PROPOSAL OF EXPONENTIALLY SENSITIVE STRESS BASED SENSOR USING FLEXURE-FET

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Abstract: In this paper, we demonstrate that a Flexure-FET [1] (flexure sensitive field effect transistor) can dramatically enhance the sensitivity of stress based chem-bio sensors. A Flexure-FET translates any change in the stress of the suspended gate into corresponding change in the drain current of the integrated transistor, thereby offering direct electrical readout of the sensor signal. Moreover, when the gate is biased close to pull-in and the transistor in sub-threshold regime, the sensor is exponentially sensitive to stress change. In contrast, all classical nanomechanical sensors are limited to linear sensitivity and need complex optical instrumentation for sensing. The simplicity and exponential sensitivity of Flexure-FET may broaden applications of stress-based chem-bio sensors.

Motivation/Background: Stress based nanomechanical sensors involving either a cantilever (Fig. 1(a)) or a fixed-fixed beam (Fig. 1(b)) have shown great promise for bio-molecules sensing [2], vapor/gas sensing [3][4], pH sensing[5], etc. In these sensors, interaction of stimuli (i.e., surface adsorption of bio or gas molecules) with the sensing layer introduces a stress in the cantilever and fixed-fixed beam (Figs. 1(a)-(b)). This stress bends the cantilever (tip deflection y) and changes the resonance frequency (f). The strength of the stimuli is determined by measuring the changes in y or f. Unfortunately, the sensor response is at best linear. For example, static mode cantilever sensors follow Stoney’s equation y ∝ Δσ [6], Δσ being the change in surface stress in N/m. Similarly, a cantilever based pH sensors respond only linearly to pH change (Fig. 1(c)) [5]. On the other hand, one finds that f ∝ Δσ = σ − σc, with σ being the stress in the beam and σc being the critical buckling stress for a fixed-fixed beam both below [7] and above buckling transition [8]. The sub-linear response suggested by theory is consistent with the experimental data [3] of buckled-beam vapor sensors (Fig. 1(d)). This linear/sub-linear response of nanomechanical sensors therefore makes detection of small amount of stimuli very difficult. Moreover, they typically need complex optical instrumentation for measurement of y or f, making their integration with hand-held devices difficult. Therefore, a simpler readout scheme and super-linear response is needed to broaden applications of stress based sensors.

Proposal of Flexure-FET for Stress based Sensing: The classical limits of stress based sensors can be circumvented and super-linear response can be achieved by a new class of critical-point sensors known as Flexure-FET (Fig. 1(e)) [1]. A Flexure-FET consists of a movable gate suspended above the channel of a field effect transistor (Fig. 1(e)), which is structurally similar to a NEMFET[9] or resonant gate transistor[10]. Initially, a carefully chosen gate voltage biases the gate close to the pull-in point (but bias lower than the pull-in voltage). As an example of vapor sensor, reaction of water vapor with hygroscopic polymer coated on the gate introduces a compressive stress in the gate due to swelling of the polymer. As a result, gate further bends towards the dielectric increasing the drain current of the transistor. Thus, a simple electrical measurement of the change
in drain current directly correlates to the signal induced by water vapor. Indeed, we predict that optimally designed and appropriately biased Flexure-FET can achieve orders of magnitude change in the drain current for small change of stress (Fig. 1(f)) and therefore can achieve super-linear sensitivity beyond the reach of classical nanomechanical sensors.

**Response of Flexure-FET to Stress Change:** The response of Flexure-FET is governed by the Euler-Bernoulli equation that is given by:

\[
E I \frac{d^4 y}{dx^4} + \left[ P - \frac{E A}{2L} \int_0^L \left( \frac{d y}{dx} \right)^2 \, dx \right] \frac{d^2 y}{dx^2} = - \frac{1}{2} \varepsilon_0 \varepsilon_s E_s^2 W. \tag{1}
\]

Here, \( y(x) \) is the shape of the gate, \( x \) is along the gate length, \( P = \sigma A \) is the axial load, \( \sigma \) is the stress in the gate and other symbols have their standard meaning. \( E_{\text{air}} = \varepsilon_s E_s (\psi_s) \) is the electric field in air, where \( \varepsilon_s \) is the dielectric constant of the channel material, \( E_s (\psi_s) \) is the electric field at the channel dielectric interface and \( \psi_s \) is the surface potential inside the channel. Equations 2-3 relate the applied gate voltage \( V_G \) with \( \psi_s \) and \( y \) as follows:

\[
E_s (\psi_s) = \sqrt{\frac{2q N_A}{\varepsilon_0 \varepsilon_s} \left[ \psi_s + \left( - \frac{q \psi_s}{e_{\text{air}} T} - 1 \right) \frac{k_B T}{q} \right]^2 - \frac{n_i^2}{N_A} \left( \frac{\psi_s}{e_{\text{air}} T} - 1 \right) \frac{k_B T}{q} \right]^2}, \tag{2}
\]

\[
V_G = \psi_s + \left( \frac{\psi_s}{e_{\text{air}} T} - 1 \right) \varepsilon_s E_s (\psi_s), \tag{3}
\]

where \( N_A \) is the channel doping and other symbols have their standard meaning (see Fig. 2 caption also). Equations (1)-(3) are simultaneously solved to predict the response of Flexure-FET towards stress change. (see ref. [11] also).

Figures 2(a)-(b) show displacement of the center of the gate \( y_G \) and drain current \( I_{DS} \) before \((\Delta \sigma = 0)\) and after \((\Delta \sigma = 5 \text{ MPa})\) the stimulus is introduced. Compressive stress in the gate reduces effective restoring force (left hand side in Eq. 1) and thereby increases gate deflection (Fig. 2(a)), which in turn is reflected in increased gate capacitance and drain current (Fig. 2(b)). Corresponding change in the deflection of center of gate \((\Delta y_G = y_G (\Delta \sigma = 0) - y_G (\Delta \sigma = 5 \text{ MPa}))\) is shown in Fig. 2(c). Interestingly, \( \Delta y_G \) increases with \( V_G \) and is maximized close to pull-in due to the spring-softening effect. Because of the exponential dependence of the drain current on the gate deflection in sub-threshold regime, the ratio \( S = I_{DS2} (\Delta \sigma) / I_{DS1} (\Delta \sigma = 0) \) increases exponentially with \( \Delta y_G \) and becomes maximum close to pull-in (Fig. 2(d)) (see ref. [1] for more details). For a Flexure-FET optimized for maximum sensitivity, the channel should be so doped such that transistor is biased in sub-threshold regime below pull-in. It should be noted that compressive stress developed in the gate due to the stimulus, decreases the pull-in voltage of Flexure-FET. Therefore, Flexure-FET should be biased at \( V_G \) lower than the pull-in voltage to avoid pull-in after development of compressive stress in the gate. Finally, Fig. 1(e) shows \( S = I_{DS2} (\Delta \sigma) / I_{DS1} (\Delta \sigma = 0) \) (ratio computed at pull-in voltage) as a function of \( \Delta \sigma \), confirming the exponential sensitivity of Flexure-FET towards stress change.

**Conclusions:** We have shown that the response of Flexure-FET with change in stress is improved exponentially over that of the current state-of-the-art nanomechanical sensors. Moreover, the technique simplifies the readout dramatically and should in principle be easily integrated into handheld platforms. The concept is very general and therefore can be used for biomolecules sensing, vapor/gas sensing, pH sensing, photothermal deflection spectroscopy, etc. We also believe that critical-point sensing of Flexure-FET should inspire new sensor designs.