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

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Motivation: Impedance is Everywhere

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

- Strain/Pressure: Resistance
- Level: Capacitance
- Displacement: Inductance
Focusing on the example of contactless capacitive sensing, let’s see the scaling trend from macro to micro size applications.
Electrodes are protected from the liquid, the capacitance increases linearly with the tank level.

Air $\varepsilon_r = 1$

Liquid $\varepsilon_r > 1$

Range 10-1000pF
Macro: Contactless Capacitance Tomography

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

<table>
<thead>
<tr>
<th>Test structures</th>
<th>Obtained Maps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic bars $\varepsilon_r = 3$</td>
<td>![Map of plastic bars]</td>
</tr>
<tr>
<td>Air $\varepsilon_r = 1$</td>
<td>![Map of air]</td>
</tr>
<tr>
<td>Plastic beads $\varepsilon_r = 3$</td>
<td>![Map of plastic beads]</td>
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</tbody>
</table>

Pipe cross-section

Range 10-100pF
Mini: Capacitive Touchscreen

Range
10-100fF
Milli: Capacitive Fingerprint Scanner

Range 5-50fF
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
• Transimpedance 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**

\[ |Z| \]

fixed f

**Spectroscopy**

\[ |Z| \]

f
Plotting Impedance Spectra

Two alternative ways to present impedance spectra:

**Bode Plots**

- Magnitude ($|Z|$)
- Phase ($\angle Z$)

**Cole-Cole Plot**

- Real part ($\text{Re}(Z)$)
- Imaginary part ($\text{Im}(Z)$)

Electronic engineering and automation/control science

Electrochemical & biosensors community

Equivalent!
Microfabrication 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 $\text{voltage}$ (limited by biology or $\text{dielectric breakdown}$), the $\text{current}$ flowing through the system $\text{decreases}$:

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:

\[ i(t) = \text{signal}(t) + d(t) + n(t) \]

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 \( \sigma \)

\[
\text{SNR} = \frac{\text{Signal Amplitude}}{\text{Noise Amplitude}} = \frac{\text{Signal}}{\sigma_{\text{rms}}}
\]
Noise Power Spectrum

Description in the frequency domain:

Noise spectral density

\[ T \approx \frac{1}{f} \]

\[ S(f) = \frac{n_f^2(t)}{\Delta f} \]

\[ n_f^2(t) = \int_{0}^{\infty} S(f) df \]

\[ \text{RMS} = \sqrt{n_f^2(t)} = \sqrt{\int_{0}^{\infty} S(f) df} \]
Impedance Measurement Techniques

• Sinusoidal stimulation: 
  • 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

\[ V_{AC}\sin(2\pi f_0 t) + V_{DC} \]

\[ i(t) \]

Current detector

\[ \sin(2\pi f_0 t) \]

\[ \cos(2\pi f_0 t) \]

Sample

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:

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

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

Minimize \( C_{Stray} \)!
Getting Rid of Silicon When Not Needed

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: $R_F = 1\,\text{G}\Omega, C_F = 0.2\,\text{pF} \rightarrow S_i = 4\,\text{fA/}\sqrt{\text{Hz}}$, $\text{BW} = 800\,\text{Hz}$
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

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

$V_{out}/i_{in}$

Cascade

2° stage

1° stage
2.1 - Discrete Time: Reset Switch

Switch periodically closed to discharge the capacitor:

Limits the maximum measurement time

For example: $I_{IN-DC} = 1\text{nA}$, $C_F = 1\text{pF} \rightarrow (5\text{V}) \quad T_{MAX} = 5\text{ms}$
2.2 - Continuous Time: Active Reset

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

Transfer Functions

Two separate paths and gains:

- DC and low frequency
- High frequency

\[ V_{OUT-DC} = -R_{DC} I_{IN} \]
\[ V_{OUT-AC} = \frac{C_D}{C_F} R_{FD} I_{IN} \]

For wideband impedance spectroscopy, large \( R_{DC} \) is required.
Mitigation of Source Noise: Differential Sensing

Limited by matching!

Significant noise reduction

- Single-ended
- Differential
- No compensation
- Compensated (same range)
- Compensated (range reduced)

Capacitance noise: [aF rms]
- No compensation
- Compensated

Conductance noise: [nS rms]
- No compensation
- Compensated

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**

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

- $\rho_{\text{PBS}} = 66 \Omega \text{cm}$
- $\varepsilon_{\text{PBS}} = 78$
- $C_{\text{MEM}} = 0.01 \text{pF/} \mu \text{m}^2$
- $\rho_{\text{CYTO}} \sim \rho_{\text{PBS}}$
- $\varepsilon_{\text{CYTO}} = 60$
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 adhesion, spreading and growth can be monitored

Lo, Keese, Giaever, *Biophys J.* 69 1995
Comparison of Sensing Geometries

\[ R_{\text{sol}} = \frac{\rho}{4r} \]

\[ C_{\text{dl}} = C_0 \cdot \pi \cdot r^2 \]

Conformal Mapping
Comparison with HeLa Cells

![Graph showing cell index over time for Coplanar and Vertical orientations.](image)

- **Coplanar**
- **Vertical**
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)

K. Cheung et al., *Cytometry* 77A 2010
Electrodes Configurations
Design of Sensing Electrodes

- Simple technology → coplanar
- Ease of alignment → transverse
- Target cells 5-15\(\mu\)m → 20 x 40\(\mu\)m²
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
Four regions in the impedance spectrum:

- Interface
- Shallow channel
- Transition
- Infinite channel
- Bulk
- Operating Frequency Range

Operating Frequency

CDL RSOL

$C_{DL}$ $R_{SOL}$

$C_S = 0.7 \text{pF}$

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

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

Real-Time Peak Detection

<table>
<thead>
<tr>
<th>#</th>
<th>$t_1$</th>
<th>$t_2$</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.2</td>
<td>12.1</td>
<td>1.51mV</td>
</tr>
<tr>
<td>2</td>
<td>15.1</td>
<td>17.3</td>
<td>1.53mV</td>
</tr>
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</table>
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

![Graph showing impedance tracking and FPGA peak counting](image)
System Validation with Beads

- 10\(\mu\)m polystyrene beads in PBS
- 50 beads/s (1\(\mu\)l/min)
- \(V_{AC} = 50\text{mV}, f_0 = 100\text{kHz}, 5\text{kSa/s}\)

As expected:
Counting Yeast

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

![Graph showing resistance over time with threshold level highlighted.](image)
Counting Yeast

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

![Graph showing HP Voltage over Time with a threshold marked]

10\(\mu\)m scale bar
Yeast: Peak Analysis

**Pulse Width:**

Consistent with:

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

A Novel Technique: Electrical Detection

Real-time capacitive detection of single PM particles

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

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

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

Choice of the Sensing Configuration

Key design choices:

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

![Diagram showing different electrode configurations](image)

Also in the coplanar geometry, $\Delta C$ has a volume dependence.

Also in the coplanar geometry, $\Delta C$ has a volume dependence.

![Diagram](image)

$\Delta C_{\text{FEM}} [aF]$ vs. Particle Diameter $D [\mu m]$ for different dielectric constants $\varepsilon_r$.

- $\varepsilon_r=15$
- $\varepsilon_r=2$

Resolution limit:

- $H = 10 \mu m$
- $G = 2 \mu m$

The graph shows the dependency of $\Delta C_{\text{FEM}}$ on $D$ for different $\varepsilon_r$ values. The resolution limit is indicated by the dashed line.
Electrode Geometry Optimization

Fine tuning of the electrode parameters with FEM simulations

(a) \(G = 10\), \(D = 10\), \(L = 20\), \(\varepsilon_r = 2\)

(b) \(G = 10\), \(D = 10\), \(L = 20\), \(\varepsilon_r = 2\)

(c) \(G = 10\), \(H = 10\), \(D = 10\), \(\varepsilon_r = 2\)

(d) \(G = 10\), \(H = 10\), \(D = 10\), \(L = 20\)

Gap: min. Height: min. Length: 30\(\mu\)m

• 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

$\Delta C$ consistent with simulations
PM$_{10}$: Talc Detection

Real-time deposition tracking ($\Delta t = 10$ ms)  \(\varepsilon_r = 2.2\)
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

Dedicated ASIC  | Dedicated discrete-components  | General purpose instrumentation

<table>
<thead>
<tr>
<th></th>
<th>( \sigma ) [zF]</th>
<th>BW [Hz]</th>
<th>( V_{AC} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog Devices</td>
<td>12</td>
<td>0.1</td>
<td>10.5</td>
</tr>
<tr>
<td>M. Carminati et al.</td>
<td>5</td>
<td>1.6</td>
<td>6</td>
</tr>
</tbody>
</table>

Silicon Photonics: great promise for communications and sensing

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
At $\lambda = 1550\text{nm}$ the Si waveguide is **transparent** but...
To avoid perturbation of the radiation

ContactLess Capacitive Access

Detection Architecture

Low-noise impedance tracking platform

ContactLess Integrated Photonic Probe

Low-noise current amplifier

Lock-in demodulator

Optimized electrode layout

1 μm
C_A SiO_2

220 nm
Si

480 nm
SiO_2

Metal

R_{WG} \sim 150 M\Omega
\Delta G \sim nS
C_A = 5 fF
C_E = 500 fF
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-threshold 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

Advantages of integration:
- Multipoint monitoring
- Miniaturization
- CMOS compatibility
- Reduction of $C_E \rightarrow$ lower noise

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

Current Noise [A/√Hz]

10kΩ Transimpedance

25x

100k 1M 10M

Frequency [Hz]

2pS rms
ASIC Characterization

100MHz bandwidth

- Transfer Function [dB]
  - 41 mVP
  - 82 mVP
  - 163 mVP
  - 325 mVP
  - 650 mVP
  - 1.3 Vp

- Frequency [Hz]
  - 10k
  - 100k
  - 1M
  - 10M
  - 100M

Same SNR of external lock-in

- External lock-in
  - 640nV rms

- On-chip demodulator
  - 565nV rms
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.*, 13 (2014)
• 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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Breaking the Barriers of Optical Integration