Differential Cyclic Voltammetry - 
a Novel Technique for Selective and Simultaneous 
Detection using Redox Cycling Based Sensors

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Abstract — Redox cycling (RC) is an effect that is used to amplify 
electrochemical signals. However, traditional techniques such as 
cylic voltammetry (CV) do not provide clear insight for a 
mixture of multiple redox couples while RC is applied. Thus, we 
have developed a new measurement technique which delivers 
electrochemical spectra of all reversible redox couples present 
based on concentrations and standard potentials. This technique 
has been named differential cyclic voltammetry (DCV).

We have fabricated micrometer-sized interdigitated electrode 
(IDE) sensors to conduct DCV measurements in mixtures of 
1mM catechol and 4mM [Ru(NH3)6]Cl3. To simulate 
the electrochemical behavior of these sensors we have also 
developed a finite element model (FEM) in Comsol®. The 
experimental data corresponds to the calculated spectra 
obtained from simulations. Additionally, the measured spectra 
can be used to easily derive standard potentials and 
concentrations simultaneously and selectively.

I. INTRODUCTION

Redox cycling (RC) is an electrochemical detection 
method that can be utilized to determine redox active species 
in the presence of interfering compounds [1-5]. With this 
method it is even possible to achieve single molecule 
detection [6].

In most RC schemes a reversible redox couple is cycled 
between an oxidating and a reducing electrode. Each cycle 
between the two electrodes contributes to the measured 
current effectively amplifying the current in an 
(electro)chemical manner [7].

Most papers on RC make use of an interdigitated array 
electrode [8-22]. With such an electrode a RC amplification of 
up to ~65 times is reported in bulk [2]. An amplification of 
100 times is reported for IDEs used in nanochannels [23]. 
Zevenbergen et al. [24] fabricated a device with two parallel, 
nanometer-spaced electrodes which resulted in an even higher 
RC amplification factor of ~400 times.

Using the same electrode structure as Zevenbergen et al., 
Wolfrum et al. [5] report cyclic voltammetry (CV) where only 
265 molecules are involved. During scanning electrochemical 
microscopy (SECM) the so-called feedback mode uses the RC 
effect to amplify the current measured between a disk-shaped 
ultramicroelectrode and a (biased) substrate. Using this 
method Fan and Bard [6] report the detection of single 
molecule activity.

It is feasible to achieve selective detection using RC since 
only the current of cycling species is amplified. For example, 
it is shown that small amounts of catechol can be detected in 
presence of interfering species such as ascorbic acid [5]. Both 
ascorbic acid and catechol are oxidized easily; however only 
catechol forms a reversible redox couple with quinone. 
Therefore, only the current measured from catechol 
conversion is amplified by RC. Also, it is possible to obtain 
selective detection in a mixture of multiple reversible couples, 
if e.g. ferrocyanide and dopamine are both present in solution 
[1, 2]. The key issue in the latter case is to apply appropriate 
potentials to both electrodes such that only dopamine is 
subjected to RC.

In publications reported so far one electrode is usually set 
to a fixed potential while the potential of the other electrode is 
controlled using CV. Data obtained this way is often not as 
conclusive as desired, since it is difficult to obtain direct 
information on the concentrations of the species present.

In this contribution we present a novel technique which we 
have named differential cyclic voltammetry (DCV). DCV is 
based on RC, and delivers immediate information on all 
reversible redox species present within the solution. The 
resulting data resembles a differential pulse voltammogram 
(DPV) or the electrochemical equivalent of a mass 
spectrogram. On the x-axis (unit: volt) peaks indicate the 
standard potential of a reversible redox couple, whereas on the 
y-axis (unit: ampere) the concentration of this couple is 
indicated. Compared to DPV DCV has the added benefit of 
more selectivity and a simpler potential waveform. We have 
tested this new technique both theoretically and practically 
using a finite element model and IDE sensors.
II. THEORY

A. Governing equations

The basic governing equations used in the FEM model are the Nernst-Planck equation and the continuity equation. Diffusion is assumed as the only means of mass transport, which is valid if geometric dimensions are much larger than the Debye-length and sufficient excess supporting electrolyte is present. The resulting domain equation is as follows:

\[ \frac{\partial C_j}{\partial t} = D_j \nabla^2 C_j \]  

(1)

where \( C_j \) is the concentration (mol/m³) and \( D_j \) the diffusion coefficient (m²/s) of redox active species \( j \). For reversible redox reactions, the general chemical reaction is described by:

\[ O + z \cdot e^- \leftrightarrow R \]  

(2)

where \( z \) indicates the number of electrons involved during oxidation or reduction of a single electroactive species. The forward (\( k_f \), reduction) and backward (\( k_b \), oxidation) reaction rates (m/s) are described by the Butler-Volmer equations [7]:

\[ k_f = k_s \cdot \exp[-\alpha \cdot (E_{appl} - E^\circ) \cdot F/(R \cdot T)] \]  

(3)

\[ k_b = k_s \cdot \exp[(1-\alpha) \cdot (E_{appl} - E^\circ) \cdot F/(R \cdot T)] \]  

(4)

where \( k_s \) is the standard rate constant, \( \alpha \) the transfer coefficient, \( E^\circ \) the standard potential of the redox couple and \( E_{appl} \) the applied electrode potential. \( F \), \( R \), and \( T \) are the Faraday constant, the gas constant, and the temperature, respectively. For the second redox couple with a two electron transfer reaction it is assumed that one of the electrons transferred determines the overall reaction rate, thus \( z \) is not included in equations 3 and 4 [7]. Values and units of all parameters are listed in table 1.

TABLE I. PARAMETERS USED IN THE FEM MODEL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>F – Faraday constant</td>
<td>96485</td>
<td>[C/mol]</td>
</tr>
<tr>
<td>R – Gas constant</td>
<td>8.31</td>
<td>[J/K]</td>
</tr>
<tr>
<td>T – Temperature</td>
<td>290</td>
<td>[K]</td>
</tr>
<tr>
<td>( D_{1O} ) – Diffusion coefficient, oxidized sp. 1 [25]</td>
<td>7.5E-10</td>
<td>[m²/s]</td>
</tr>
<tr>
<td>( D_{1R} ) – Diffusion coefficient, reduced sp. 1 [25]</td>
<td>7.5E-10</td>
<td>[m²/s]</td>
</tr>
<tr>
<td>( D_{2O} ) – Diffusion coefficient, oxidized sp. 2 [26]</td>
<td>7.6E-10</td>
<td>[m²/s]</td>
</tr>
<tr>
<td>( D_{2R} ) – Diffusion coefficient, reduced sp. 2 [26]</td>
<td>7.6E-10</td>
<td>[m²/s]</td>
</tr>
<tr>
<td>( C_{1O} ) – Bulk concentration, oxidized sp. 1</td>
<td>4</td>
<td>[mol/m³]</td>
</tr>
<tr>
<td>( C_{1R} ) – Bulk concentration, reduced sp. 1</td>
<td>0</td>
<td>[mol/m³]</td>
</tr>
<tr>
<td>( C_{2O} ) – Bulk concentration, oxidized sp. 2</td>
<td>1</td>
<td>[mol/m³]</td>
</tr>
<tr>
<td>( C_{2R} ) – Bulk concentration, reduced sp. 2</td>
<td>0</td>
<td>[mol/m³]</td>
</tr>
<tr>
<td>( k_{s1} ) – Rate constant, redox couple 1 [27]</td>
<td>5E-3</td>
<td>[m/s]</td>
</tr>
<tr>
<td>( k_{s2} ) – Rate constant, redox couple 2 [28]</td>
<td>4.6E-4</td>
<td>[m/s]</td>
</tr>
<tr>
<td>( E_1^\circ ) – Standard potential, redox couple 1 [25]</td>
<td>-0.16</td>
<td>[V]</td>
</tr>
<tr>
<td>( E_2^\circ ) – Standard potential, redox couple 2 [5]</td>
<td>0.2</td>
<td>[V]</td>
</tr>
<tr>
<td>( v ) – Scan rate</td>
<td>50</td>
<td>[mV/s]</td>
</tr>
<tr>
<td>( z_1 ) – Number of electrons transferred per sp.1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>( z_2 ) – Number of electrons transferred per sp.2</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Two reversible redox couples (sp.1 and sp.2) are used with standard potentials, diffusion coefficients, and rate constants matching Ru(NH₃)₆ and catechol respectively [5, 25, 26, 27, 28].

B. Geometric model

The geometric model is depicted in figure 1. To minimize computing time and required computing memory only one finger pair of the IDE sensor is simulated. This model simplification is valid if the number of fingers is large compared to the amount of fingers at the edge of the IDE structure. The vertical walls of the model are set to symmetrical boundary conditions as described by the following (zero flux) boundary condition:

\[ -D_j \nabla C_j = 0 \]  

(5)

Due to symmetry considerations, the electrodes are 2µm wide in the model which is equivalent to a finger width of 4µm in reality. The gap width between the two electrodes is equal to 4µm.

At a position far from the electrode surface concentrations are set to the initial bulk concentrations as listed in table 1. To ensure a real bulk situation this position is estimated by:

\[ y_{top} = \sqrt{(2 \cdot D_{max} \cdot t_{tot})} \]  

(6)

where \( y_{top} \) is the vertical distance between the electrodes and the bulk boundary condition, \( t_{tot} \) the total simulation time and \( D_{max} \) the fastest diffusion coefficient of all ions present. In this simulation the total simulated time was 66s, resulting in a
distance of 317µm between the bulk condition boundary and the electrodes.

C. Applied potentials

The key point for using DCV is the application of appropriate potentials to both electrodes. These potentials are illustrated in figure 2. The potential of one electrode is shown in red, and the potential waveform of the other electrode in blue. Between the two waveforms a fixed offset is maintained. The value of this offset is related to the peak width observed in the data obtained using DCV. The optimal offset for maximized resolution is related to the peak separation in conventional CV, which is [7]:

$$\Delta E_p = 2.2 \cdot R \cdot T / (z \cdot F)$$  \hspace{1cm} (7)

For a single electron transfer reaction at 25°C $\Delta E_p$ equals 57mV.

III. EXPERIMENTAL

A. Sensor fabrication

The IDE sensors are fabricated using conventional lithography and lift-off processes. A 550nm layer of lift-off resist (LOR5a, Microchem) and 1.7µm of positive resist (OIR 907/17, Fujifilm) is spun on a 500µm borofloat wafer followed by exposure and development for structure definition.

The electrodes are deposited by sputtering a 25nm titanium adhesion layer and a 500nm gold layer. Excess metal is removed by lift-off in acetone. Afterwards, the wafer is diced into individual chips of 2x5mm. For convenient handling the chips are glued to a printed circuit board (PCB) using Loctite® M-31CL™ Hysol®. Electrical connections from the PCB to the IDE sensor on the chip are made using a wirebonder (Westbond). Finally, an additional layer of Hysol is added to shield the contact pads and wirebonds from the solution.

The resulting sensor is depicted in figure 3. In the middle the entire sensor assembly is visible, in the upper left corner the individual chip and on the lower right corner a microscope image of the IDE sensor. Each individual finger is 557µm long and 4µm wide, with a 4µm gap in between. The total electrode height is 525nm, and the IDE sensor contains 20 finger pairs.

B. Chemicals

A solution of 4mM $[\text{Ru(NH}_3)_6\text{Cl}_3]$ and 1mM catechol in 100mM phosphate buffer ($\text{KH}_2\text{PO}_4/\text{K}_2\text{HPO}_4$, pH 7) is used for electrochemical measurements. The solution is purged with Ar for at least 15min prior DCV is conducted, and additionally kept under Ar atmosphere during experiments. All chemicals are obtained from Sigma-Aldrich.

C. Methods

All potentials reported here are measured versus a Ag/AgCl (saturated KCl) reference electrode (Radiometer Analytical), and a platinum counter electrode is utilized. For electrochemical measurements a bipotentiostat is used (Bio-Logic SAS). Each channel is programmed by using conventional CV, however with a fixed potential offset between the two channels. Both channels are started synchronously using standard options in the control software of the bipotentiostat.

IV. RESULTS AND DISCUSSION

A. FEM model results

The simulated results are shown in figure 4. The current contribution of the first redox couple ($sp_1$, $E^0=0.16V$, $C^*=4mM$) is indicated in red, and the current contribution of the second redox couple ($sp_2$, $E^0=0.2V$, $C^*=1mM$) in green. The total current is illustrated in blue. Note that due to the two dimensional nature of the FEM model the current has A/m as a unit. Two peaks are clearly visible at the position of the two standard potentials of both redox couples. The peak currents of the first and second couple are 10µA/m and 4.1µA/m, respectively, thus the ratio between both peak currents is 2.4.
The expected peak ratio is 2 since catechol has a 4 times lower concentration but a two times higher contribution to the current due to a two-electron transfer. The slightly different ratio is caused by the difference in rate constants between couple 1 and 2. The rate constants used for the simulations are aimed to be close to the actual rate constants of Ru(NH₃)₆ and catechol, which differ approximately by one order of magnitude as indicated in table 1.

B. Experimental results

In figure 5 the experimental result of a DCV measurement is shown. In this measurement two peaks can be observed at -0.17V and 0.19V corresponding to the standard potentials of [Ru(NH₃)₆]Cl₃ and catechol, respectively [5, 27]. The peak height is determined by compensating for the baseline drift using the red line illustrated in figure 5. Using this compensation the peak heights are determined to be 2.29µA and 0.54µA for the left and right peak, respectively. Therefore, the ratio between the peaks is 4.2.

C. Model and experimental agreement

Comparing the results from simulated and experimental data we observe that the ratio of peak heights is slightly different in both cases. We believe this to be caused by adsorption of catechol to the gold surface during the experiments. Also, if the results from the theoretical model are multiplied with the length and amount of finger pairs of the IDE sensor, the resulting peak heights become 2.28µA and 0.91µA. Especially the value of the Ru(NH₃)₆ is in fair agreement with experimentally obtained values.

V. CONCLUSION

We propose a novel electrochemical measurement technique based on redox cycling, which can be used for selective and simultaneous measurements in mixtures of multiple reversible redox couples. This technique which we have named DCV is based on recording two cyclic voltammograms with a small potential offset. CV is performed at two electrodes placed in close proximity for achievement of sufficient redox cycling amplification. Current amplification only occurs if one electrode is at a reducing potential while the other electrode is at an oxidizing potential for a specific reversible redox couple. As such, a strong increase in current is only observed if the potentials of both electrodes are surrounding the standard potential of a reversible redox couple. Therefore, the obtained data is comparable to the results obtained with differential pulse voltammetry (DPV). Compared to DPV, DCV has the added benefit of more selectivity even in the presence of high amounts of interfering non-reversible redox active species.

We have developed a finite element model to test this technique and compared theoretical with experimental results. The model and experimental results are in good agreement illustrating the usability of this novel technique. Using DCV we have determined standard potentials and concentrations in a mixture of 4mM [Ru(NH₃)₆]Cl₃ and 1mM catechol simultaneously.

Future work will be focused towards sensors showing higher redox cycling amplification and measurements in solutions containing high concentrations of interfering compounds like ascorbic acid.

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REFERENCES


