Simulation of the pH Sensing Capability of an Open-Gate GaN-based Transistor

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GATOR Engineering

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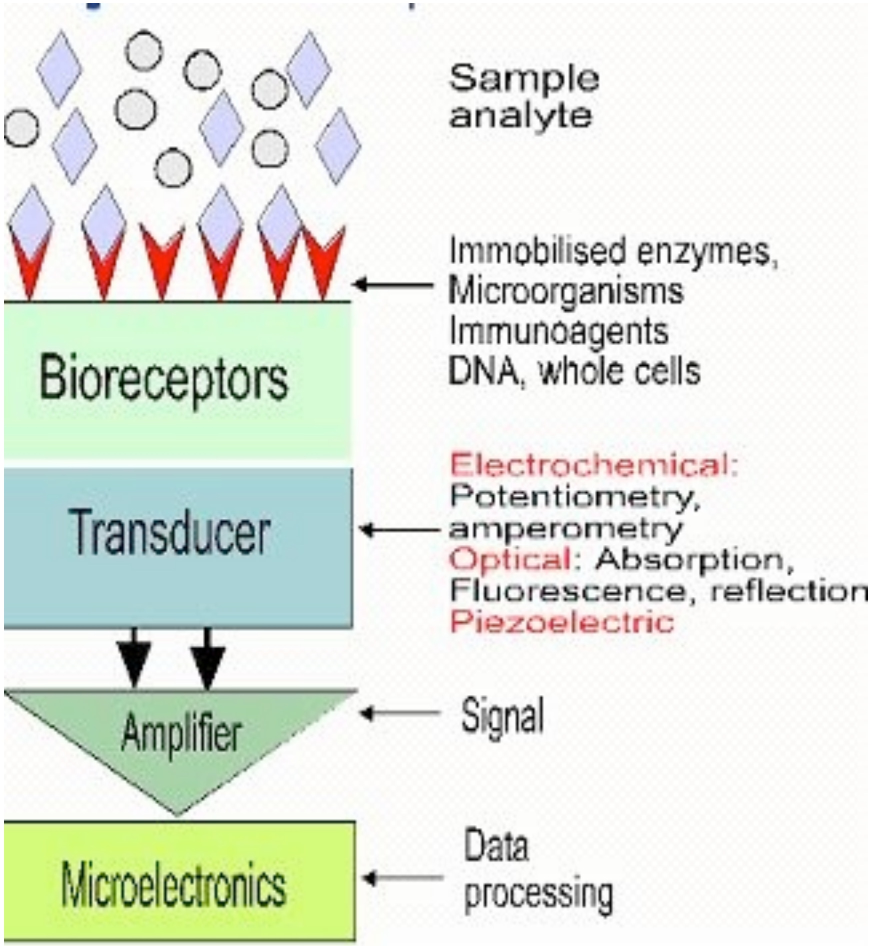
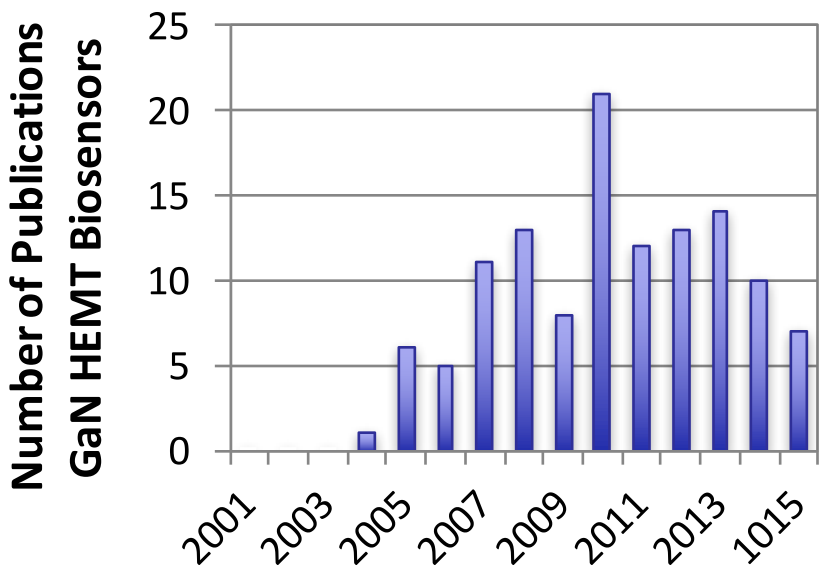
GaN HEMT Biosensor Technology



Source: bccResearch, Global Markets and Technologies for Sensors, Published: April 2013
bccResearch Report Code: IAS006E



- Mature experimental studies
- No existing commercial software package for this purpose
- Need for sensor optimization via simulation

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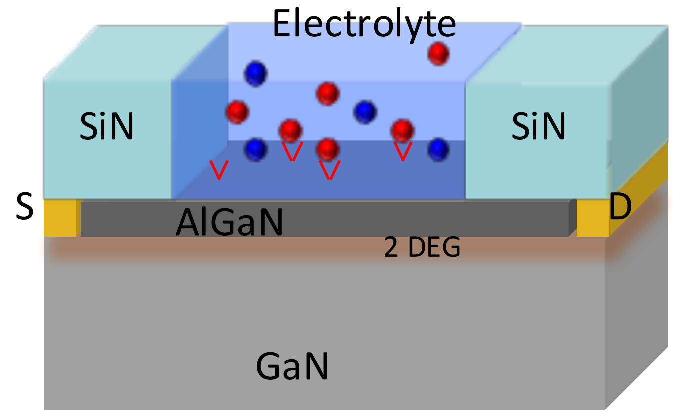
Approach

- Simulation of pH Sensor
- Using FLorida Object-Oriented Device Simulator (FLOODS)



Physics

Bulk Semiconductor	Contacts	Bulk Electrolyte	Electrolyte/Semiconductor Interface
Electron/hole transport Electrostatic potential Polarization charge	Source /Drain - Ohmic	Ion transport Electrostatic potential	Surface reactions Adsorbed molecular charge

Approach: Bulk Electrolyte

Conservation of Charge (Poisson Eq.)

$$\varepsilon \nabla^2 \psi = q([Na^+] - [Cl^-] + [H^+] - [A^-])$$

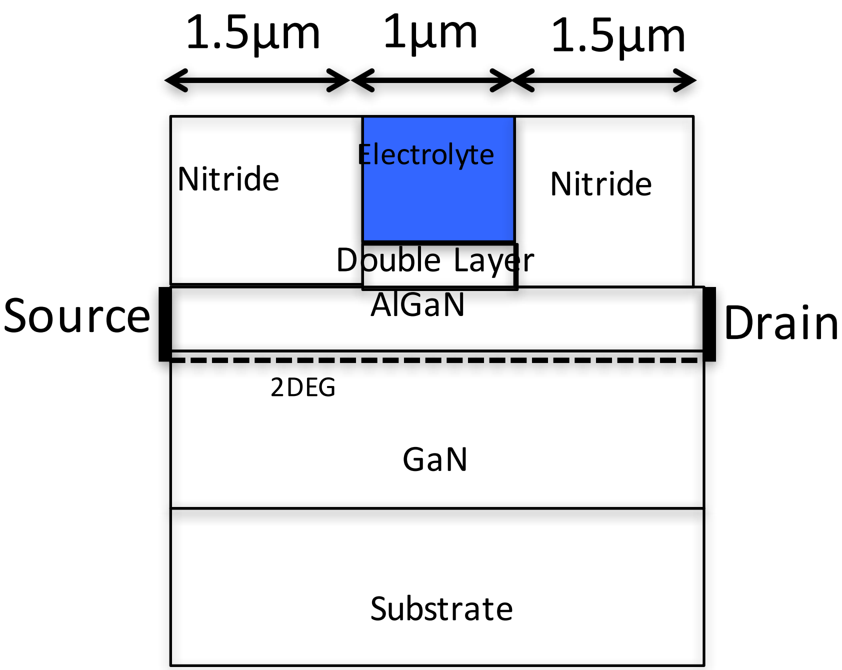
Mass Balance (Continuity Eq.)

$$\frac{d[Na^+]}{dt} = \nabla(q\mu_{Na^+}[Na^+]\nabla\psi + (D_{Na^+})\nabla[Na^+])$$

$$\frac{d[Cl^-]}{dt} = \nabla(-q\mu_{Cl^-}[Cl^-]\nabla\psi + (D_{Cl^-})\nabla[Cl^-])$$

$$\frac{d[H^+]}{dt} = \nabla(q\mu_{H^+}[H^+]\nabla\psi + (D_{H^+})\nabla[H^+])$$

$$\frac{d[A^-]}{dt} = \nabla(-q\mu_{A^-}[A^-]\nabla\psi + (D_{A^-})\nabla[A^-])$$



Approach: Bulk Semiconductor

Conservation of Charge (Poisson Eq.)

$$\varepsilon\nabla^2\psi = q(n - p + N_D - N_A)$$

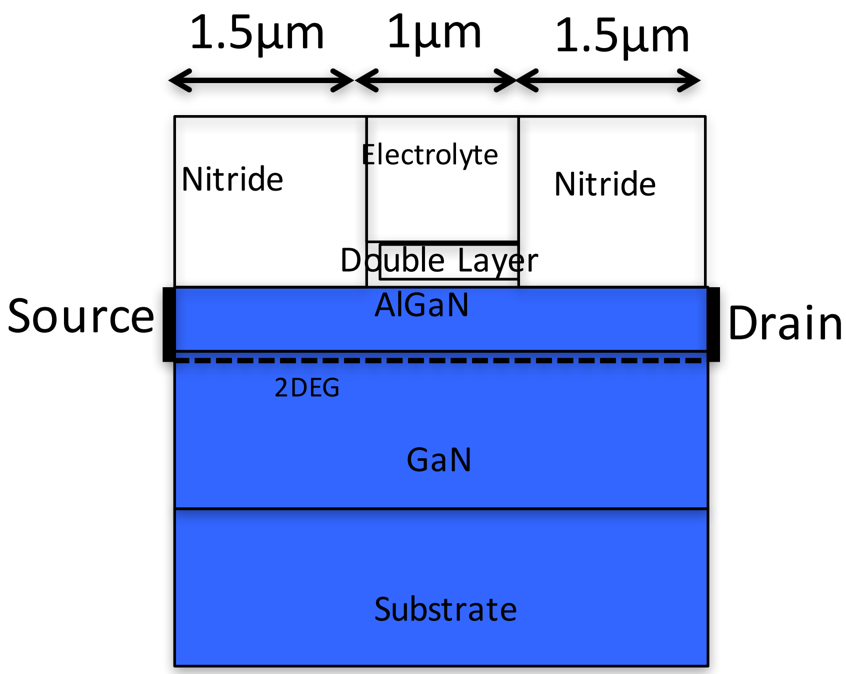
Mass Balance (Continuity Eq.)

$$\frac{dn}{dt} = -nq\mu_n\nabla^2\phi_{f_n}$$

$$\frac{dp}{dt} = pq\mu_p\nabla^2\phi_{f_p}$$

$$n = N_c e^{-(E_c - \phi_{fn})/V_t}$$

$$p = N_v e^{-(\phi_{fp} - E_v)/V_t}$$



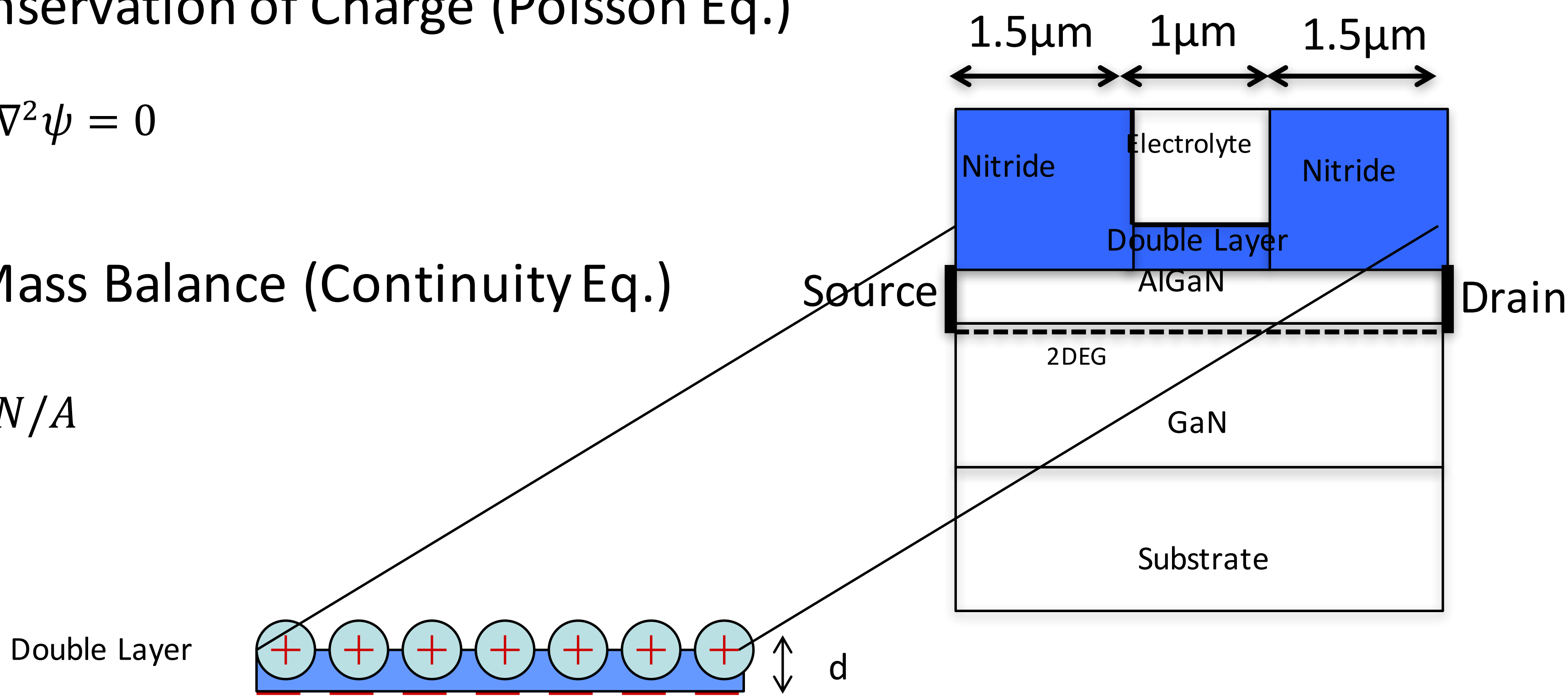
Approach: Double Layer / Oxide / Nitride

Conservation of Charge (Poisson Eq.)

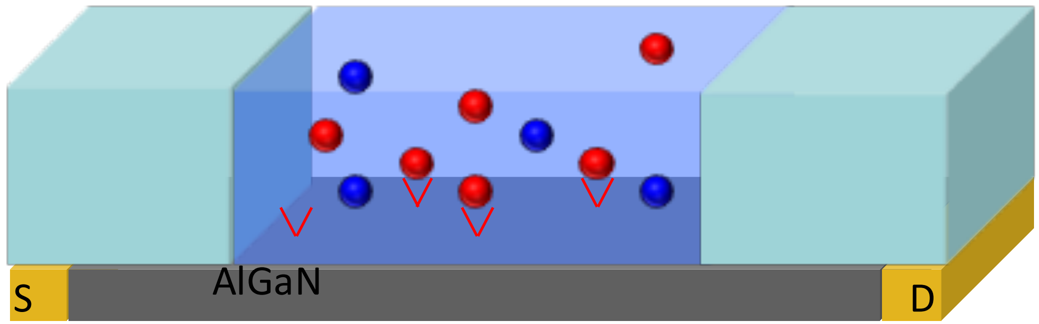
$$\varepsilon \nabla^2 \psi = 0$$

Mass Balance (Continuity Eq.)

$$N/A$$



Approach: Surface Adsorption



Site-binding Model
(oxide/electrolyte interface)

$$\frac{d[SOH_2^+]}{dt} = K_1(N_s - [H^+]) - K_2[H^+]$$

$$\frac{d[SO^-]}{dt} = K_3(N_s - [H^+]) - K_3[H^+]$$

$$[SO^-] = N_S - [SOH_2^+]$$

$$SOH_2^+ \rightleftharpoons SOH + H^+$$

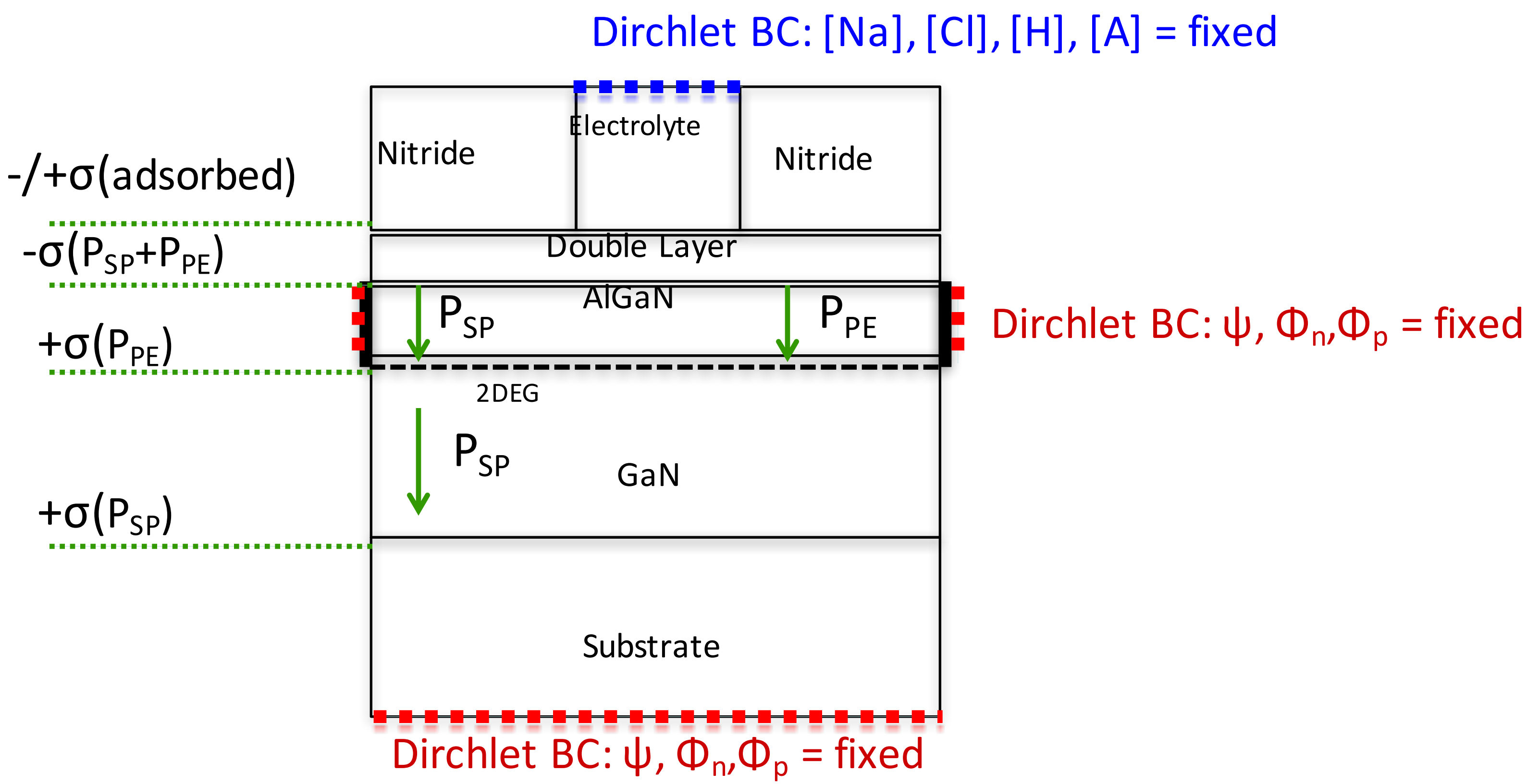
$$SOH \rightleftharpoons SO^- + H^+$$

∨ = neutral surface site

● = hydrogen ion

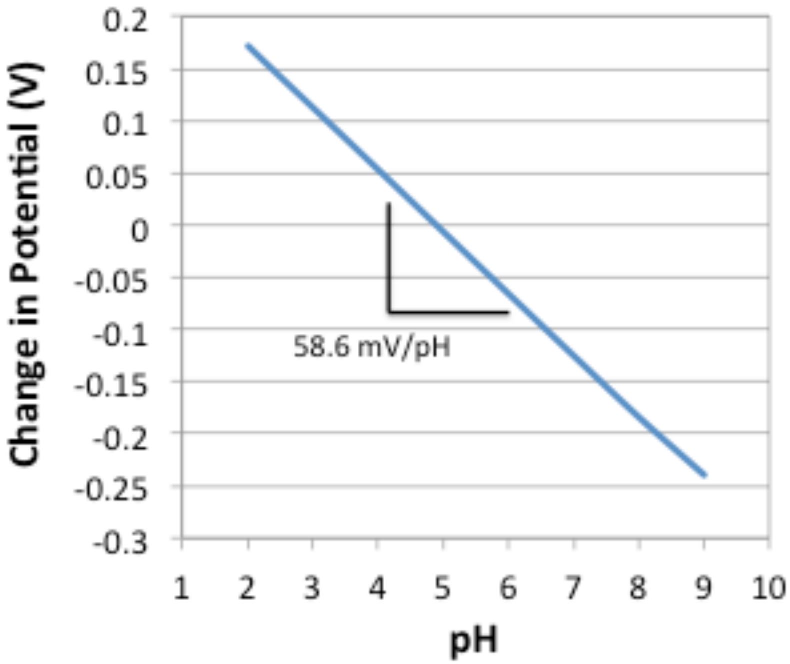
● = other ions

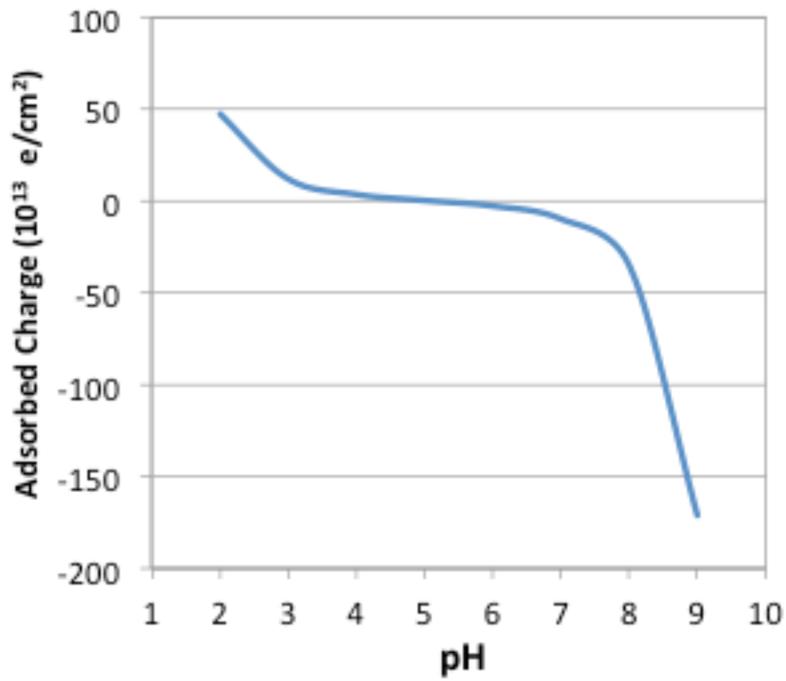
Boundary Conditions



pH Sensor Simulation Results

Double layer only, V_{ds}= 5 V

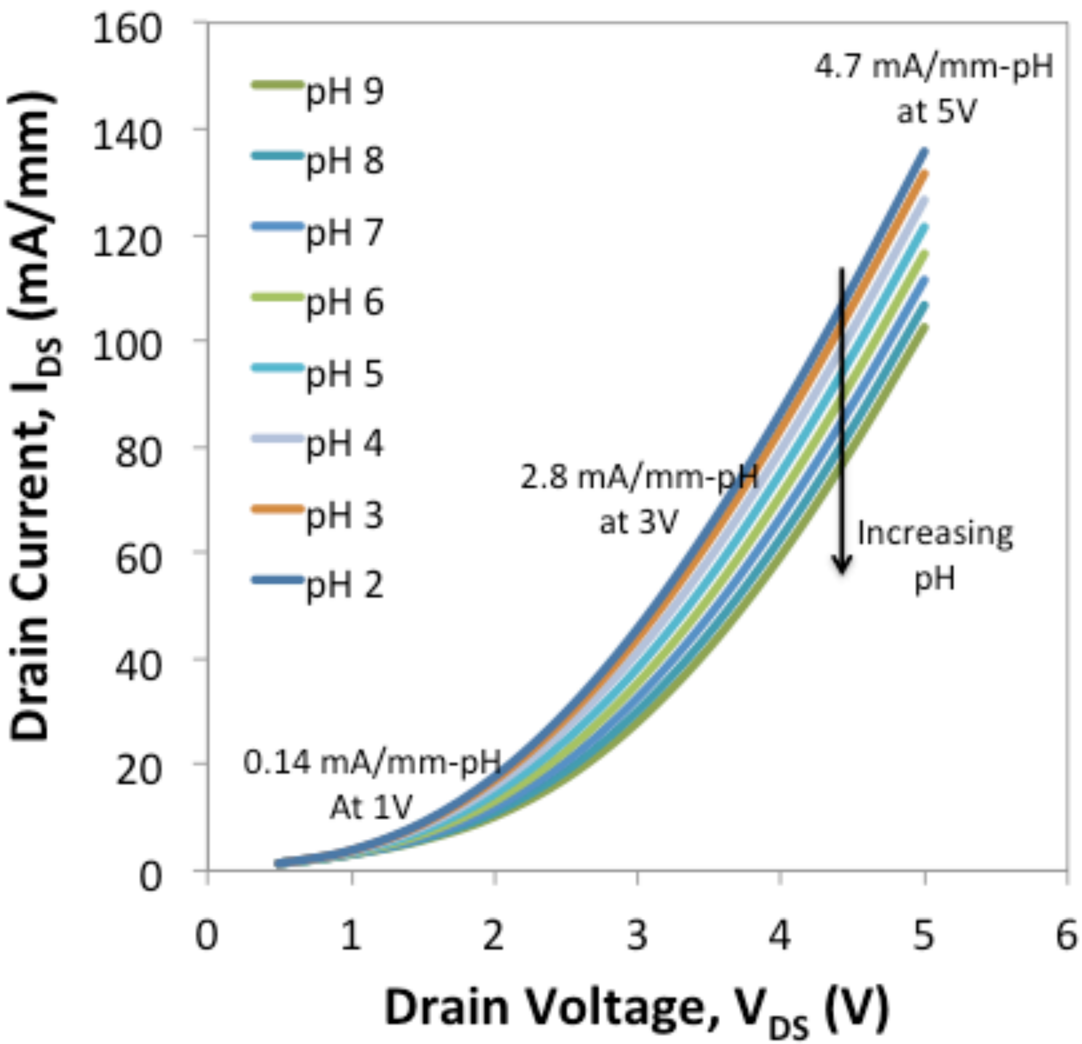




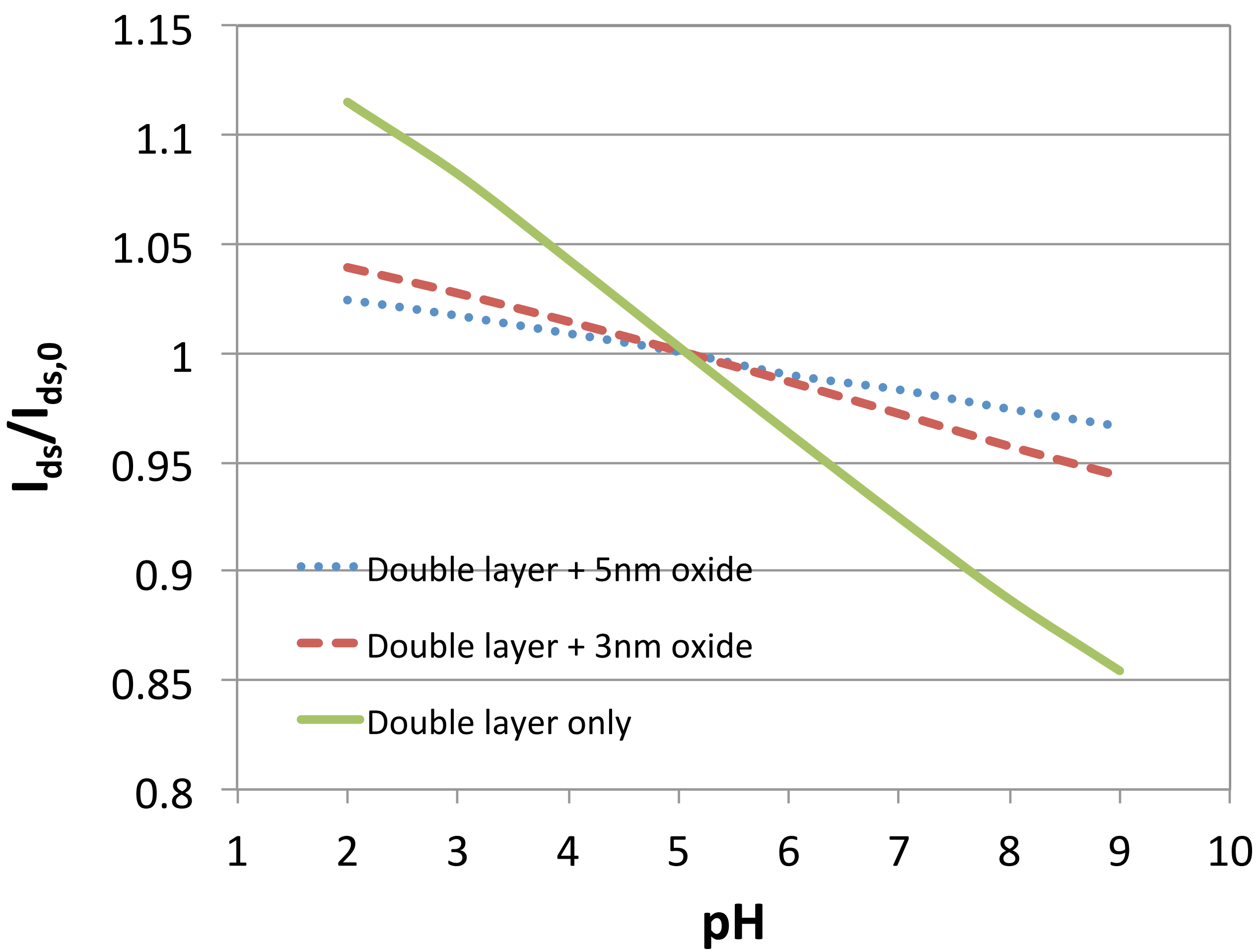
Theoretical Nernstian sensitivity

ψ_0= 2.303 kT/q ΔpH = 59.2 mV/pH

pH Sensor Simulation Results



Effect of oxide layers

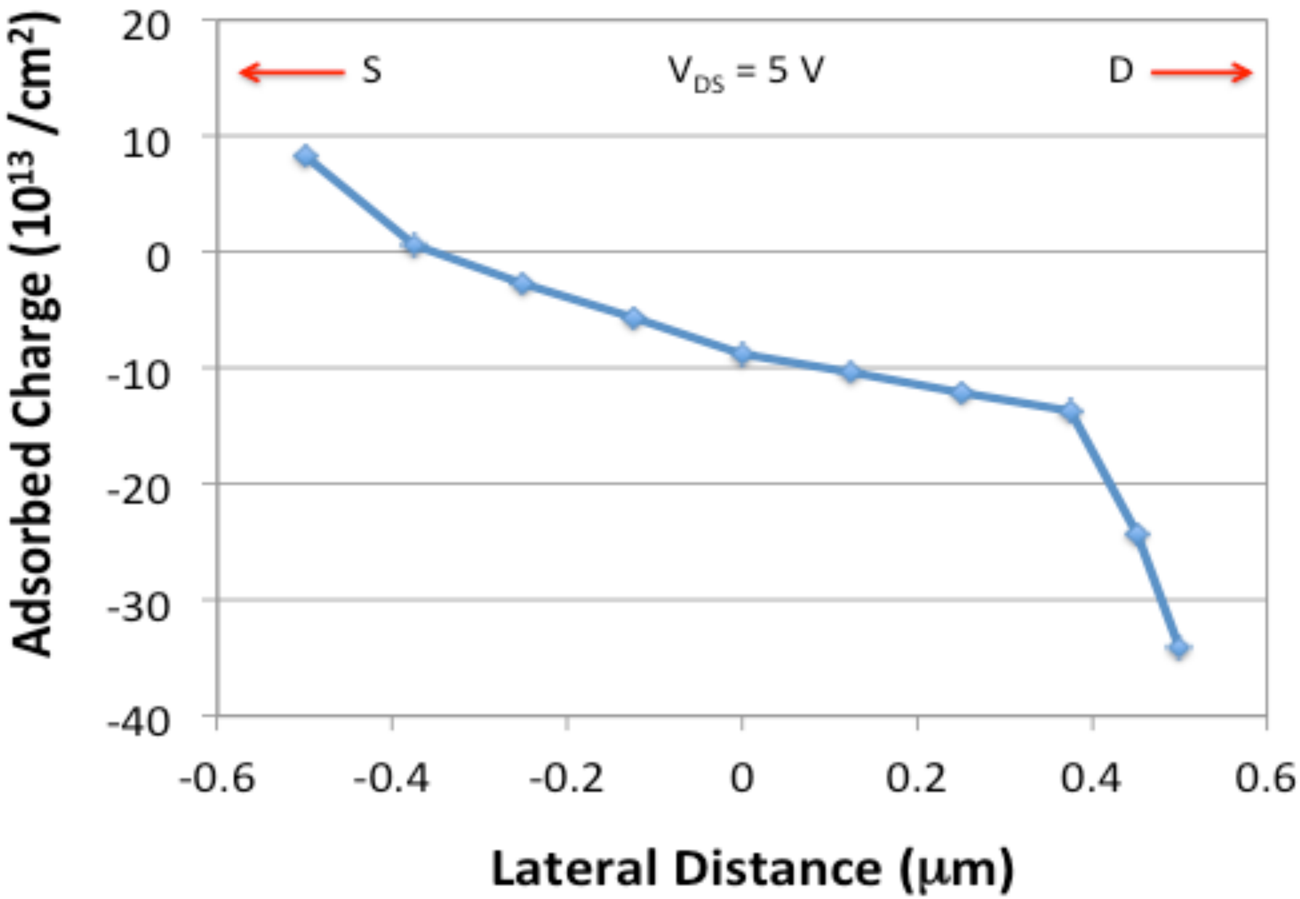


Reduction in Sensitivity

DL + 3nm oxide = 63%

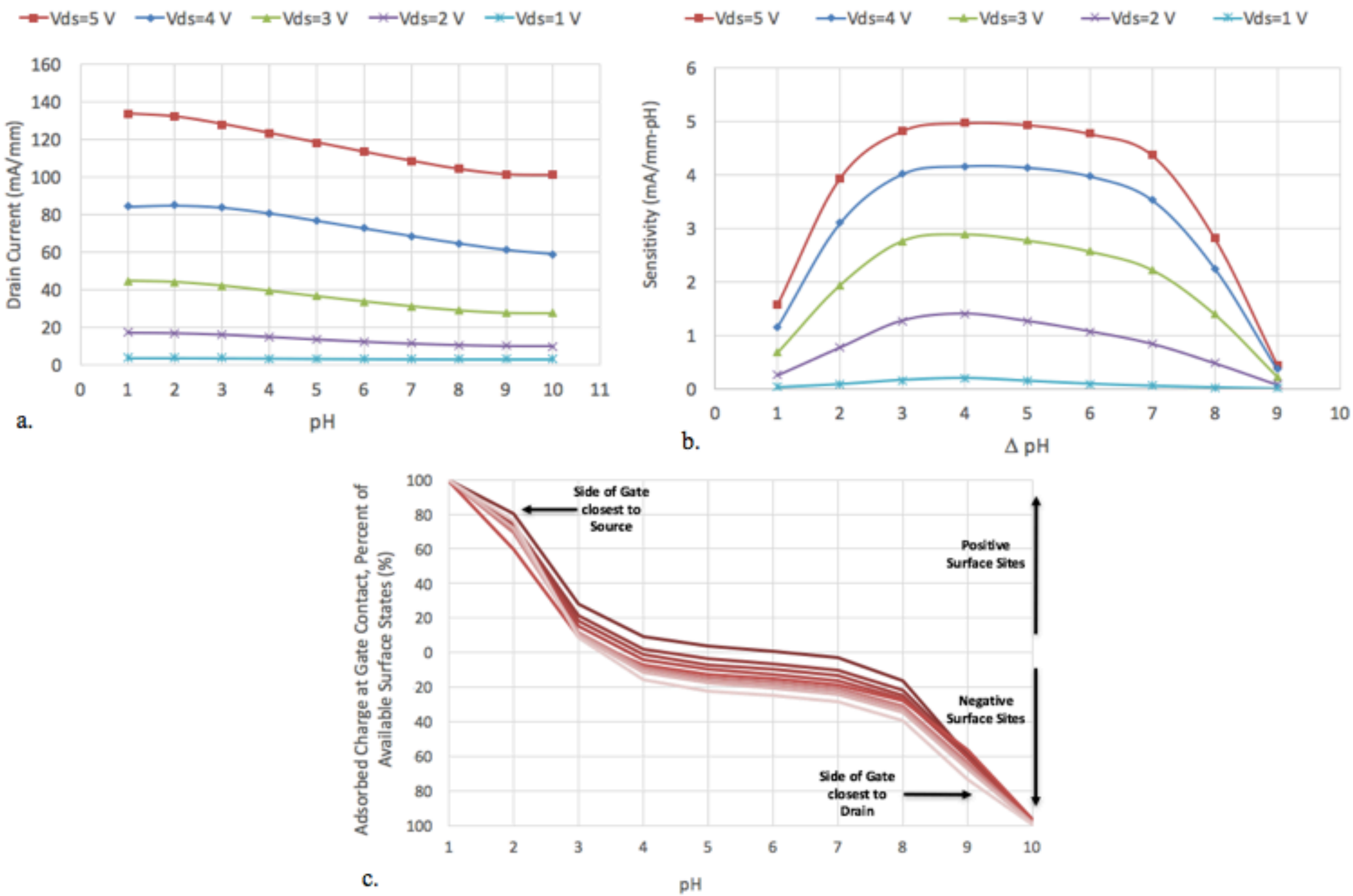
DL + 5nm oxide = 77%

Need for 2-D Simulation



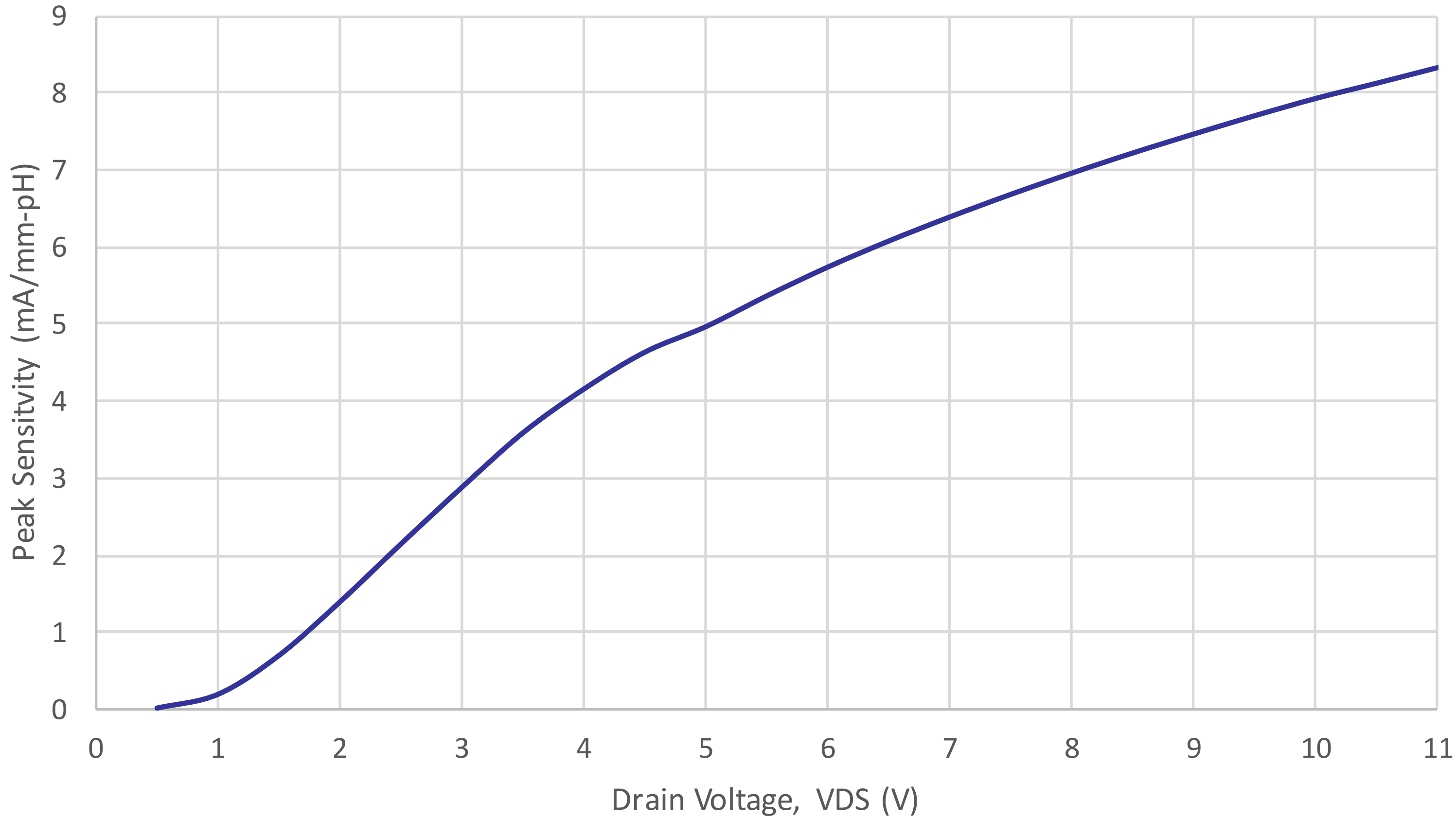
Double layer only, V_{ds}= 5 V

Results for a 1 μm gate device

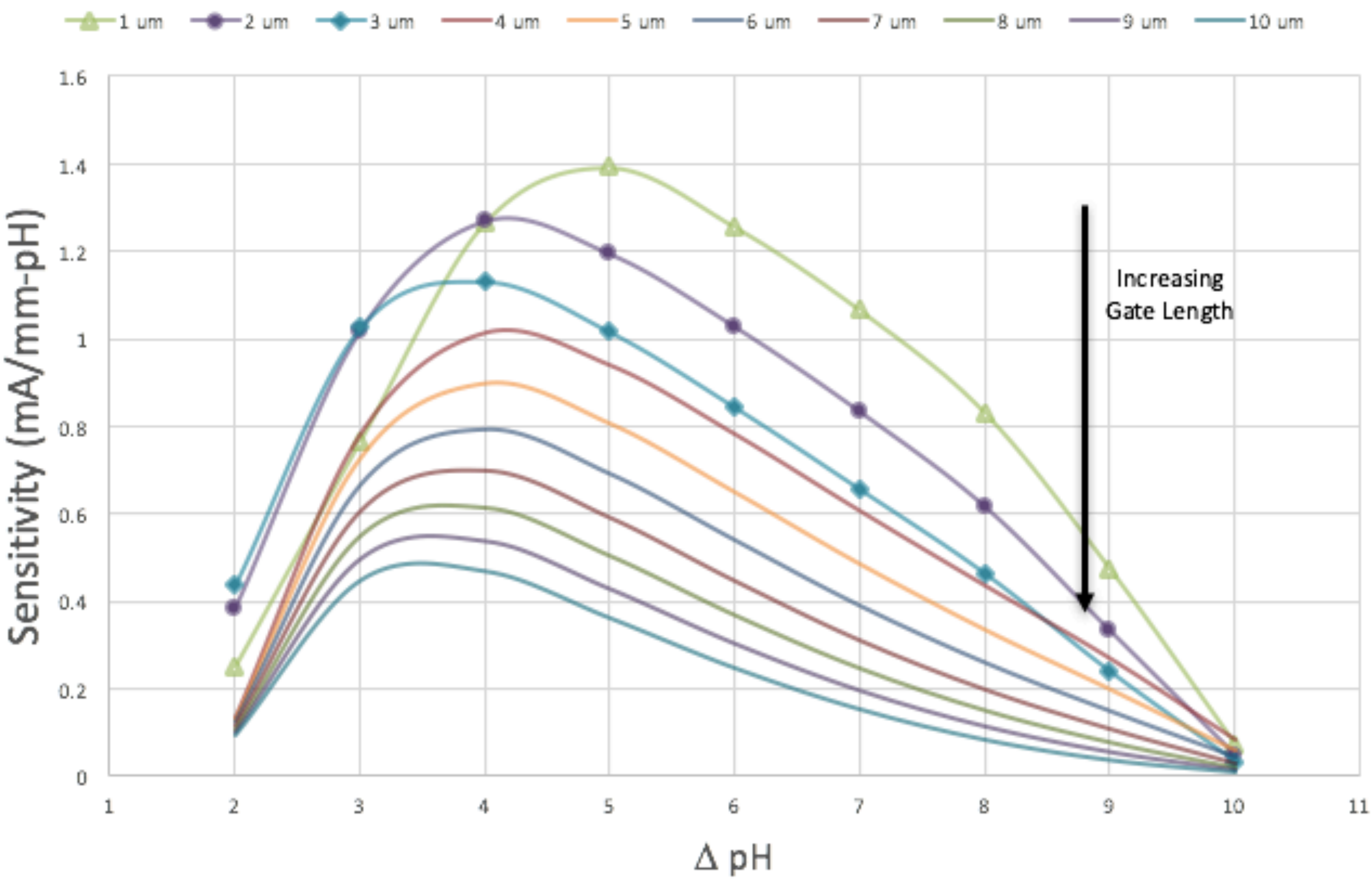


"Gate" Length Trend

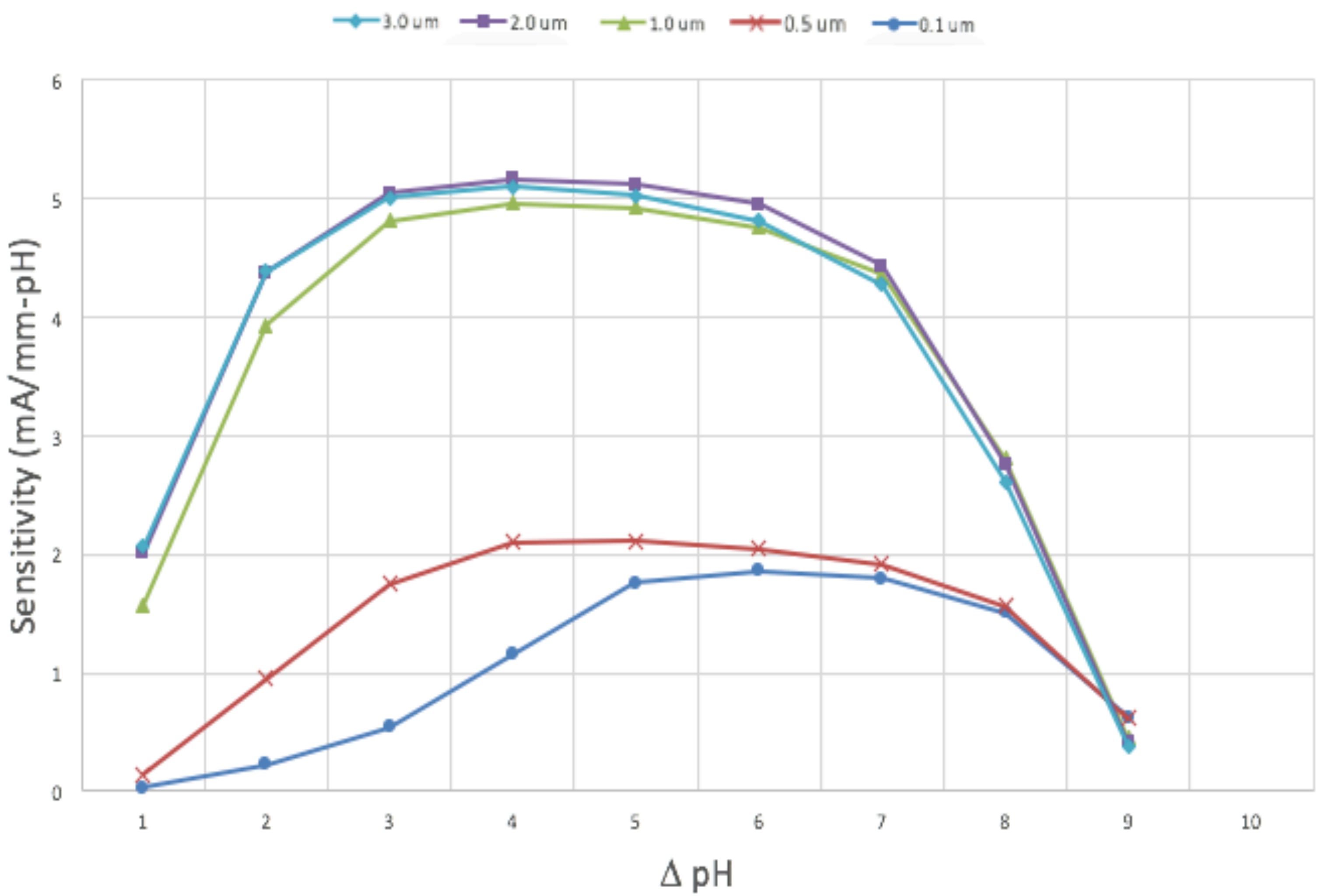
Double layer only, V_{ds}= 5 V



Effect of Drain Bias (Vds=2 V)



Effect of Drain Bias (Vds = 5 V)



Summary

- Mathematical framework for simulation of AlGaN/GaN-based Biosensors
- First simulation of 2-D effects
  - Important for high bias conditions
- Trends
  - Higher sensitivity for higher drain bias
    - May be limited by velocity saturation of carriers (future work)
  - Higher sensitivity for longer "gate" length