Principles of Electronic Nanobiosensors

Unit 3: Sensitivity

Lecture 3.12: Cantilever-based Sensors:
Nonlinear Sensing – Flexure FET

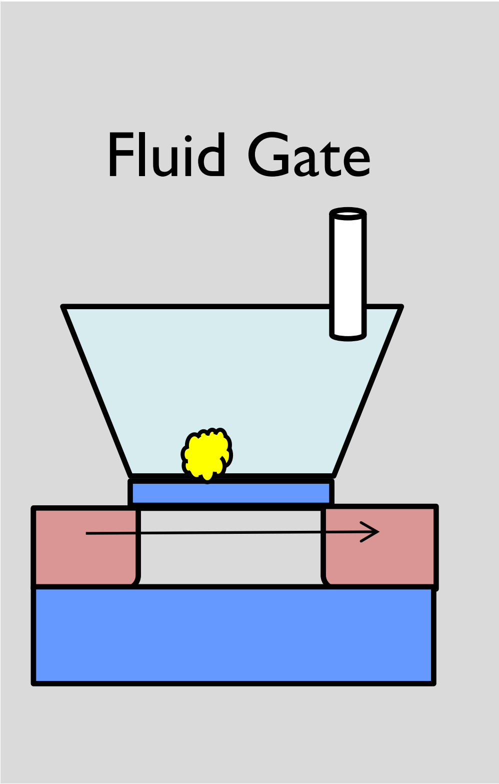
By Muhammad A. Alam
Professor of Electrical and Computer Engineering
Purdue University
alam@purdue.edu

Outline

- Introduction: Weakening the spring
- Electro-mechanical sensors (Capacitor-oscillator)
- Electro-mechanical sensors
  - Basics of transistor physics
  - Transistor in sub-threshold
- Conclusion
- Appendix

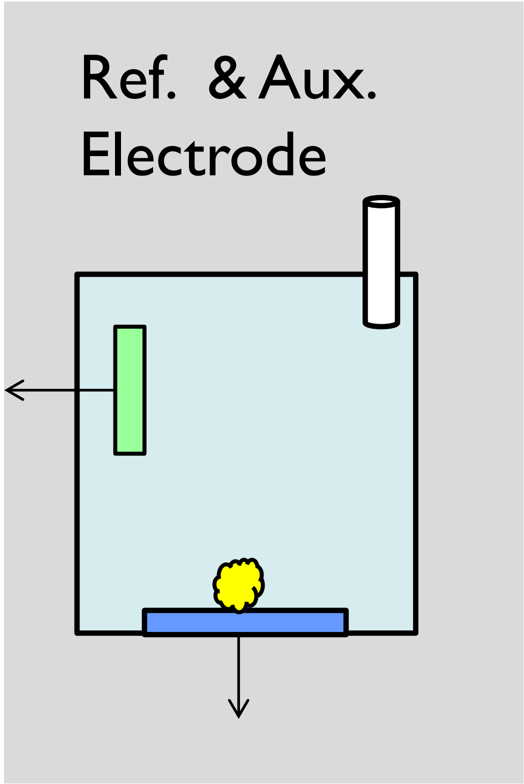
Three types of sensors

Potentiometric



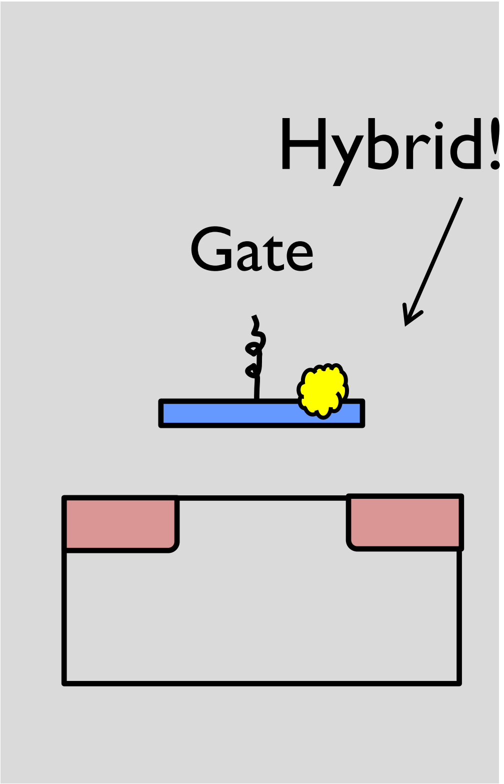
Charge to current

Amperometric



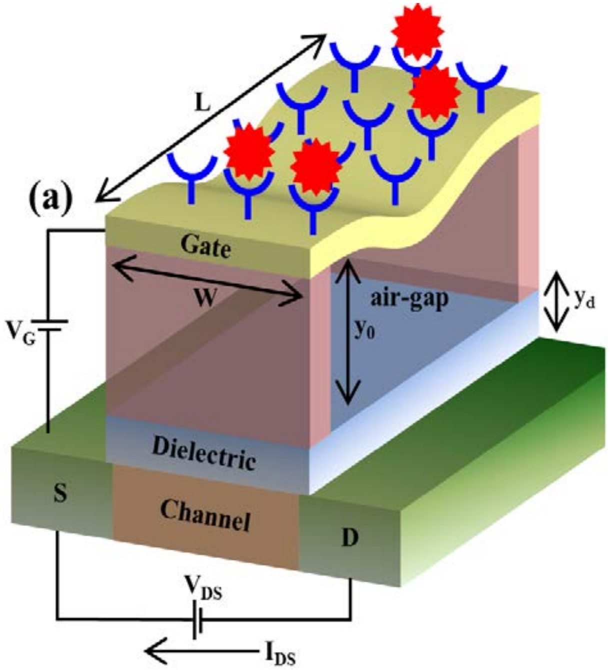
Chemical to current

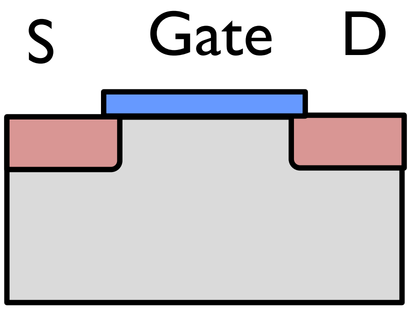
Mechanical

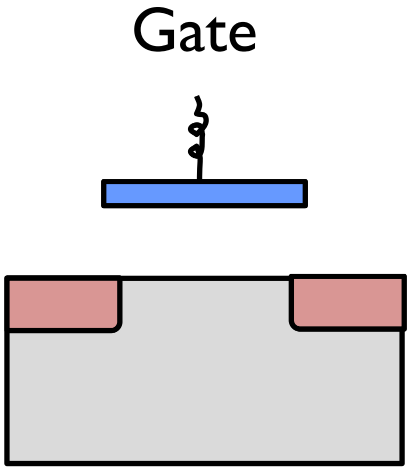


Stress to current

Basics of Flexure-FET

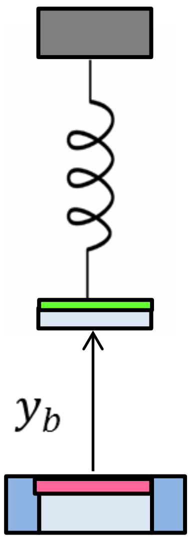


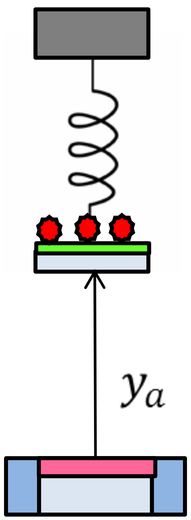




Before and after capture of molecules

$$k(y_0 - y) = -\frac{d}{dy}\left(\frac{C(y)V^2}{2}\right) = \frac{V^2 \varepsilon A}{2y^2}$$





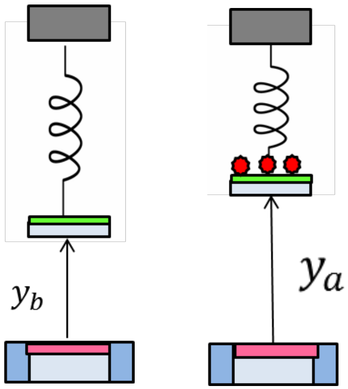
$$k_b(y_0 - y_b) = \frac{\varepsilon V^2}{2y_b^2}$$

$$k_a(y_0 - y_a) = \frac{\varepsilon V^2}{2y_a^2}$$

Capacitive response at the critical point

$$2k_b(y_0 - y_b)\,y_b^2 = V^2\varepsilon$$

$$2k_a(y_0 - y_a)\,y_a^2 = V^2\varepsilon$$



$$2(k_b + \Delta k)(y_0 - y_b - \Delta y)(y_b + \Delta y)^2 = V^2\varepsilon$$

$$(3y_b - y_0)\Delta y^2 + y_b\Delta y(3y_b - 2y_0) = (V^2\varepsilon)\frac{\Delta k}{2k_b{}^2}$$

$$\Delta y^2 = \frac{2(\varepsilon V^2)}{3y_b - y_0} \times \frac{\Delta k}{2k_b{}^2} \sim \gamma_1 N_S$$

$$\left(y_b \rightarrow \frac{2}{3} y_0 \right)$$

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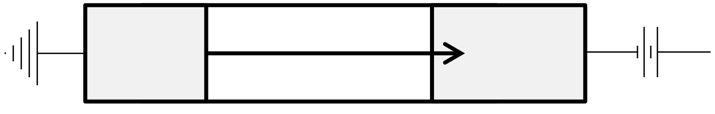
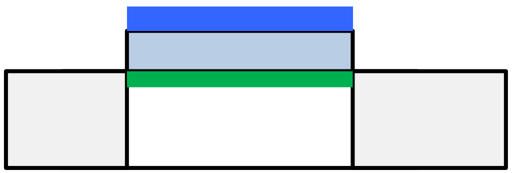
Recall: Transistor Physics

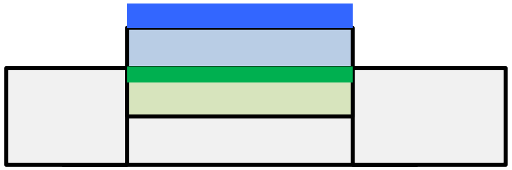
Resistor



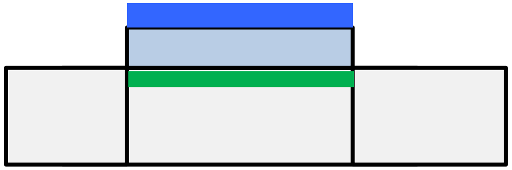
Accumulation



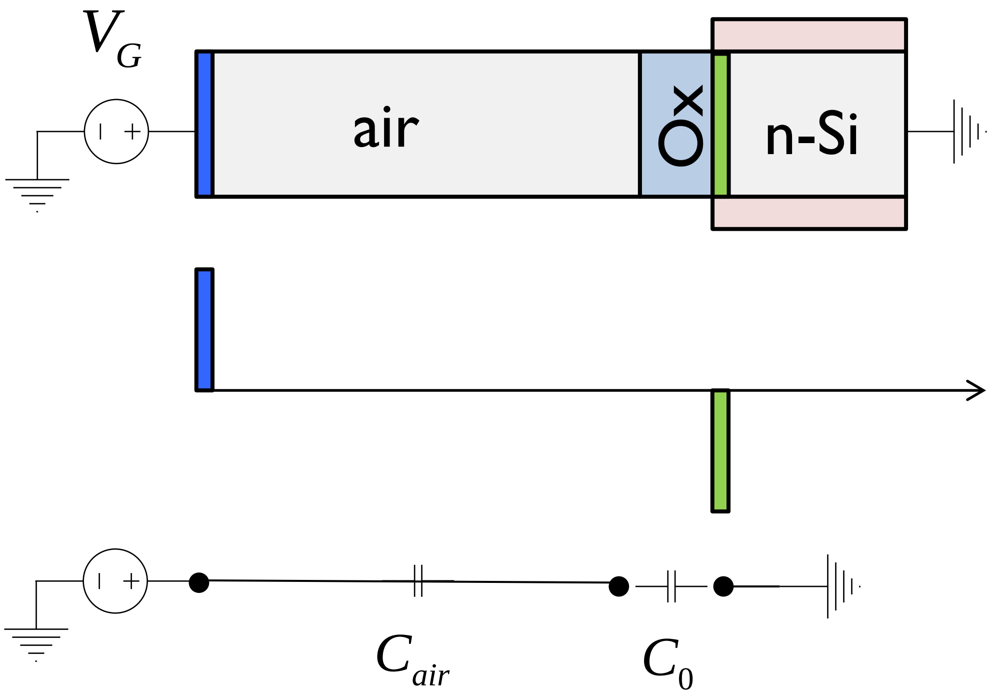
Depletion



Inversion



Flexure-FET in accumulation

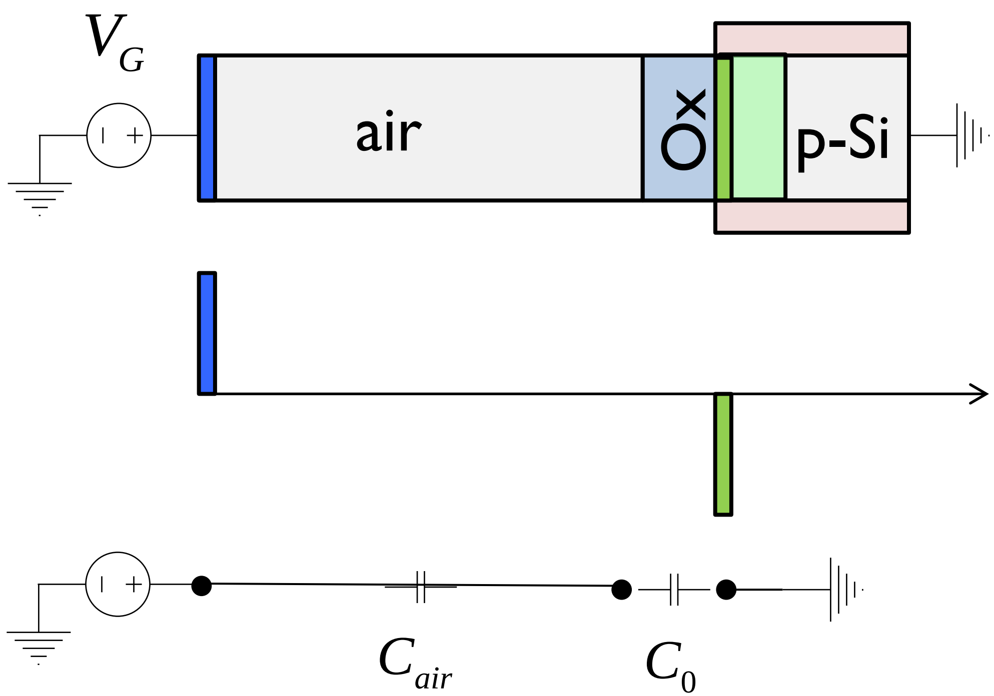


$$C_{eq} = \frac{C_0 C_{air}(y)}{C_0 + C_{air}(y)}$$

$$Q_{MOS} = C_{eq} V_G$$

$$I = Q_{MOS}\upsilon = Q_{MOS}\frac{\mu V_D}{L}$$

Flexure-FET in inversion



$$C_{eq} = \frac{C_0 C_{air}(y)}{C_0 + C_{air}(y)}$$

$$Q_{MOS} = C_{eq}(V_G - V_{th})$$

$$I = Q_{MOS}\upsilon = Q_{MOS}\frac{\mu V_D}{L}$$

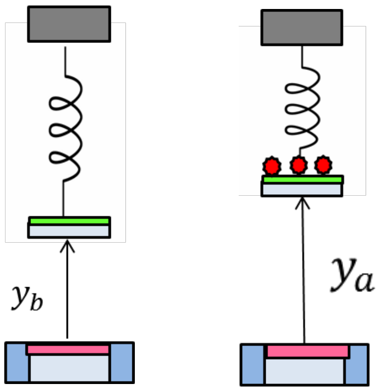
Transistor: Reading at inversion

$$I_{DS} = Q_{MOS} \times \frac{\mu V_{DS}}{L} \Rightarrow \Delta I_{DS} \propto \Delta Q_{MOS}$$

$$Q_{MOS} = C_{eq}(\mathrm{V}_G - \mathrm{V}_{th})$$

$$\Delta I_{DS} \sim \Delta C = \varepsilon(y_b{}^{-1} - y_a{}^{-1}) = \varepsilon \frac{\Delta y}{y_b^2}$$

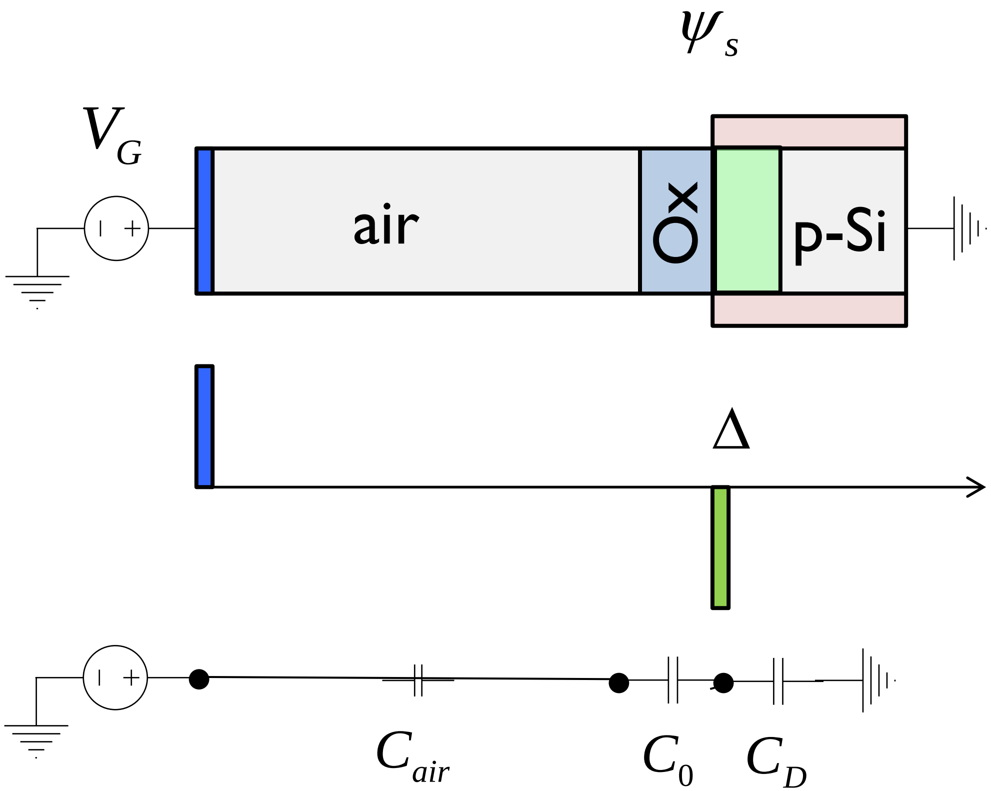
$$\Delta\, \mathrm{y}^2 = \frac{2\varepsilon\, \mathrm{V}^2}{3y_b - y_0} \times \frac{\Delta k}{2k_b{}^2} \sim \gamma_1 N_S$$



$$\Delta I_{DS} \propto \frac{\Delta y}{y_b^2} \propto \sqrt{\gamma_1 N_S}$$

Recall potentiometric sensor

Flexure-FET in sub-threshold



$$\phi_s = \frac{C_{eq}}{C_{eq} + C_D} V_G$$

$$Q_{MOS} = q \frac{n_i^2}{N_A} \times e^{\frac{q\phi_s}{k_B T}} \times \Delta$$

$$I = Q_{MOS} \upsilon = Q_{MOS} \frac{D}{L}$$

The surface potential is defined by depletion capacitance; Charges simply respond to the potential.

Reading at sub-threshold

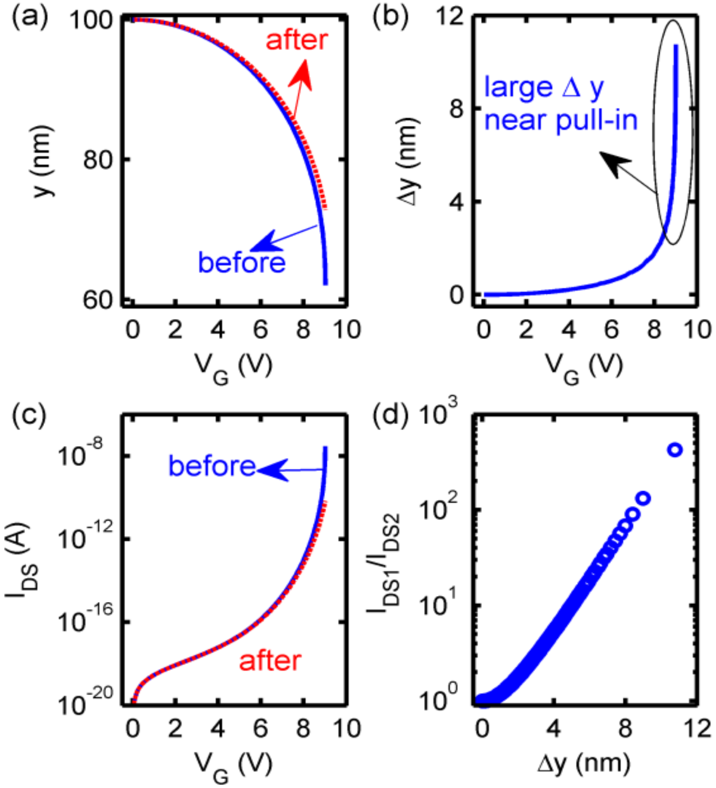
$$\Delta I_{DS} \sim (\mathrm{qn}_i^2 / \mathrm{N}_A) \times \mathrm{e}^{\frac{q\Delta\phi_s}{k_B T}}$$

$$\Delta\phi_s = \gamma_1 N_s - \gamma_2 \sqrt{N_s}$$

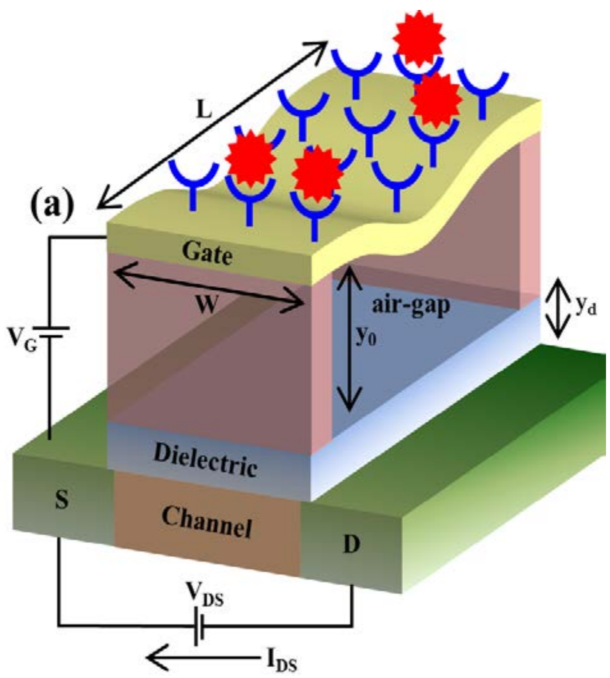
$$\gamma_1 \equiv k\beta / (\mathrm{k}_B \mathrm{T}\,\varepsilon_s\,\mathrm{N}_A \mathrm{A})$$

$$\gamma_2 \equiv \frac{3(\mathrm{y}_0 - \mathrm{y})\,\mathrm{A}_t\,H_t}{k_B T \varepsilon_s\,\mathrm{N}_A \mathrm{AH}}$$

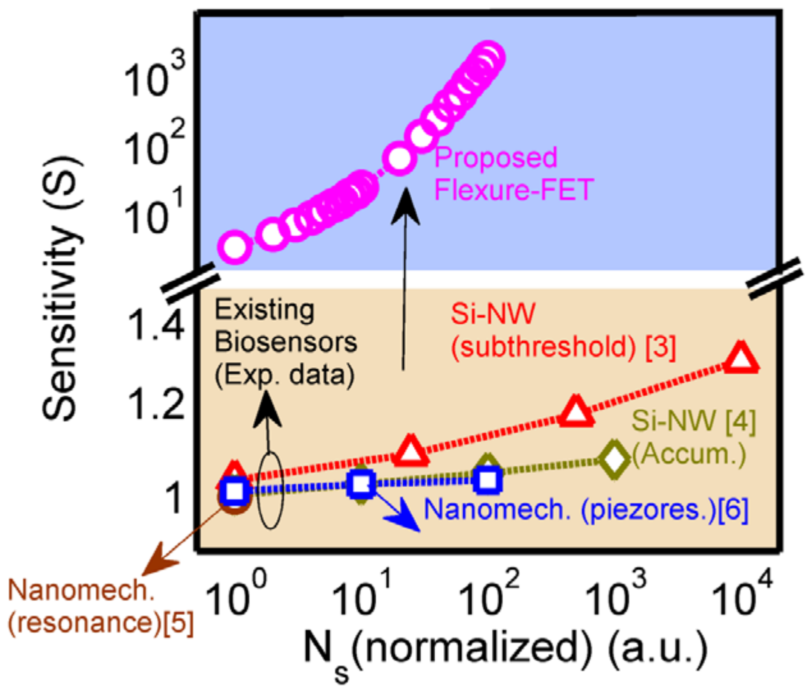
$$S_{Flexure} \equiv \frac{I_{DS1}}{I_{DS2}} \approx e^{(\gamma_1\sqrt{N_s} - \gamma_2 \mathrm{N}_s)}$$



Supersensitive Flexure-FET



Jain et. al., PNAS 2012



- Electromechanical response gives rise to exponential sensitivity
- Eliminates the reference electrode

Conclusions

- Spring softening is the key to enhanced sensitivity of nonlinear transistor-coupled cantilever sensors.
- Sub-threshold conduction gives rise to the exponential response. Response scales as square-root of biomolecule density at inversion or accumulation.
- The key to enhanced response is irrelevance of salt screening.
- Like other cantilever sensors, settling time and selectivity remain independent concerns for flexure-FET.