Proposal of Exponentially Sensitive Stress based Sensor using Flexure-FET

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Outline

**Flexure-FET**

Sub-Linear vs. Exponential Response

**Modeling Framework**

\[
EI \frac{\partial^4 y}{\partial x^4} + \left( P - \frac{EA}{2L} \int_0^L \left( \frac{\partial y}{\partial x} \right)^2 \, dx \right) \frac{\partial^2 y}{\partial x^2} = -\frac{1}{2} \varepsilon_0 E_{air} W
\]

\[
V_G = \left( y + \frac{y_d}{\varepsilon_d} \right) E_{air} + \psi_s
\]

Beam Mechanics and Poisson’s Equation

**Flexure-FET Response**

\[
\Delta y_c (nm) \quad V_G (V)
\]

Conclusions
Sub-Linear Response of Existing Sensors

\[ y \propto \Delta \sigma \]
\[ f \propto \sqrt{\Delta \sigma} \]
\[ R \propto \Delta \sigma \]

Deflection
Resonance Frequency
Piezo Resistance

Stimuli → Cantilever → Sensing layer → y

- pH sensor linear
- Vapor sensor sub-linear
- Piezoresistive bio-sensor logarithmic

Graphs:
- R. Bashir et al., APL, 2002
- D. R. Southworth et al., APL, 2010
- Wee K. et al., Biosens. Bioelec., 2005
1. Classical mechanical sensor for transduction
2. Field effect transistor underneath for direct electrical read-out

Exponential Response of Flexure-FET

Suspended-Gate FET

Mechanical property of gate $\rightarrow$ drain current

$S = \frac{I_{DS}(\sigma \neq 0)}{I_{DS}(\sigma = 0)}$
Essentials of Flexure-FET

\[ \sigma = 0 \rightarrow \sigma \neq 0 \]
\[ y \rightarrow y + \Delta y \]
\[ I_{DS1} \rightarrow I_{DS2} \]

Sub-threshold Conduction

\[ \frac{I_{DS2}}{I_{DS1}} \propto \exp(\Delta y) \]

Close to pull-in instability

Maximum \( \Delta y \)

Exponential Response
Modeling Framework

\[ EI \frac{\partial^4 y}{\partial x^4} + P - \frac{EA}{2L} \int_0^L \left( \frac{\partial y}{\partial x} \right)^2 dx \frac{\partial^2 y}{\partial x^2} = -\frac{1}{2} \varepsilon_0 E_{air}^2 W \]

\[ V_G = \left( y + \frac{y_d}{\varepsilon_d} \right) E_{air} + \psi_s \]

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Conclusions
1. Beam Mechanics

\[ EI \frac{\partial^4 y}{\partial x^4} + \left( \sigma A - \frac{EA L}{2L} \left( \frac{\partial y}{\partial x} \right)^2 dx \right) \frac{\partial^2 y}{\partial x^2} = -\frac{1}{2} \epsilon_0 E_{air}^2 W \]

2. Kirchhoff’s Voltage Law

\[ V_G = \left( y + \frac{y_d}{\epsilon_d} \right) E_{air} + \psi_s \]

3. Poisson’s Equation

\[ E_{air} = \frac{\sqrt{2q\epsilon_s N_A}}{\epsilon_0} \left[ \psi_s + \left( \exp \left( -\frac{q\psi_s}{k_B T} \right) - 1 \right) \frac{k_B T}{q} \right]^{1/2} \]

Equation of beam mechanics and Poisson’s equation are solved self-consistently.

H. Kam et al., TED, 2009
A. Jain et al., UGIM, 2010
A. Jain et al., IRPS, 2012
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Beam Mechanics and Poisson's Equation

Flexure-FET Response

Conclusions
Combining pull-in instability and sub-threshold conduction will lead to optimal sensitivity towards stress change.
Flexure-FET Response

Exponential change in drain current for slight change in stress.
Flexure-FET is Better in Every Aspect

**Piezoresistive**
- Wee K. et al., Biosens. Bioelec., 2005
- A. Boisen et al., Mat. Today, 2009
- G. Yoshikawa et al., Nano Lett., 2011

**Integrated FET**
- G. Shekhawat et al., Science, 2006
- V. Seena et al., JMEMS, 2012

**Linear response**
- Piezoresistive
- Integrated FET

**Electrical**
- Flexure-FET
- Static mode

**Optical**
- Flexure-FET
- Electrical
- Super-linear

**Dynamic**
- Issue of fluid damping

**Static**
- Dynamic

**Laser**
- PSD

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D. R. Southworth et al., APL, 2010
R. Bashir et al., APL, 2002
N. V. Lavrik et al., Rev. Sci. Ins., 2004
J.L. Arlett et al., Nature Nano., 2011
Conclusions

Flexure-FET combines classical MEMS and FET behavior to overcome the fundamental bottlenecks of nanomechanical sensors.

Exponential sensitivity of Flexure-FET can enable early stage detection of fatal diseases like cancer.

Simpler read-out of Flexure-FET can simplify the design of hand-held health care devices.