Simulation of Neurotransmitter Sensing by Cyclic Voltammetry under Mechanical Motion of a Neural Electrode

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NORFOLK STATE UNIVERSITY

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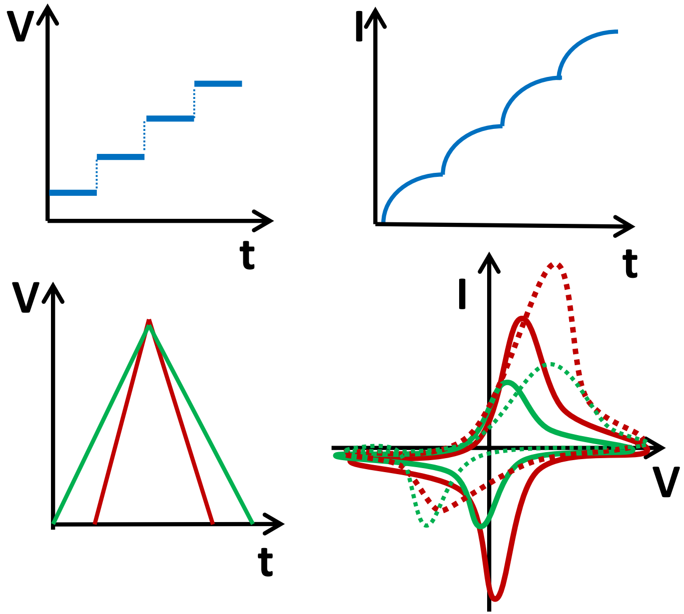
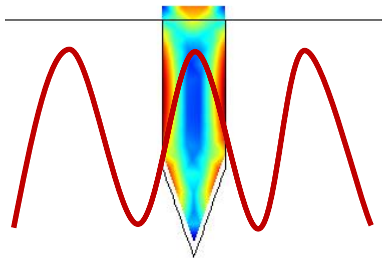
OLD DOMINION UNIVERSITY IDEA FUSION

Electrochemical sensing of neurotransmitters by applying voltage

Mechanical disturbance on neural electrode from motion while sensing



Form of applied voltages and resulting currents



Introduction

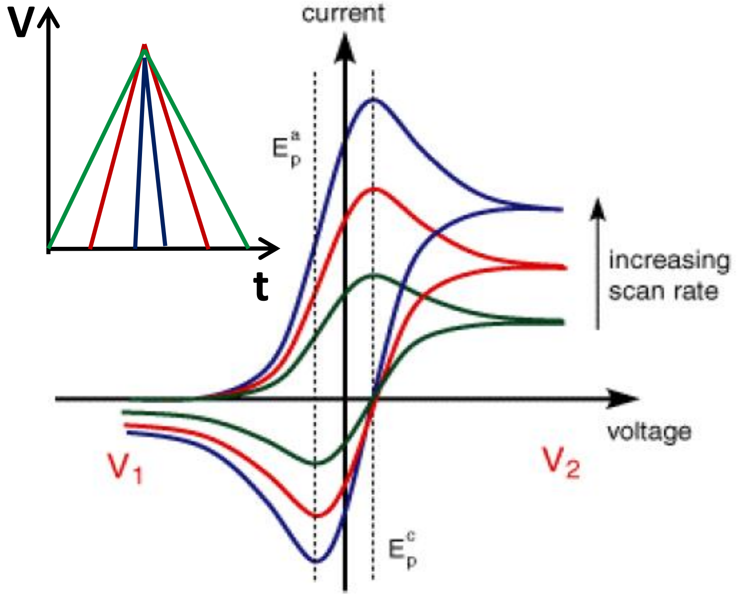
Problem statement

Electrical signals from neurotransmitters can be distorted or too noisy by motion of subject, which has a neural electrode in the brain.

- Movements from walking, breathing and pulsation make periodic motion.
  - Up to 25 µm, 1-2 Hz for breathing and 1-4 µm, 3-4 Hz for pulsation

- Electrode properties such as its material, geometry and interface will affect the quality of electrochemical signals from diffusion of neurotransmitters.
  - Chemical kinetics of electrode : form of applied voltage, double layer capacitance and the standard rate constant.
  - Mechanical conditions : stiffness of electrode and friction condition between brain and electrode

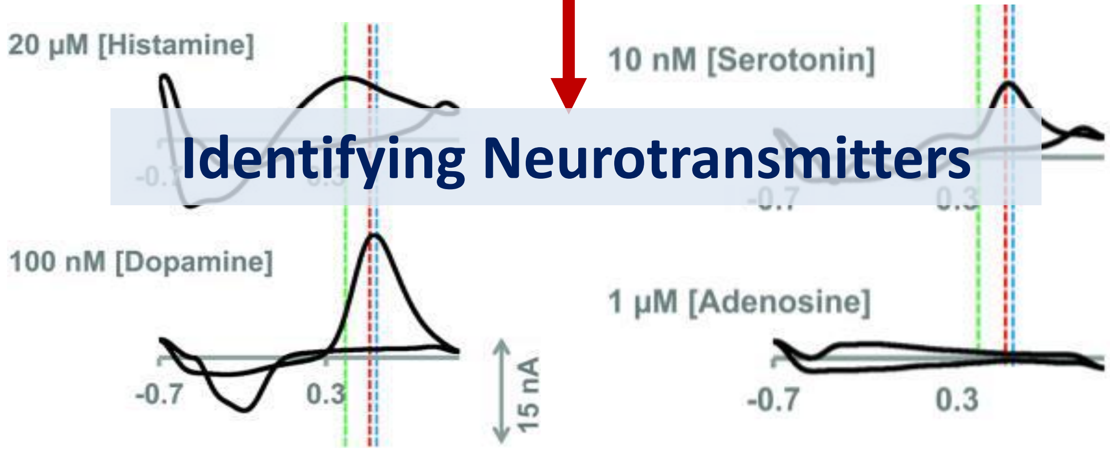
Neurotransmitter Sensing by Cyclic Voltammetry



Teaching note on department of chemical engineering and biotechnology in University of Cambridge

A variety of Graphs with different Peak potential(E_p^a, E_p^c) & current (I_p^a, I_p^c)

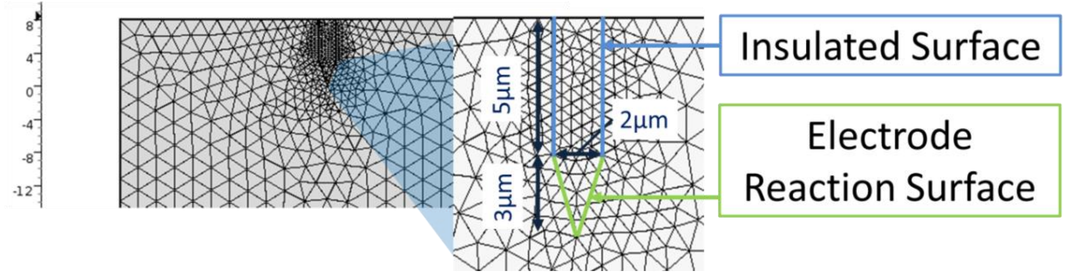
Identifying Neurotransmitters



In vivo histamine voltammetry in the mouse premammillary nucleus, Srimal Samaranayake, **Analyst**, 2015

Simulation Methods

A. 2D Geometry and Mesh



- Insulated surface is normally coated with parylene.
- Friction coefficient of reaction surface is affected by astro-glial sheath formation on electrode.

Table 1. Material Properties

Material	Young's Modulus (Pa)	Poisson's Ratio	Density (kg/m^3)
Polyimide [5]	2.8 x 10^9	0.33	1330
Brain [6]	15000	0.45	1050

- Polyimide is the representative material for flexible electrode.
- The brain was modeled using the Kelvin-Voigt viscoelastic material model with 12.5ms relaxation time.

Simulation Methods

B. Applied Physics

1) Diffusion and Transport

$$\frac{\partial c_i}{\partial t} + \nabla \cdot (-D_i \nabla c_i) = R_i \ , \ R_i = \frac{v_i i_{loc}}{nF}$$

< v_i : stoichiometric coefficient, n=number of electrons, F= Faraday constant>

2) Electrochemical analysis

$$i_{loc} = nFk_0 \left(c_{red} exp \frac{(n-\alpha_C)F\eta}{RT} - c_{ox} exp \frac{(-\alpha_C)F\eta}{RT} \right) (\eta = \phi_{s,ext} - E_{eq})$$

$$i_{dl} = (\frac{\partial \phi_s}{\partial t}) C_{dl}$$

< Butler-Volmer equation / double layer capacitance>

Electroanalysis module

3) Solid Mechanics

Electrode : $\rho \frac{\partial^2 \boldsymbol{u}}{\partial t^2} - \nabla \cdot \sigma = \boldsymbol{F}\nu$ (ν = poisson's ratio)

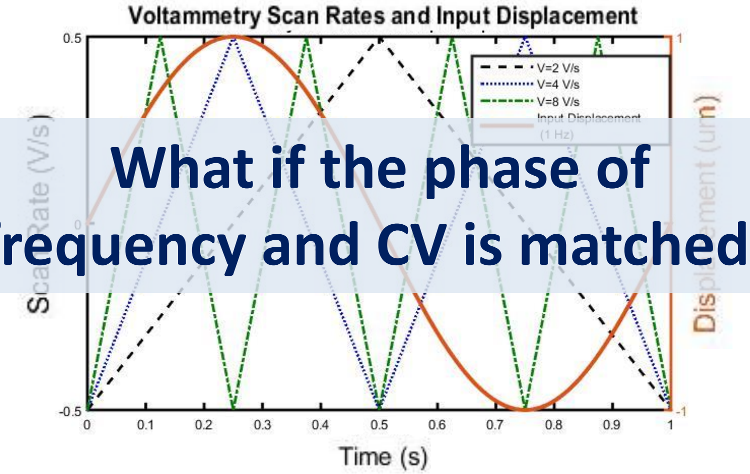
Brain : Kelvin-Voigt viscoelastic with a relaxation 12.5 ms time

Dynamics : 0.1Hz and 1Hz sinousodial motion of electrode

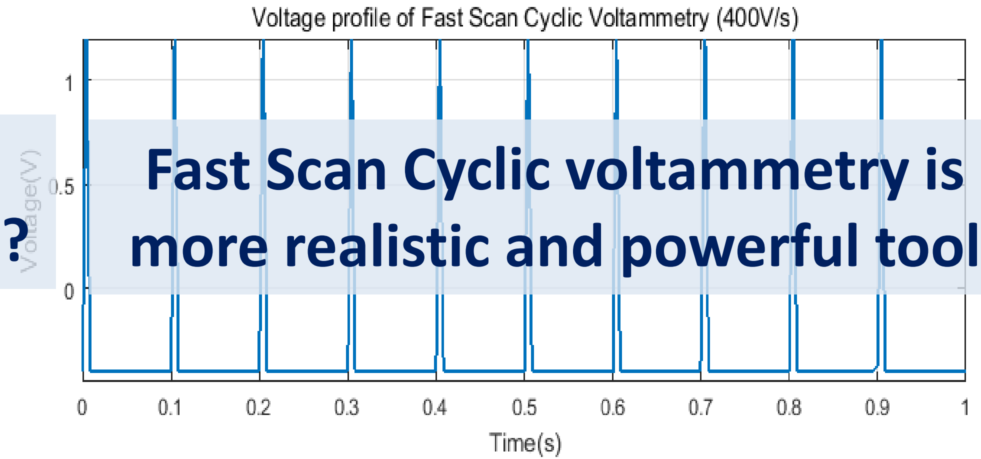
Structural module

Simulation Methods

C. Simulation Variables and Parameters (By using Parametric sweep option)



What if the phase of frequency and CV is matched?

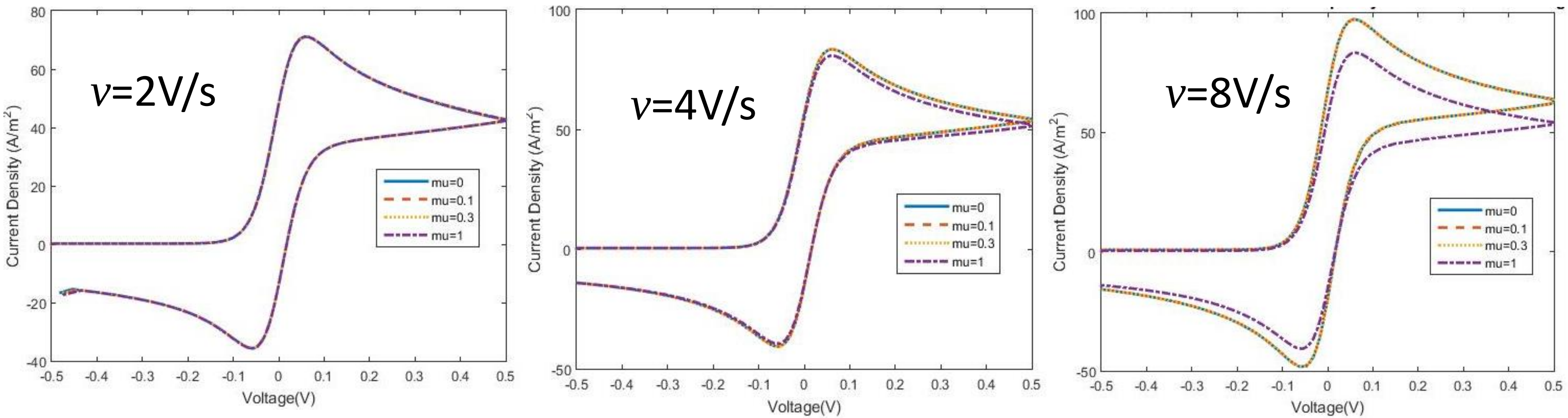


Fast Scan Cyclic voltammetry is more realistic and powerful tool

	Variables	Notation	Values(unit)
Electrochemistry	Double layer capacitance	C	0.01, 0.1(F/m^2)
	Scan rate	v	2, 4, 8 and **400** (V/s)
Dynamics	Amplitude	A	1(μm) sinusoidal
	Frequency	f	0.1, 1 (Hz)
	Friction coefficient	μ	0, 0.1, 0.3, 1

Result 1(a)

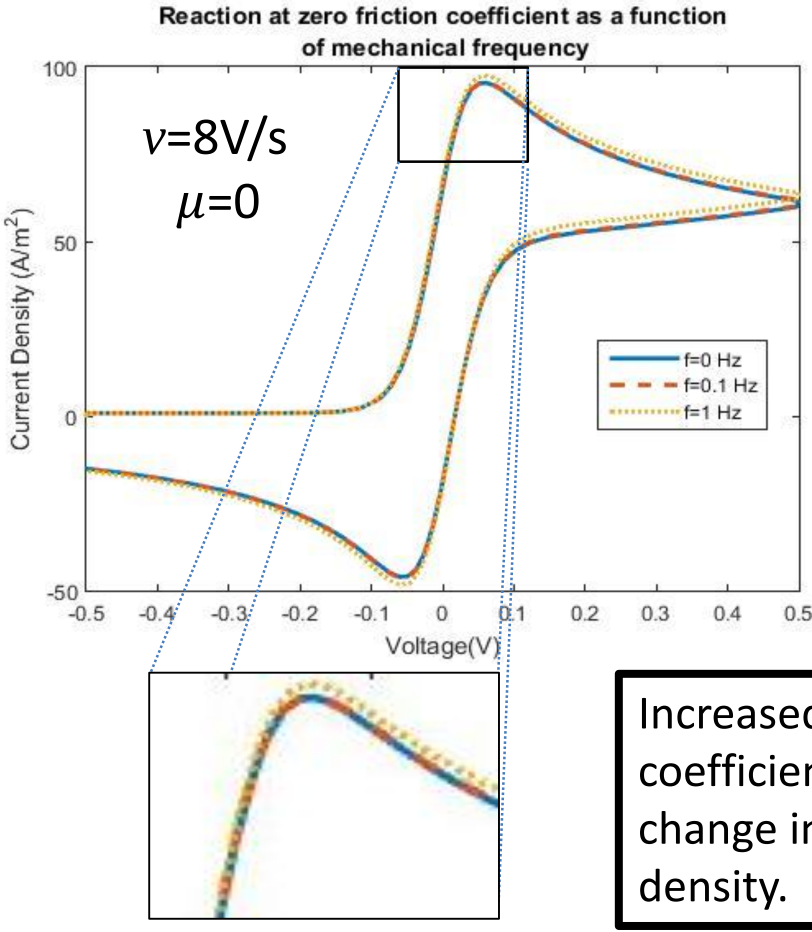
$$\mu = 0, 0.1, 0.3 \; and \; 1$$

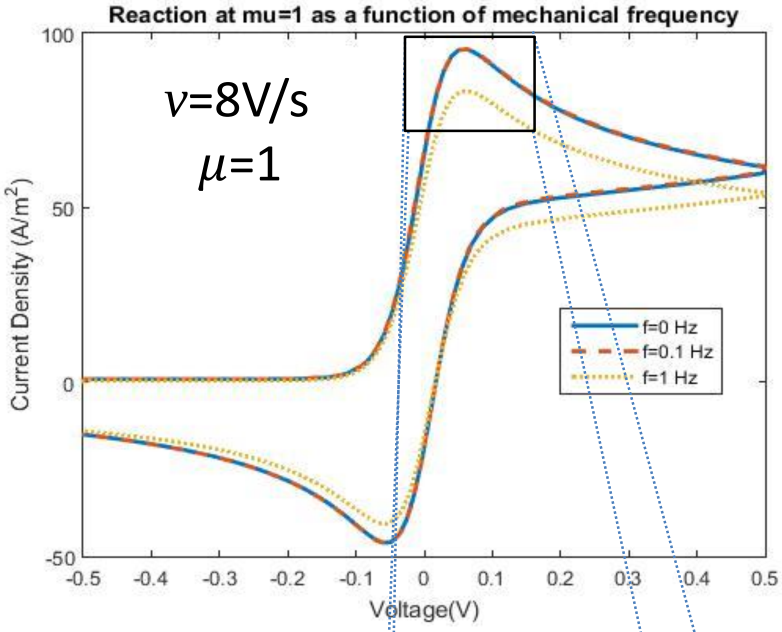


Scan rate magnifies the effect of motion.

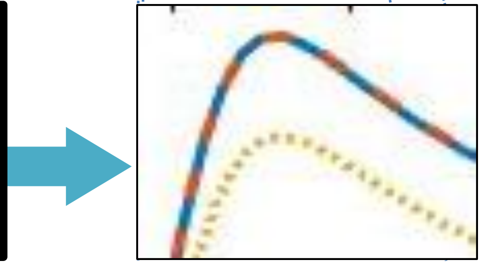
Result 1 (b)

$f = 0, 0.1 \; and \; 1 \; Hz$





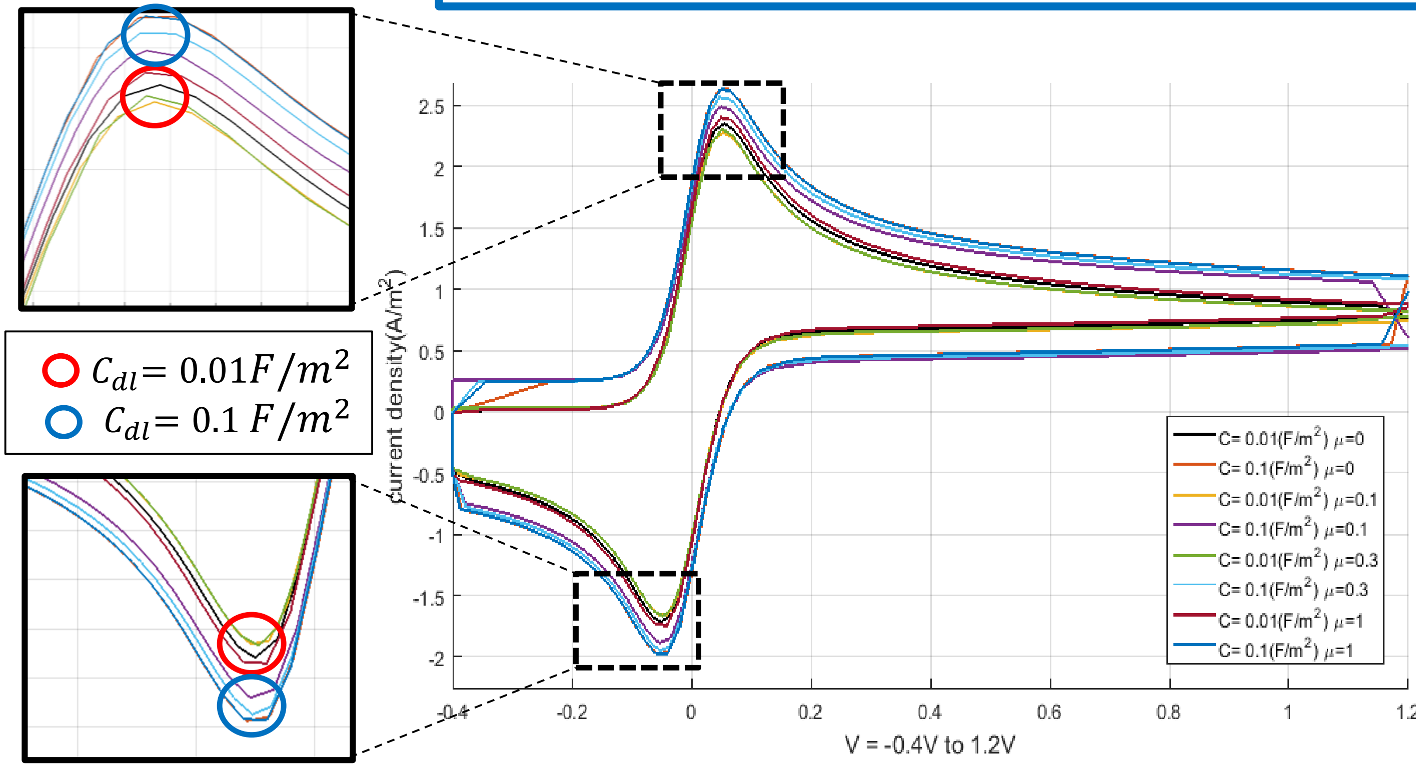
Increased friction coefficient makes large change in the current density.

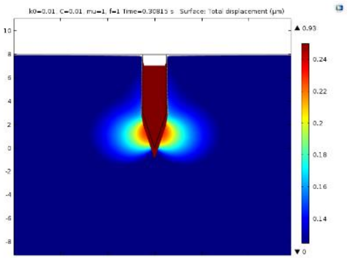


Result 2

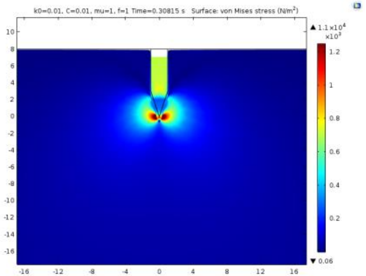
v=400V/s(Fast Scan CV) , f=1Hz

$\mu\ = 0, 0.1, 0.3\ and\ 1,\ C_{dl} = 0.01\ and\ 0.1\ F/m^2$

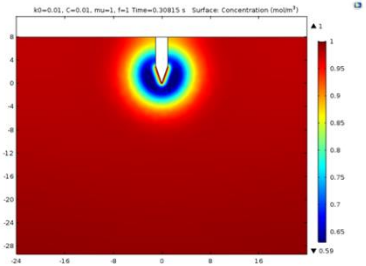




(a)Displacement



(b) Stress



(c) Concentration

Discussion & Conclusion

- The study provides understanding the implications in the brain's micromotion disturbance and analyzing neurochemical sensing signals depending on the condition of astro-glial sheath formation.
    - Astro-glial sheath formation can change mechanical bonding condition and double layer capacitance of the electrode-brain interface, and these conditions will affect the sensing quality.

- Increased scan rate also maximizes the effect of micromotion, and signal is less affected when the frequency is relatively smaller than scan rate.

- Regarding double layer, increased capacitance makes high current density difference, but the effect of capacitance tends to decrease when high mechanical friction coefficient is introduced.

References

1. J. Subbaroyan, D.C. Martin, D.R. Kipke "A finite-element model of the mechanical effects of implantable microelectrodes in the cerebral cortex," Journal of Neural Engineering, 2, pp.103-113, (2005).
2. A. Lavacchi, U. Bardi, C. Borri, S. Caporali, A. Fossati, I. Perissi, "Cyclic voltammetry simulation at microelectrode arrays with COMSOL Multiphysics^TM" Applied Electrochemistry, 39, pp. 2159-2163, (2009).
3. J.C. Patel. Voltammetry: Electrochemical Detection of Neurotransmitters in the Brain. S. John Wiley & Sons Ltd, Chichester, (2016).
4. A.J. Bard., L.R. Faulkner. Electrochemical Methods: Fundamentals and Applications. Wiley, New York, (2001).
5. A. Mercanzini, K. Cheung, D. Buhl, M. Boers, A. Maillard, P. Colin, J. Bensadoun, A. Bertsch, A. Carleton, P. Renaud. "Determination of cortical recording and reduced inflammatory response using flexible polymer neural probes," in *Proceedings of the IEEE MEMS Conference Kobe (Japan*), (2007).
6. Hyunjung Lee, Ravi V Bellamkonda, Wei Sun and Marc E Levenston, "Biomechanical analysis of silicon microelectrode-induced strain in the brain", *J. Neural Engineering*, 2 (2005) 81–89

Thank you!

Q & A