Advanced Course on
High Resolution Electronic Measurements in Nano-Bio Science

Electrochemical Instrumentation
Probing the Interface
Marco Carminati

April 10th 2019
Outline

• Review of major **electrochemical techniques**:
  - Cyclic voltammetry / Square wave voltammetry
  - Amperometry
  - Potentiometry
  - Impedance spectroscopy

• **Instrumentation**:  
  - Design criteria of a potentiostat
  - Low-noise potentiostat
  - Bipotentiostat and multichannel systems
  - Miniaturization and CMOS potentiostats
Potentiostatic configuration:

- Apply a voltage $V_{\text{CELL}}$ and measure the current $I_{\text{CELL}}$
  
  2 sections: generation and sensing

- Multiple measurement types by changing stimulation waveform
Detection techniques:

- Potential step/pulse methods
- Potential sweep methods
- Controlled-current techniques
- Methods based on impedance
- Scanning Electrochemical Microscopy
Families of Analytical Techniques

Major ones:
- Cyclic Voltammetry
- Amperometry
- Impedance Spectroscopy and Tracking
Cyclic Voltammetry

- Triangular wave: slope = scan rate

- Important parameters:
  - \( E_{pa} \) and \( E_{pc} \)
  - \( i_{pc} \) and \( i_{ac} \)
  - \( E^0 = (E_{pa} + E_{pc})/2 \)
  - \( \Delta E = |E_{pa} - E_{pc}| \)

- \( E^0 \) formal redox potential
- detection of chemical reactions
- evaluation of electron transfer kinetics and diffusion rates
Peak Current (Reversible Systems)

\[ i_p = 0.4463 \, n \, F \, A \, C \, (D \, S \, R \, n \, q / kT)^{1/2} \]

- **n**: n. of electrons
- **F**: Faraday’s constant (96485 C/mol)
- **A**: electrode area;
- **C**: concentration (mol/litre)
- **D**: diffusion coefficient (cm²/sec).
- **SR**: scan rate

\[ i_{pa} = i_{pc} \] for a reversible system

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**Anodic peak current**

- **Current**: µA
- **Scan Rate**: mV/s
Peak Potential

\[ \Delta E_p = |E_{pa} - E_{pc}| = \frac{59}{n} \text{ mV at 25}^\circ \text{C} \]

independent of SR

\[ n, \text{ reversibility} \]

Chemical fingerprint
Quasi-Reversible or Irreversible

B - Quasi-reversible:
- $\Delta E_p > 59$ mV and $\Delta E_p$ increases with increasing SR

A - Irreversible:
- no return wave, 2 waves do not overlap
Multi-Electron Transfer

\[ A + e^- \leftrightarrow B \quad E_{0AB} \]
\[ B + e^- \leftrightarrow C \quad E_{0BC} \]
Spurious Effects

1) Capacitive current

\[ i_{dl} = C_{dl} \frac{dV}{dt} = C_{dl} \nu \]

\[ i_p \propto \sqrt{\nu} \]

2) \( iR_{\text{sol}} \) drop

3) \( C_{dl}R_{\text{sol}} \) time constant
Square Wave Voltammetry

Evolution of linear sweep voltammetry: superposition of a square wave with large amplitude $\Delta E$ and take $i_{\text{max}} - i_{\text{min}}$

Obtain the derivative of the voltammogram (differential square wave voltammetry)
Square Wave Voltammetry

2 approaches:
• Integrate over time $u, v$
• Sample final value

$\tau$ delay $\rightarrow$ Avoid the capacitive current!!

Better detection limit!
Multiple Square Wave Voltammetry

\[ I_j = \sum_{i} (I_{f,i} - I_{r,i}) \]
\[ I_{j+1} = \sum_{i} (I_{f,i} - I_{r,i}) \]

\[ M = \frac{\text{Staircase pulse time}}{\text{Pulse time}} \]

N. Fatouros, *J. Electroanal. Chem.*, 213
Amperometry

Recording current over time at a fixed WE potential

\[ i \propto \text{concentration} \]

Fixed voltage 0.4V

Step response

\[ 0 \rightarrow 0.4V \]
Electrochemical Impedance Sensing

Sinusoidal excitation:
- Small signal (1-10mV) for linearity and minimal perturbation
- Wide frequency span: from <Hz to 100kHz-1MHz

Time tracking:
- Frequency sweep:

\[
\begin{align*}
\Delta \text{Capacitance [F]} & \quad \text{Time [s]} \\
+30\text{mV} & \quad 50 \quad 100 \quad 150 \quad 200 \quad 250 \\
+20\text{mV} & \\
+10\text{mV} & \\
-10\text{mV} & \\
\end{align*}
\]

\[
\begin{align*}
\text{Impedance Magnitude [Q]} & \quad \text{Frequency [Hz]} \\
1G & \quad 100m \quad 1 \quad 10 \quad 100 \quad 1k \quad 10k \quad 100k \quad 1M \\
100M & \\
10M & \\
1M & \\
100k & \\
10k & \\
1k & \\
100 & \\
10 & \\
1 & \\
\end{align*}
\]

CPE:
- Q = 10μF/cm²
- n = 0.92

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Impedance Spectroscopy Application

Very sensitive to **interfacial properties**

**Applications:**
- Coatings (paint)
- Corrosion
- Surface roughness
- Affinity biosensors
- Dielectric properties
- Battery SoC

**Impedance Magnitude [Ω]** vs **Frequency [Hz]**

- \( W = \text{Au} \ C = \text{Au} \ (25 \mu \text{m}) \)
- \( W = \text{Au} \ C = \text{Ag/AgCl} \)
- \( W = \text{Ag/AgCl} \ C = \text{Ag/AgCl} \)

Fitting: CPE + R

- \( Q = 25 \text{pF}, n = 0.93 \)
- \( R = 20 \text{kΩ} \)

- \( Q = 50 \text{pF}, n = 0.91 \)
- \( R = 10 \text{kΩ} \)
The Cole-Cole Plot

EIS spectra visualization: a very common representation in Electrochemistry, alternative to Bode (Nyquist diagram)
Cole-Cole Parameter Extraction

\[ Z'' = C = \frac{1}{2\pi f_0 R} \]

\[ \omega_{\text{max}} = \frac{1}{R \cdot C} \]

\[ \text{Graph showing Cole-Cole plot with impedances} \]

\[ \text{Graph showing frequency response with } 150\text{Hz} \text{ and } 1.3\text{Hz} \]

\[ \text{Diagram showing circuit with } C_{DL}, R_{CT}, R_{SOL} \]

\[ \text{Graph showing impedance vs. frequency} \]

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Two-Electrode Measurement

oxide

Gold
Two-Electrode Measurement

Potential $V$:
- $\Delta V_1$ electrode-electrolyte
- $i \cdot R$ drop within electrolyte
- $\Delta V$ across the sample
- $\Delta V_2$ sample-gold

$\Delta V_1$, $i \cdot R$ and $\Delta V_2$ change with current

$\Delta V$ across the sample is current-depend

$\rightarrow$ not well controlled
Three-Electrodes Setup

Third electrode (reference) to measure the voltage near the sample

\[ \Delta V \] across the sample

- Avoids internal polarization of reference electrode
- \( \Delta V_R \) constant: **no current**; silver-silver chloride, calomel…
- Reference electrode near the sample to compensate for major portion of cell iR drop
A New Instrument: the Potentiostat

Combining current detection and voltage-control loop
Reference Electrodes

**Purpose:** provide *stable potential* against which other potentials can be reliably measured

**Criteria:**
- stable in potential (time, temperature)
- reversible
- reproducible
- potential shouldn’t be altered by passage of small current = not polarizable
- easy fabrication and handling
- convenient for use
The Silver/Silver Chloride Electrode

Ag wire coated with AgCl(s), immersed in NaCl or KCl solution.

It is stable in liquid that has large quantity of Cl\(^-\) such as the biological fluid.

\[
\text{AgCl (s) + e}^- \leftrightarrow \text{Ag (s) + Cl}^- (aq) \\
E^\circ = +0.222 \text{ V} \\
\text{Stable to +275°C}
\]

From BAS www-site
Instrument Design Specifications

Generation (cyclic voltammetry):

- Accuracy: $\sim 1\text{mV}$ (59mV characteristic feature)
- Bandwidth: $\text{BW [Hz]} = 40 \cdot \text{SR [V/s]}$

$$\Delta V_{\text{error}} = \tau \cdot \text{SR} = 4\text{mV} \rightarrow 1/(2\pi \cdot \tau) = \text{SR}/(2\pi \cdot 4\text{mV})$$

- Capacitive load $>1\text{nF}$

Sensing:

- Sensitivity: scales with electrode area, $\sim 1\text{pA} - 1\text{mA}$
- Bandwidth: adequate for impedance and voltammetry
A simplified model of the interface can be adopted for design purposes (stability) + stray capacitances

- $R_{sol} = \rho/4r$ (66$\Omega$cm PBS)
- $R_x = $ charge transfer
- $C_x = 0.1pF/\mu m^2$ (PBS)

Modulated by the sample
Current sensing:
• Shunt resistor $R_m$
• Transimpedance $R_f$
Switches change range $R_m/R_f$
### Commercial Workstations

**Wide current range**

![Commercial Workstations Image](image)

#### Low Current Option

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell control</td>
<td>2, 3, 4 or 5 terminals (+ ground)</td>
</tr>
<tr>
<td>Compliance</td>
<td>20 V adjustable from ±10 V to 0-20 V</td>
</tr>
<tr>
<td>Maximum current</td>
<td>±600 mA continuous</td>
</tr>
<tr>
<td>Maximum potential resolution</td>
<td>±300 μA on 20 V</td>
</tr>
<tr>
<td>Resolution</td>
<td>programmable down to ±5 μA on 200 mV</td>
</tr>
<tr>
<td>Maximum current</td>
<td>0.004% of the dynamic range resolution</td>
</tr>
<tr>
<td>Accuracy (DC)</td>
<td>&lt; 0.1% FSR*</td>
</tr>
<tr>
<td>Rise time</td>
<td>(10% - 90%) ≤ 2 μs (No load)</td>
</tr>
<tr>
<td>Acquisition time</td>
<td>20 μs</td>
</tr>
</tbody>
</table>

#### Current measurement

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ranges</td>
<td>Automatic on every range</td>
</tr>
<tr>
<td>Maximum resolution</td>
<td>±10 μA to ±400 mA (7 ranges)</td>
</tr>
<tr>
<td>Accuracy (DC)</td>
<td>&lt; 0.1% FSR*</td>
</tr>
<tr>
<td>Acquisition speed</td>
<td>200000 samples/second</td>
</tr>
</tbody>
</table>

#### Potential measurement

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ranges</td>
<td>±2.5 V, ±5 V, ±10 V, ±10 V adjustable</td>
</tr>
<tr>
<td>Accuracy (DC)</td>
<td>0.0015% FSR*, down to 75 μV</td>
</tr>
<tr>
<td>Acquisition speed</td>
<td>200000 samples/second</td>
</tr>
<tr>
<td>Bias current</td>
<td>&lt; 5 μA</td>
</tr>
</tbody>
</table>

### EIS Option

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impedance</td>
<td>10 MΩ to 1 V</td>
</tr>
<tr>
<td>Frequency range</td>
<td>10 μHz to 1 MHz</td>
</tr>
<tr>
<td>Amplitude</td>
<td>1 mV to 1 V</td>
</tr>
<tr>
<td>General</td>
<td>0.1% to 50% of the current range</td>
</tr>
</tbody>
</table>

#### Electrometer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impedance</td>
<td>10^14 ohms in parallel with 1 pF</td>
</tr>
<tr>
<td>Bias current</td>
<td>60 μA typical, 150 μA max at 25 °C</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>1 MHz</td>
</tr>
</tbody>
</table>

#### General

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>435 x 335 x 95 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>8.0 kg</td>
</tr>
<tr>
<td>Power</td>
<td>85-264 V, 47-640 Hz</td>
</tr>
<tr>
<td>PC configuration</td>
<td>Pentium IV, Windows 2000, XP or Vista</td>
</tr>
</tbody>
</table>

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[Commercial Workstations Image]

29
Commercial vs. Custom Instruments

Pros:
• Wide catalog of off-the-shelf products
• Versatile: wide range of currents and operating modes
• Professional software

Cons:
• Bulky (portable models are emerging)
• Few channels, rigid configuration/parameters
• Not optimized (performance can be improved for a specific application)
Enhanced Nanoscale Potentiostat

Carminati et al., Rev. Sci. Instrum 80, 2009
Achievable Performance

<table>
<thead>
<tr>
<th>HEAD</th>
<th>$R_{DC}$</th>
<th>$C_i$</th>
<th>$G_{DC}$</th>
<th>$G_{AC}$</th>
<th>BW</th>
<th>Noise</th>
<th>Max. $I_{DC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMOS</td>
<td>45MΩ</td>
<td>0.1pF</td>
<td>45MΩ</td>
<td>66MΩ</td>
<td>2MHz</td>
<td>3fA/sqrt(Hz)</td>
<td>10nA</td>
</tr>
<tr>
<td>Integrator different.</td>
<td>1GΩ</td>
<td>1pF</td>
<td>1GΩ</td>
<td>400MΩ</td>
<td>1MHz</td>
<td>7fA/sqrt(Hz)</td>
<td>10nA</td>
</tr>
<tr>
<td></td>
<td>1GΩ</td>
<td>10pF</td>
<td>1GΩ</td>
<td>40MΩ</td>
<td>1MHz</td>
<td>10fA/sqrt(Hz)</td>
<td>10nA</td>
</tr>
<tr>
<td></td>
<td>10MΩ</td>
<td>100pF</td>
<td>10MΩ</td>
<td>4MΩ</td>
<td>1MHz</td>
<td>70fA/sqrt(Hz)</td>
<td>1μA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10MHz</td>
<td>6pA/sqrt(Hz)</td>
<td>4mA</td>
</tr>
</tbody>
</table>

Standard transimpedance with $R_{feedback} = 1kΩ$

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Input Current Noise [A/Hz$^{1/2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td></td>
</tr>
<tr>
<td>1k</td>
<td></td>
</tr>
<tr>
<td>10k</td>
<td></td>
</tr>
<tr>
<td>100k</td>
<td></td>
</tr>
<tr>
<td>1M</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CMOS ($I_{DC} = 10nA$)

<table>
<thead>
<tr>
<th>Capacitance [fF]</th>
<th>Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1GΩ - 1pF ($I_{DC} = 5mA$)</td>
<td>764.51</td>
</tr>
<tr>
<td>100Ω - 100pF ($I_{DC} = 1μA$)</td>
<td>764.48</td>
</tr>
<tr>
<td>10MΩ - 100pF ($I_{DC} = 1μA$)</td>
<td>764.49</td>
</tr>
</tbody>
</table>

$A = 100mV, f = 24kHz, BW = 1Hz$
Galvanostatic Regulation

Set the current and measure the voltage:

wide bandwidth more difficult (transimp. amp. in the feedback)
A particular galvanostatic case: current set-point = 0
Measure the equilibrium potential of the interface

The loop must be stable
Multichannel Systems

Multiple working electrodes:
• to control the potential of different interfaces
• to address multi-electrode systems

Trade-off: parallel replication vs. multiplexing
• cost and size (routing, acquisition channels)
• input signal degradation
• scan time
Critical MUX Design

Channel addressing

- Use of single switches
- Minimize parastatics
- Bias disconnected electrodes
- Control the potential
- Reduced cross-talk (coupling)

No MUX
ADG1234
ADG333
ADG1434

Input-referred Noise \([A/\sqrt{Hz}]\)

Frequency \([Hz]\)
Practical critical issues for signal integrity:

- Shielding
- Long cables → stray capacitance
- Stirrer motor noise
Setup Miniaturization Trends

• From macro to **micro-electrodes**
• From static to **microfluidics**
  • precise manipulation of fluid samples
  • same size scale of biology
  • less reagent waste
  • faster reactions
  • miniaturization/portability

Lab-on-a-Chip!
Electronics Integrated with the Setup

Array of cell culture chambers
Multichannel Potentiostat
Control and analysis software
Acquisition unit
Microfluidics

24 Channels, 100kHz BW

M. Vergani et al. TBCAS 2012

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Example: 54 Channels

54 Channels, 8kHz BW
3pA resolution
Connectivity issues
Power issues: 3.8W

M. Vergani et al. BioCAS 2012
Example of Electrochemical Imaging

Tracking in real time the diffusion of the redox molecules:

M. Vergani et al. *BioCAS* 2012

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Moving to an **integrated circuit** allows:

- Miniaturization
- Parallelization (multichannel)
- Reduction of parasitics
Single-Chip CMOS Potentiostat

Single channel, **improving performance**: matched-mosfets

- 0-1MHz BW
- sub-pA
- sub-aF
- 120dB DR

![Circuit Diagram]

**Impedance Magnitude [Ω]**

**Frequency [Hz]**

**Impedance Magnitude [Ω]**

**Current [nA]**

**Potential vs. Ag/AgCl [V]**

- CPE: $Q = 10 \mu F/cm^2$
  - $n = 0.92$
Multichannel CMOS Potentiostat

100 nM complementary 30-mer average area change (N=46): -38%

F. Heer et al. ISSCC 2008
Commercial Single-Chip Potentiostat

General-purpose interface for electrochemical sensors
Electrochemistry on Chip

Challenges for using the chip PADs as electrodes:

Material issues:
- Packaging (world-to-chip)
- Pad metal: aluminum vs. gold
- Surface roughness and functionalization

System issues:
- Addressing and multiplexing
- On-chip vs. off-chip elaboration
Pseudo Reference Electrodes

What happens if the RE is not ideal:

- Potential shift
- Distortion

![Graph showing current vs. applied potential for different reference metals: Ag/AgCl, Ag, Au, Pt.](image)

REF METAL:
- Ag/AgCl
- Ag
- Au
- Pt

Current [µA]
Applied Potential vs. REF [V]

-40 -20 0 20 40
-0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6

Current [µA]
A suitable **package** should provide:

- Protection of the chip from the liquid
- Protection of the bonding wires (without breaking them)
- Patternable exposure of the electrodes to the liquid
- Long-term sealing for re-usable chips
- Connectors/interface with the rest of the system

A standard biochip packaging approach is still missing. Several artisanal solutions have been proposed. Industry need an automatable approach.
Packaging Approaches

A Simplest
For large chips, but Si area is expensive

B Rigid microfluidics
Sealing issues
Packaging Approaches

Cover with photo-patternable soft passivation

Sacrificial layer
Direct Sacrificial 3D Printing
Figures of Merit for Comparison

Table 1: Evaluation of the packaging methods that have been used for integrating CMOS chips with microfluidics. Each of the packaging methods in Fig. 7 is represented except for those not done using active chips or that remain theoretical. Entries were inferred or estimated (indicated by *) whenever possible from the available information if they were not given explicitly in the paper. (The ESI explains the methods by which the metrics were determined.) Codes: — = not reported, * = estimated, † = not estimated, BP = before packaging, BW/C = bond wire/chip height, F = flip-chip, H = high, L = low, NA = not applicable, TAB = tape automated bonding, TF = thin film, W = wire-bonded

<table>
<thead>
<tr>
<th>References</th>
<th>Type (Fig. 7)</th>
<th>Chip size (mm)</th>
<th>Bonding method</th>
<th>Sensor type</th>
<th>Fluid barrier material</th>
<th>Area efficiency*, η</th>
<th>Lifetime (days)</th>
<th>Barrier distance (μm)*</th>
<th>Number of steps</th>
<th>Vertical step height, h (μm)</th>
<th>Post-processing possible?</th>
<th>Microfluidics integrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>A</td>
<td>Large e</td>
<td>W</td>
<td>Magnetic</td>
<td>PDMS/plastic</td>
<td>L</td>
<td>≥10</td>
<td>≤100</td>
<td>≥4*</td>
<td>H</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>29</td>
<td>B</td>
<td>5 × 47</td>
<td>W</td>
<td>Optical</td>
<td>SiO2</td>
<td>H</td>
<td>—</td>
<td>≥500</td>
<td>≥9</td>
<td>NA</td>
<td>BP</td>
<td>Y</td>
</tr>
<tr>
<td>34</td>
<td>C</td>
<td>—</td>
<td>W</td>
<td>ISFET</td>
<td>Parylene</td>
<td>H</td>
<td>H*</td>
<td>&lt;100</td>
<td>4*</td>
<td>300*</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>5</td>
<td>D</td>
<td>4.4 × 4.4</td>
<td>W</td>
<td>Electrical</td>
<td>Epoxy &amp; PDMS</td>
<td>L</td>
<td>≥28</td>
<td>&gt;1000</td>
<td>≥6*</td>
<td>H</td>
<td>BP</td>
<td>N</td>
</tr>
<tr>
<td>25</td>
<td>D</td>
<td>6.5 × 6.5</td>
<td>W</td>
<td>Electrical</td>
<td>Epoxy &amp; PDMS</td>
<td>L</td>
<td>≥56</td>
<td>&gt;1000</td>
<td>≥6*</td>
<td>H</td>
<td>BP</td>
<td>N</td>
</tr>
<tr>
<td>41</td>
<td>D</td>
<td>3 × 3</td>
<td>W</td>
<td>Electrochemical</td>
<td>Parylene</td>
<td>H</td>
<td>H*</td>
<td>—</td>
<td>≥6*</td>
<td>BW/C</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>40</td>
<td>D</td>
<td>3.2 × 3.2</td>
<td>W</td>
<td>Electrical</td>
<td>Silastic 9161 RTV</td>
<td>H</td>
<td>≥14</td>
<td>≥200</td>
<td>≥8*</td>
<td>H</td>
<td>BP</td>
<td>Y</td>
</tr>
<tr>
<td>40</td>
<td>D</td>
<td>3.2 × 3.2</td>
<td>W</td>
<td>Electrical</td>
<td>Hysol CB064</td>
<td>H</td>
<td>≥14</td>
<td>≥200</td>
<td>≥8*</td>
<td>H</td>
<td>BP</td>
<td>Y</td>
</tr>
<tr>
<td>50</td>
<td>D</td>
<td>5.2 × 6.5</td>
<td>W</td>
<td>Electrical</td>
<td>Epoxy</td>
<td>L</td>
<td>≥1</td>
<td>≥1000</td>
<td>≥4*</td>
<td>H</td>
<td>BP</td>
<td>N</td>
</tr>
<tr>
<td>12</td>
<td>E</td>
<td>2 × 2</td>
<td>W</td>
<td>Magnetic &amp; temperature</td>
<td>SU-8</td>
<td>L</td>
<td>—</td>
<td>&gt;1000</td>
<td>≥6*</td>
<td>Low*</td>
<td>Y</td>
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<td>E</td>
<td>1 × 2.4</td>
<td>W</td>
<td>Optical</td>
<td>Epoxy &amp; PDMS</td>
<td>H</td>
<td>L*</td>
<td>≥100</td>
<td>≥4*</td>
<td>BW/C</td>
<td>N</td>
<td>Y</td>
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<td>Capacitive</td>
<td>Epoxy</td>
<td>L</td>
<td>—</td>
<td>NA</td>
<td>≥5*</td>
<td>BW/C</td>
<td>N</td>
<td>Y</td>
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<td>E</td>
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<td>W</td>
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<td>Polyimide</td>
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<td>≥1000</td>
<td>≥7</td>
<td>BW/C</td>
<td>N</td>
<td>Y</td>
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<td>≥6</td>
<td>BW/C</td>
<td>N</td>
<td>Y</td>
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Multichannel Bipotentiostat Integrated With a Microfluidic Platform for Electrochemical Real-Time Monitoring of Cell Cultures

Marco Vergani, Marco Carminati, Member, IEEE, Giorgio Ferrari, Member, IEEE, Ettore Landini, Claudia Caviglia, Arto Heiskanen, Clément Comminges, Kinga Zór, David Sabourin, Martin Dufva, Maria Dimaki, Roberto Raiteri, Ulla Wollenberger, Jenny Emméus, and Marco Sampietro

Compact Potentiostat for Cellular Electrochemical Imaging with 54 Parallel Channels

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