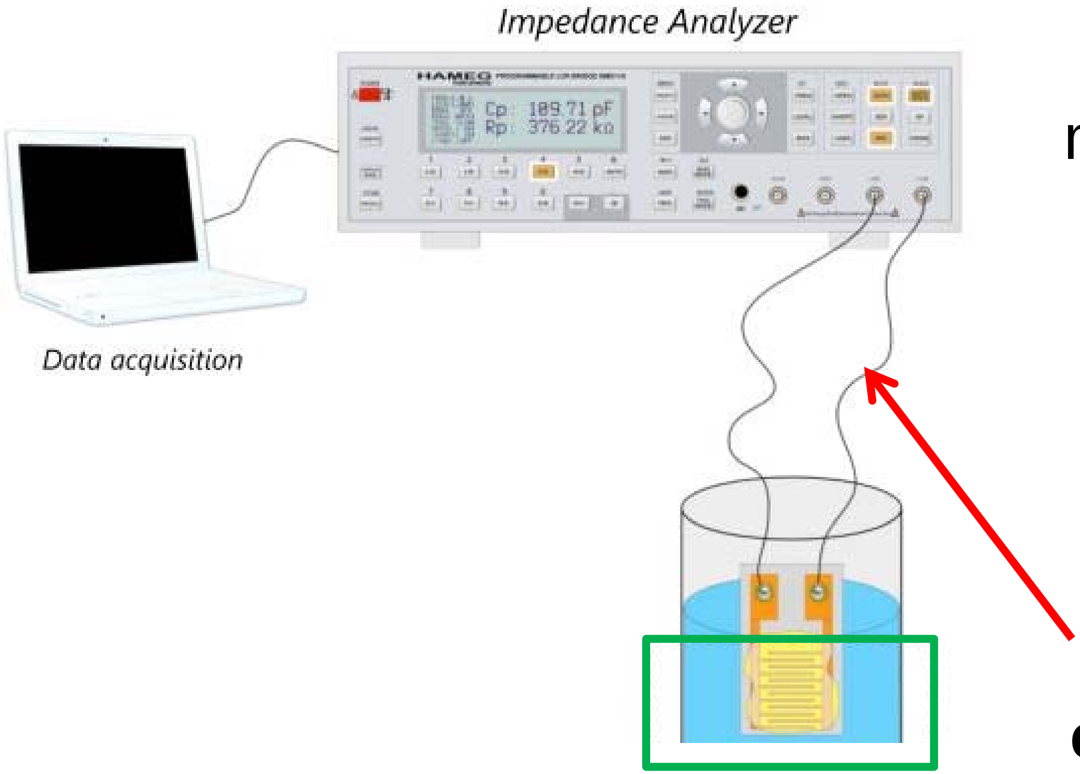


Electrochemical & biosensors community

Equivalent!

Microscale Impedance Sensing

Microfabriaction allows the realization of **microelectrodes** to interface with microscale samples (such as biological cells).



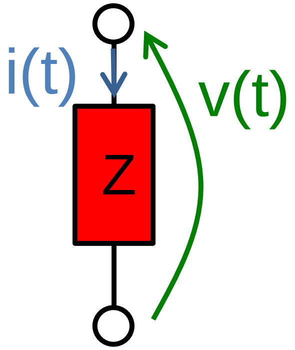
The impedance of the micro sample **scales** with the size

while

the parasitic impedance of the macroscopic **connections** stays fixed.

Noise Becomes Important

If Z increases, given the same excitation voltage (limited by biology or *dielectric breakdown*), the current flowing through the system **decreases:**



It becomes harder to measure a smaller current

The noise of the instrument (current reader) becomes significant!

The noise is a property of the detection instrument but might depend on the sample and on the connections.

What is Noise?

Any electrical signal is affected by disturbances and **noise**:

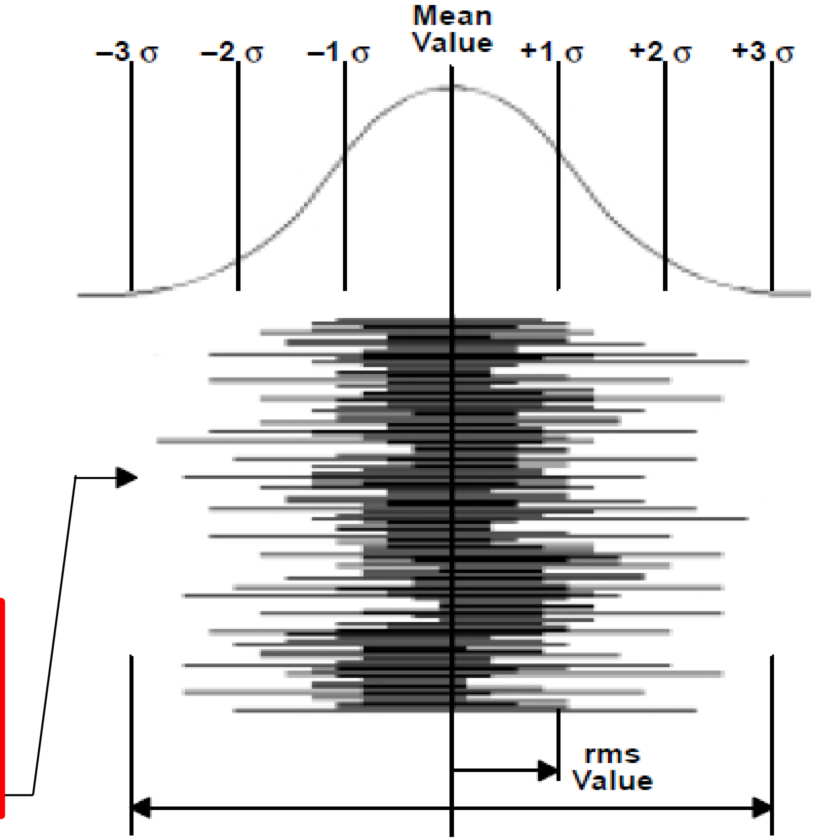
$$i(t) = signal(t) + d(t) + n(t)$$

Disturbances are signals of external origin that can be filtered.

Noise is a random fluctuation of the electrical variables due to the physical behaviour of *internal* components of the circuit.

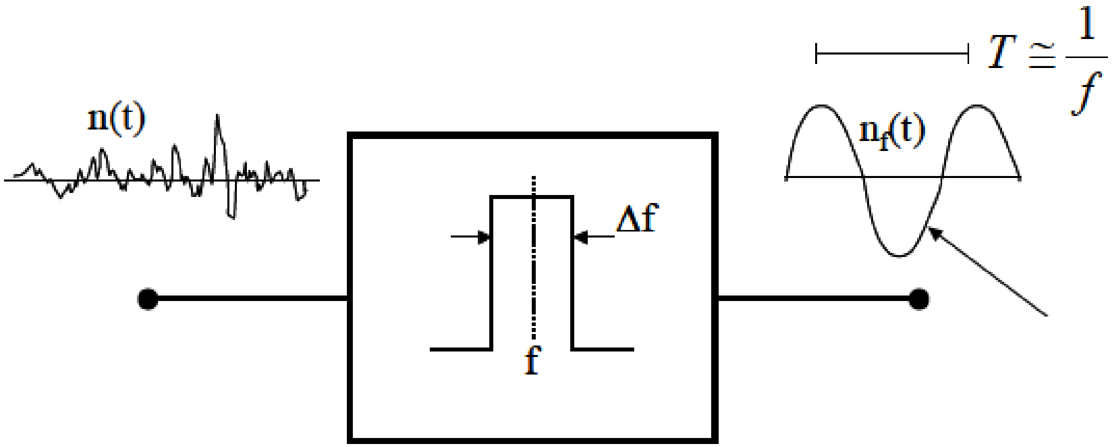
Described by standard deviation σ

$$SNR = \frac{Signal\ Amplitude}{Noise\ Amplitude} = \frac{Signal}{\sigma_{rms}}$$



Noise Power Spectrum

Description in the frequency domain:

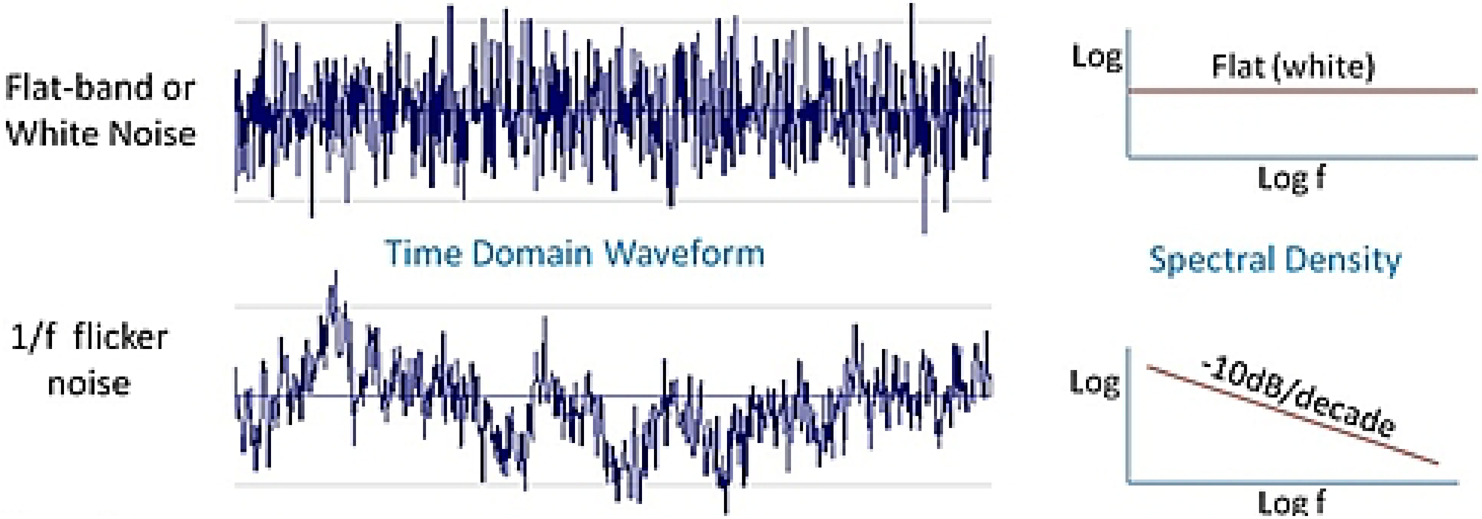


Noise spectral density

$$S(f) = \overline{n_f^2(t)} \Big/ \Delta f$$

$$\overline{n^2(t)} = \int_0^\infty S(f)\,df$$

$$\mathrm{RMS} = \sqrt{\overline{n^2(t)}} = \sqrt{\int_0^\infty S(f)\,df}$$



Impedance Measurement Techniques

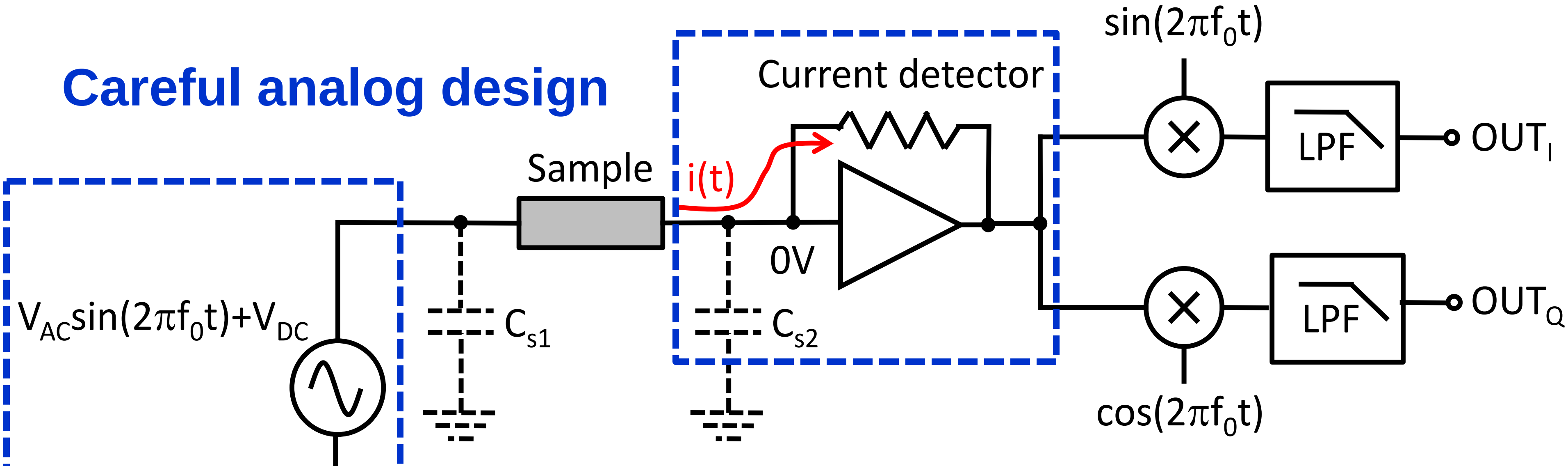
Sinusoidal stimulation:	**(Measurand)**
Wheatstone bridge	(voltage)
Ratiometric	(voltage)
Resonant	(frequency)
Current sensing + lock-in	(current)

most versatile approach, better rejection of parasitics

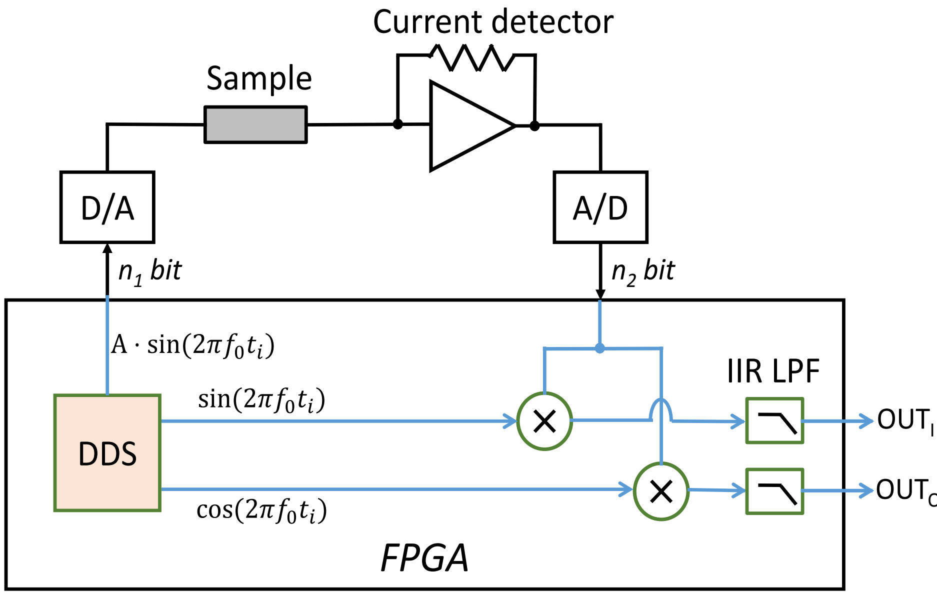
Non sinusoidal stimulation:	
Multi-sine or pseudo noise FFT-based	(current)
Time-domain fitting of step response	(current/voltage)
Capacitance charge and discharge	(current/time)

Impedance Detector Architecture

Careful analog design



Lock-in digital implementation:



FPGA embedded processing for:

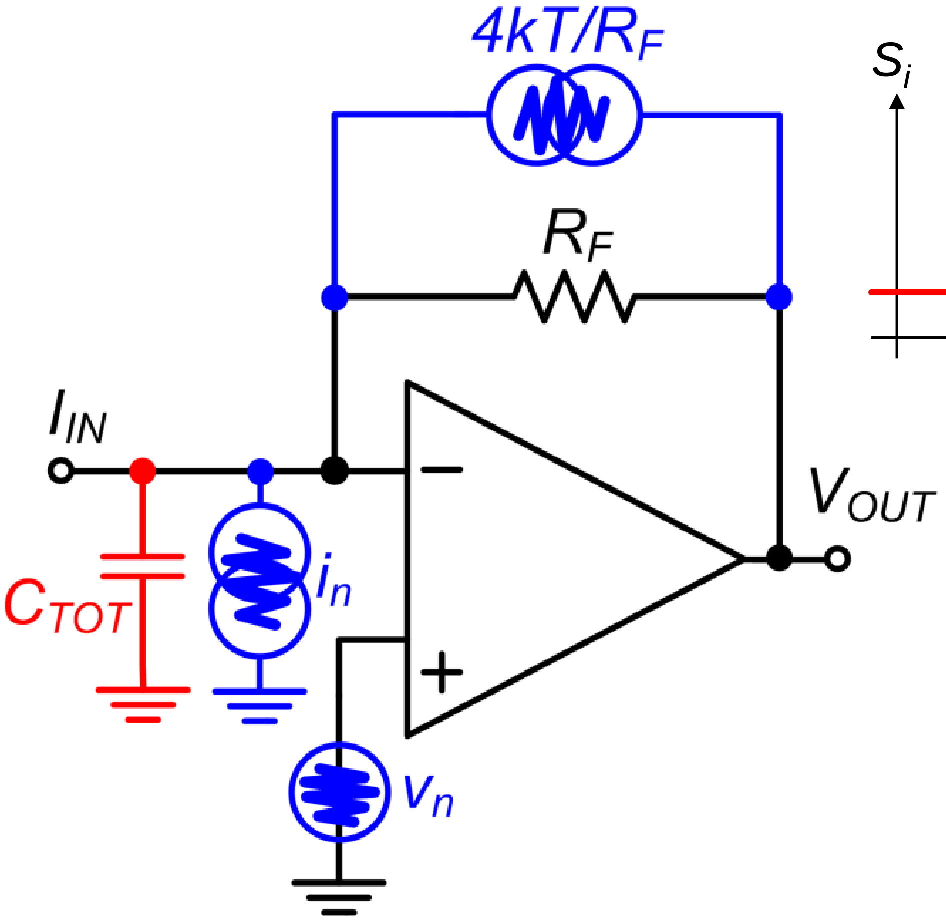
- speed
- versatility (multi-freq.)

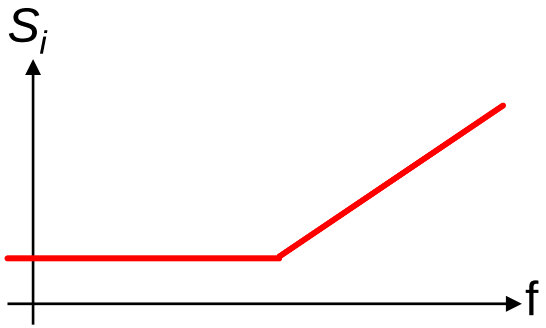
M. Carminati, *IEEE I2MTC.* 2012

Transimpedance Amplifier: Noise Analysis

Input-referred total current noise:

$$S_i^{\,2}(f) = i_n^{\,2} + \frac{4kT}{R_F} + \frac{v_n^{\,2}}{R_F^{\,2}} + v_n^{\,2}(2\pi f \boxed{C_{TOT}})^2$$

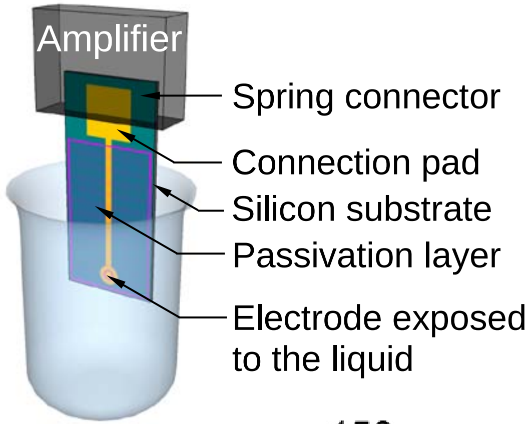


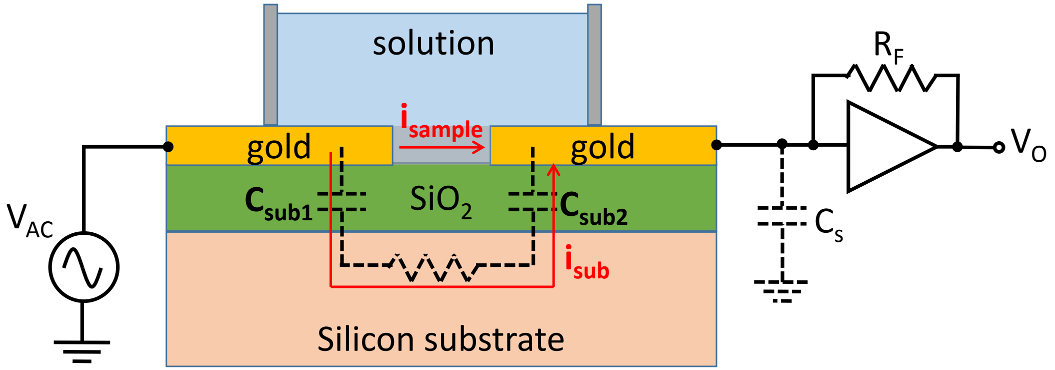


Minimize C_{Stray}!

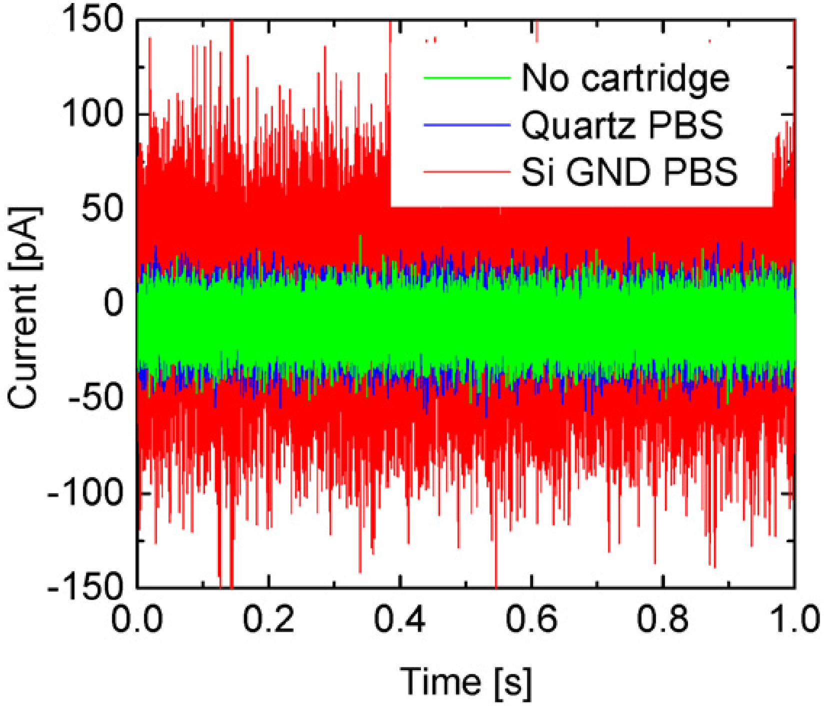
- Minimization of parasitics
- Major motivation for front-end integration
- Accurate modeling of the sensor impedance

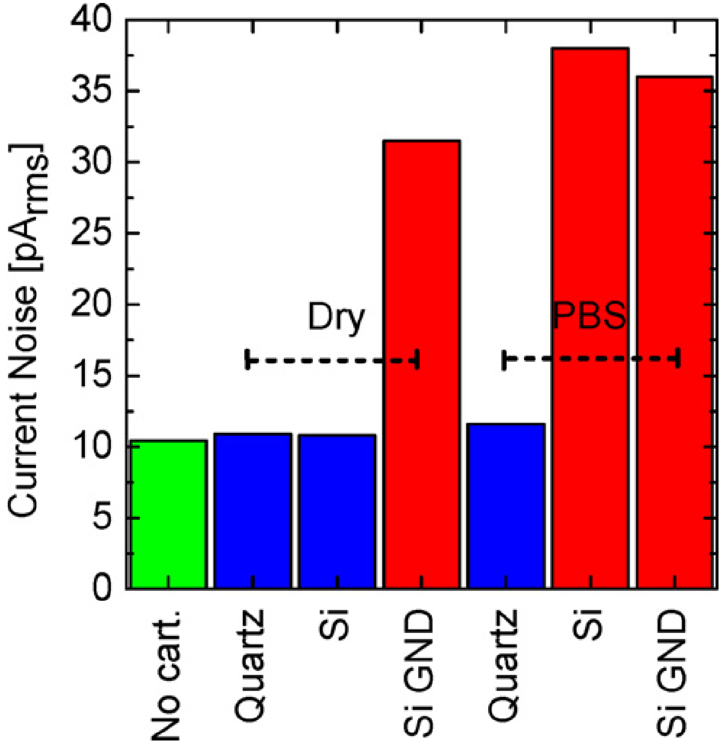
Getting Rid of Silicon When Not Needed





Substrate comparison

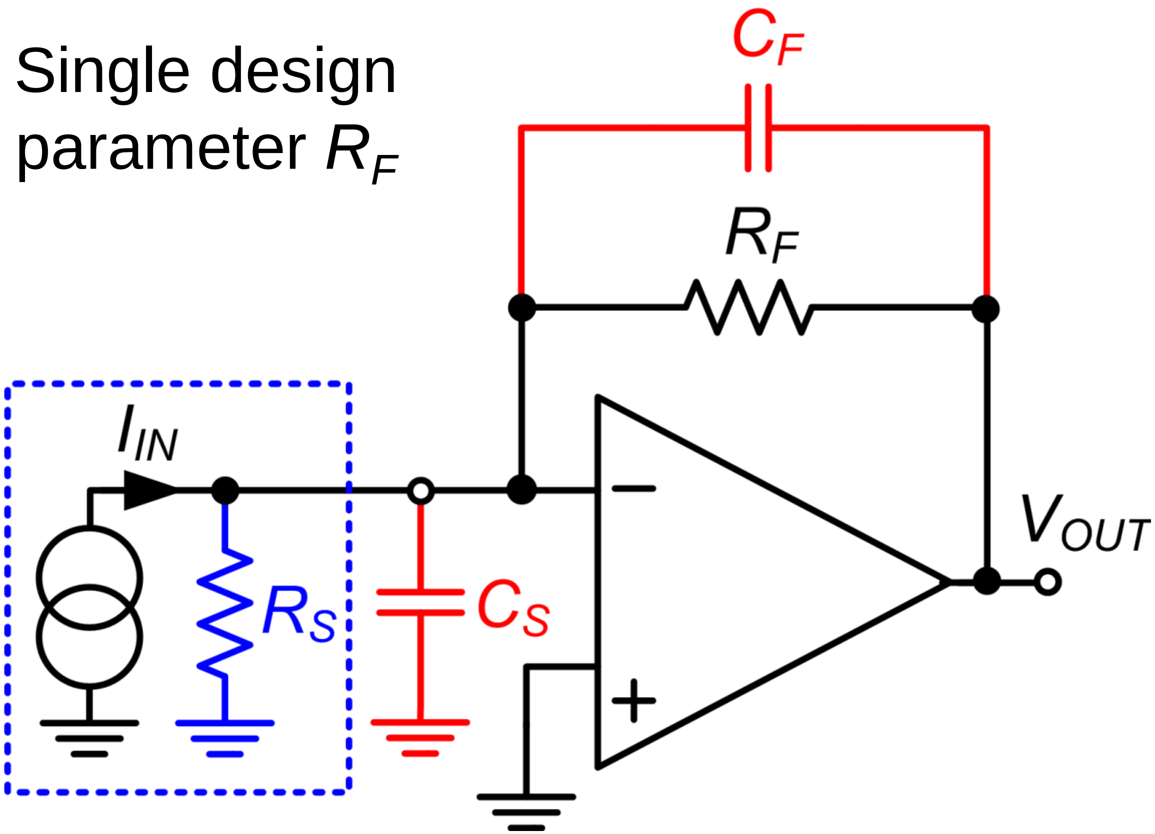




M. Carminati, “Accuracy and resolution limits in quartz and silicon substrates with microelectrodes for electrochemical biosensors”, *Sens. Act. B*, **174**, 2012.

Transimpedance Amplifier: Limits

Single design parameter R_F



- gain $\sim R_F$
- noise $\sim \sqrt{4kT/R_F}$
- BW $\sim 1/(R_F\, C_F)$

Resolution/speed trade-off

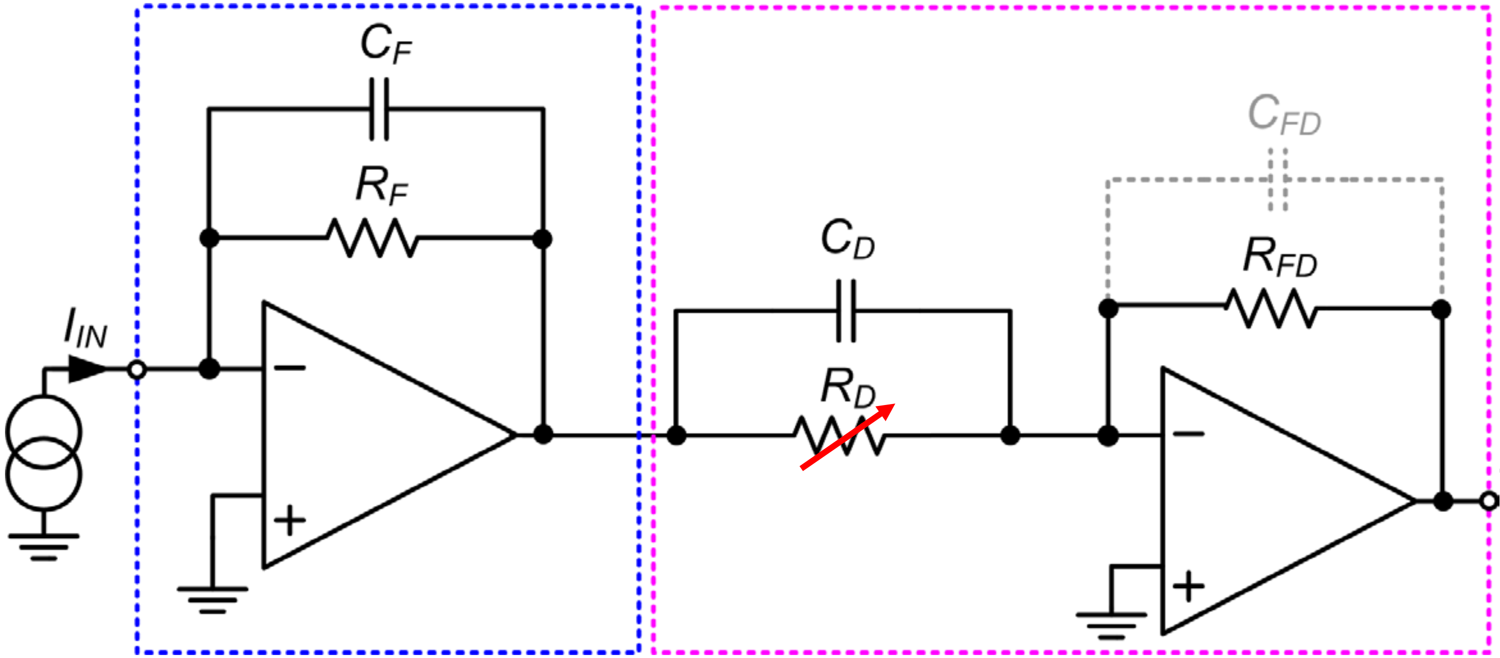
Need for enhanced topologies

C stray SMD package

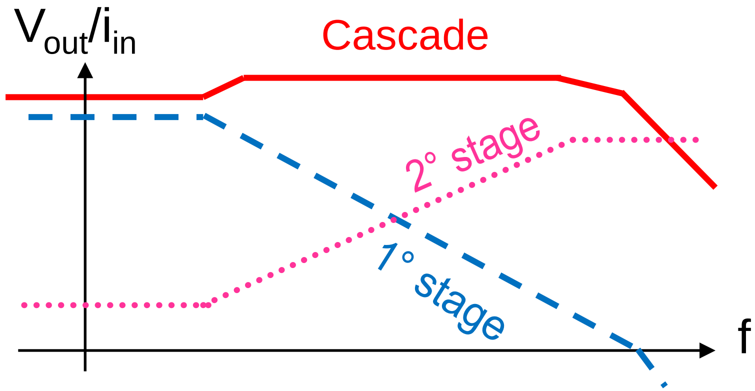
For example: $R_F = 1\mathrm{G}\Omega$ $C_F = 0.2\mathrm{pF}$ → $S_i = 4\mathrm{fA}/\sqrt{\mathrm{Hz}}$ BW = 800Hz

1 - Compensated TIA

Introduce a zero that cancels the pole: $R_F \cdot C_F = R_D \cdot C_D$



$$\frac{V_{OUT}}{I_{IN}} = R_{FD}\frac{R_F}{R_D}$$



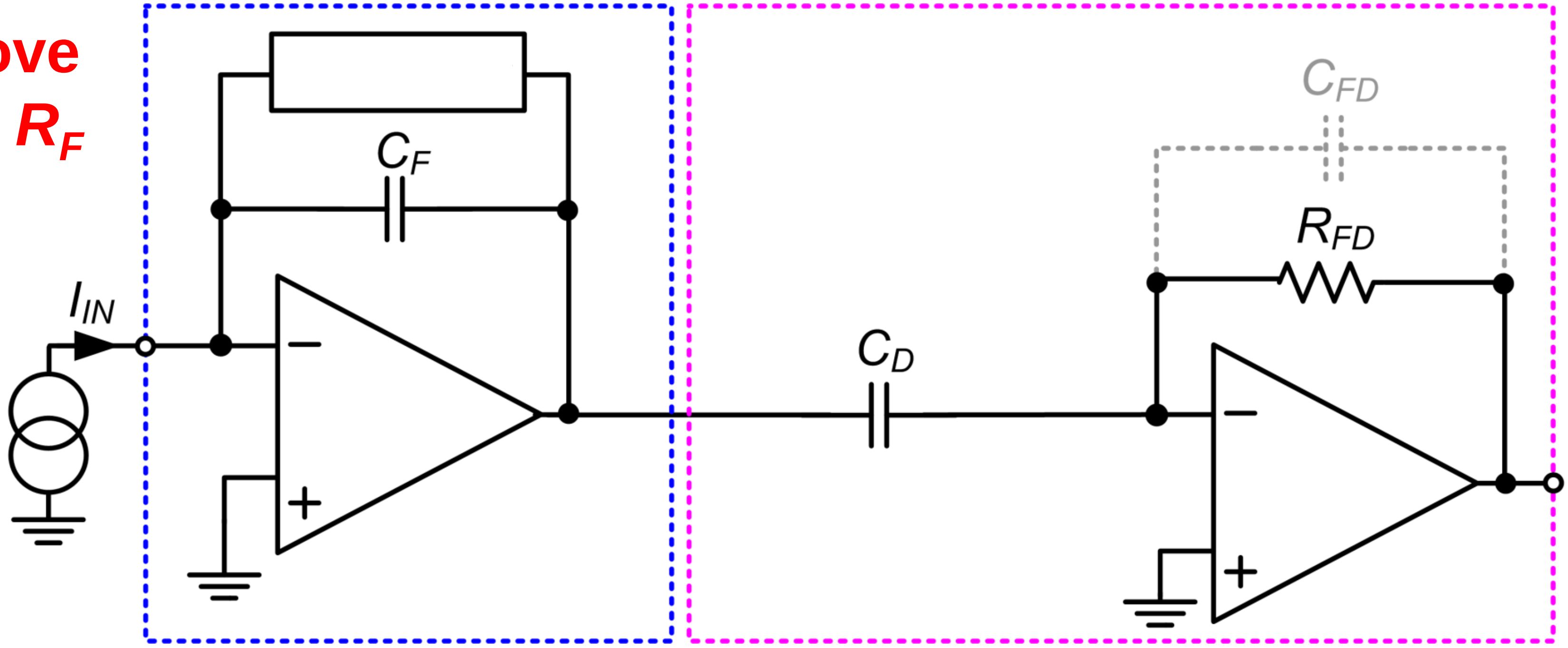
☺ Wider bandwidth, low noise

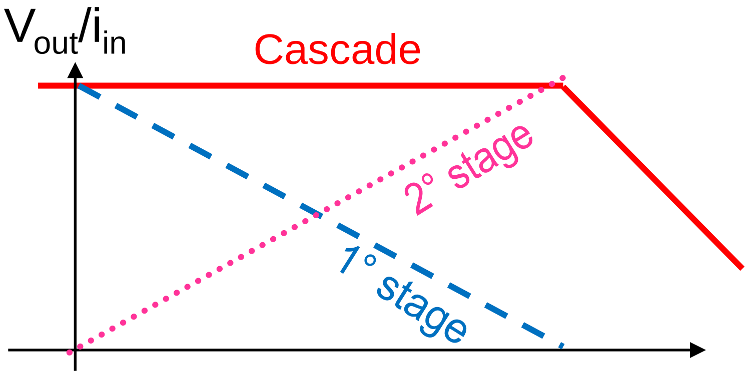
☹ Manual adjusting of the zero

Ciofi, *IEEE Instr.& Meas.* **55** 2006, M. Carminati, *Analog IC Sig. Process.* 2013

2 - Integrator-Differentiator Cascade

Remove noisy R_F





$$\frac{V_{OUT}}{I_{IN}} = R_{FD}\frac{C_D}{C_F}$$

☺ Robust, linear, no calibration

☹ Handling input DC current

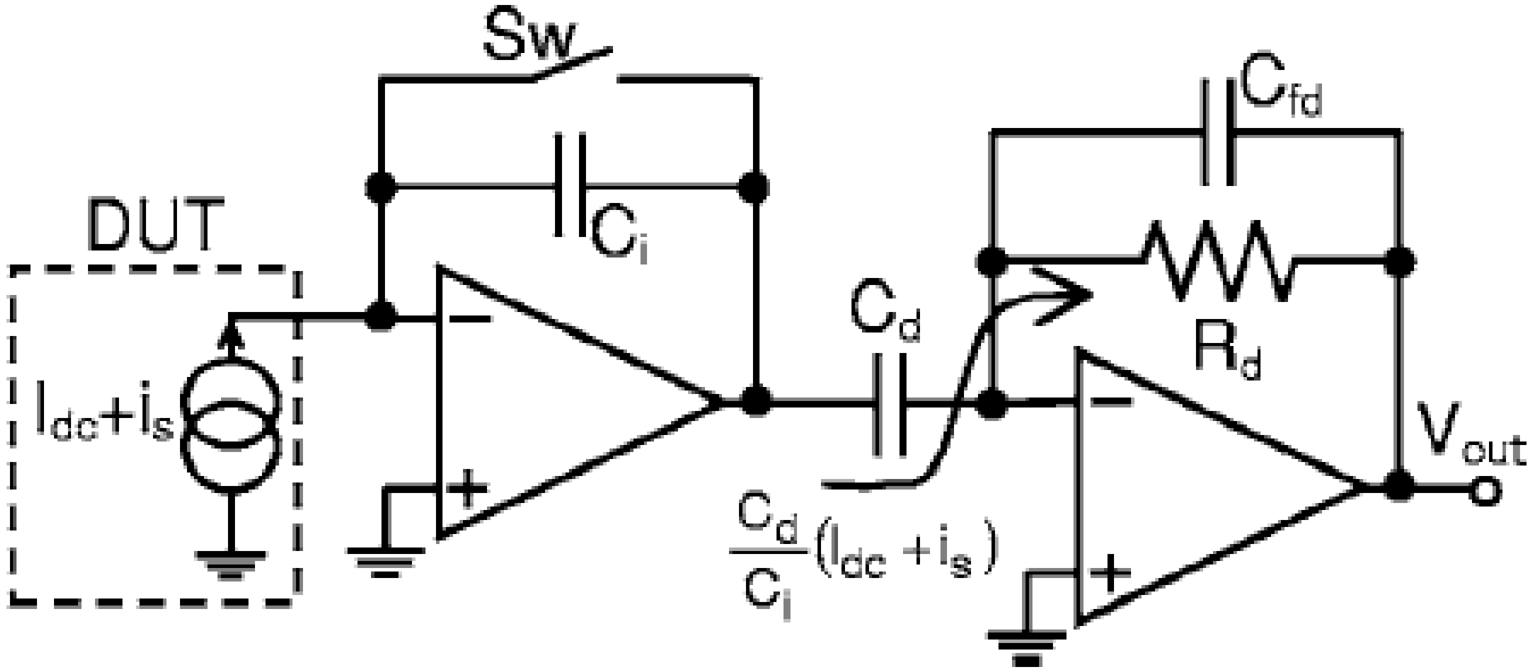
2.1 - Discrete Time: Reset Switch

Switch periodically closed to discharge the capacitor:

⇓

Limits the maximum measurement time

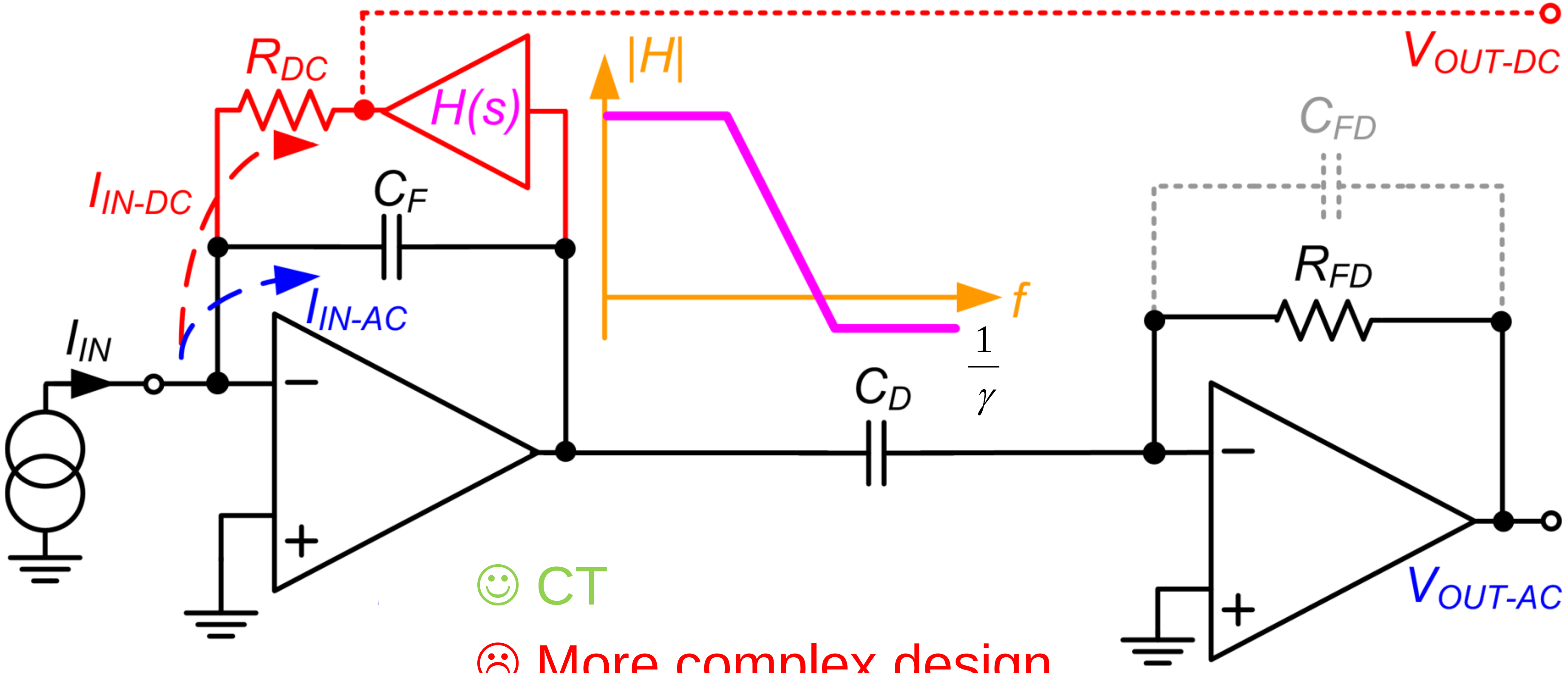
For example: $I_{IN\text{-}DC}$ = 1nA, C_F = 1pF → (5V) T_{MAX} = 5ms



M. Bennati, M. Tartagni , A Sup-pA Delta-Sigma Current Amplifier for Single Molecule Nanosensors", *IEEE ISSCC* 2009

2.2 - Continuous Time: Active Reset

To achieve continuous-time operation: additional feedback branch *H(s)* with high gain at low frequency:



☺ CT

☹ More complex design

G. Ferrari, *RSI* **78** 2007 & *IEEE JSSC* 2009, M. Carminati, *RSI* **80** 2009.

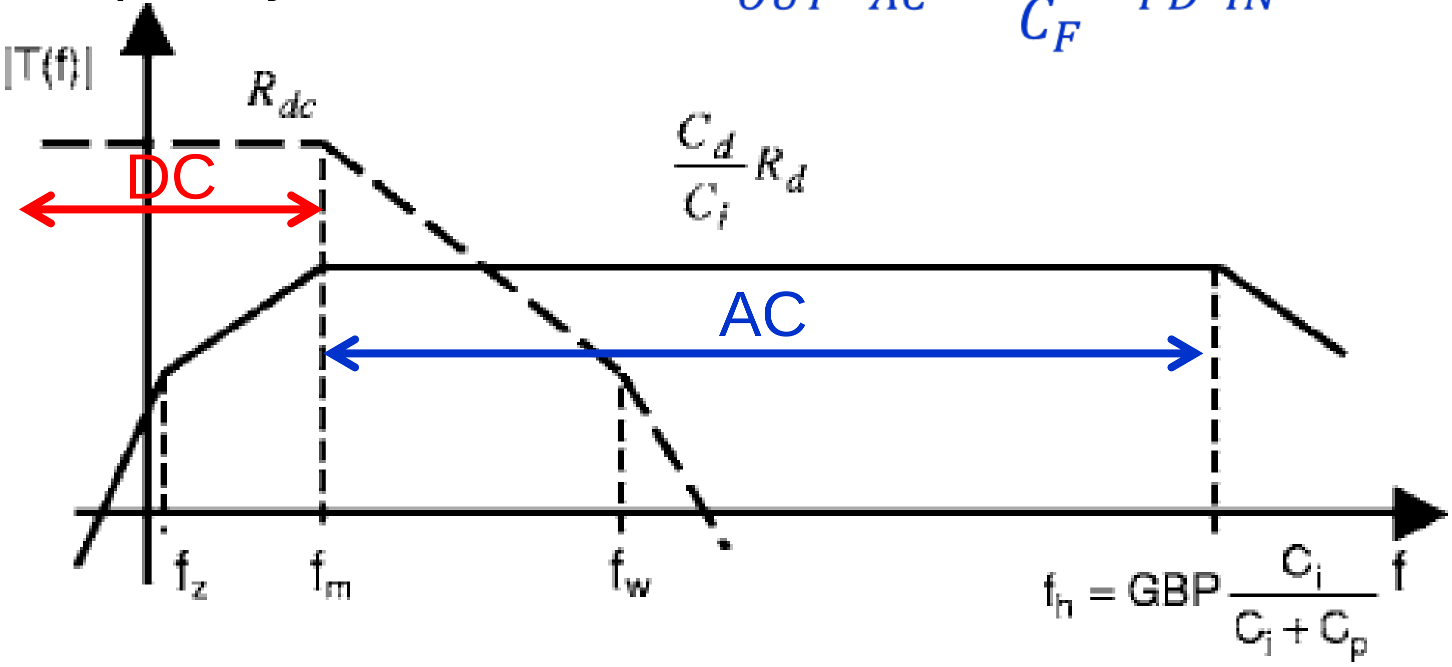
Transfer Functions

Two separate paths and gains:

- DC and low frequency
- High frequency

$$V_{OUT-DC} = -R_{DC} I_{IN}$$

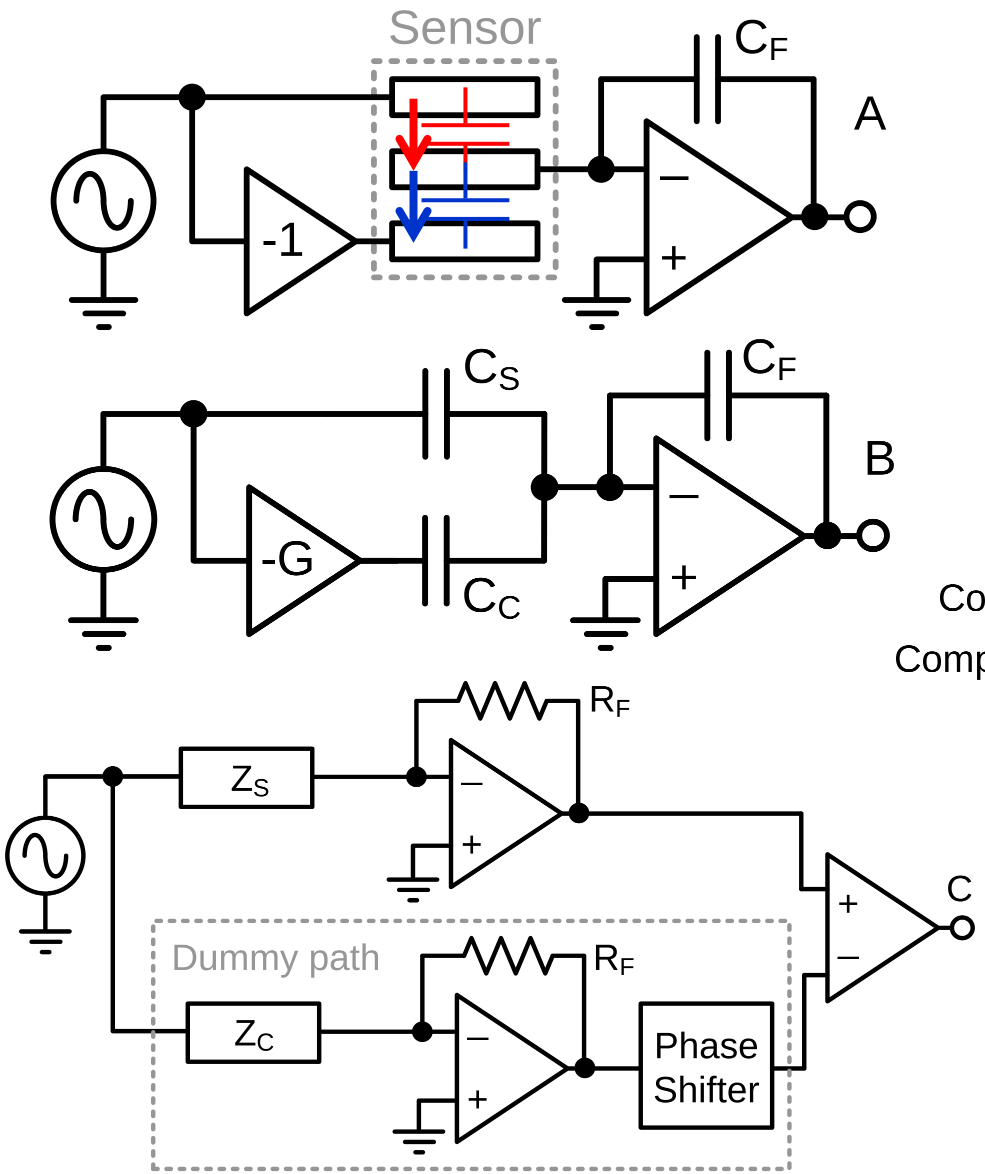
$$V_{OUT-AC} = \frac{C_D}{C_F} R_{FD} I_{IN}$$



$$f_m = \frac{1}{2\pi C_F R_{DC} \gamma}$$

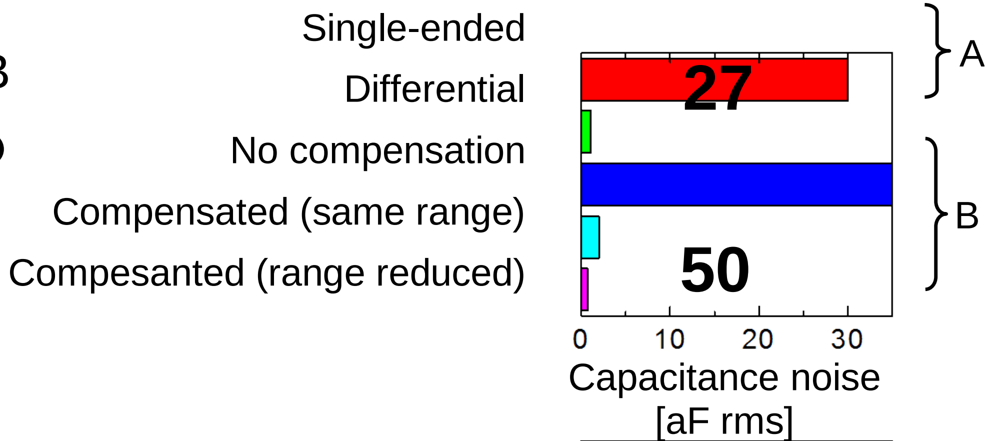
For wideband impedance spectroscopy, large R_{DC} is required

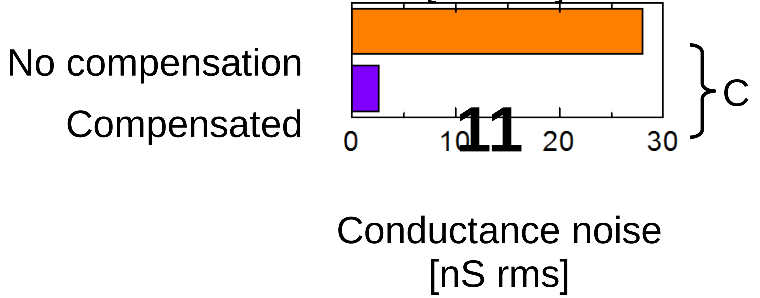
Mitigation of Source Noise: Differential Sensing



Limited by matching!

Significant noise reduction





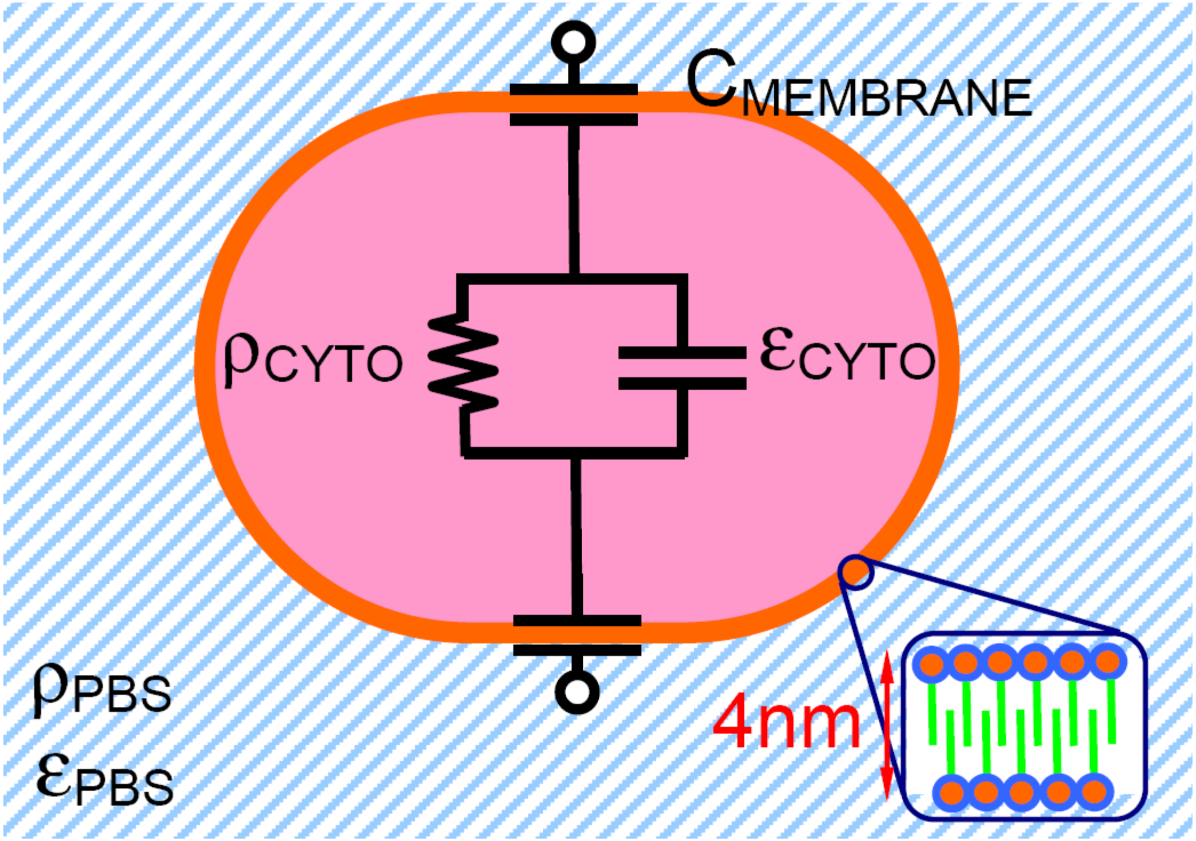
M. Carminati, *Proc. IEEE SSD* 2014 (Best Paper Award).

Example of Micro-Scale Applications

1. Biological Cells (*resistance*)
2. Airborne Dust (*capacitance*)
3. Silicon Photonics (*resistance in AC*)

Applications to Cell Biology

Small signal equivalent of a passive cell: the **single shell model**



- $\rho_{PBS} = 66\Omega cm$
- $\varepsilon_{PBS} = 78$
- $C_{MEM} = 0.01 pF/\mu m^2$
- $\rho_{CYTO} \sim \rho_{PBS}$
- $\varepsilon_{CYTO} = 60$

At low frequency (<1MHz), the cell can be treated as an insulating sphere (resistivity contrast)

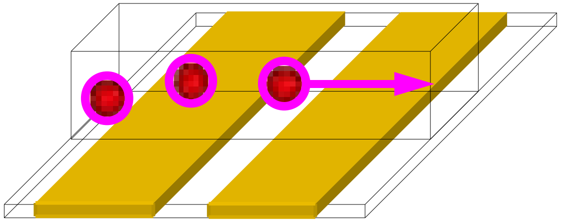
Cell Counting

The presence of cells can be sensed by impedance as a perturbation of the electrical field between two electrodes

Two approaches:

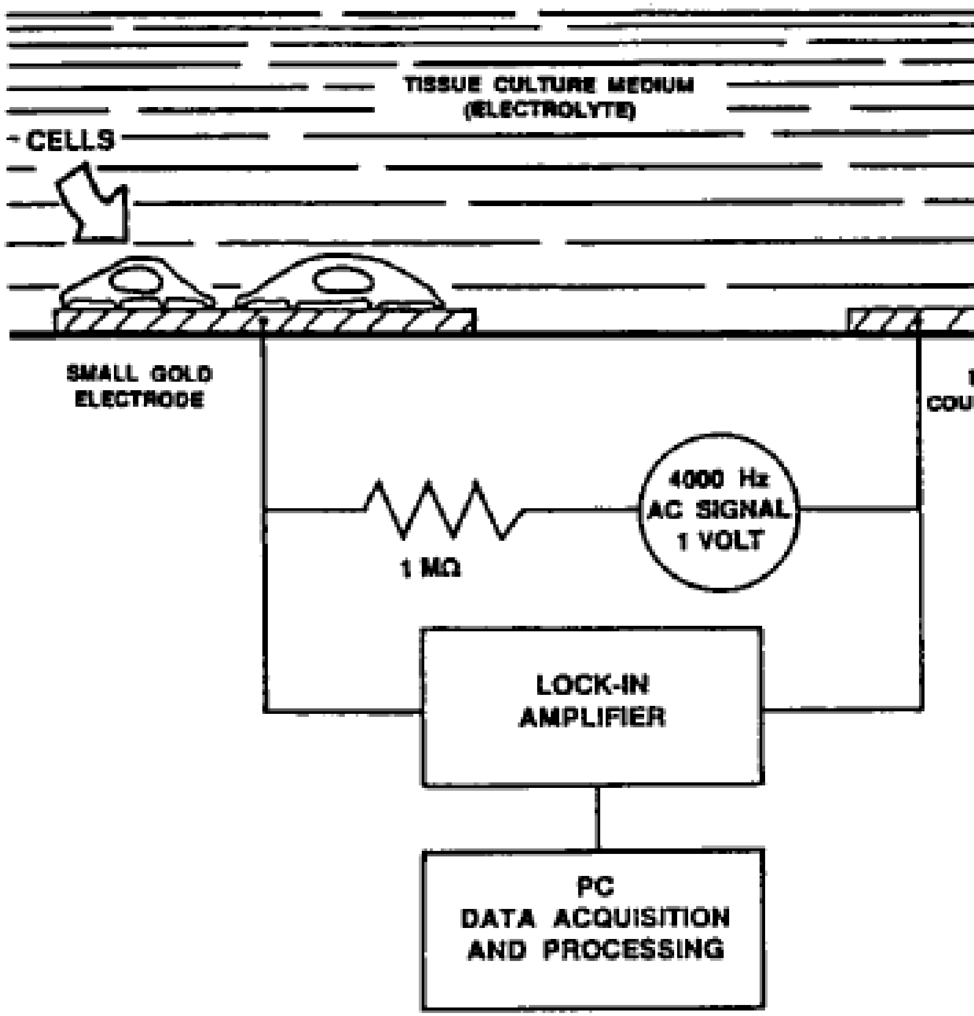
“Static”

“Dynamic”

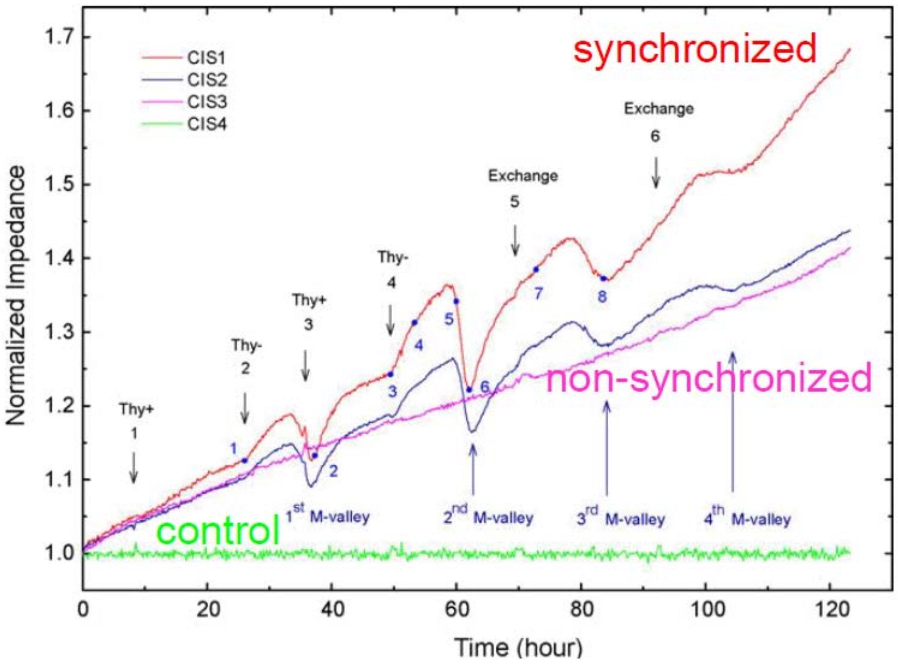


Electric Cell-substrate Impedance Sensing

ECIS Technique invented by Giaever and Keese

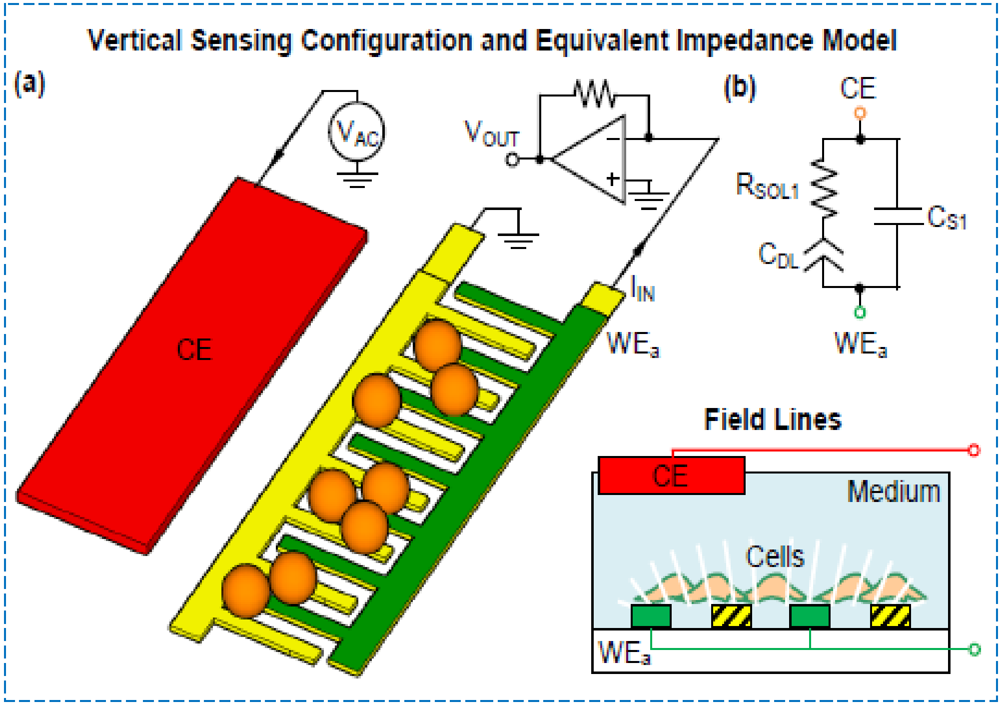


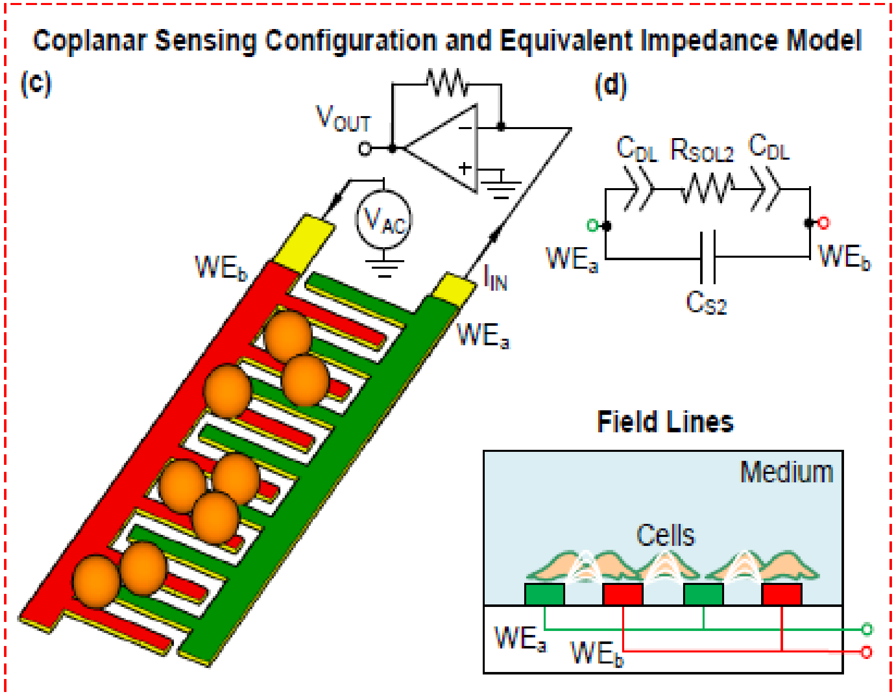
Cell adeshion, spreading and growth can be monitored



Lo, Keese, Giaever, *Biophys J.* **69** 1995

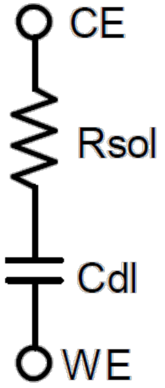
Comparison of Sensing Geometries

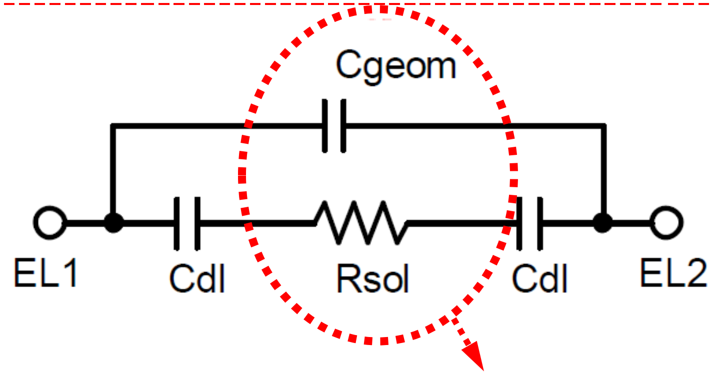

Vertical Sensing Configuration and Equivalent Impedance Model


Coplanar Sensing Configuration and Equivalent Impedance Model

$$R_{sol} = \frac{\rho}{4r}$$

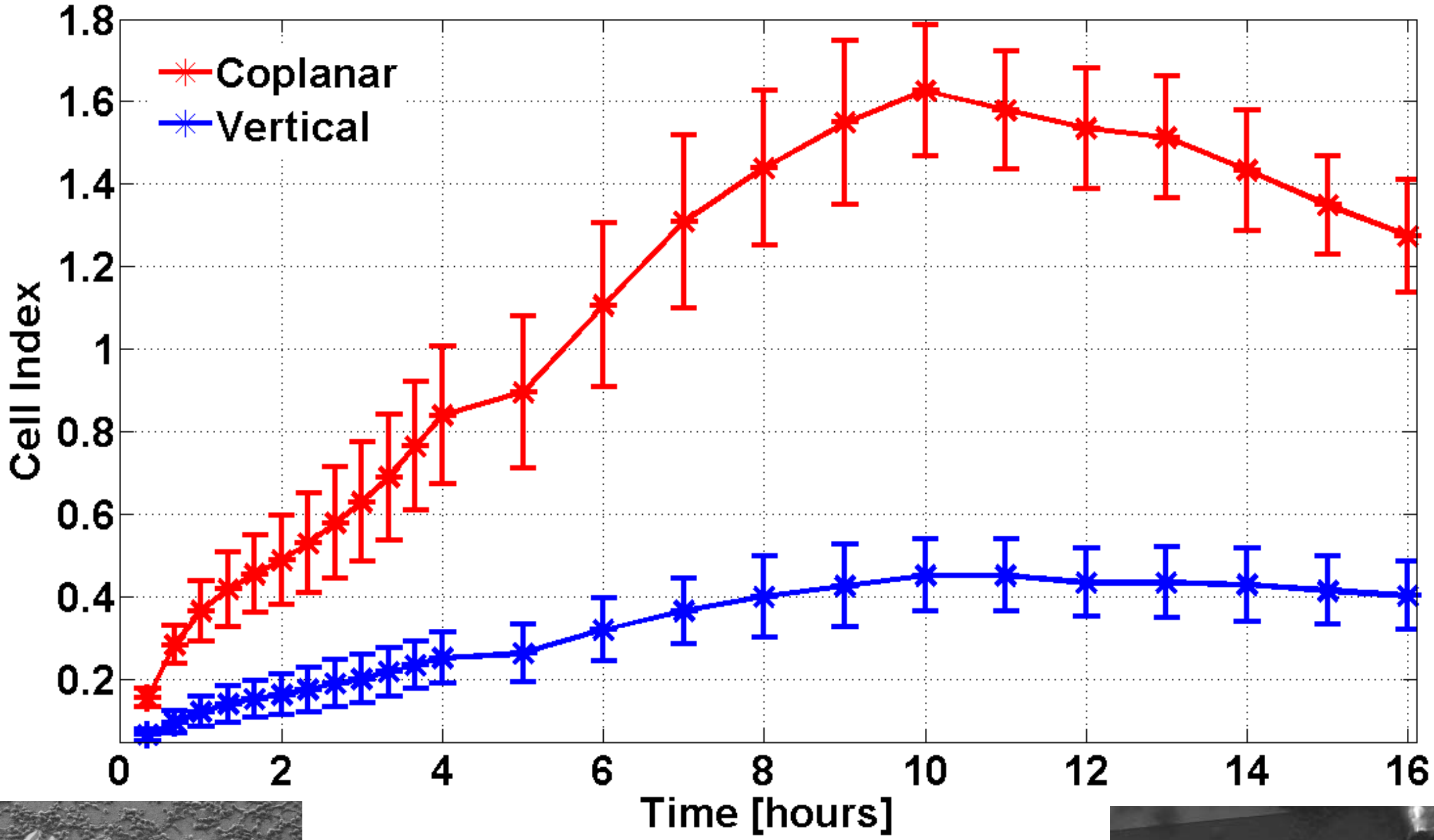
$$C_{dl} = C_0 \cdot \pi \cdot r^2$$

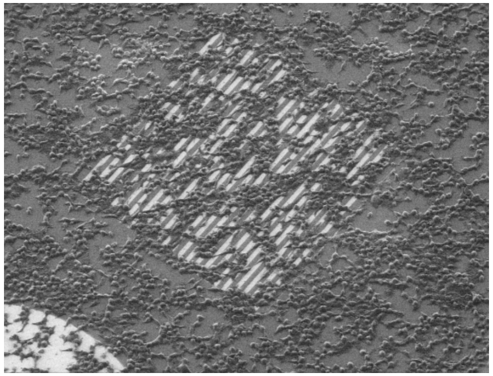


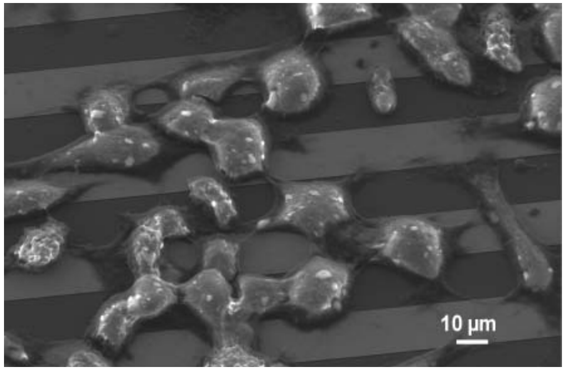


Conformal Mapping

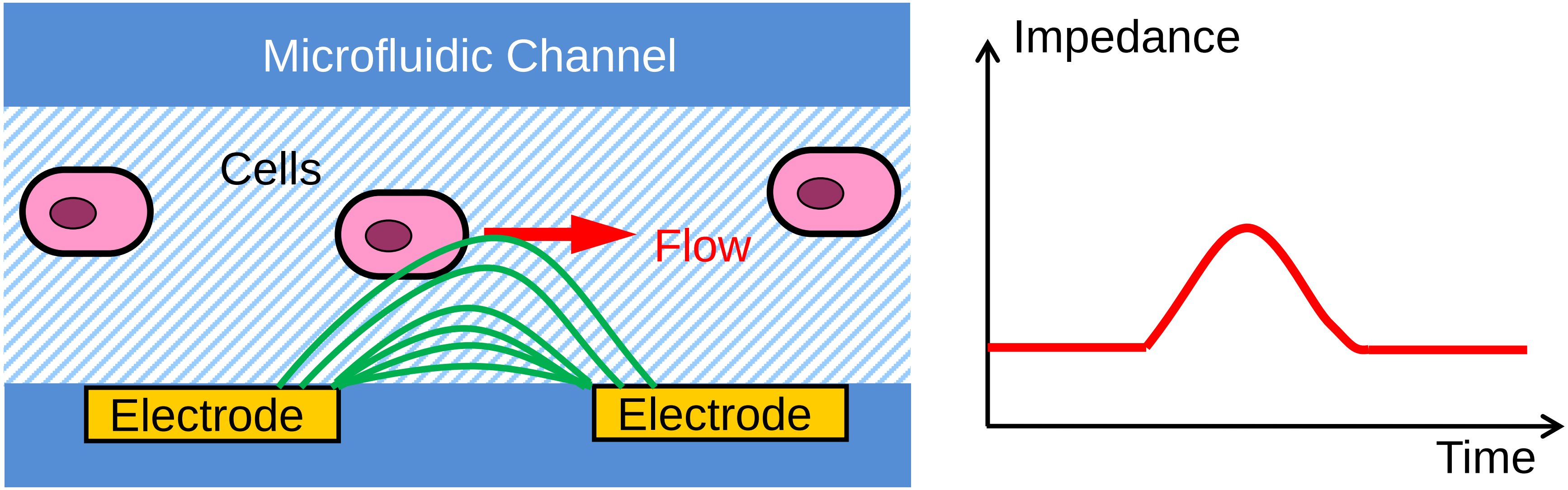
Comparison with HeLa Cells







Impedance Flow Cytometry

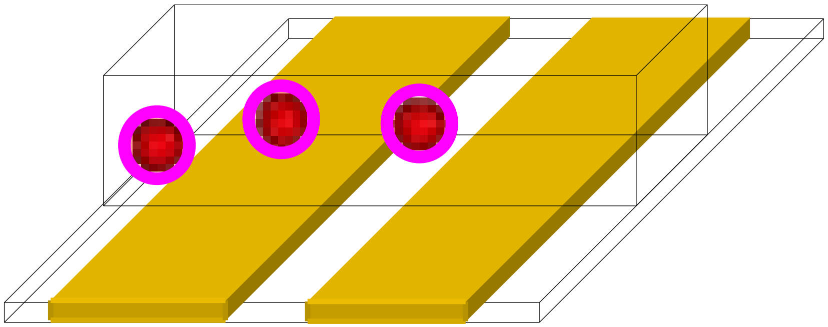


- A novel approach, pioneered by Morgan and Renaud (~2000)
- Tracking impedance between close electrodes over time
- High-throughput single-cell analysis (beyond sizing)

T. Sun & H. Morgan, *Microfluid. Nanofluid.* **8** 2010

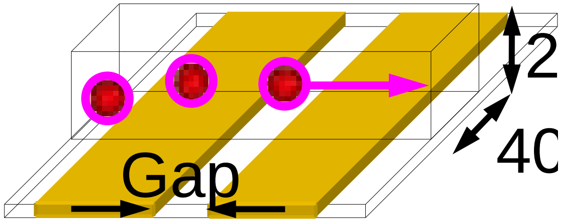
K. Cheung *et al.*, *Cytometry* **77A** 2010

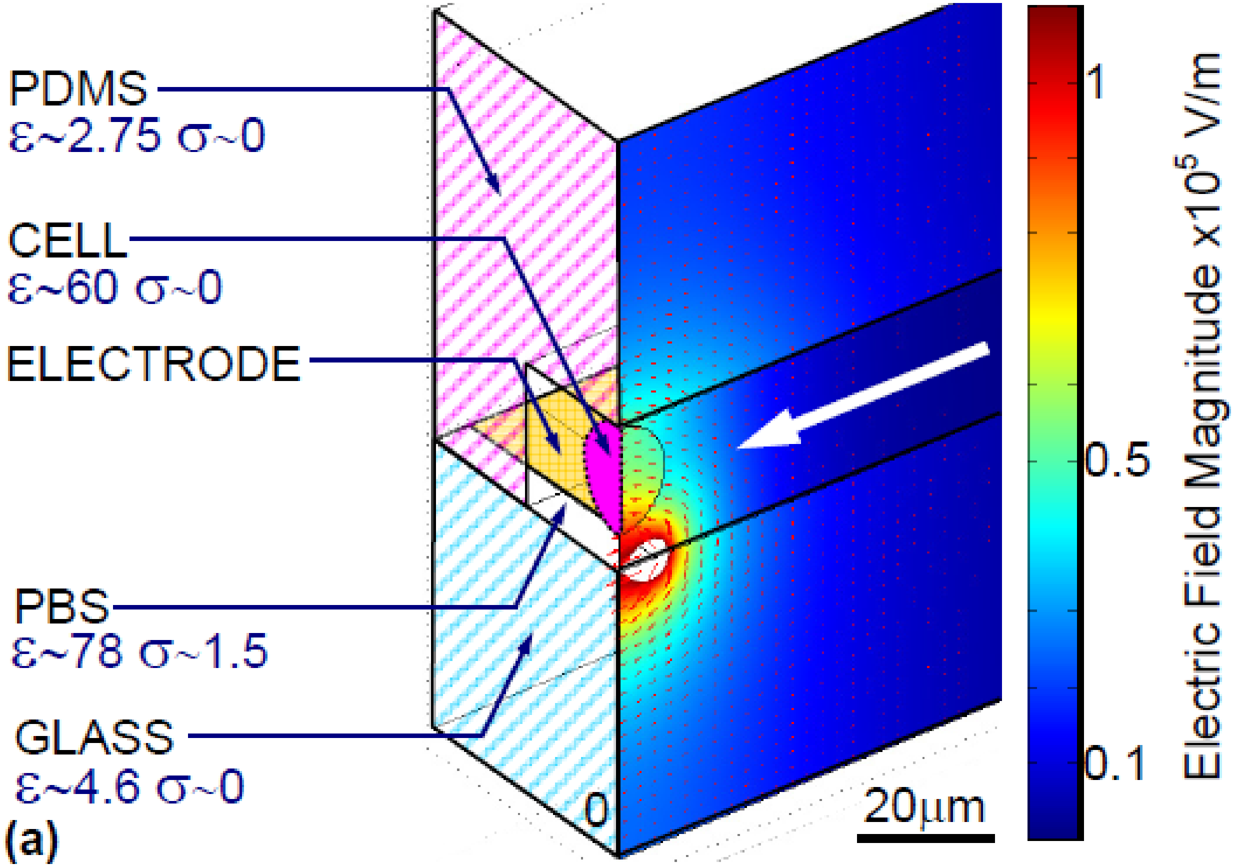
Electrodes Configurations



Design of Sensing Electrodes

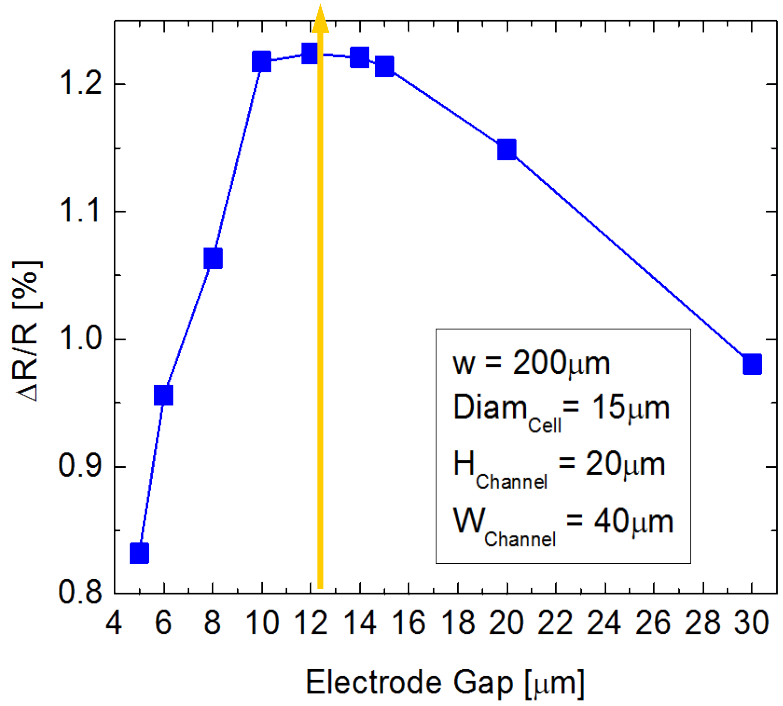
- Simple technology → coplanar
- Ease of alignment → transverse
- Target cells 5-15μm → 20 x 40μm^2

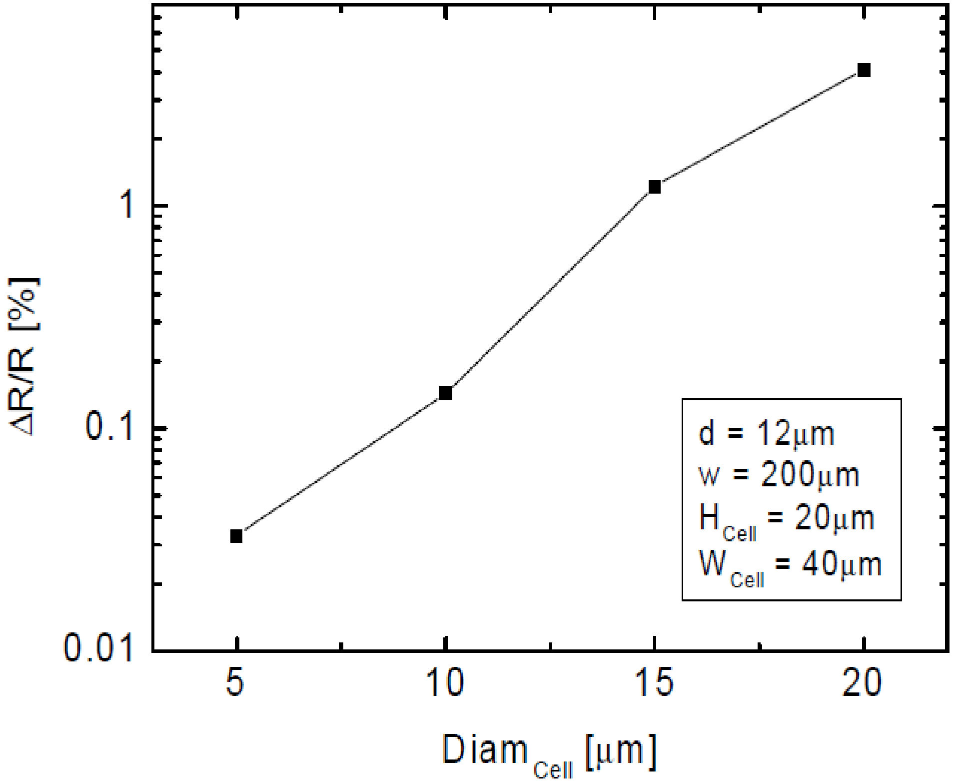




Optimal Electrode Design

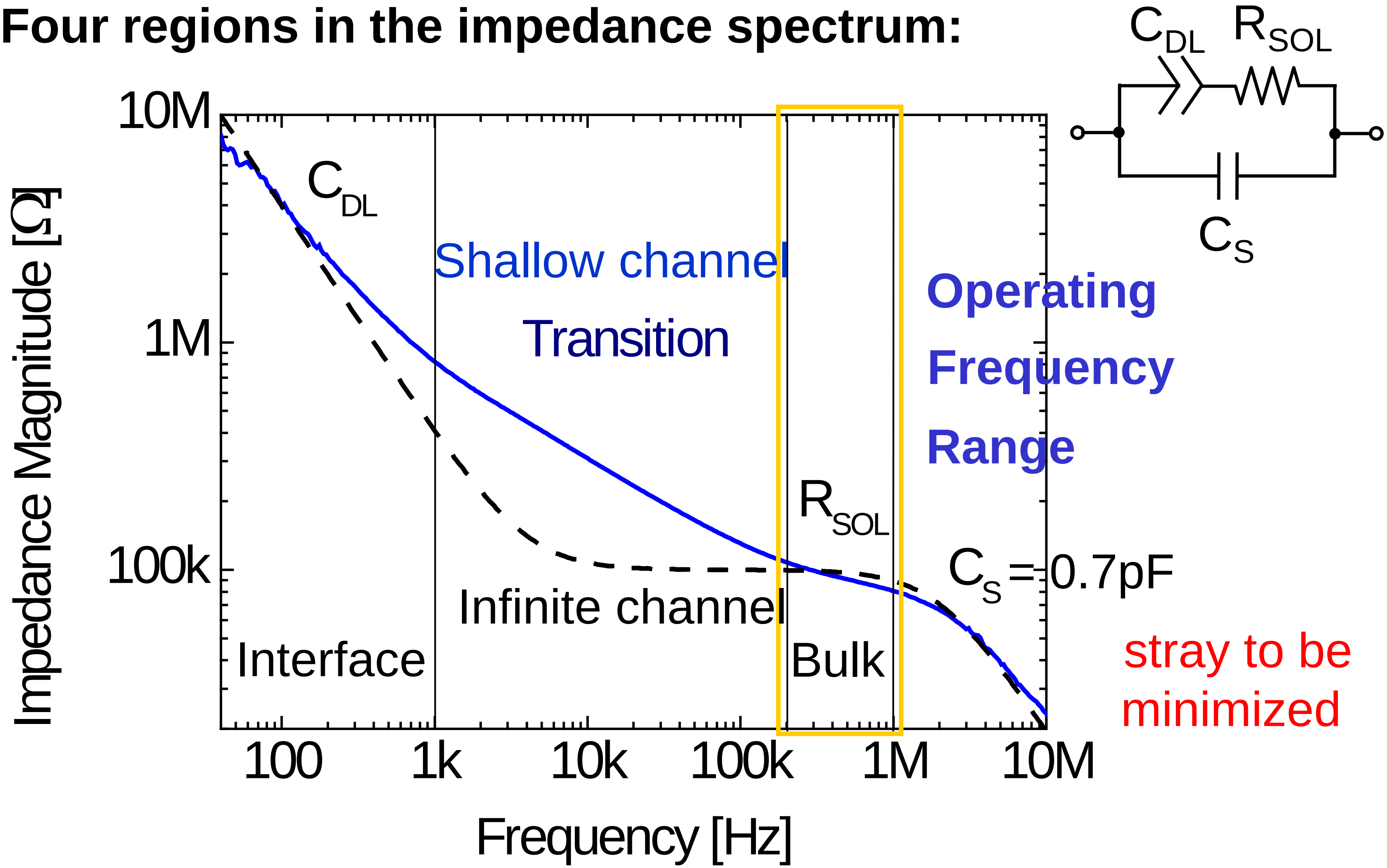
- The gap sets the vertical extension of the sensing volume
- An optimal gap exists for a given cell diameter
- Sensitivity scales with cell volume and vertical height





Operating Frequency

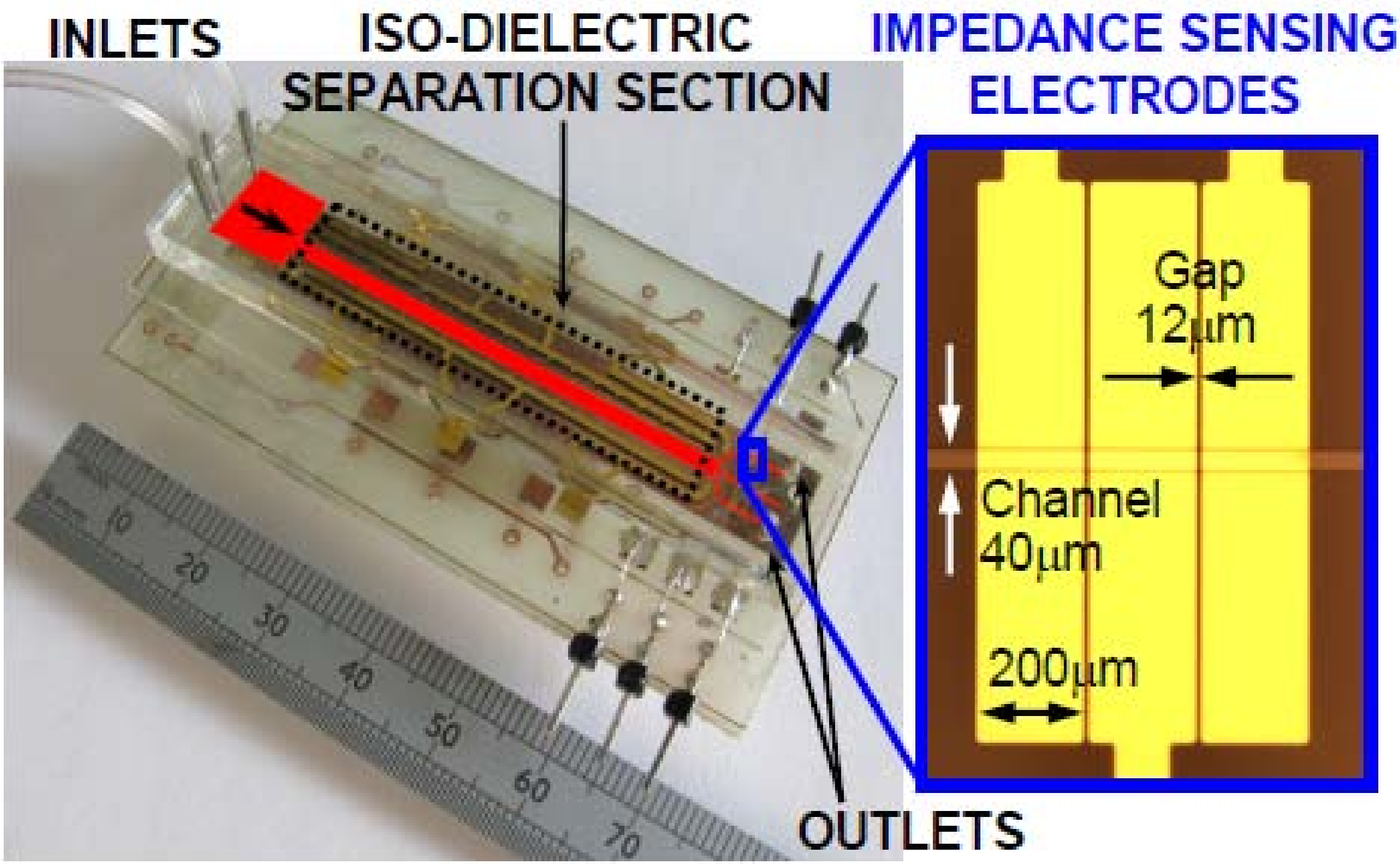
Four regions in the impedance spectrum:



Operating Frequency Range

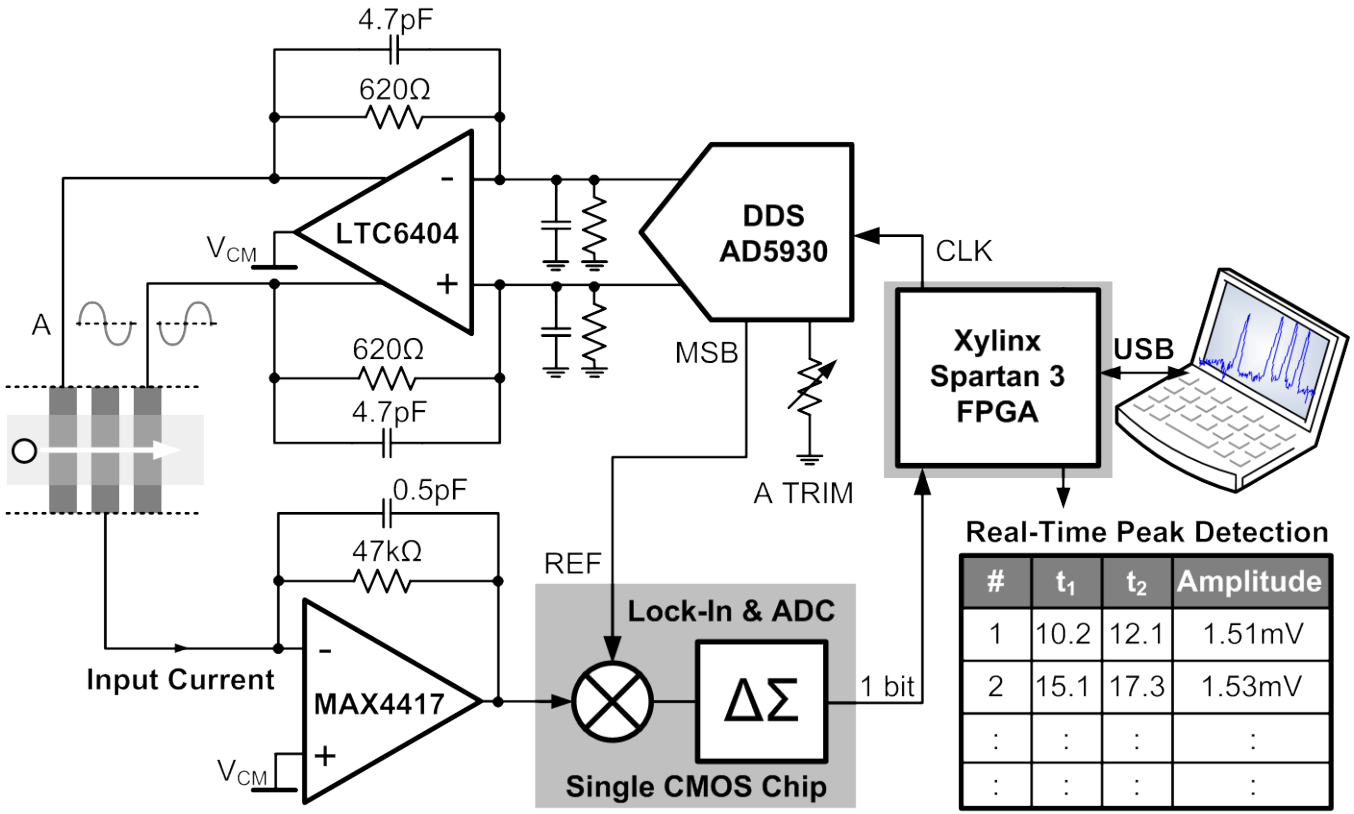
stray to be minimized

Enhanced Device Architecture



- Integrated into the device with no size increase
- Third electrode available for differential sensing (drift)

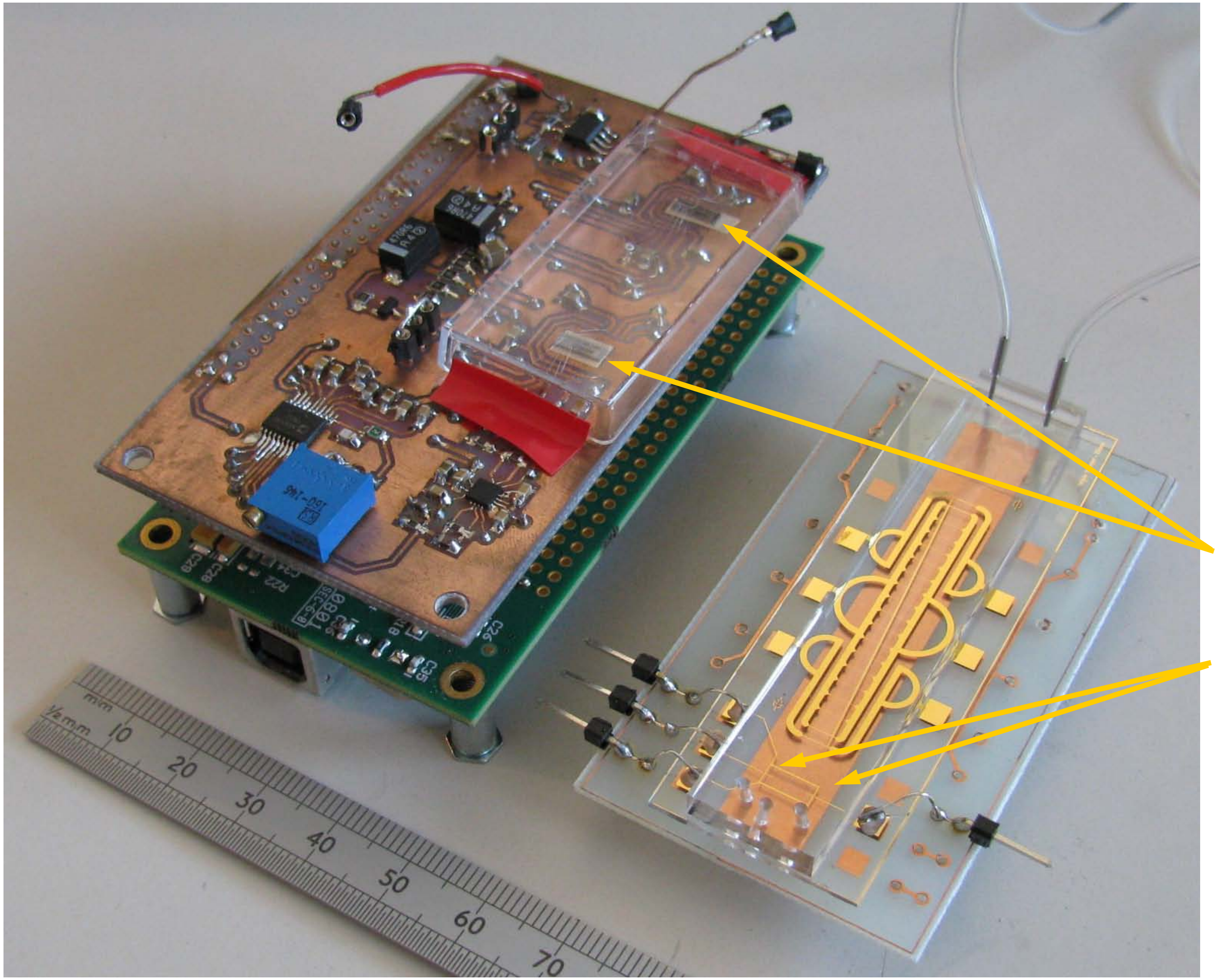
Miniaturized Impedance Detector



#	t_1	t_2	Amplitude
1	10.2	12.1	1.51mV
2	15.1	17.3	1.53mV
:	:	:	:
:	:	:	:

- On-board signal generator
- ASIC 1MHz CMOS lock-in and 20bit ΣΔ converter
- Real-time FPGA peak detection algorithm
- Digital USB data acquisition

Credit Card Sized Implementation



Ultra compact system

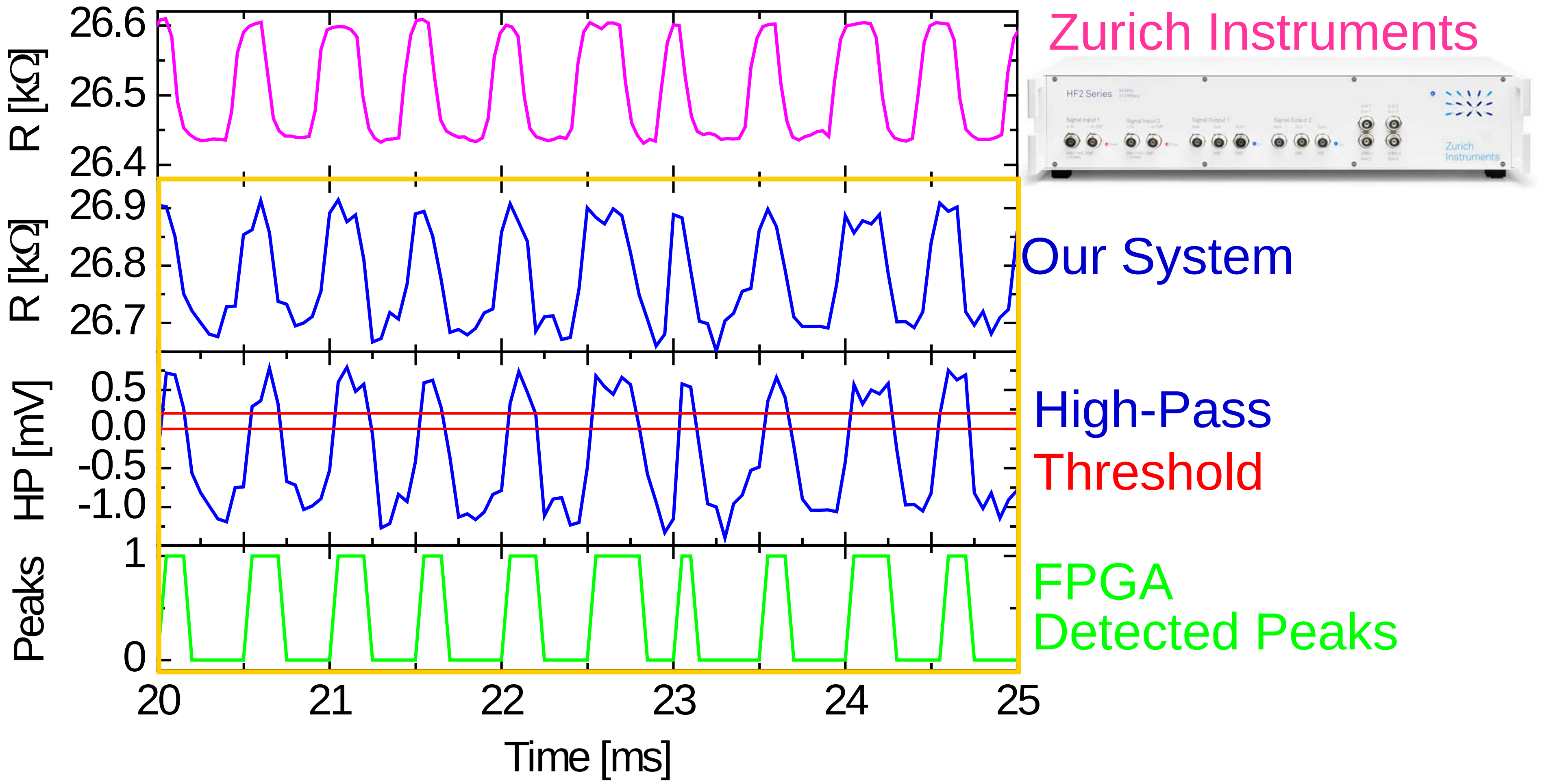
3.3V USB Power Supply

2 channels:

- 2 outlets
- Complex impedance

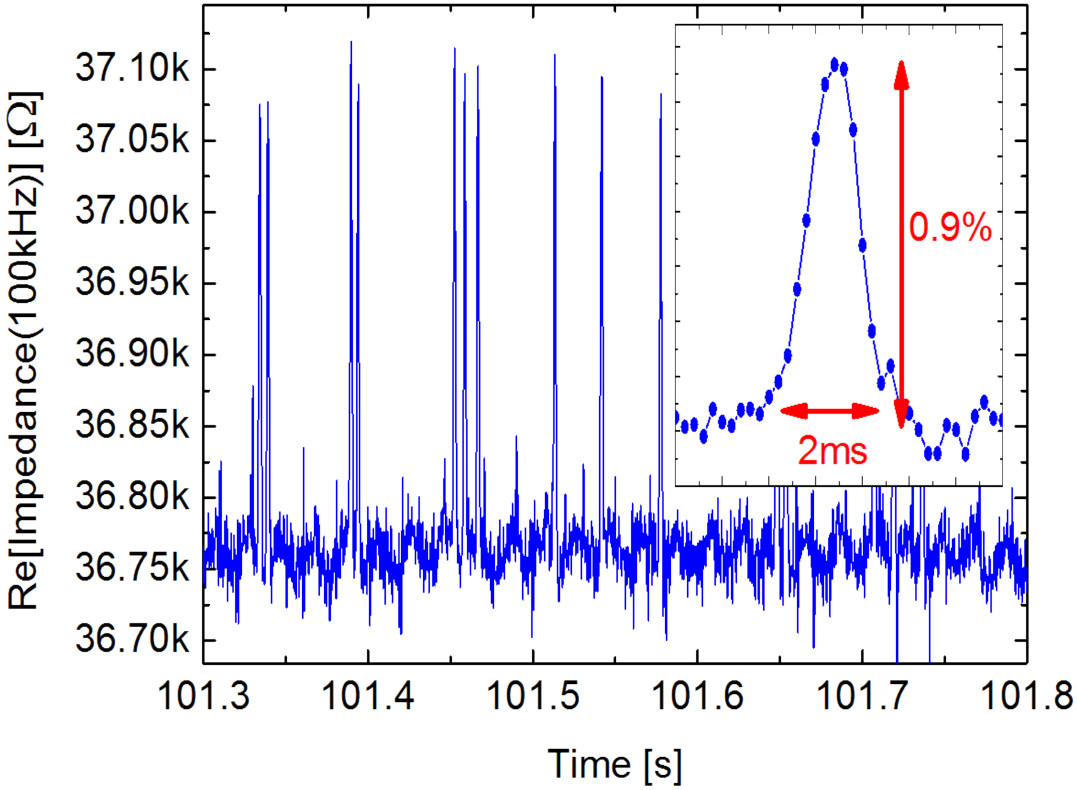
Performance Assessment

- Impedance tracking comparable with state-of-art instrument
- Error-free real-time FPGA peak counting at 2000 events/s

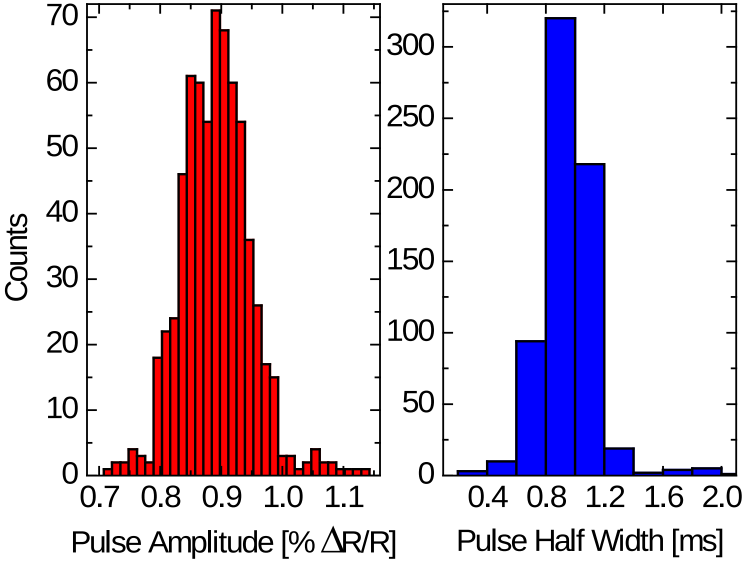


System Validation with Beads

- 10μm polystyrene beads in PBS
- 50 beads/s (1μl/min)
- V_{AC} = 50mV, f_0 = 100kHz, 5kSa/s

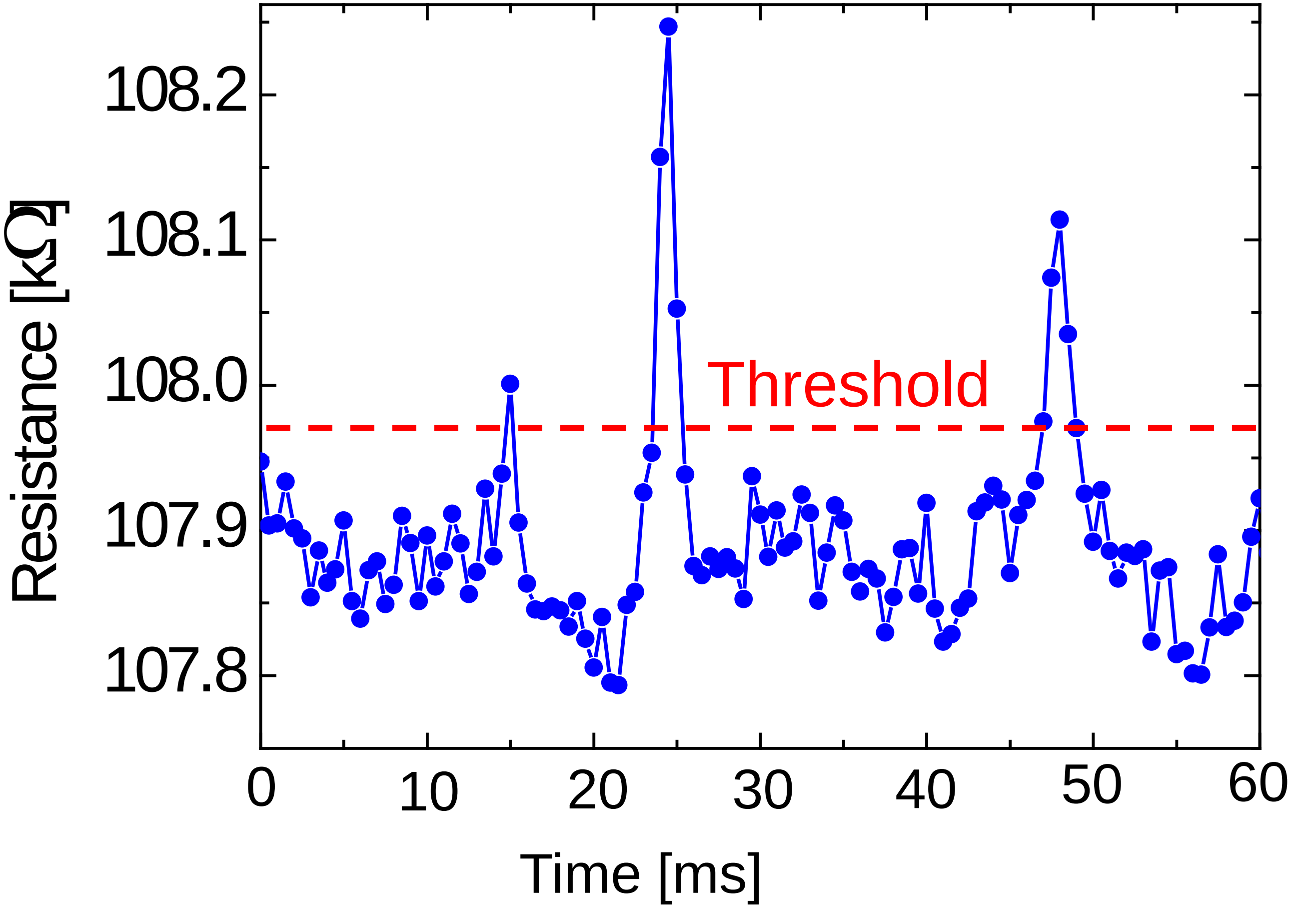


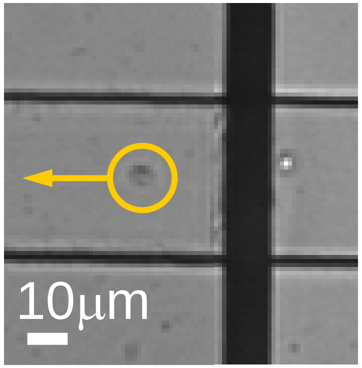
As expected:



Counting Yeast

- *Sacc. Cerevisiae* (5μm)
- 10^5 cells/ml in 0.35S/m medium (with BSA)
- V_{AC} = 650mV, f_0 = 100kHz, 2kSa/s





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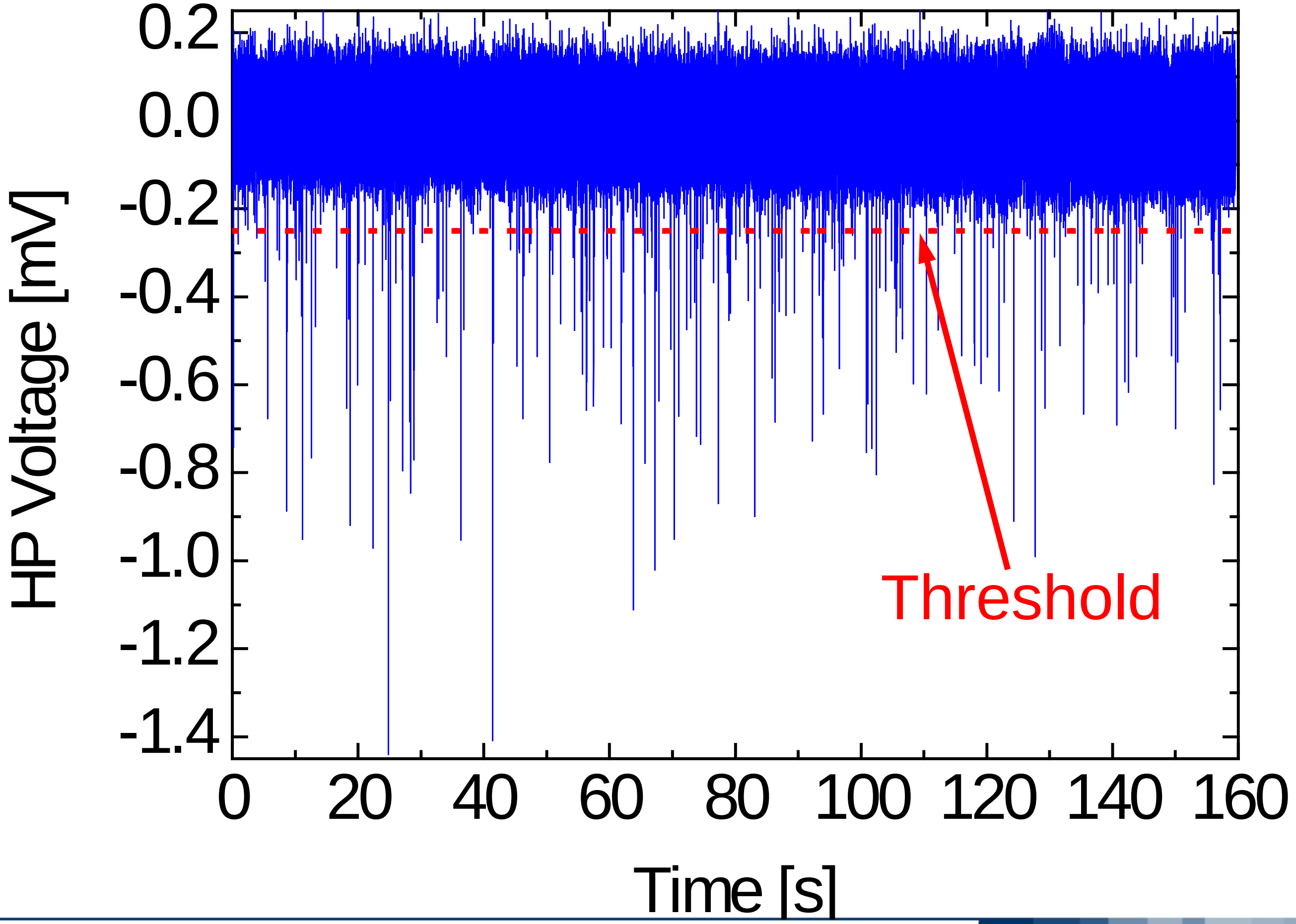
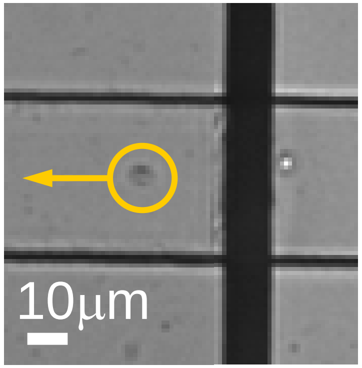
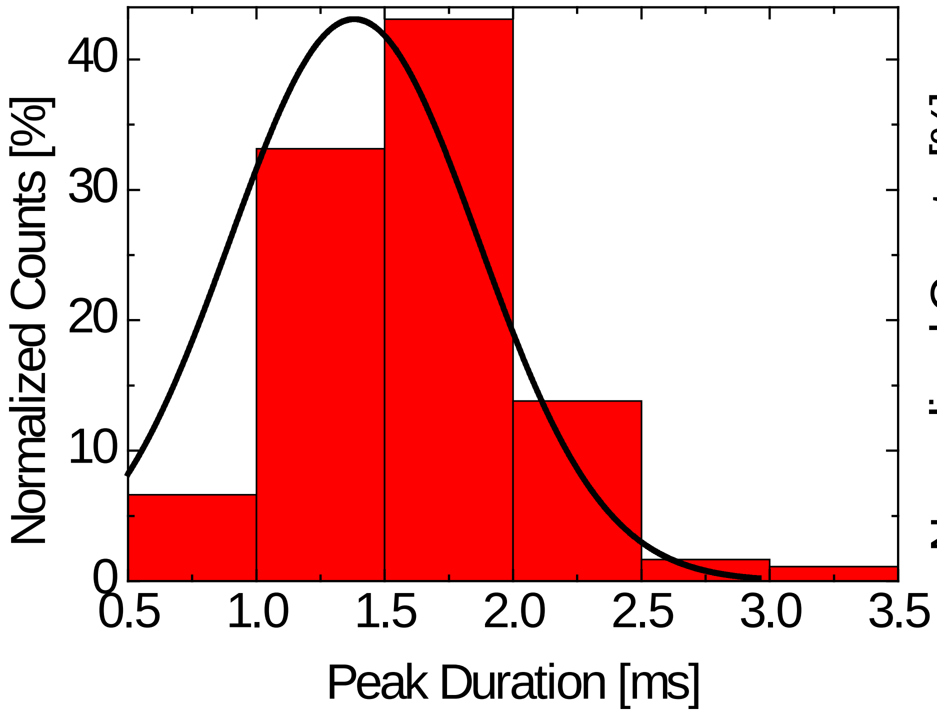


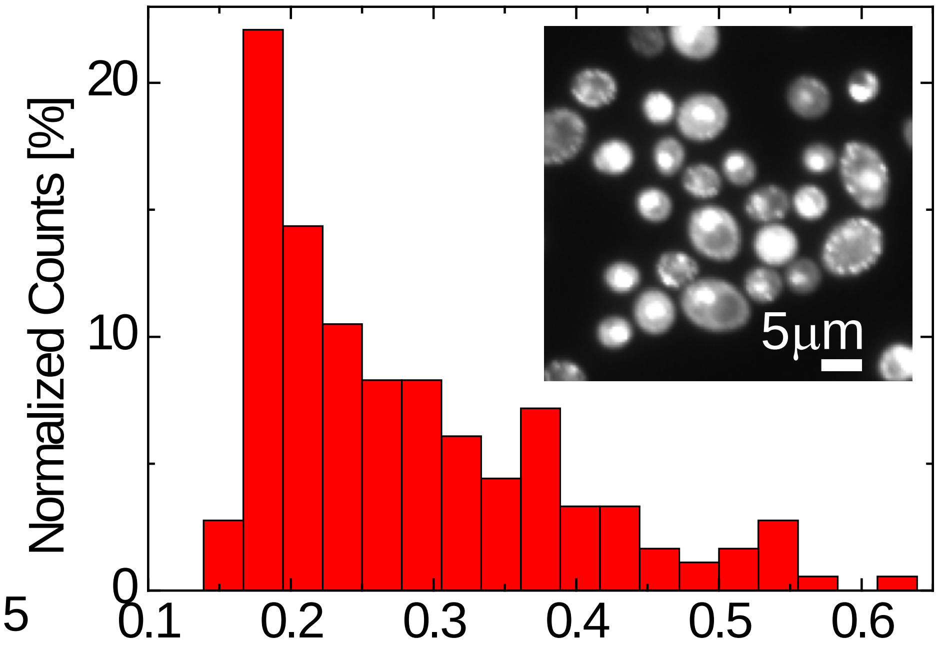


Yeast: Peak Analysis

Pulse Width:

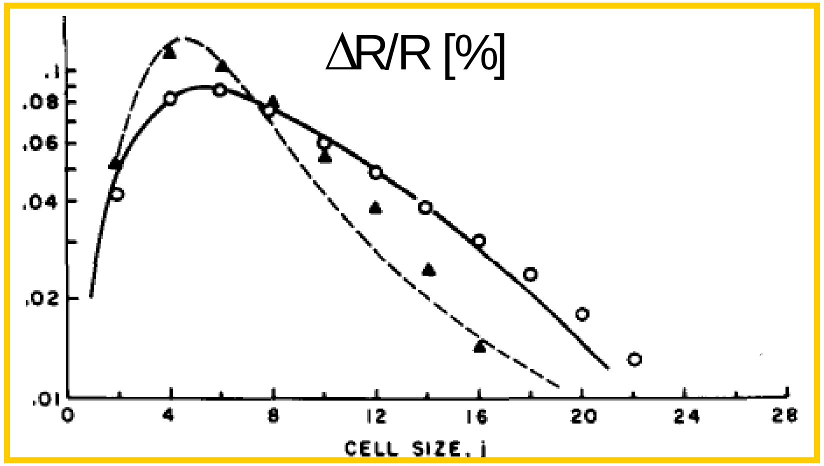


Amplitude:



Consistent with:

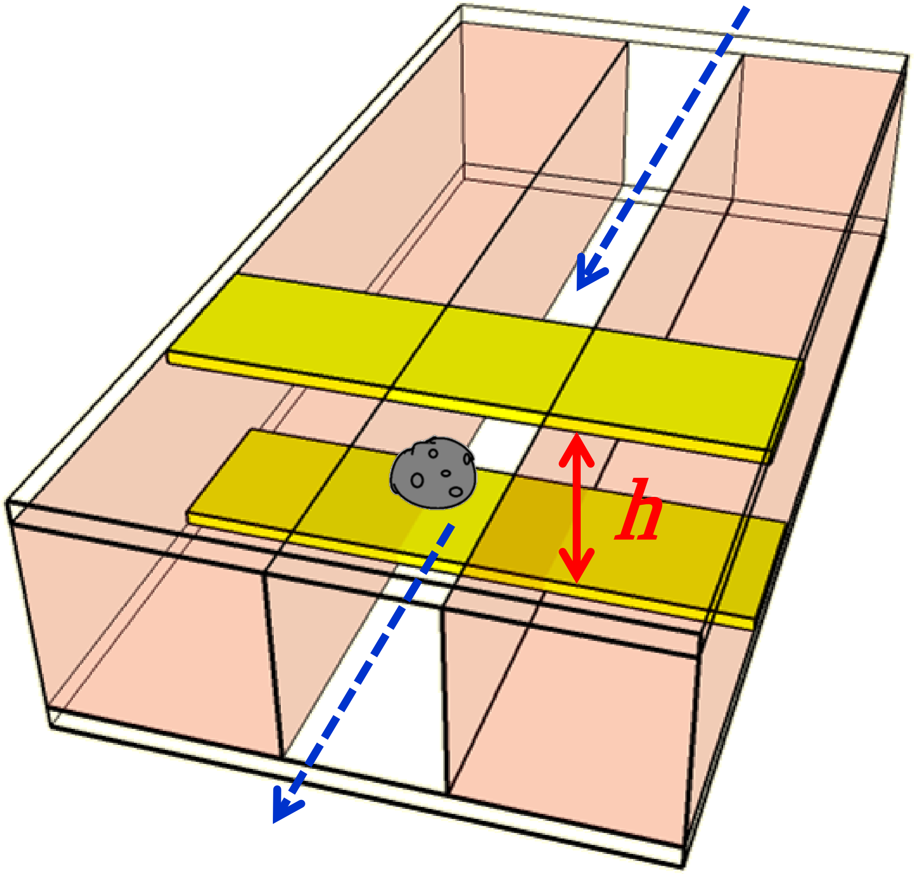
- cell velocity (3cm/s)
- cell volume (10µm beads/8)
- cell size distribution



P.Palatt and G. Saidel, *Ann. Biomed. Eng.* **7** 1979

A Novel Technique: Electrical Detection

Real-time capacitive detection of single PM particles



$$\frac{\Delta C}{C} = \frac{Volume_{particle}}{Volume_{total}} \cdot \Delta\varepsilon$$

$$\Delta C = \frac{4}{3} \cdot \pi \cdot \frac{R^3}{h^2} \cdot \Delta\varepsilon \cdot \varepsilon_0$$

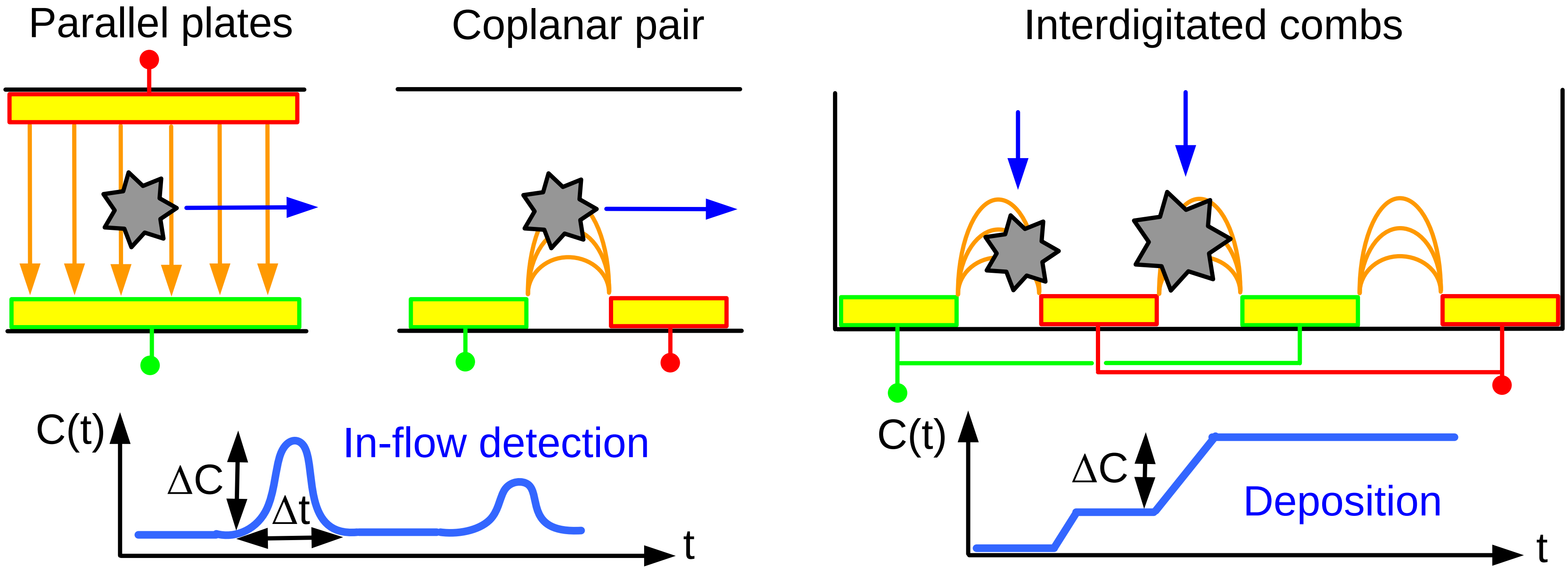
$$R = \sqrt[3]{\frac{\Delta C \cdot h^2}{\frac{4}{3} \cdot \pi \cdot \Delta\varepsilon \cdot \varepsilon_0}}$$

M. Carminati, Capacitive detection of micrometric airborne particulate matter for solid-state personal air quality monitors, *Sensors Actuators A* **219**, 2014.

Choice of the Sensing Configuration

Key design choices:

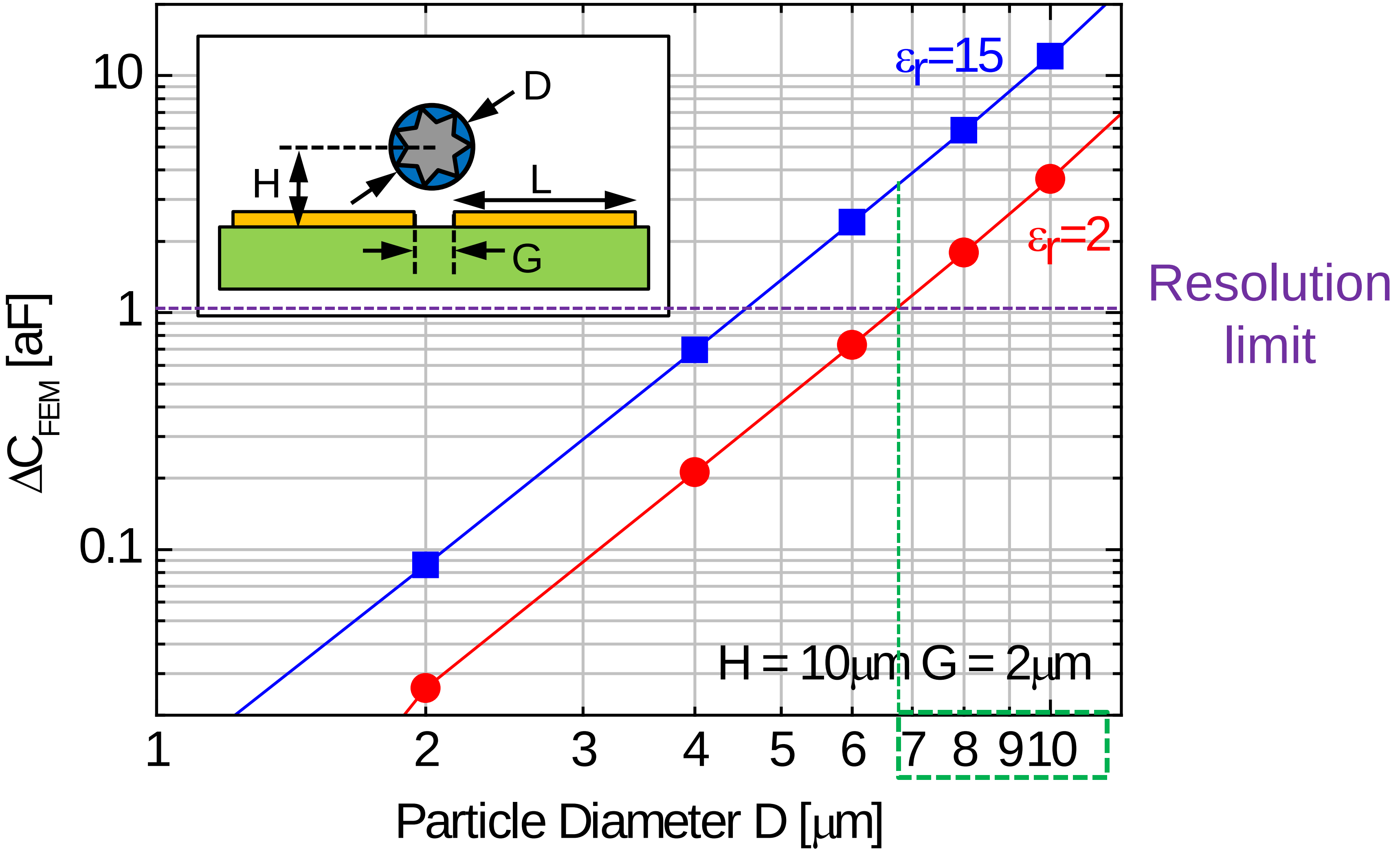
- **Air** vs liquid
- Electrode configuration:



M. Carminati, Capacitive detection of micrometric airborne particulate matter for solid-state personal air quality monitors, *Sensors Actuators A* **219**, 2014.

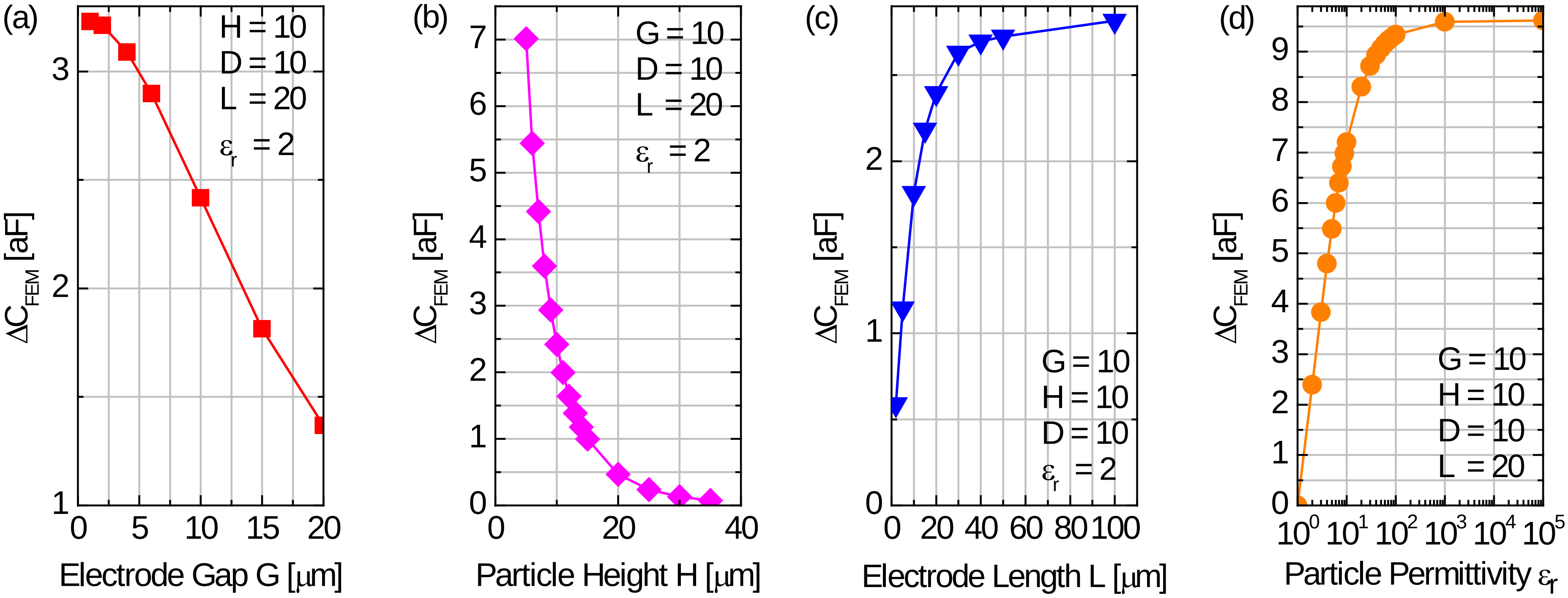
Preliminary FEM Simulations

Also in the coplanar geometry, ΔC has a volume dependence



Electrode Geometry Optimization

Fine tuning of the electrode parameters with FEM simulations



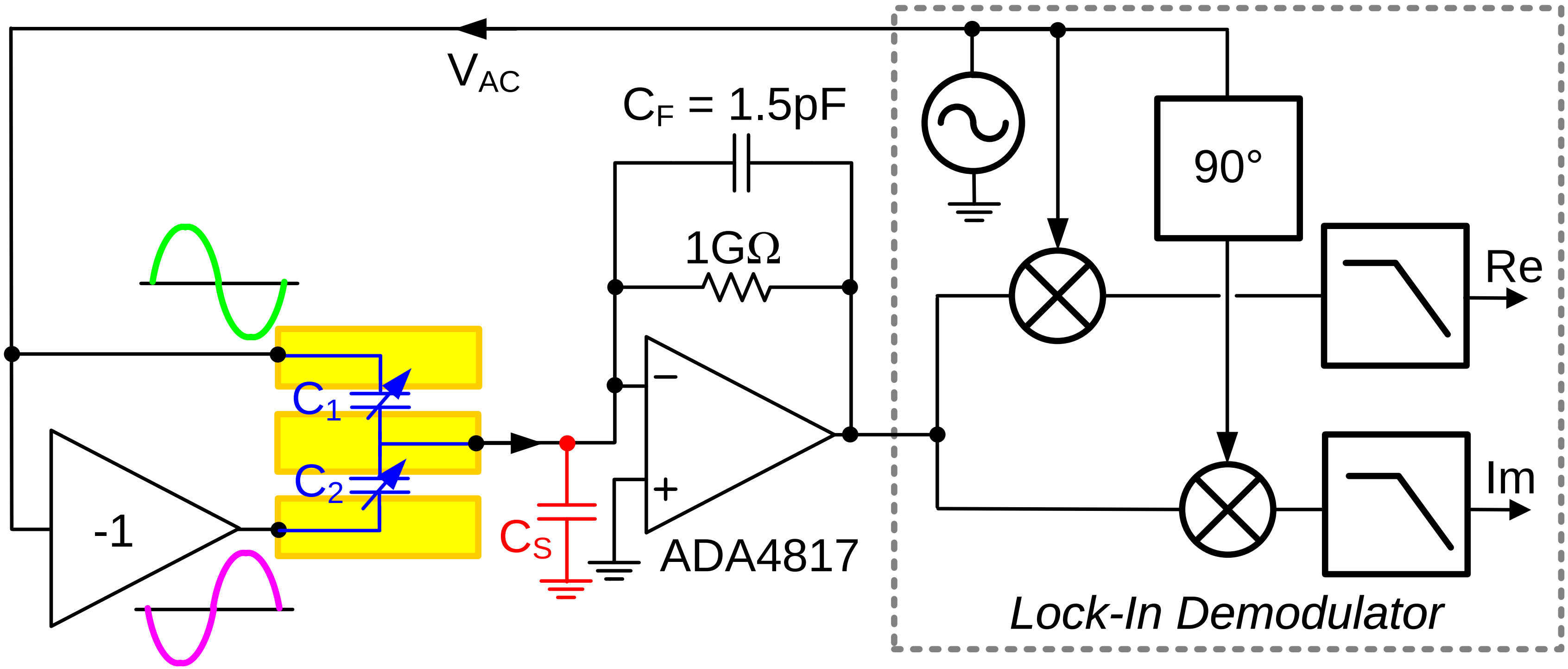
Gap: min.

Height: min.

Length: 30μm

M. Carminati, Capacitive detection of micrometric airborne particulate matter for solid-state personal air quality monitors, *Sensors Actuators A* **219**, 2014.

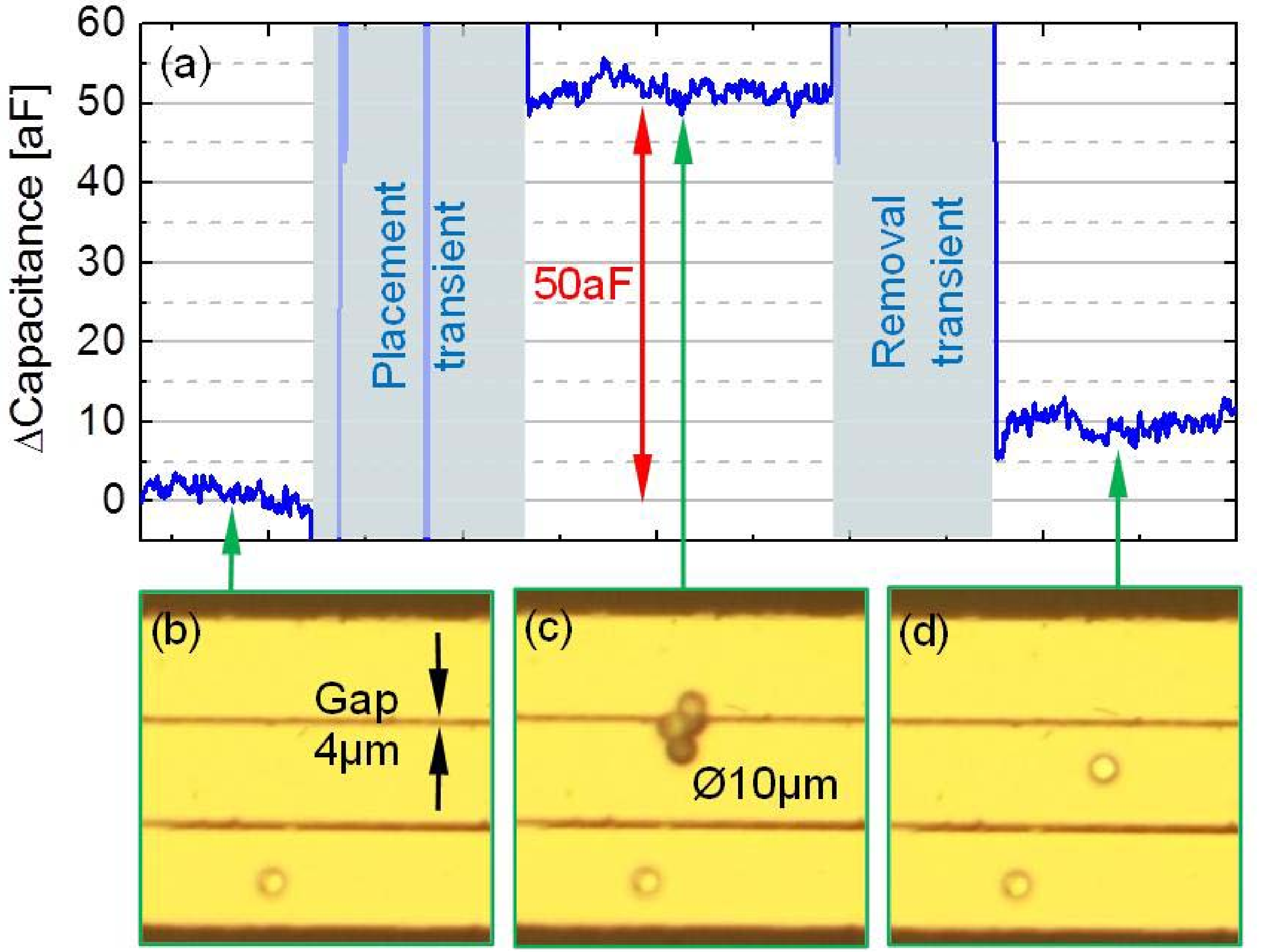
Low-Noise Detection Electronics



- Low-noise custom front-end (integrator)
- Differential sensing configuration to reduce generator noise
- 1.1aF resolution with 1sec response time (5aF with 1ms)

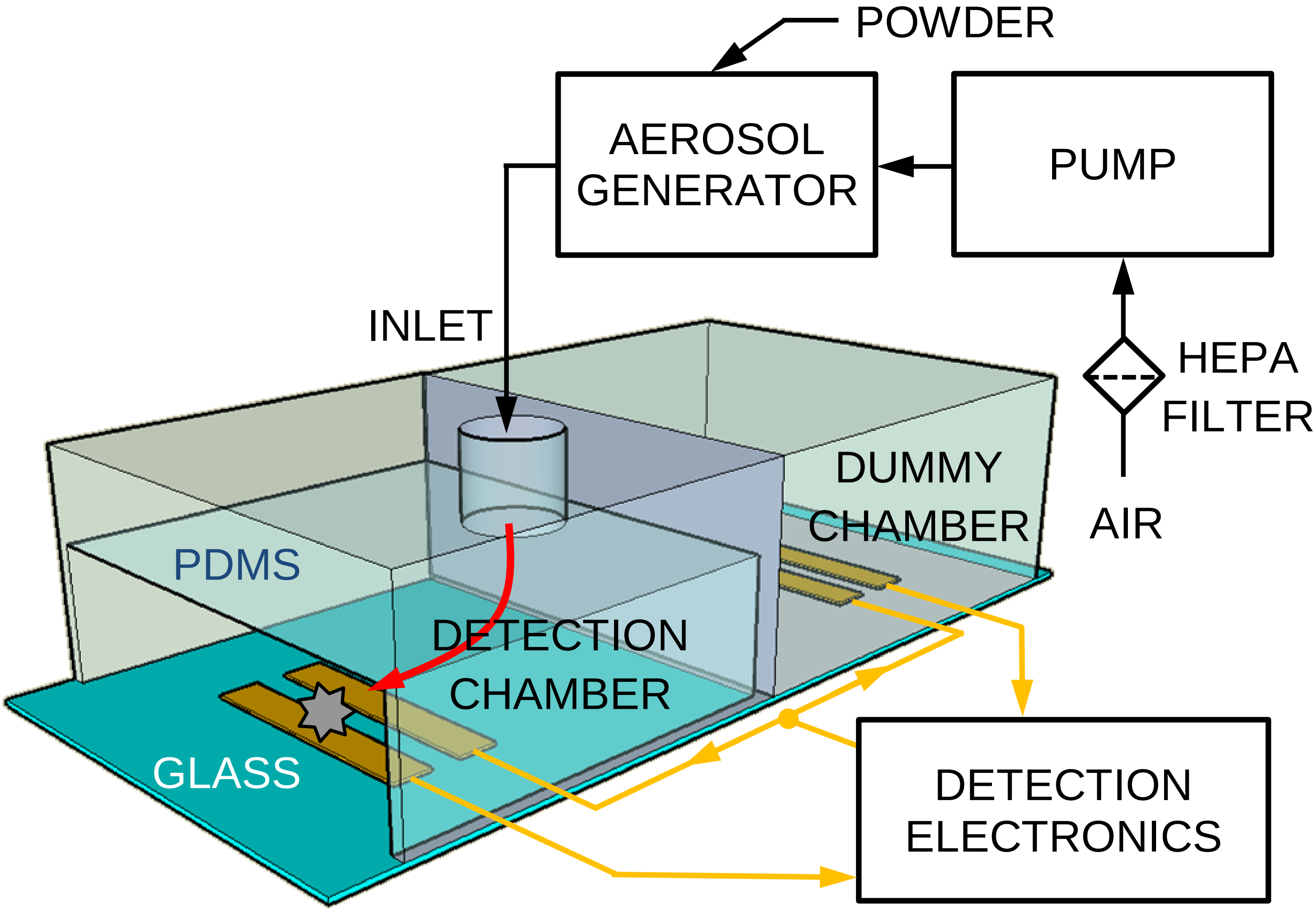
Static Characterization: PM_{10} Detection

Validation with calibrated polystyrene 10μm beads

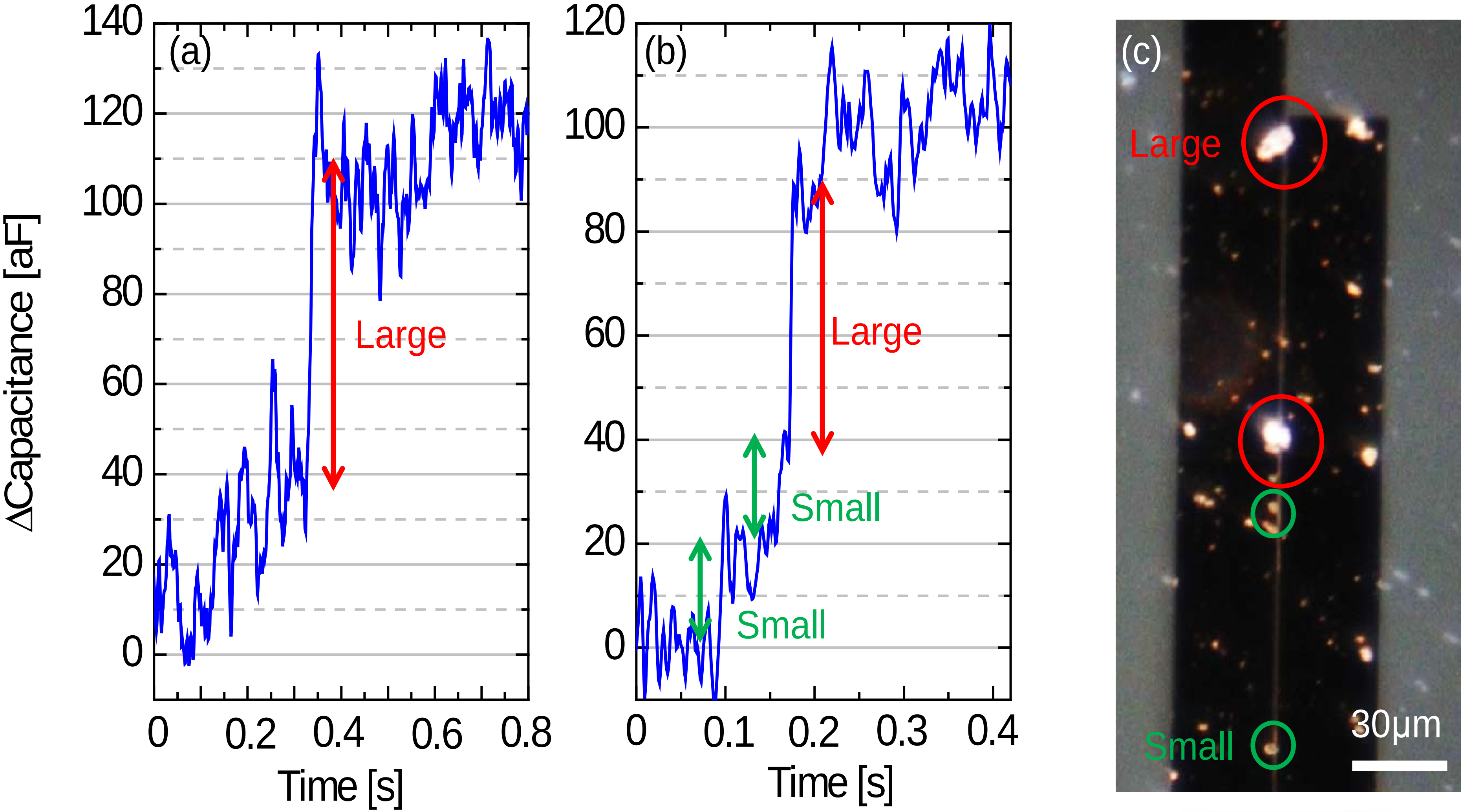


ΔC consistent with simulations

Full Detection System



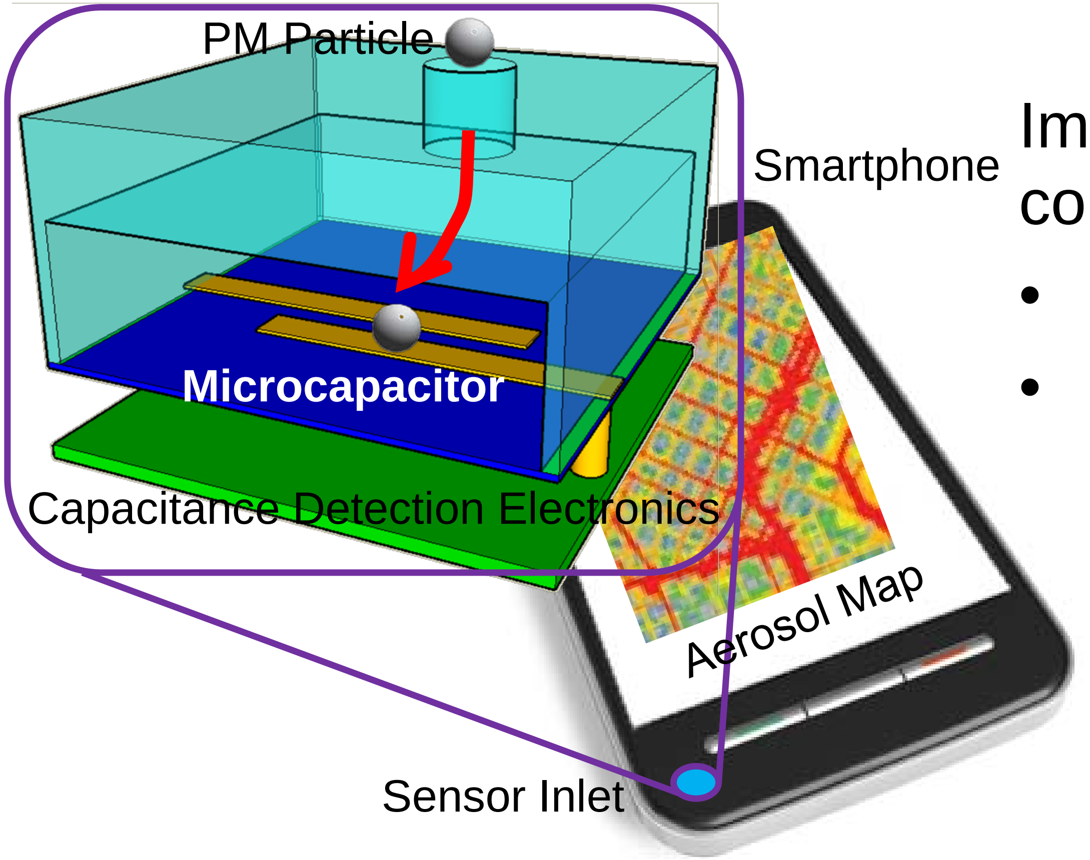
PM_{10}: Talc Detection



Real-time deposition tracking (Δt = 10ms)

$\varepsilon_r = 2.2$

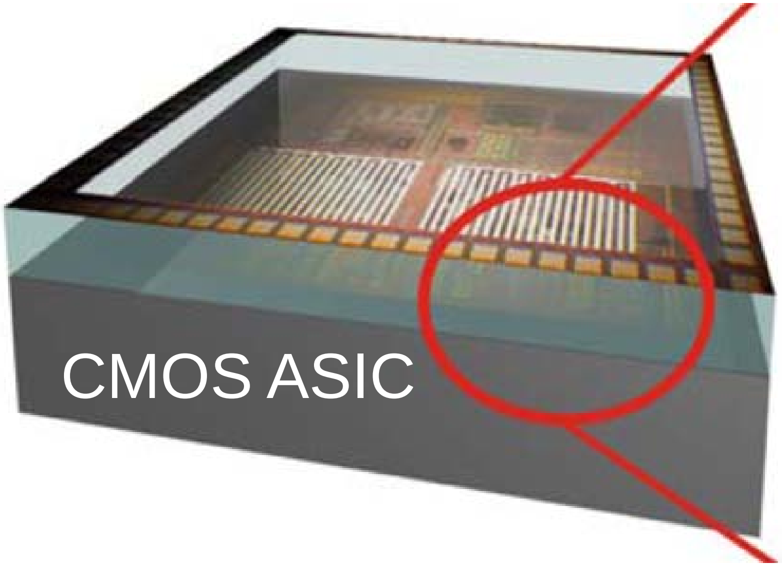
Single-Chip Detector: Towards Smartphones



Improving the resolution by combining **on the same chip**:

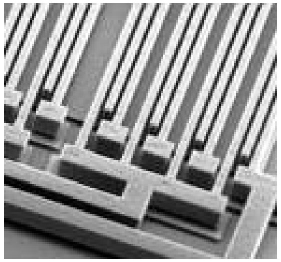
- Scaled lithography
- Integrated electronics with ZeptoFarad resolution

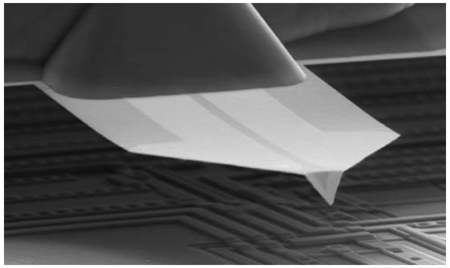
Targeting 1 μm PM

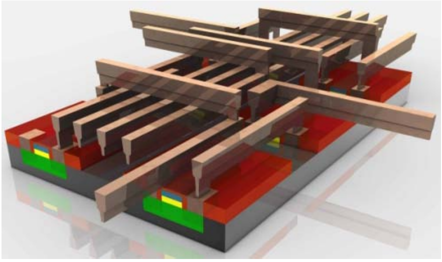


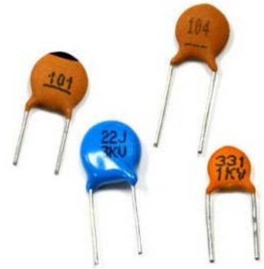
Cap. Resolution: Spanning Orders of Magnitude

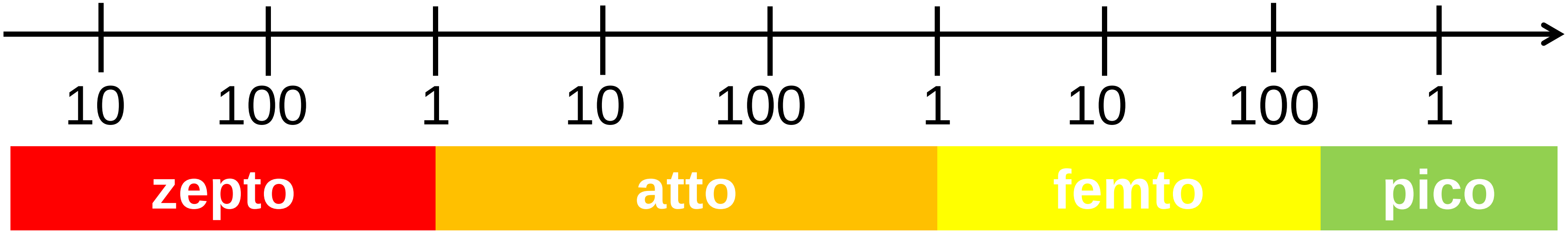
MEMS Microsensors AFM CMOS Parasitics COTS











10 100 1 10 100 1 10 100 1

zepto atto femto pico

Dedicated
ASIC

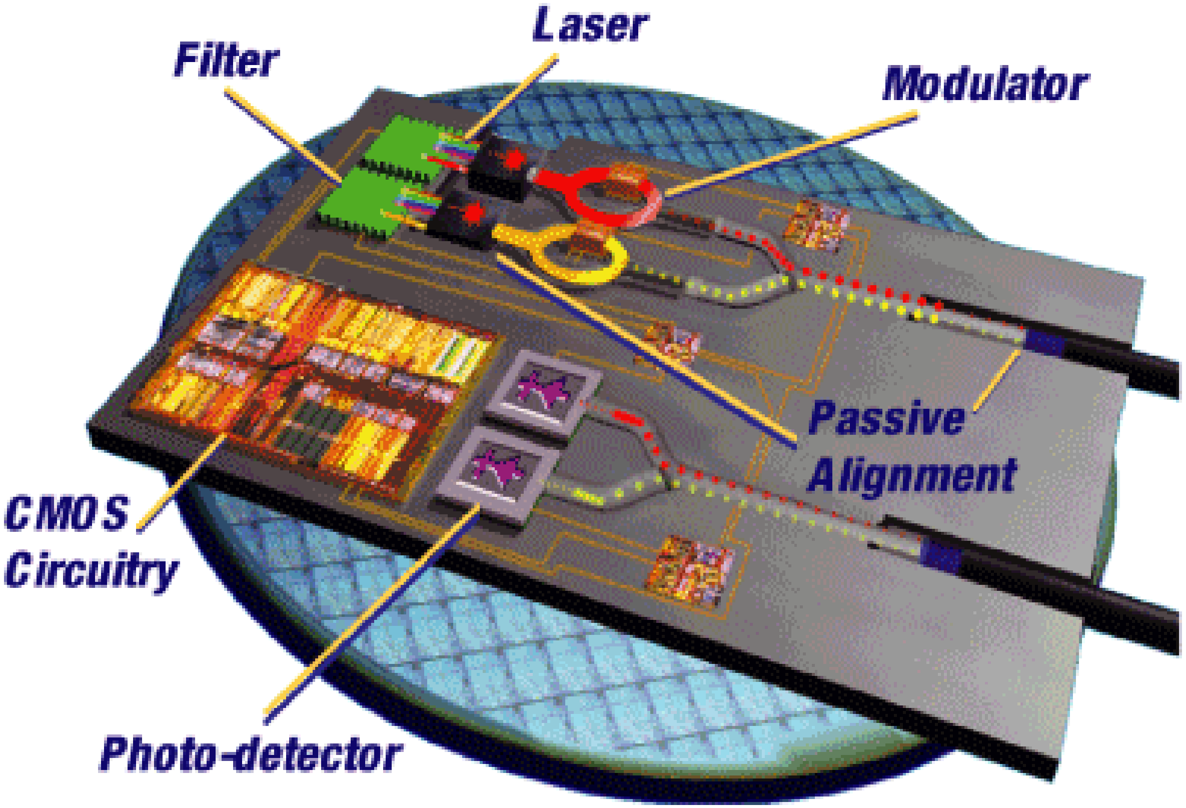
Dedicated
discrete-components

General purpose
instrumentation

	σ [zF]	BW [Hz]	V_{AC}
Analog Devices	12	0.1	10.5
M.Carminati *et al.*	5	1.6	6

M. Carminati *et al.* “ZeptoFarad capacitance detection with a miniaturized CMOS current front-end for nanoscale sensors”, *Sens. Act. A*, **172** 2011.

Integrated Photonics: Context and Motivation



Silicon Photonics:

great promise for communications and sensing

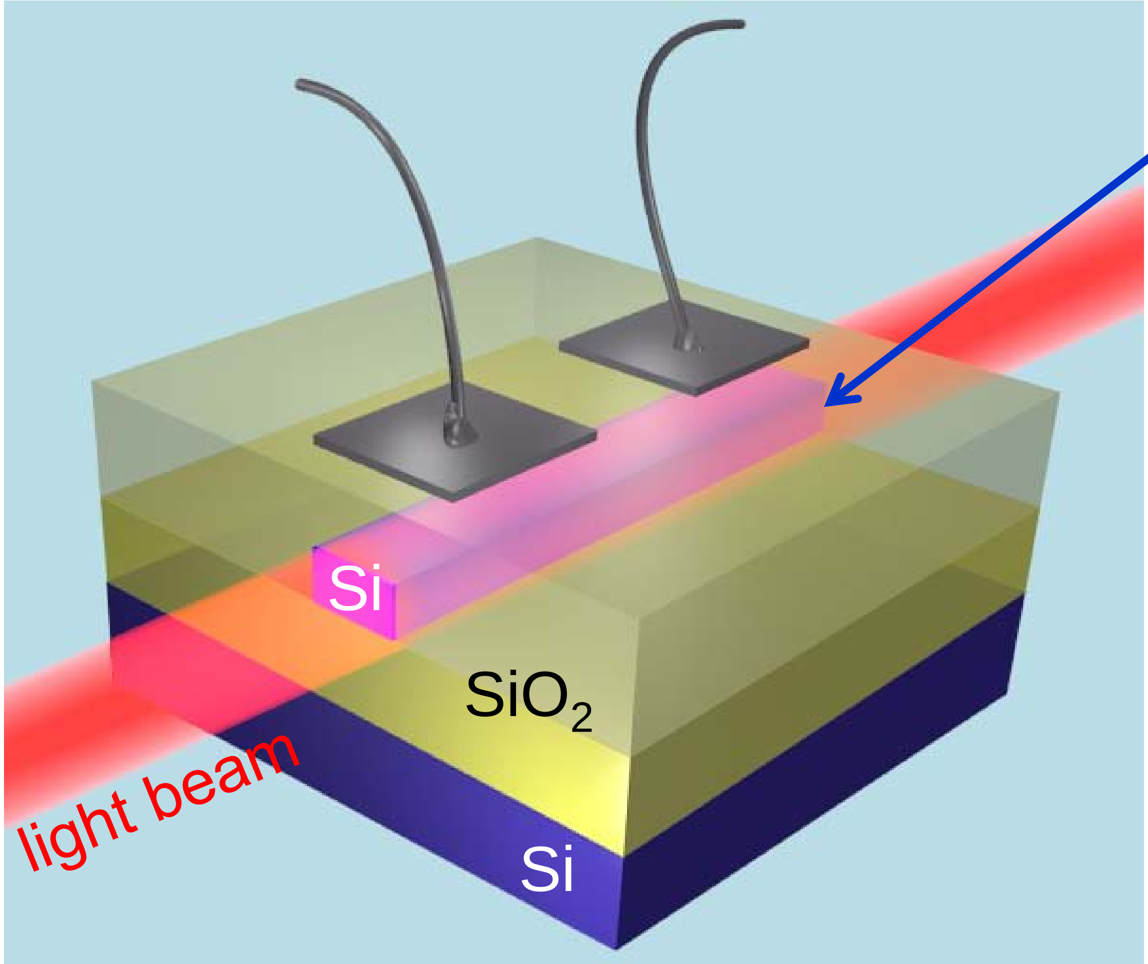
but

Large-scale integration of several components is limited by:

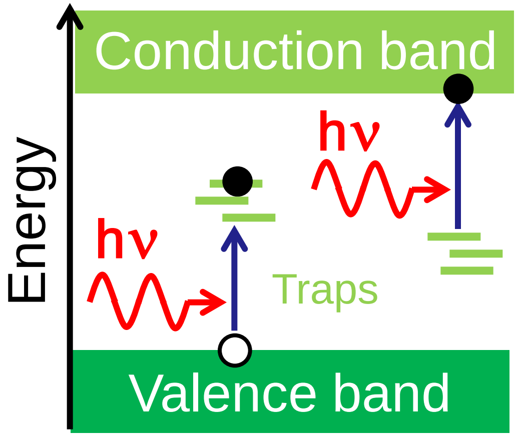
- lack of a consolidated/standard fabrication approach
- lack of **local feedback** to counterbalance drifts, variations
- limited integration with CMOS circuits

A Novel Transparent Light Monitoring Technique

At λ = 1550nm the Si waveguide is **transparent** but



defects at the Si/SiO$_2$ interface produce surface states



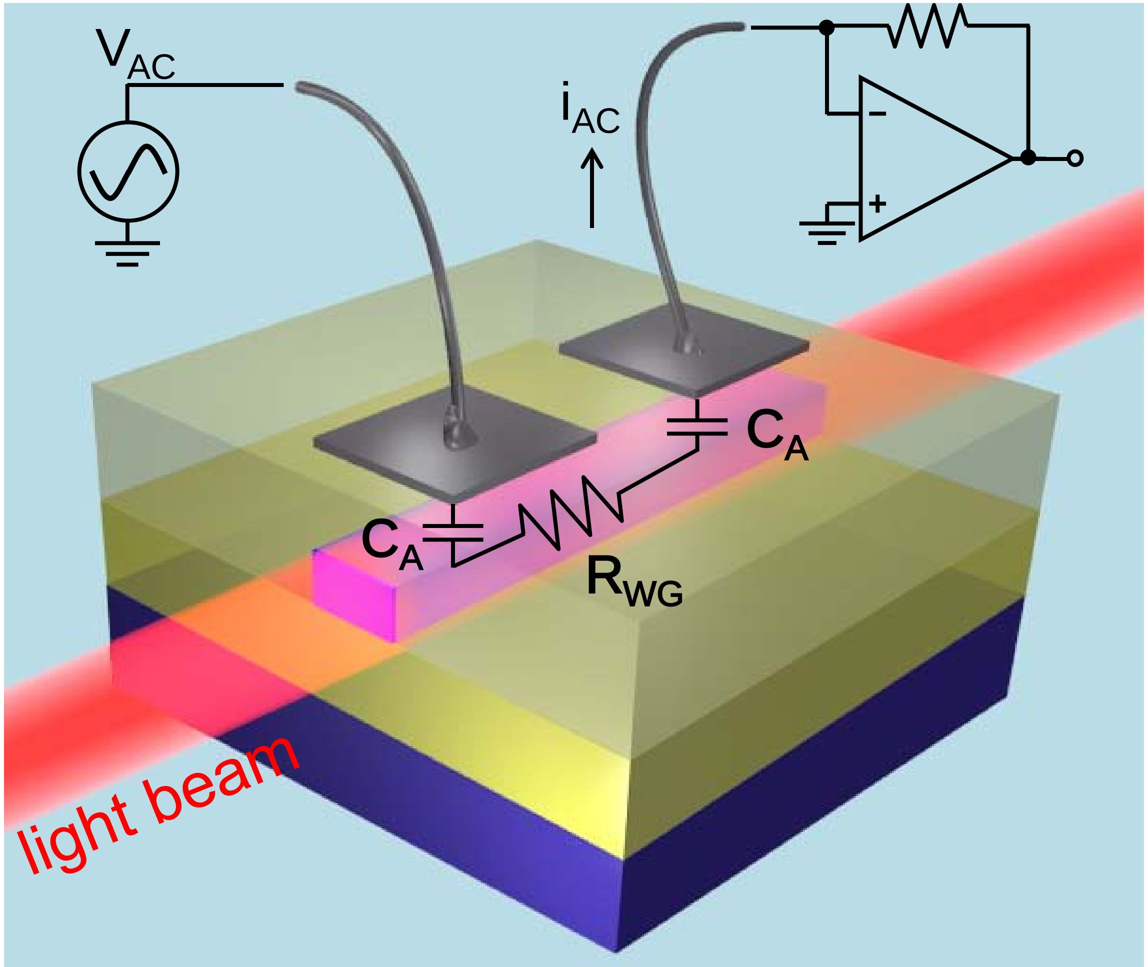
Photogenerated carriers

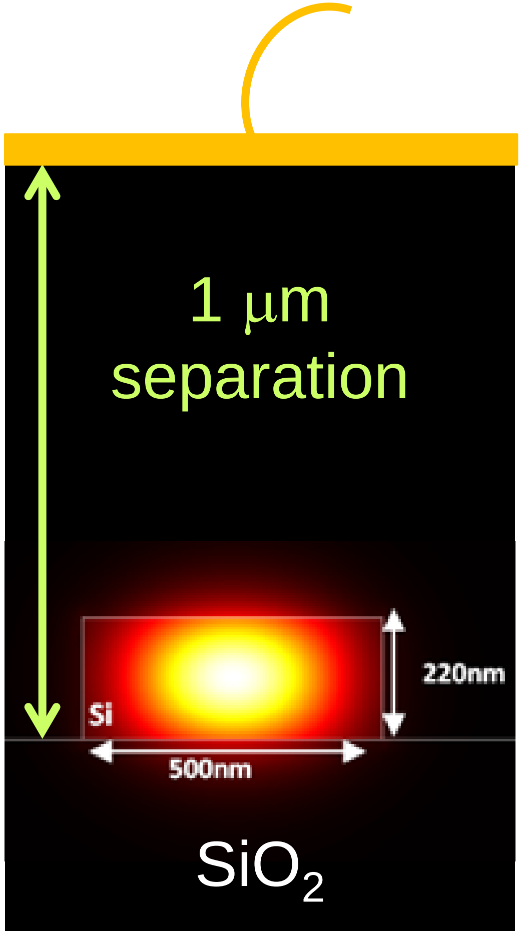
F. Morichetti et al., *IEEE J. Sel. Top. Quant. Electron.*, **20** (2014) .

A Novel Transparent Light Monitoring Technique

To avoid perturbation of the radiation

ContactLess Capacitive Access



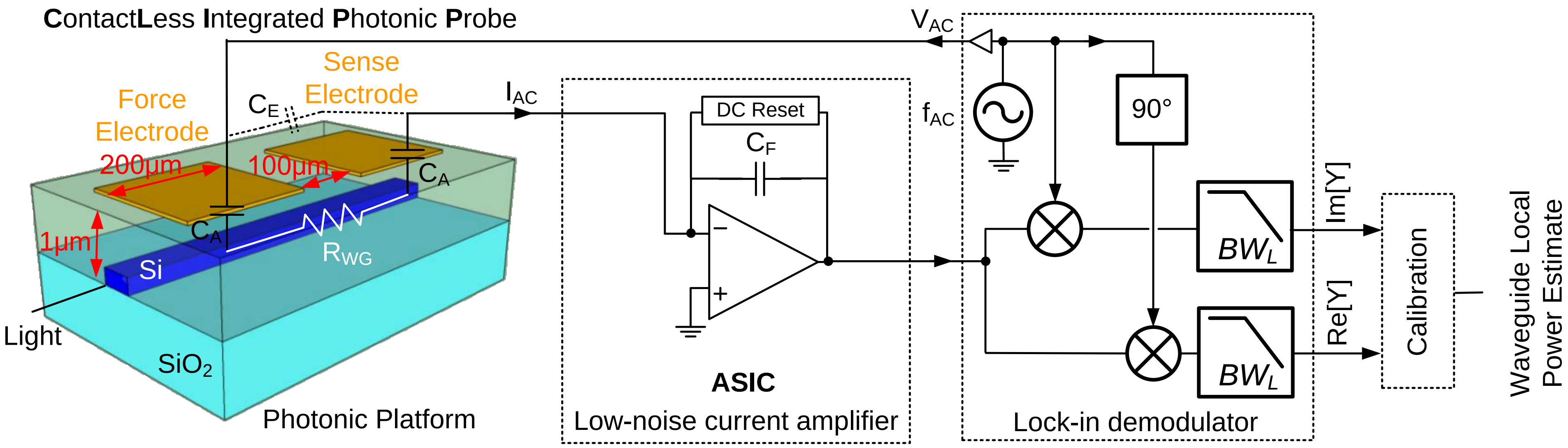


F. Morichetti et al., *IEEE J. Sel. Top. Quant. Electron.*, **20** (2014) .

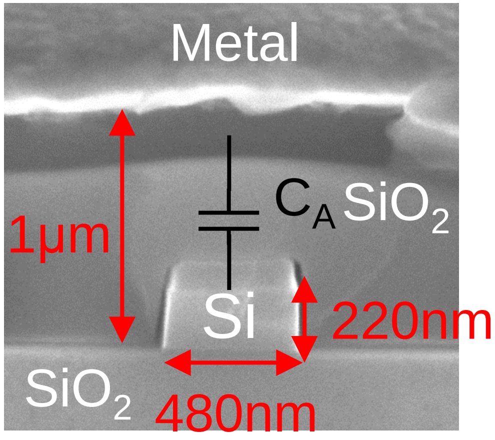
PATENTED!

Detection Architecture

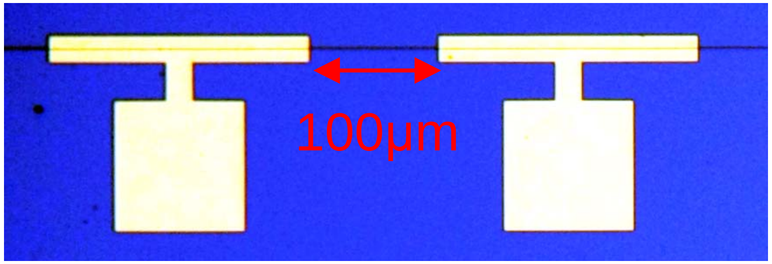
Low-noise impedance tracking platform



Optimized electrode layout



Cross section



Top view

R_{WG} ~150MΩ

ΔG ~nS

C_A = 5fF

C_E = 500fF

Non-Invasivity Enables Multipoint Monitoring

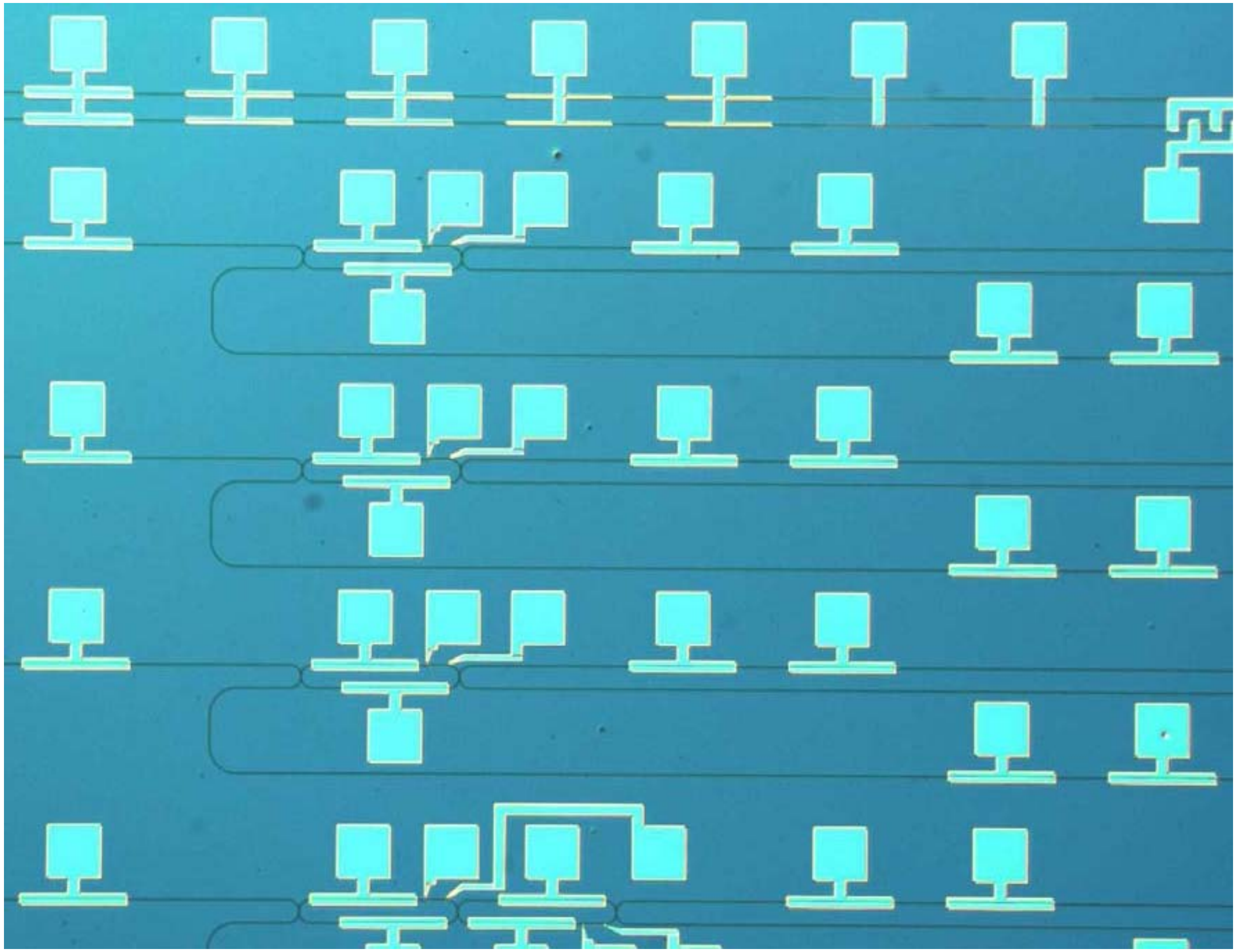
No extra light absorption

↓

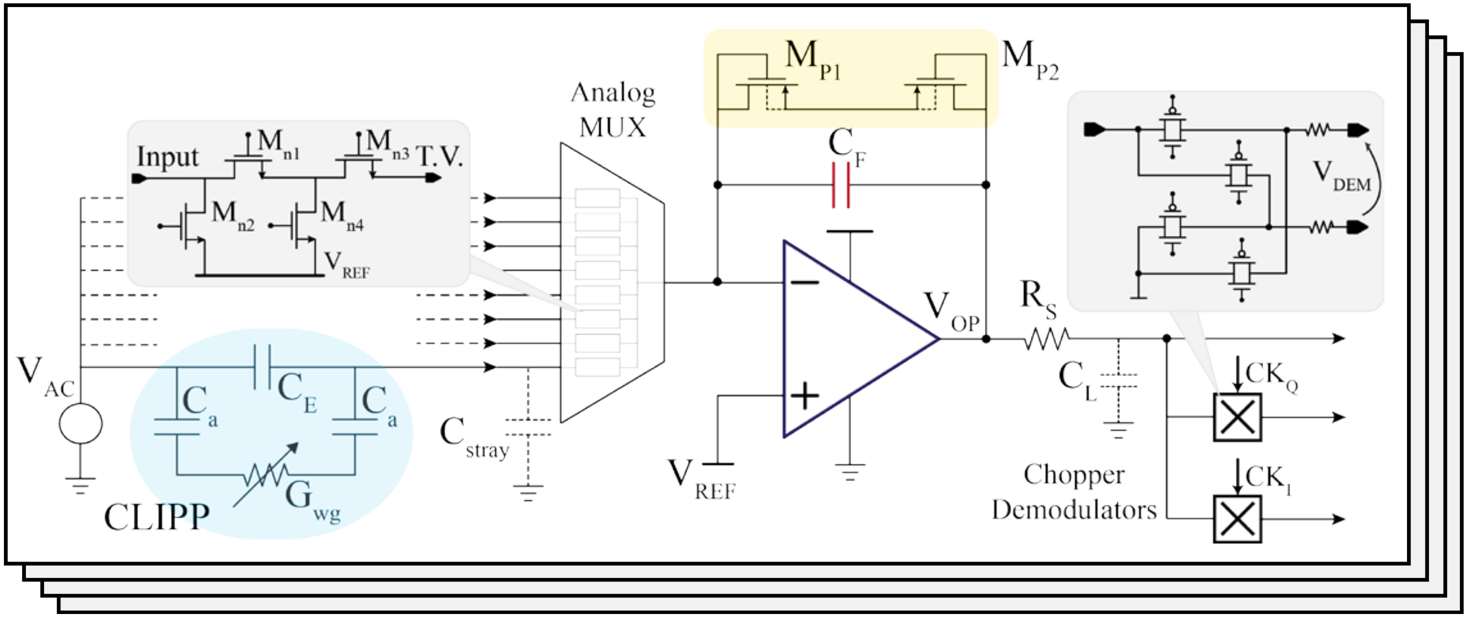
Multisite monitoring in complex circuits

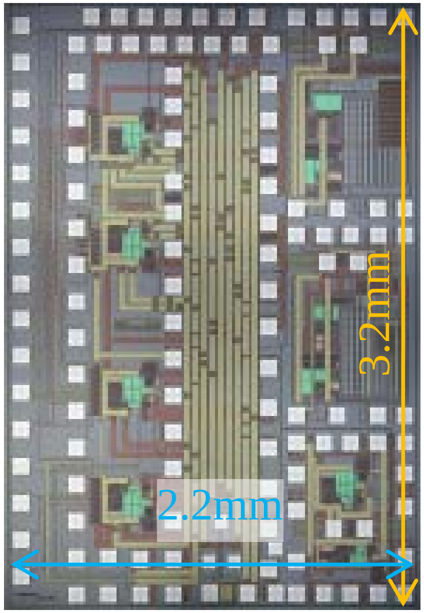
↓

Multichannel ASIC is required



ASIC Design

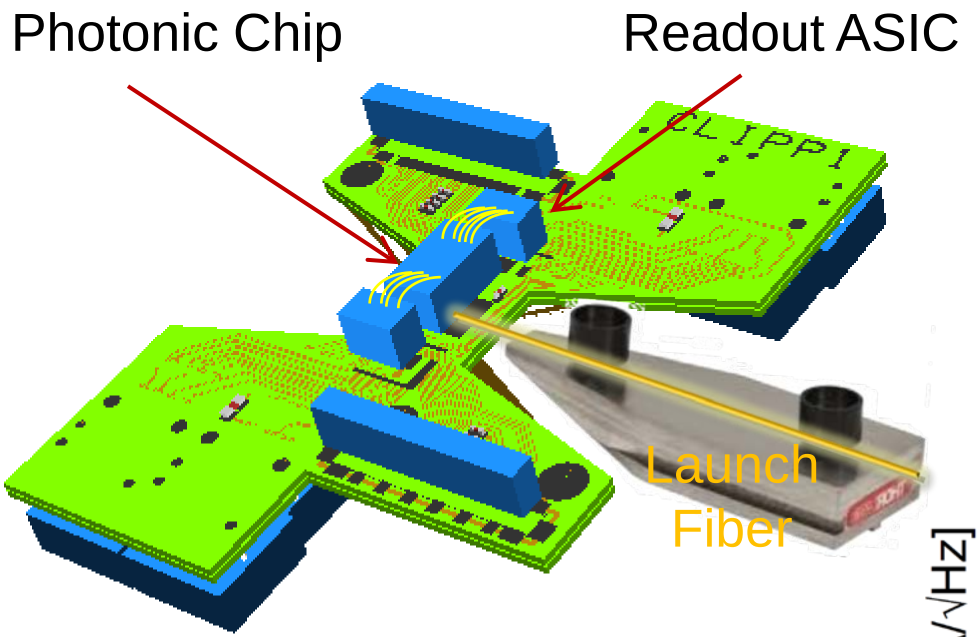




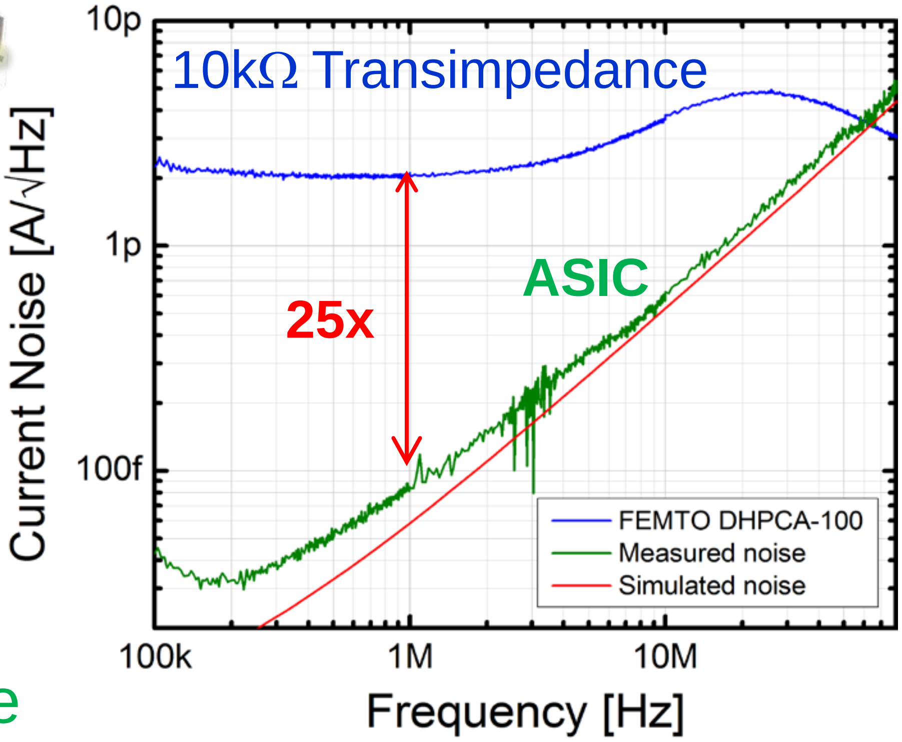
- Integrator front-end (C_F = 1pF)
- DC handling network with sub-threshlod transistors
- 8-channel low-parasitics MUX
- 2 square-wave multipliers

- 32 channels (4 parallel acquisition chains)
- 3.3V, 8mA current consumption, AMS 0.35µm CMOS

Performances of the Integrated Setup



Radical **reduction of parasitic capacitance** C_E of connections from 500fF to 2fF



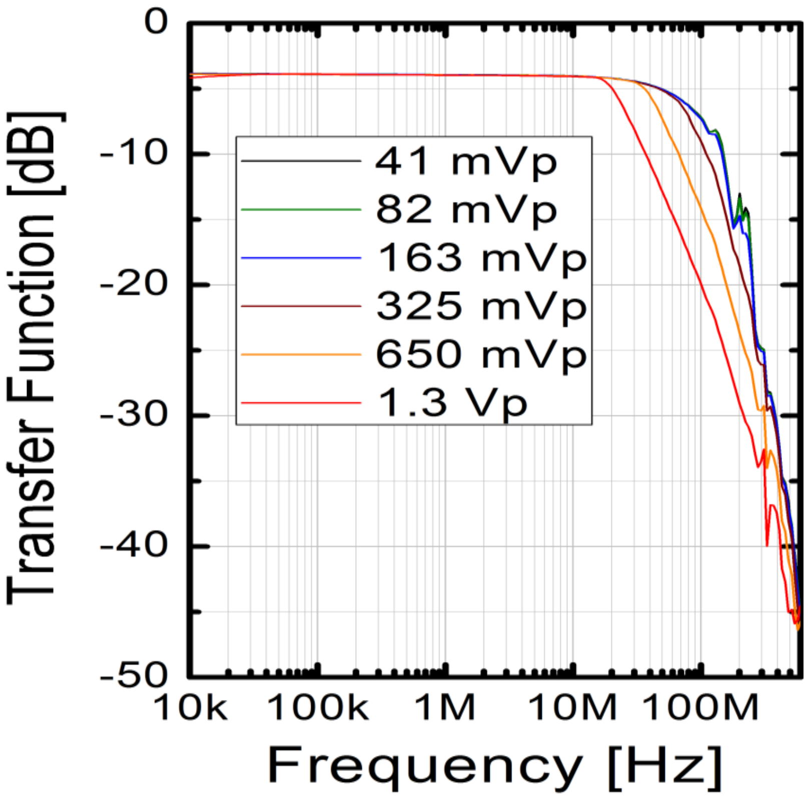
Advantages of integration:

- Multipoint monitoring
- Miniaturization
- CMOS compatibility
- Reduction of C_E → lower noise

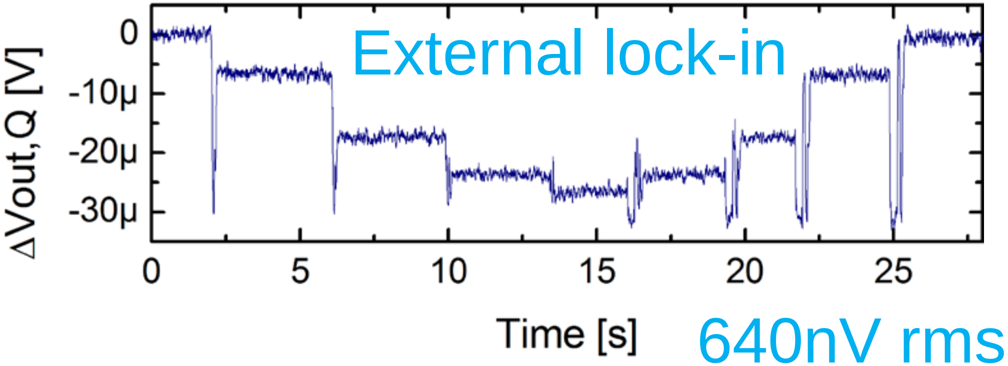
2pS rms

ASIC Characterization

100MHz bandwidth

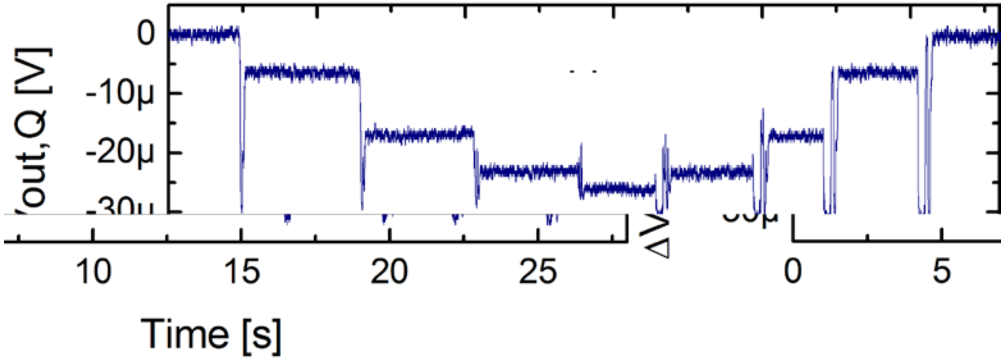


Same SNR of external lock-in



External lock-in

640nV rms

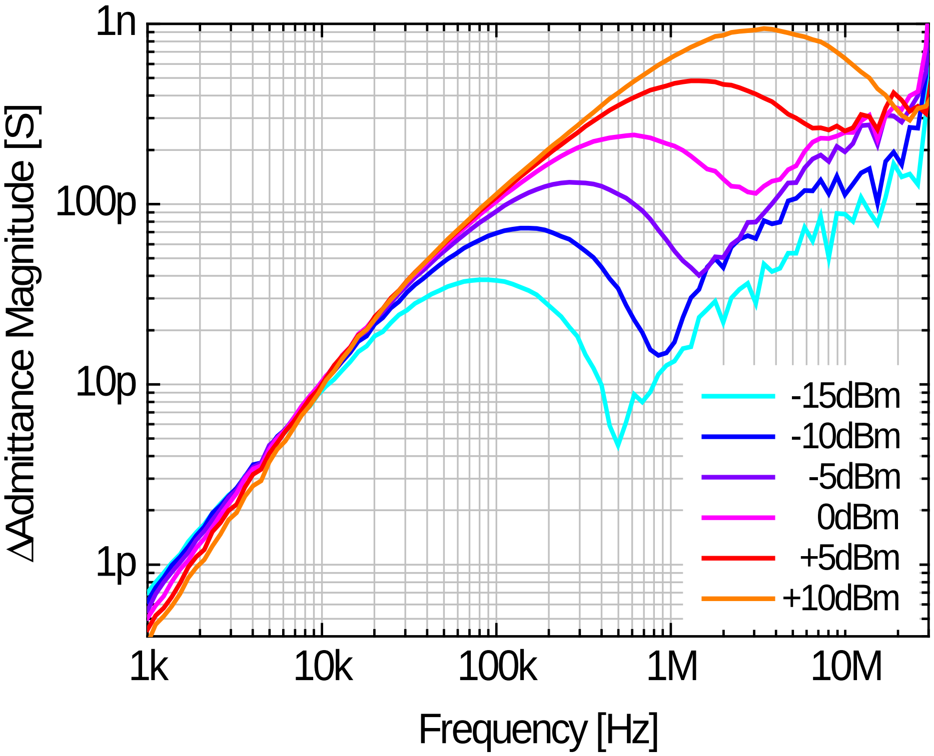


On-chip demodulator

565nV rms

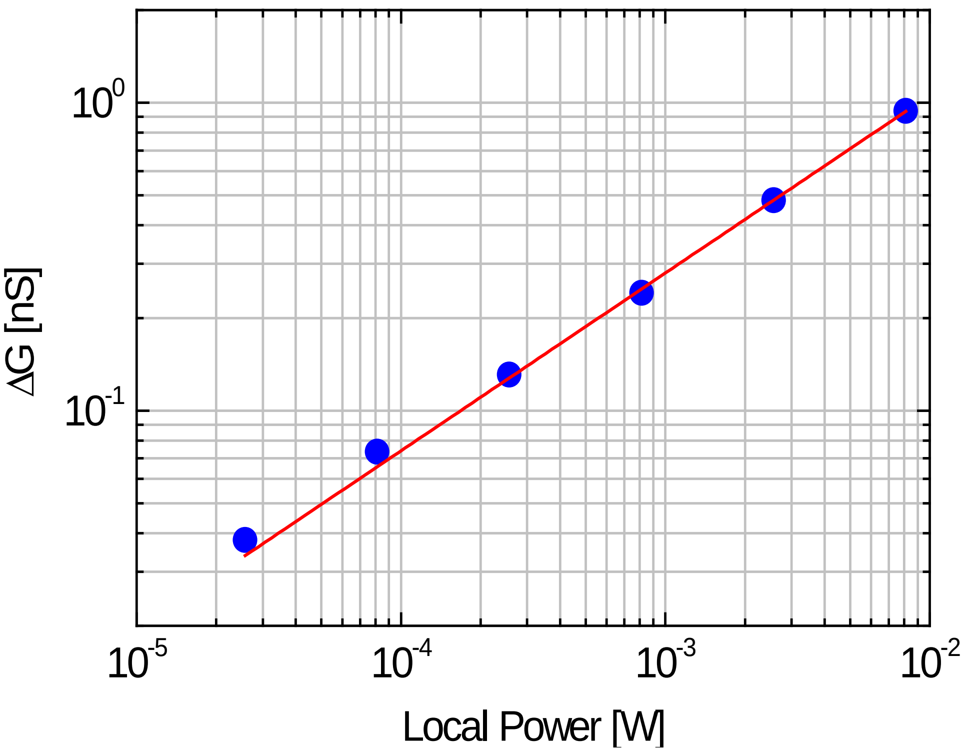
CLIPP Characterization: Power Monitor

Admittance spectroscopy for a wide range of optical power levels



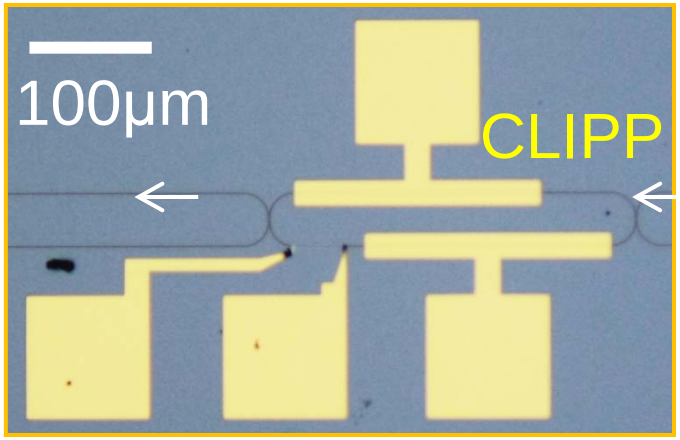
Monitor response curve

$$\Delta G \propto P^{0.6}$$



Min power: -30dBm, 40dB dynamic range

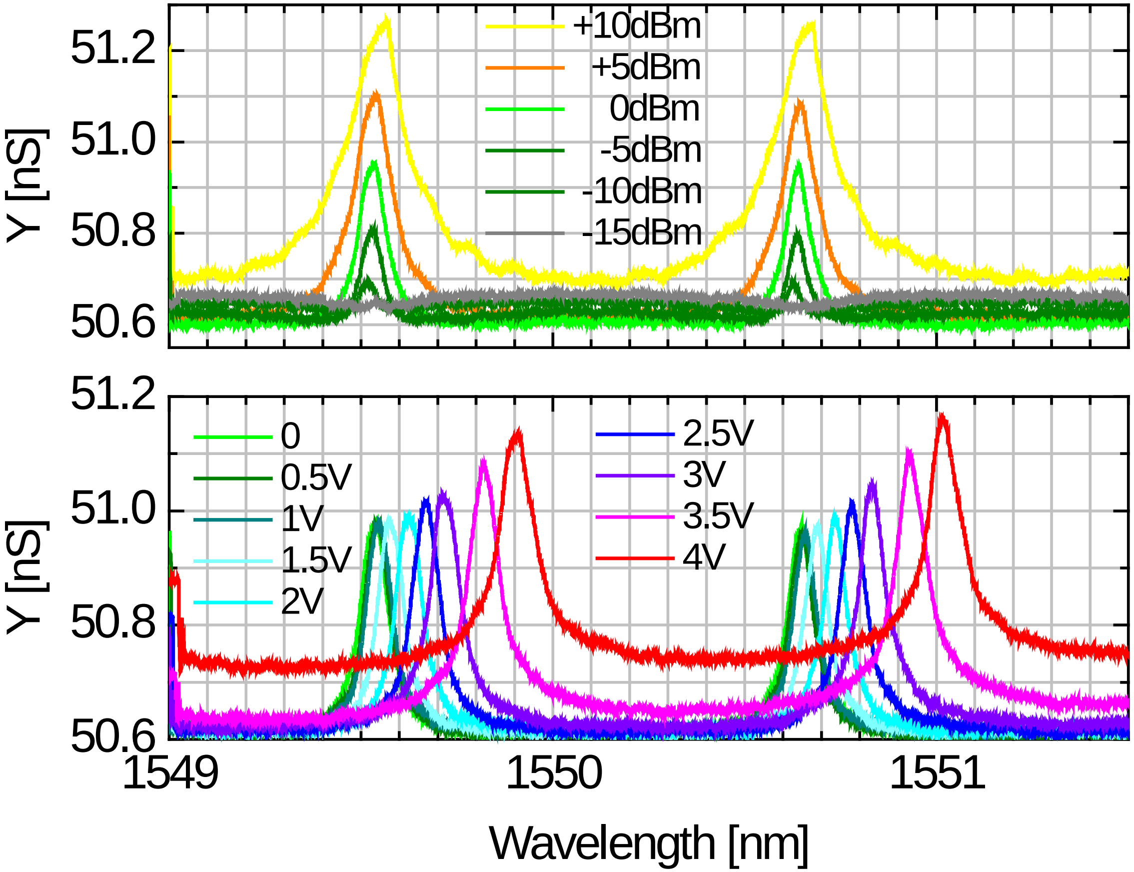
Looking Inside a Ring Resonator



Thermo-optic Actuator

No perturbative effect of V_{AC} on the resonance!

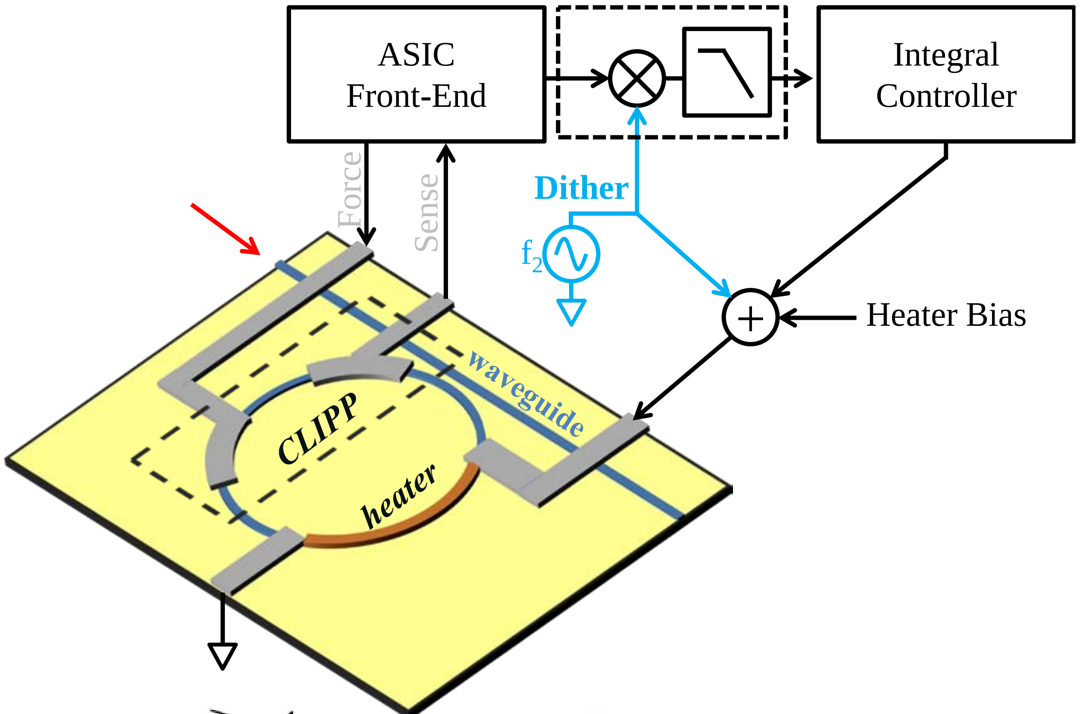
Tracking input power

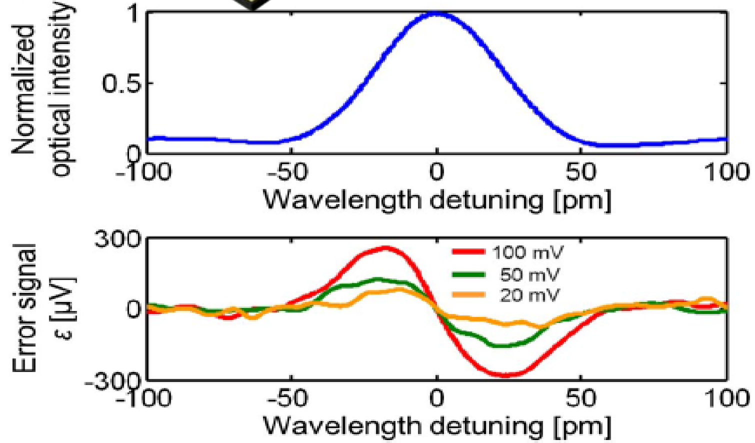


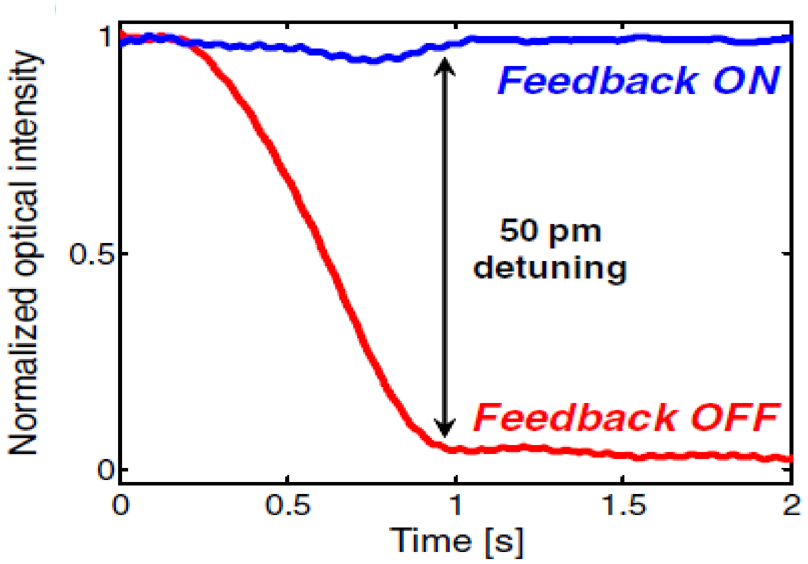
Tracking actuator voltage

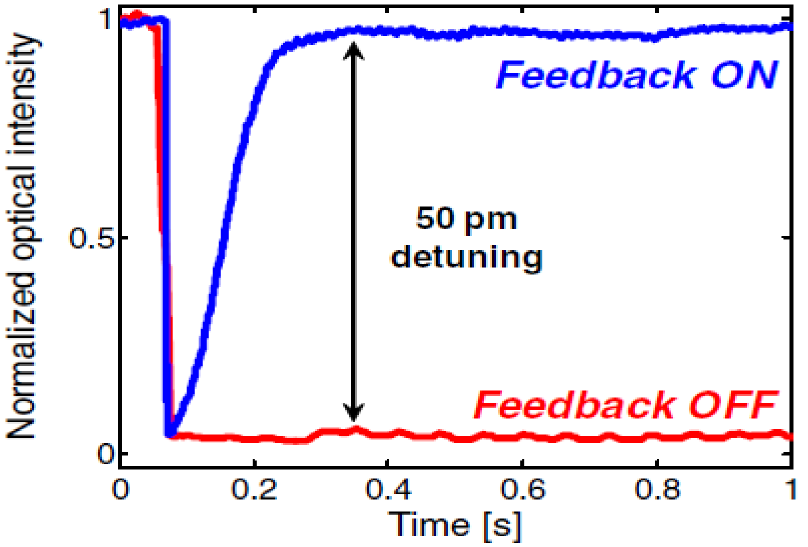
Closing the Loop

S. Grillanda et al., *Optica*., **1** 3 (2014)









Summary

- Not all the impedance measuring techniques are equivalent in terms of noise and suitability for impedance spectroscopy.
- When measuring impedance at the **microscale**, the signals decrease and **noise** (unavoidable property of the electronic components) becomes relevant.
- The **current sensing** front-end coupled with a **lock-in** demodulator represents the best solution.
- The input capacitance must be **minimized**, paying attention to short coax cables and preferably insulating substrates.
- The **transimpedance amplifier** allows neutralization of the input stray impedance, but is prone to a noise/bandwidth trade-off, that can be relaxed by means of advanced topologies such as the integrator/differentiator cascade.

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