Principles of Electronic Nanobiosensors

Unit 3: Sensitivity

Lecture 3.9: Amperometric Sensors:

Beating the Diffusion Limit by Nanogap Amperometry

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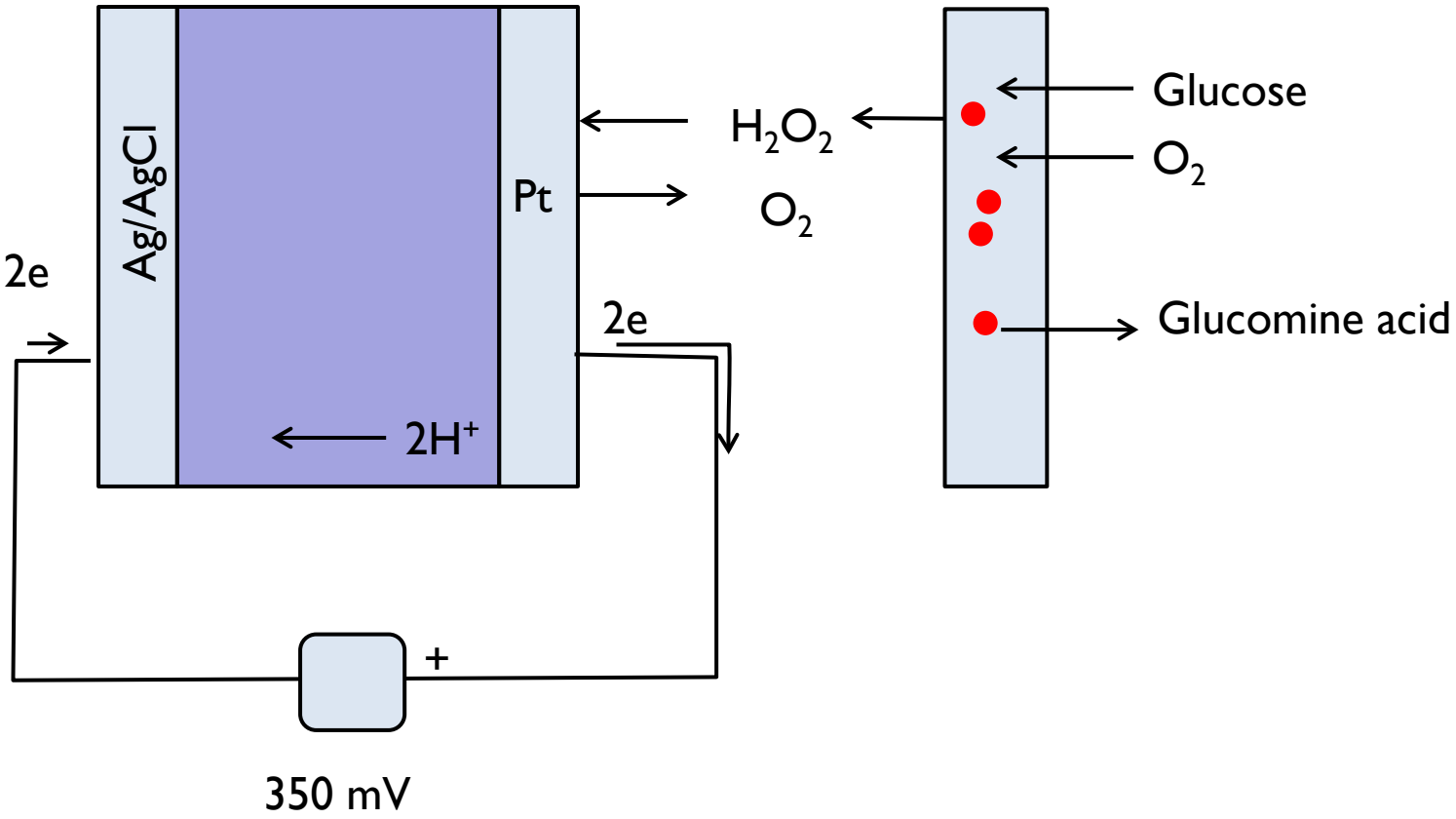
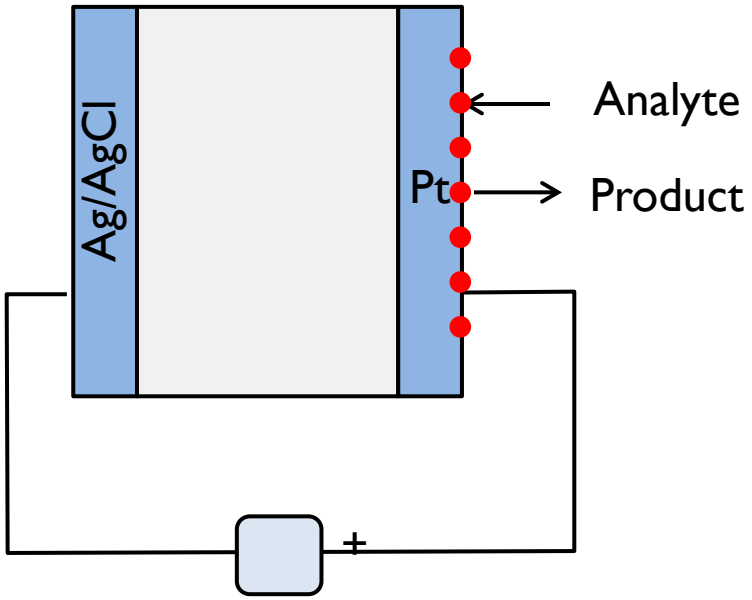
Outline

- Recall: Diffusion-limit of amperometric sensors
- Improving the limits by Nanogap amperometry
- DNA sensing by amperometric electrochemistry
- Conclusion

Glucose detection by amperometry



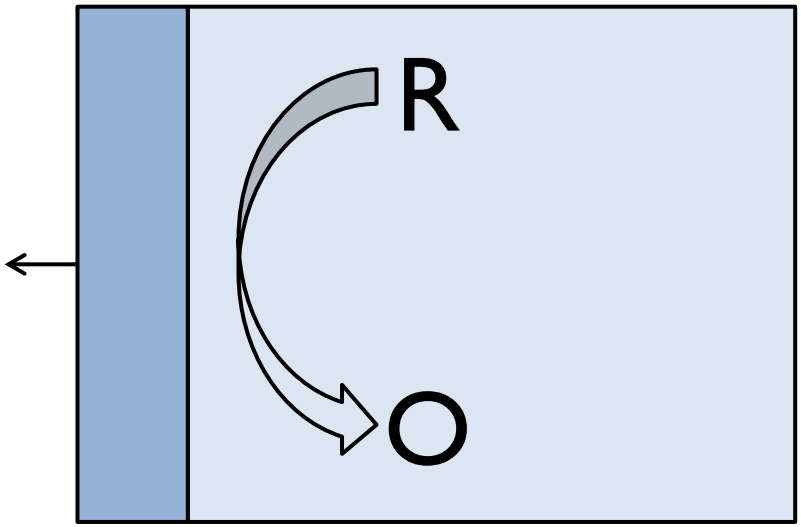
Essence of Amperometric Detection

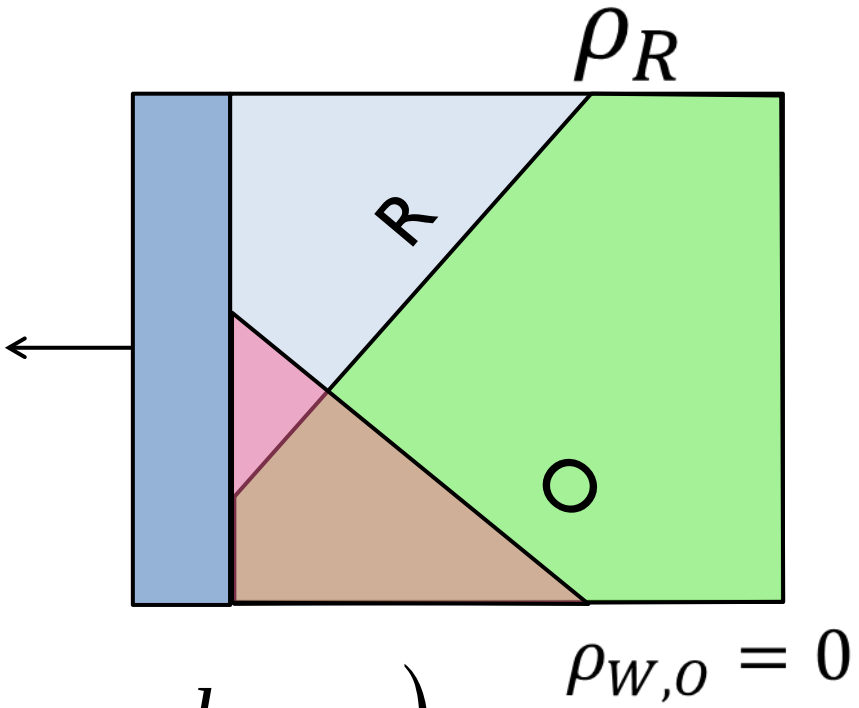


Assumed that analyte concentration is high,
So that there was no diffusion limit

Oxidation-Reaction with Diffusion

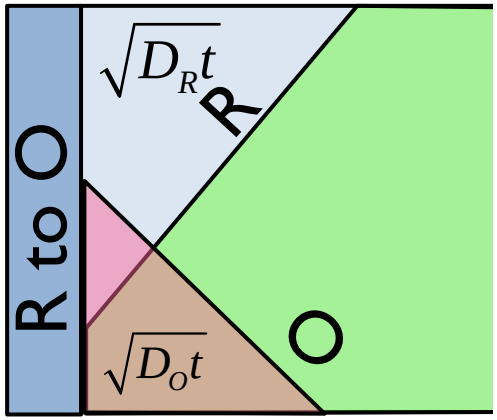
A reversible reaction at the WE electrodes is balanced by diffusion of reactants and products



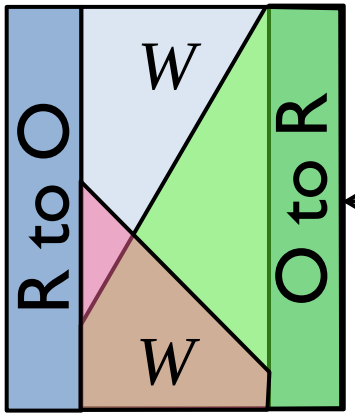


$$I = A_e q\left(k_f \rho_{s,R} - k_b \rho_{s,O}\right)$$

Beating diffusion limit by Redox Cycling

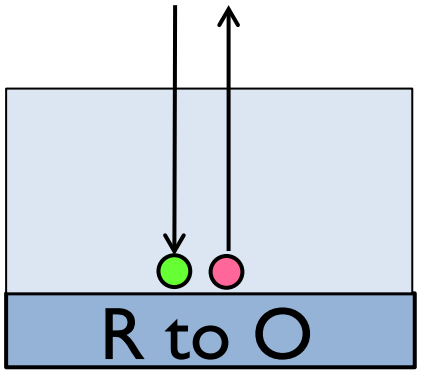


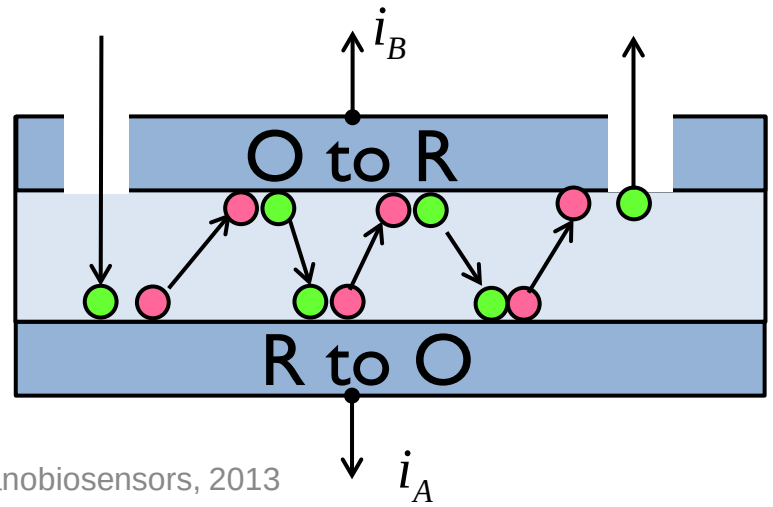
Recall plant-animal CO2 recyling



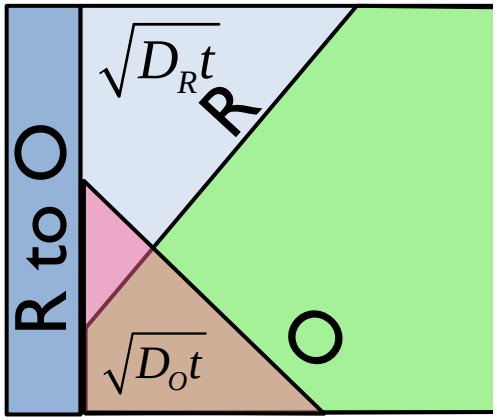
2nd WE recycles the current

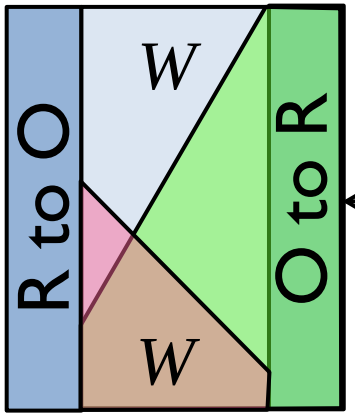
~50nm





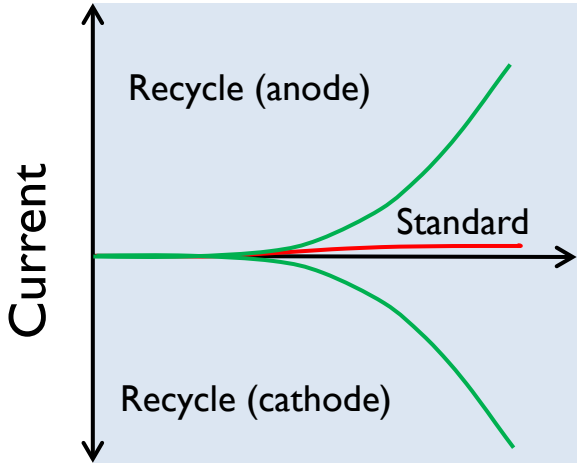
Beating diffusion limit by Redox Cycling





2nd WE recycles the current

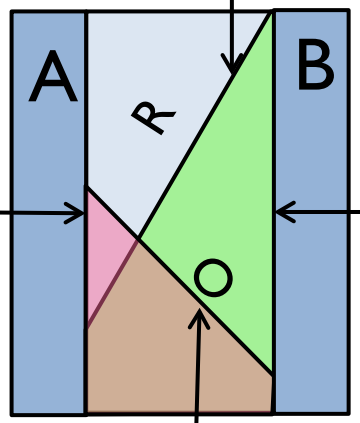
$i \sim \rho_{b,O} / \sqrt{D_O t}$



$i \sim \rho_{b,O} / W$

Balance the Flux, find the densities

$$i_R = qA_e D\left(\frac{\rho_{A,R} - \rho_{B,R}}{W}\right)$$



$$\frac{i_A}{qA_e} = k_0\rho_{A,R}e^{(1-\alpha)f\eta_A} - k_0\rho_{A,O}e^{-\alpha f\eta_A}$$

$$\frac{i_B}{qA_e} = k_0\rho_{B,R}e^{(1-\alpha)f\eta_B} - k_0\rho_{B,o}e^{-\alpha f\eta_B}$$

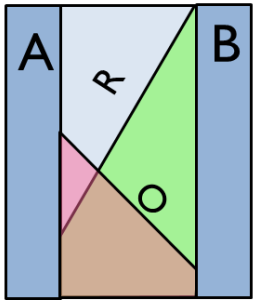
$$i_O = qA_e D\left(\frac{\rho_{A,O} - \rho_{B,O}}{W}\right)$$

$$i = i_A = i_B = i_O = -i_R$$

$$f \equiv F/RT$$
$$\eta_A = E_t - E_0$$
$$\eta_B = E_b - E_0$$

Flux recycling for Planar Electrodes: Power of nanoscale detection

$$i = i_A = i_B = i_O = -i_R$$



$$\frac{\rho_{A,o} + \rho_{B,o}}{2} + \frac{\rho_{A,R} + \rho_{B,R}}{2} = \bar{\rho}$$

$$i = \frac{i_{\lim}\left(\frac{e^{-f\eta_A}}{1+e^{-f\eta_A}} - \frac{e^{-f\eta_B}}{1+e^{-f\eta_B}}\right)}{1+\frac{D/W}{k_0}\left(\frac{e^{\alpha f\eta_A}}{1+e^{f\eta_A}} + \frac{e^{\alpha f\eta_B}}{1+e^{f\eta_B}}\right)}$$

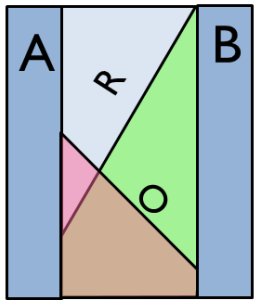
$$i_{\lim} = \frac{qA_e D\bar{\rho}}{W}$$

For relatively fast reaction, $i = i_{\max}$

Flux recycling: arbitrary electrode geometry

$$i_A = qC_{D,SS}\left(\rho_{A,R} - \rho_{B,R}\right)$$
$$i_B = qC_{D,SS}\left(\rho_{B,O} - \rho_{A,O}\right).$$

$C_{D,SS}$ Includes area



$$i = A_a qk_0\left(e^{(1-\alpha) f\eta_A}\rho_{A,R} - e^{-\alpha f\eta_A}\rho_{A,O}\right)$$
$$= -A_b qk_0\left(e^{(1-\alpha) f\eta_B}\rho_{B,R} - e^{-\alpha f\eta_B}\rho_{B,O}\right).$$

$$i = q\bar{\rho}C_{D,SS}\left(\frac{\dfrac{e^{-f\eta_B}}{1+e^{-f\eta_B}} - \dfrac{e^{-f\eta_A}}{1+e^{-f\eta_A}}}{1+\left(\dfrac{C_{D,SS}}{k_0}\right)\left(\dfrac{1}{A_a}\dfrac{e^{\alpha f\eta_A}}{1+e^{f\eta_A}} + \dfrac{1}{A_b}\dfrac{e^{\alpha f\eta_B}}{1+e^{f\eta_B}}\right)}\right).$$

A general formula for flux recycling

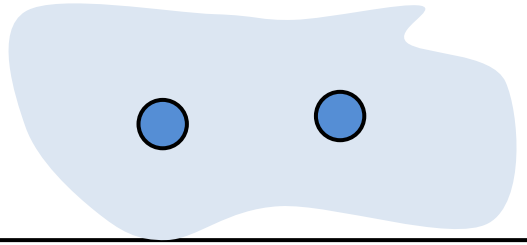
$$i = q\bar{\rho} C_{D,SS} \left(\frac{\dfrac{e^{-f\eta_A}}{1+e^{-f\eta_A}} - \dfrac{e^{-f\eta_B}}{1+e^{-f\eta_B}}}{1+\left(\dfrac{C_{D,SS}}{k_0}\right)\left(\dfrac{1}{A_a}\dfrac{e^{\alpha f\eta_A}}{1+e^{f\eta_A}} + \dfrac{1}{A_b}\dfrac{e^{\alpha f\eta_B}}{1+e^{f\eta_B}}\right)} \right).$$

Planar

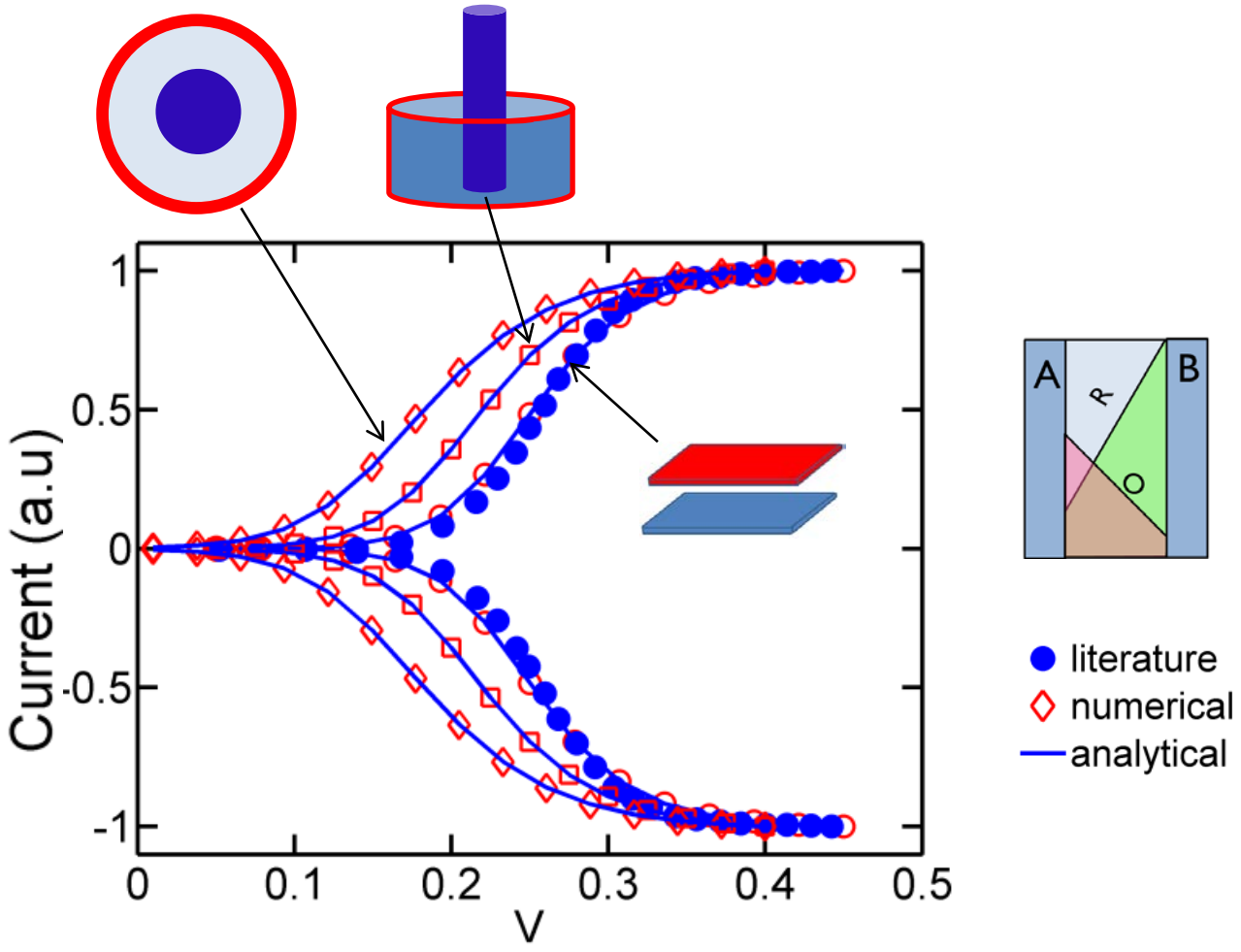
$$C_{D,SS} = A_e \frac{D}{W}$$

Pair of NWs

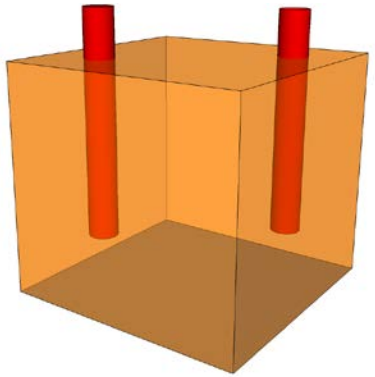
$$\frac{C_{D,SS}}{L_{NW}} = \pi D \left(\log\left(W/a_0 + \sqrt{\left(W/a_0\right)^2 - 1} \right) \right)^{-1},$$

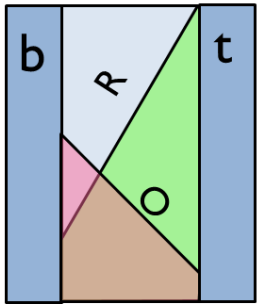


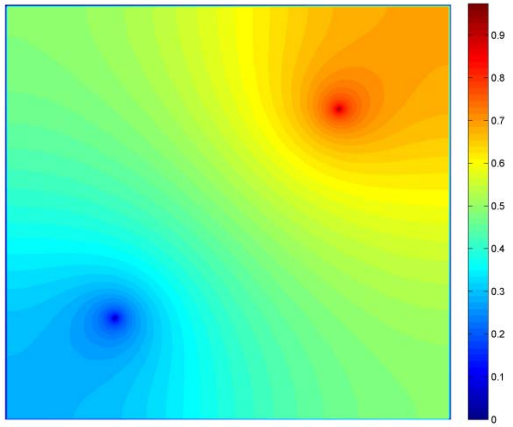
Finite gap Amperometry: Examples

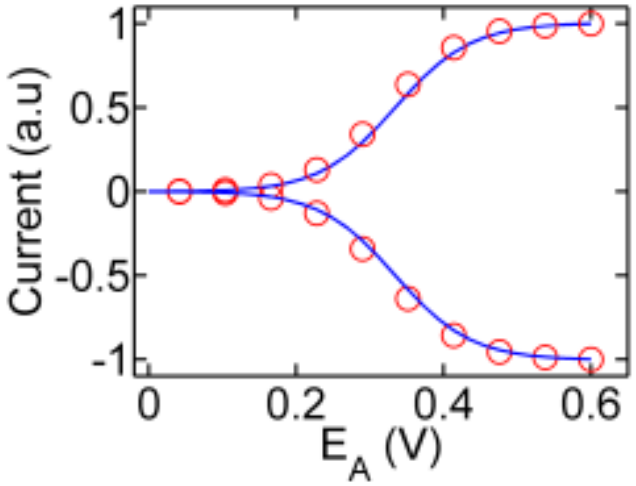


Finite gap Amperometry: Examples

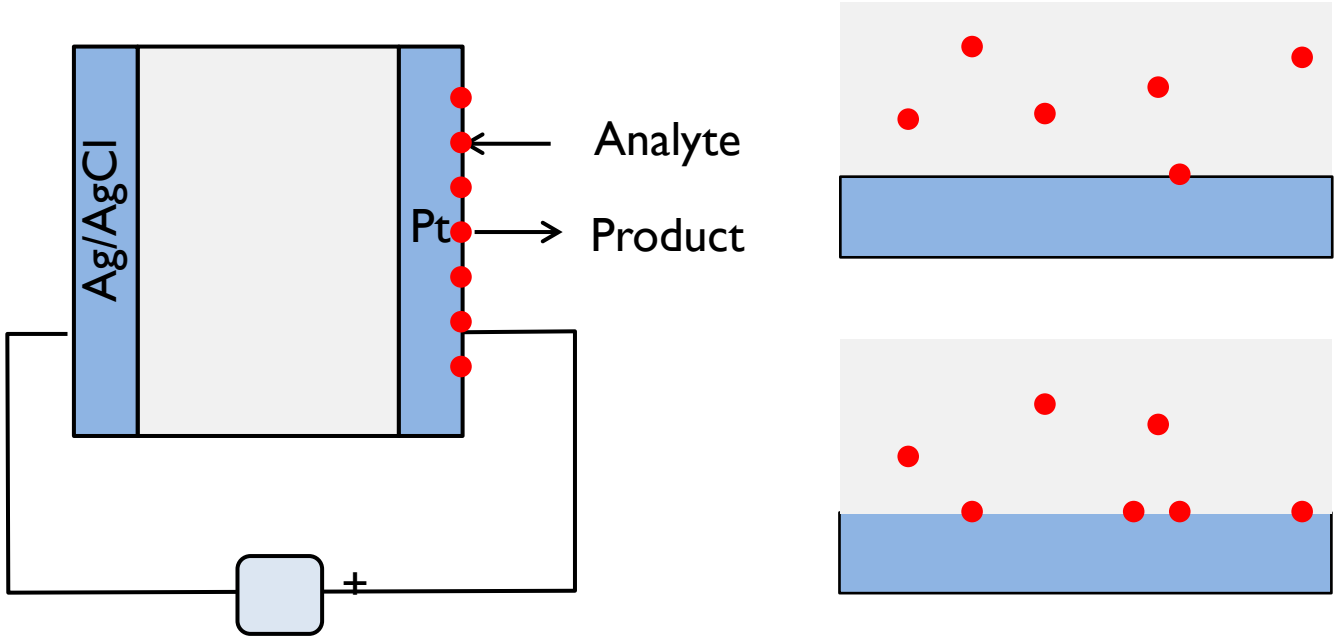






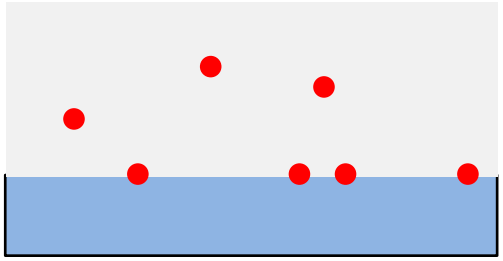


DNA Detection by Amperometry



In glucose sensors,: finite glucose, with abundant enzyme
In DNA sensors: finite enzyme, with abundant analyte

Amperometric DNA Detection



Concentration dependent

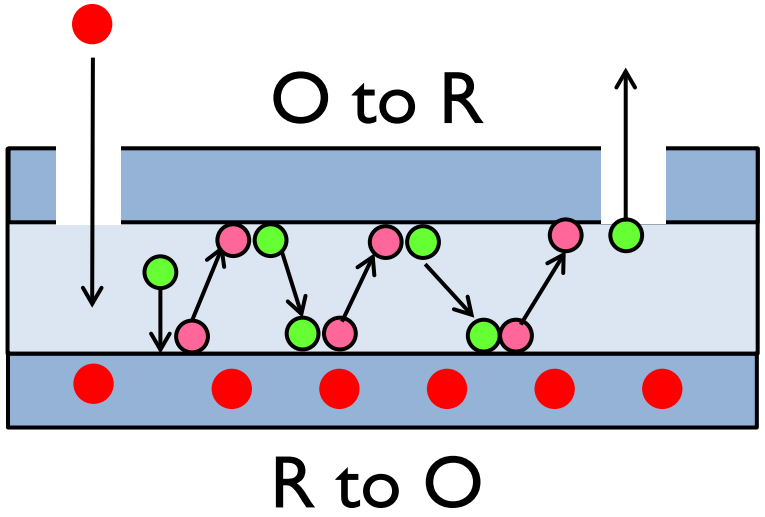
$$V_{\max} = k_{cat}[E]_0$$

$$\propto k_{DNA} N_{DNA} n_{bp}$$

$$\frac{1}{i_{ss}} = \left(\frac{k_M}{i_{\max}}\right)\frac{1}{S} + \frac{1}{i_{\max}}$$

$$i_{\max} \equiv qV_{\max}$$

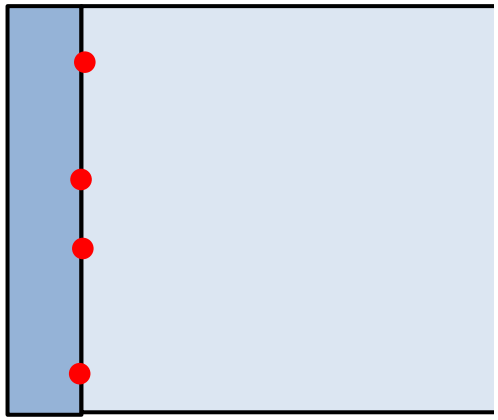
DNA detection by nanogap amperometry

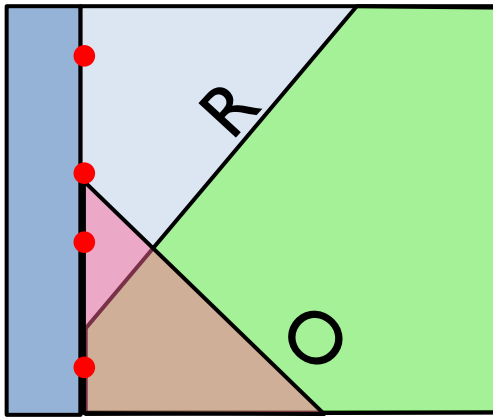


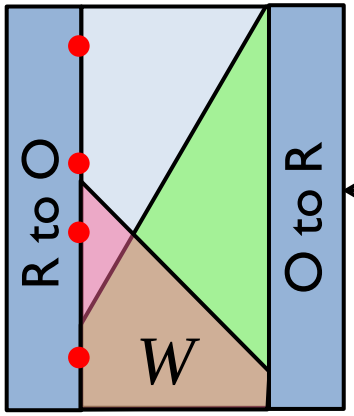
DNA enables cyclic reaction

DNA detection by nanogap amperometry

$$\frac{i_A}{qA_e} = k_0(\rho_{DNA})\left[\rho_{A,R}e^{(1-\alpha)f\eta_A} - \rho_{A,O}e^{-\alpha f\eta_A}\right]$$





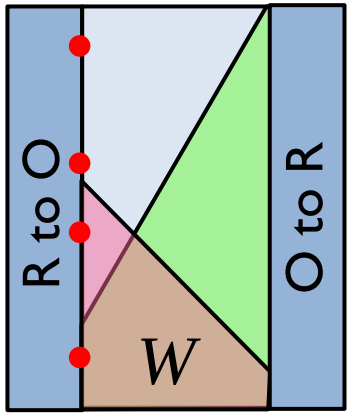


2nd WE recycles the current

DNA sequencing by nanogap amperometry

Steady state DNA concentration

$$N_{DNA} = \frac{k_M N_0 \rho_{DNA}}{1 + k_M \rho_{DNA}}.$$



$$i \propto q\bar{\rho} C_{D,SS} \left(\frac{e^{-\alpha\eta_B}}{e^{(1-\alpha)\eta_B} + e^{-\alpha\eta_B}} - \frac{e^{-\alpha\eta_A}}{e^{(1-\alpha)\eta_A} + e^{-\alpha\eta_A}} \right)$$
$$\times \left(1 + \left(\frac{C_{D,SS}}{k_0 \left(N_{DNA} \right)} \right) \left(\frac{A_a^{-1}}{e^{(1-\alpha)\eta_A} + e^{-\alpha\eta_A}} + \frac{A_b^{-1}}{e^{(1-\alpha)\eta_B} + e^{-\alpha\eta_B}} \right) \right)^{-1}$$

Conclusions

- An amperometric sensor can be a sensitive monitor of analyte density, such as DNA. Nanogap interdigitated sensors may approach pM sensitivity (subject to diffusion limit).

- The enzymic reaction provides built-in selectivity for the sensor. However, parasitic reactions continue to be a challenge.

References

- *Zevenbergen, Marcel AG, et al. "Fast electron-transfer kinetics probed in nanofluidic channels." Journal of the American Chemical Society 131.32 (2009): 11471-11477.*
- *Goluch, Edgar D., et al. "Redox cycling in nanofluidic channels using interdigitated electrodes." Analytical and bioanalytical chemistry 394.2 (2009): 447-456.*
- *Zhang, Yongchao, Hyug-Han Kim, and Adam Heller. "Enzyme-amplified amperometric detection of 3000 copies of DNA in a 10-μL droplet at 0.5 fM concentration." Analytical chemistry 75.13 (2003): 3267-3269.*
- *Seidel, Michael, and Reinhard Niessner. "Automated analytical microarrays: a critical review." Analytical and bioanalytical chemistry 391.5 (2008): 1521-1544.*