SU-8 Based Flexure-FET Biosensor to Achieve Ultra sensitive Response

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ABSTRACT

This work presents a SU-8 based Flexure-FET biosensor to achieve ultra-sensitive response. Here, gate of the FET is replaced with the fixed-fixed beam. Beam is biased near to pull-in instability (V_{pi}) and FET channel is biased in sub-threshold regime (V_{th}) to take advantage of non-linear response of beam and FET respectively. We simulated the beam using polySi, gold and SU-8 as beam material in real environment using Coventorware to compare their Vpi. After selecting SU-8 as beam material, we optimized the dimensions of beam to achieve low V_{pi} using Coventorware and then modeled the FET whose $V_{th} \approx V_{pi}$. We simulated the electromechanical coupling using COMSOL Multiphysics. The non-linear deflection in beam due to biomolecules causes the change in potential of channel which results upto 4th order change in I_d of FET i.e. I_d at equilibrium is 1.1 pA and due to biomolecules, I_d becomes 17.3 nA. This result can be used for ultrasensitive detection of malignant molecules.

Keywords: Flexure-FET, Pull-in instatbility, Young's modulous, Label free detection, Cantilever , Biosensors

1 INTRODUCTION

Recent advancement in nano-electronics have resulted in a new class of exciting devices such as Flexure-Fet [1] (flexure sensitive field effect transistors). As Moore's law is expected to see an end, heterogeneous integration would be future of Microelectronics. Integration of MEMS, Nanosensors etc. with traditional MOSFET help in realizating Biochips and Lab-on-a-chip devices. Flexure-FET is an excellent example of heterogeneously integrated device. It has been theoritically proven to be more sensitive biosensor [1] than any other types of biosensor. Flexure-FET is potential candidate for detecting bio-molecules. It is regarded as ultrasensitive, label free detection of biomolecules.

Sensitivity of classical biosensors such as electrical [2] and mechanical [3] biosensors suffer from fundamental limitations. Sensitivity of electrical biosensors may be severely affected if the biomolecules to be detected are charge neutral. In addition, it also suffers from electrostatic screening due to the presence of charged molecules in the solution.

On the other hand, sensitivity of mechanical biosensors aren't limited by charged neutral biomolecules or electrostatic screening effect. Rather they are afflicted by the complex scheme of optical setup necessary to detect deflection of beam/cantilever due to capturing of the biomolecules. When a biomolecule attaches with the functionalized beam, it changes the mechanical properties of the beam by modulating the mass, stiffness and/or surface stress of the beam. This change in the mechanical properties is detected by change in resonance frequency (dynamic mode operation of cantilever/beam) or change in deflection of beam or change in resistance of peizoelectric material(static mode) [4]-[5]. Moreover, its response is linear [6] or logarathmic [7]-[9] with change in mass and surface stress of beam/cantilever.

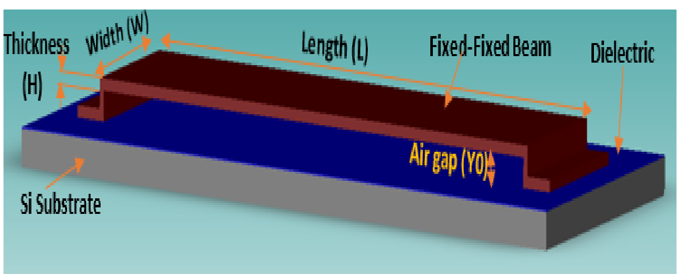
So we need a methodology which can combine advantages of nanomechanical and electrical biosensors to give ultrasensitive response. Flexure-FET is one which combines advantages of both technolgies and doesn't suffer from their limitations. The sensing involves the static nano-mechanical response of the suspended gate or Flex-gate due to the adsorption of biomolecules. Nano-mechanical response can be generated either by neutral or charged biomolecules. The magnitude of nano-mechanical response could be attributed to the concentration of the target biomolecules in an analyte. The present day challenge is to detect even the lowest concentration of specific types of biomolecules which are usually so less in the early stages of diseases like Cancer. Using Flexure-FET even the smallest of the nano-mechanical response can be transduced to a significant change in an electrical signal and hence the lowest concentration of the target bio-molecules.

2 THEORY

Flexure-FET utilizes the advantages of classical electrical and mechanical biosensors to give ultrasensitive response. Here, gate of FET is replaced with the fixed-fixed beam. Beam is biased near to pull-in instability (V_{pi}) and FET channel is biased in sub threshold regime (V_{th}). This is done to operate both devices (FET and beam) in their non-linear regime simultaneously so that sensitivity is maximum. Flexure-FET is biased in sub-threshold regime below pull-in (i.e., $V_{th} \approx V_{pi}$). It is so because displacement of the fixed-fixed beam will be non-linear near to pull-in instability. In addition to this, drain current of FET is exponentially proportion to gate potential in subthreshold regime i.e. Id $\propto \exp(V_{gs}-V_{th}/\ mkT)$ where Vgs is gate to source potential, m= 1 + (C_{dm}/C_{ox}), C_{dm} is depletion capcitance and C_{ox} is gate oxide capacitance. Thus overall effect will be a highly non-linear change in drain current. It is important to keep the pull-in potential of beam low, owing to the fact that low V_{th} FETs can be operated at a higher speed (as V_{pi} of beam and V_{th} of FET should be approximately equal, implying that low V_{pi} will require design of a FET having low V_{th}). Hence it necessitates the design and optimization of beam dimensions to have low stiffness, which in turn decides low value of V_{pi}. One of the key parameters to determine stiffness is the Young's modulus (E) of material. Furthermore a material having the smallest young's modulus exhibits the lowest V_{pi}.

2.1 Selecting beam material

As Young's modulus of material plays significant role in determining stiffness , which in turn decides V_{pi}. So first challenge is to select the material for fabricating beam. We chose polySi, gold (Au) and SU-8 as beam material and simulated the beam Fig1(a) in real environment using Coventorware to compare their V_{pi}. Obtained result is shown in Fig1(b) and value of V_{pi} is listed in *Table1.* Simulation results show that the SU-8 based beam exhibits the lowest V_{pi}.



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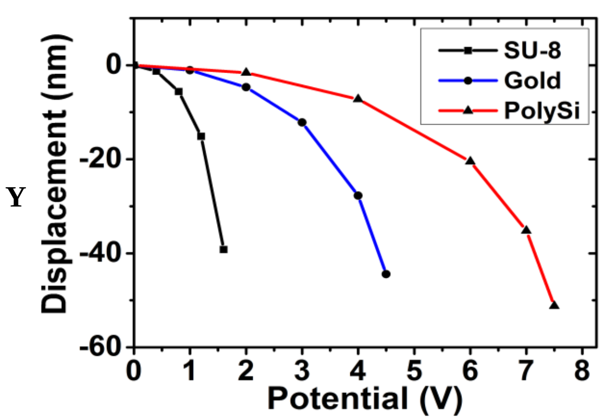


(b)

Fig.1 (a) Beam model for pull-in comparison. Parameters of beam: L= 4 µm, W = 1 µm, H = 40 nm, Y_0 = 100 nm and oxide thickness T_{ox} = 10 nm. (b) Displacement of beam (Y) vs. Potential applied (V). Here we have changed the material of beam, and simulated it in Coventorware using polySi, gold and SU-8, one at a time.

Table 1 : Pull-in potential

Material	E [GPa]	V_{pi} [V]
SU-8	2~4.4	1.75
Au	33~54	4.5
PolySi	160	7.5

2.2 Optimization of Beam's dimensions

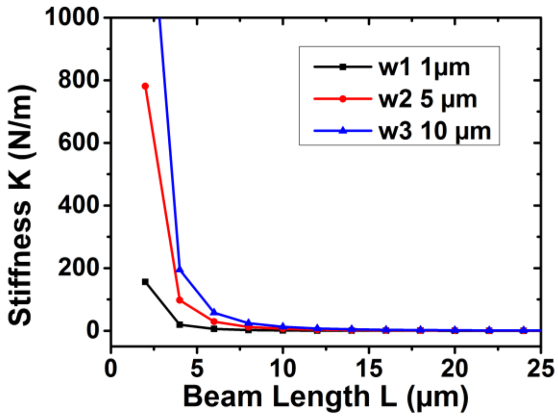
After selecting beam material (SU-8), we had to optimize the beam dimensions to keep V_{pi} of beam as low as possible. For beam , stiffness is given by k = (αEWH^3 / $12L^3$) where α = 480 for fixed-fixed beam. Fig 2(a) and (b) show the variation of stiffness with respect to beam length by keeping beam thickness (h) and beam width (w) constant respectively. Fig 2 shows that as beam length increases by keeping other parameter constant , stiffness decreases by third power of L and becomes constant after a particular value of L. Fig 2(a) shows stiffness increses linearly with the width (W) of beam whereas in Fig2(b), stiffness increses by third power of beam thickness (H).

In Flexure-FET, length and width of beam will be along the width and chanel length of MOSFET respectively. Wider MOSFET lead to strong current but it increases the overall gate capcitance. This can lead to slow response of the device so we can't keep very long length of beam. From Fig 2(a), change in stiffness becomes negligible after L = 10 µm. So we chose beam length between 6 to 10 µm. We also observe that higher value of beam width increases the stiffness. As beam's width lies across the channel length of MOSFET , so lower value of width is desirable as It will lead to stronger current in FET. So we chose beam's width w = 1µm.

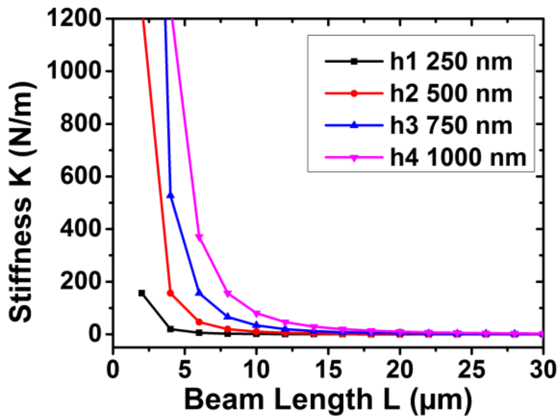
Fig2(b) shows that as film thickness of beam increases its stiffness increases too. So we have to choose lower value of beam thickness. We choose beam thickness between 250-500 nm. Thus, we chose final values of beam dimensions which is listed in *Table 2.* Air gap (Y_0) also plays a vital role to decide the pull-in potential of beam. As SU-8 is an insulator so we used very thin layer of gold (thickness of gold = 10 nm) as electrode for beam contact. We simulated this fixed-fixed beam (Fig1a). During simulation we observed that higher the value of air gap , larger the V_{pi}. For dimensions , listed in *Table 2,* we obtained V_{pi} = 6.2 V.

Table 2: Optimized beam dimensions

Parameter	Value	Description
L	8 [µm]	Beam length
W	1 [µm]	Beam width
H	250 [nm]	Beam thickness
E_t	10 [nm]	Gold electrode thickness
Y_0	100 [nm]	Air gap
T_{ox}	10 [nm]	Dielectric thickness



(a)



(b)

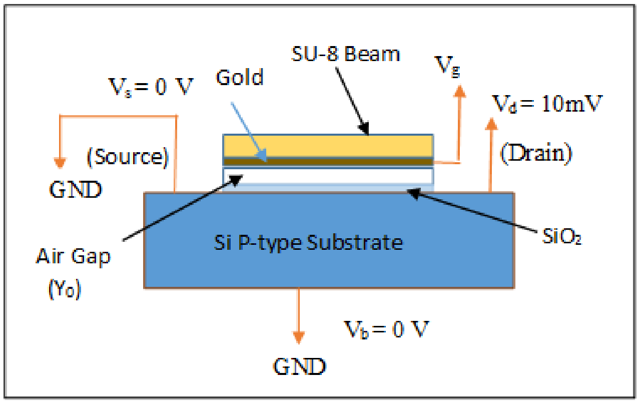
Fig.2 (a) Stiffness (k) vs. Beam Length (L) : *h* = 250 nm. (b) Stiffness (k) vs. Beam Length (L): *w* = 1 µm. Here we have chosen Young's modulus of SU-8 E=2 GPa.

2.3 Parametrs of FET

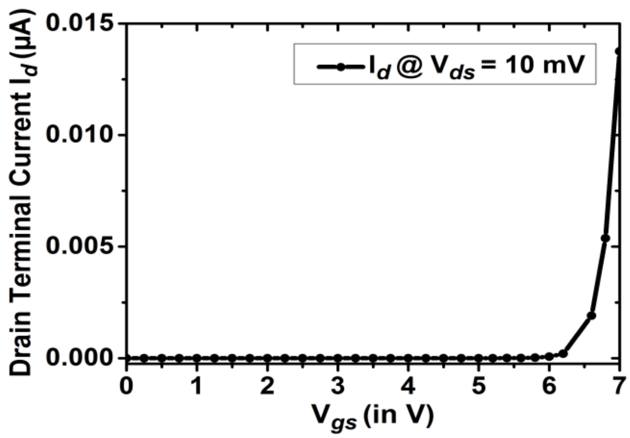
As V_{pi} of beam structure is 6.2 V. So our target is to design a FET whose V_{th} is nearly equal to V_{pi}. Different parameters of MOSFET which sets its V_{th} = 6.2 V, are listed in *table 3*. This structure Fig3(a) is simulated in COMSOL multiphysics 4.4 and result in Fig3(b) I_d vs. V_{gs} plot shows that V_{th} of FET is equal to 6.2 V.

Table 3 : MOSFET Parameter

Parameter	Value	Description
N_a	1.1e16[1/cm^3]	acceptor doping concentration
N_d	1e18[1/cm^3]	donor doping concentration of source/drain
T_{ox}	10 [nm]	gate oxide thickness
ε_{sio2}	4.5	dielectric constant of Insulator
φ_m	5.1 [eV]	metal work function



(a)



(b)

Fig.3 (a) cross sectional view of Flexure-FET. (b) I_d vs V_{gs} plot of FET.

2.4 Simulation of Electromechanical coupling in COMSOL Muliphysics 4.4

At clinically threshold concentration of biomolecules , the change in free energy density on functionalized beam due to biomolecules were reported in range of 1 to 50 mJ/m^2 [10]-[13]. This change in free energy density/surface stress (σ_s) is defined as integral of the normal stress or bulk stress (σ_m) in monolayer over its thickness:

$$\sigma s = \int_0^{tm} \sigma m \, dz \qquad (1)$$

If we substitute the surface stress 1 to 50 mJ/m2 in equation(1), we get normal stress in monolayer (thickness ~ 20 nm) in range of 50 kPa – 2.5 MPa. This bulk stress value may vary with the different type of material used for beam. We applied these bulk stress values over the top of beam and observed the change in deflection of beam.

Firstly, we simulated Fig.3(a) in COMSOL using electromechanics (emi) physics by applying bulk stress, which causes beam to deform. Then we imported the deformed beam structure into semiconductor physics and calculated the new current after deflection of the beam. This we performed over the range of bulk stress values and result

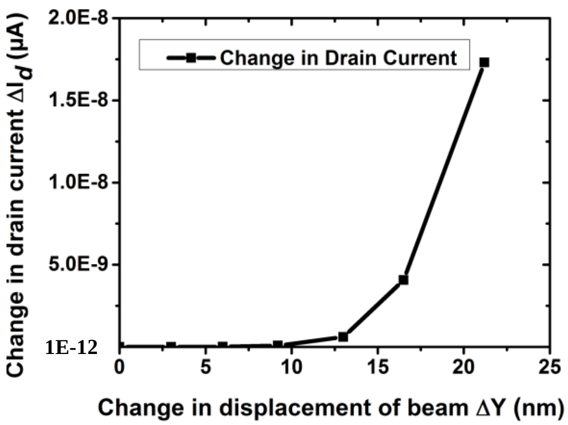


Fig.4 ΔI_d vs ΔY of the optimized beam used as gate of the FET. When SU-8 beam captures biomolecules, its stiffness changes which causes further displacement of beam from its equilibrium position at V_{pi} i.e. $\Delta Y=Y_0-Y$.

(change in current $\Delta I_d = I_2 - I_1$, where I_2 is drain current after deflectioon of beam due to attachment of biomolecules and I_1 is drain current before attachment of biomolecules) is shown in Fig.4.

3 RESULTS

When a biomolecule attaches with the functionalized beam of SU-8, it modulates the stiffness of the beam causing a non-linear deflection of beam. The non-linear deflection is attributed to the biasing of beam closed to pull-in instability. This non-linear deflection causes the change in potential of channel which results in order of change in drain current of FET (Fig.4). Fig.4 shows upto 4^{th} order change in drain current I_d.

4 CONCLUSIONS

Here, we demonstrated the Flexure-FET response using COMSOL Multiphysics 4.4. We observed that Flexure-FET can have a great outlook in biomedical field due to subtle change in drain current I_d of FET. We used gold as electrode for gate contact because SU-8 is insulator. If we can make SU-8 conductive then we can perform the same operation at much lower potential.

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