A Theoretical Study of Negative Bias Temperature Instability in p-type NEMFET

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Abstract—Negative Bias Temperature Instability (NBTI) in PMOS transistors is a major reliability concern in MOS technology. However, the effect of NBTI is yet to be studied in Nanoelectromechanical Field Effect Transistor (NEMFET). In this paper we study the NBTI for p-type NEMFET, for the first time within Reaction-Diffusion (RD) framework - well established for studying NBTI in MOS transistors. Therefore, we show that NBTI for NEMFET is worse than that for CMOSFET. Our theoretical analysis suggests that NBTI in NEMFET may significantly reduce the pull-out voltage of the device and may result in permanent failure of the device.

Keywords - NEMFET; NBTI; Threshold Voltage; Pull-out Voltage; Pull-in Voltage; CV curve; Hydrogen Relaxation.

I. INTRODUCTION

Recently a number of device concepts have been proposed to overcome the challenge of power dissipation in classical CMOS architecture. One such concept involves the reduction of sub-threshold slope by using Nanoelectromechanical Field Effect Transistor (NEMFET) [1], so that the same on-off ratio can be achieved at reduced supply voltage. During the operation of the NEMFET however, the thin gate dielectric (see Fig. 1a) is repeatedly stressed at relatively high voltage [2]. This leads to dissociation of Si-H bonds at the semiconductor/dielectric interface and gives rise to a time-dependent degradation phenomenon commonly known as Negative Bias Temperature Instability (NBTI) in classical CMOS literature [3, 4]. In this paper, we use a general theoretical framework of Si-H bond dissociation (using a Reaction-Diffusion or R-D Model [3]) to study the consequence of high oxide field in p-type NEMFET structure. We compare NBTI for NEMFET and classical p-type CMOSFET under both DC and AC conditions, and we show that NBTI is comparatively worse for NEMFET. Consequently, we illustrate how NBTI can reduce the pull-out voltage of NEMFET and thus introduce NBTI as an important reliability concern for such structure. Such presence of NBTI can be as important as the conventionally known stiction failure in RF-MEMS [5].

II. THEORETICAL FRAMEWORK

A. Model for NEMFET

Fig. 1(a)-(b) shows the schematic of NEMFET with typical dimensions. NEMFET is essentially a MOSFET with movable gate electrode which can be physically separated from gate dielectric by an air gap. The suspended gate is a doubly clamped beam anchored at two sides of its channel. Fig 1(c) shows the equivalent one dimensional lumped parameter model of NEMFET which has previously been used to study the behavior of NEMFET [1]. In this model the gate is treated as a linear spring suspended over the semiconductor channel.

Fig 1: (a) Schematic of a typical NEMFET structure. The gate is a clamped-beam physically separated from the gate dielectric. The schematic indicates the dimensions of NEMFET used in this study. (b) Top view of the NEMFET structure under study, which has dimensions like: L = 800nm, N0 = 3e18cm⁻³, Td = 1nm, Tgap = 9.7nm, W = 100nm, H = 20nm, E = 160GPa, e = 3.9. (c) Lumped parameter model of a NEMFET. (d)-(f) indicates the shape of the deflected beam corresponding to different regions of operation of the NEMFET: (d) before pull in, (e) after pull in, and (f) just before pull out. Equation (1) and (2) together with Poisson’s equation are used to solve the shape of the beam and electrostatics along the channel as a function of applied bias.
The gate and channel forms a parallel plate capacitor with an equivalent air-gap that is uniform in thickness across the transistor channel. With the application of gate voltage (Fig. 1d-f), the gate bends symmetrically and after a certain voltage called pull in voltage (\(V_{PIN}\)) the gate gets pulled in (ON state of NEMFET). In order to turn the NEMFET off, the gate voltage is reduced below the pull out voltage (\(V_{POUT} < V_{PIN}\)). So, to accurately model the switching behavior of NEMFET, non-uniform air gap due to the bending of the gate electrode must be taken into account. To study the switching behavior of NEMFET we solve the Euler-Bernoulli equation coupled with the Poisson’s equation (Eq. 1, 2) as described in [2]

\[
\frac{EI}{1 - \theta^2} \frac{d^4y}{dx^4} = \frac{0.5\varepsilon_0\varepsilon_s^2WV_{eff}(x)^2}{(T_d + \varepsilon_y(T_{gap} - y))^2} \tag{1}
\]

\[
V_{gb} = V_{fb} + V_{eff}(x) + \psi_s(x) \tag{2}
\]

Here, \(y\) is the deflection of gate electrode; \(x\) is along the length of gate electrode, \(E\) is the Young’s modulus of gate electrode, \(\theta\) is the Poisson’s ratio of gate electrode, \(I\) is the 2nd moment of area, \(T_d\) is the dielectric thickness, \(T_{gap}\) is the initial air gap, \(V_{gb}\) is the gate to body voltage, \(V_{fb}\) is the flat band voltage, \(\psi_s(x)\) is the surface potential, and \(V_{eff}(x)\) is the voltage between gate electrode and dielectric.

### B. Model for NBTI

Negative Bias Temperature Instability is one of the major reliability problem in PMOS transistor biased in inversion, i.e., have negative gate voltage with respect to source and drain.

The phenomenon is attributed to the defect formation at the Si/SiO\(_2\) interface of a PMOS transistor and can be explained using the well known Reaction-Diffusion (RD) framework [3]. In the Reaction-Diffusion formulation for interface defect generation, interface defect arises due to the hole-assisted breaking of Si-H bonds at Si/SiO\(_2\) interface (Fig. 3(a)). The rate of such defect generation is given by,

\[
d\frac{N_{IT}}{dt} = k_f(N_0 - N_{IT}(t)) - k_rN_{IT}(t)N_H^0 \tag{3}
\]

where, \(N_0\) is the initial number of Si-H bond at Si/SiO\(_2\) interface, \(N_{IT}(t)\) is the fraction of these Si-H bonds broken at time \(t\) due to NBTI stress, \(k_f\) is the dissociation constant of Si-H bond breaking process, \(k_r\) is the constant for reverse reaction, and \(N_H^0\) is the concentration of H atoms at the Si/SiO\(_2\) interface. The H atom released in the process can anneal the broken bonds described by second term of the equation (3) or may diffuse away from the interface, according to the following diffusion equation, i.e.,

\[
d\frac{N_X}{dt} = D_H \frac{d^2N_X}{dx^2} \tag{4}
\]

where, \(N_X\) is the concentration of diffusion species, which can be both H and H\(_2\) [4]. We solve Eqs. (3) and (4) in a coupled manner and hence calculate the concentration of interface defect \(N_{IT}(t)\) at different time \(t\).

### III. SIMULATION RESULTS

#### A. Mechanical-Gate Shape and Channel Potential

We solved the Euler-Bernoulli, i.e., Eqn. (1) and Poisson equation in a coupled manner and hence determine the CV curve (Fig. 2a) and the surface potential \(\psi_s\) (Fig. 2b) at the midpoint of the channel at different gate voltages.

\[\text{Fig. 2: (a) CV curve of the NEMFET (b) Surface potential at the midpoint (x = 400nm) of the channel at different voltages. (c) Shape of the membrane and (d) surface potential (\(\psi_s\)) along the channel for a p-type NEMFET at \(V_{gb} = 1.2V\). Unlike classical MOSFET, \(\psi_s\) vary along the channel. Abrupt pull in behavior (i.e., abrupt jump in capacitance and \(\psi_s \) at pull in) can provide subthreshold swing of much less than 60mV/dec [1].}\]

\[\text{Fig. 3: According to Reaction Diffusion (R-D) model (governed by equations (3) and (4)) [3,4], NBTI stress breaks the Si-H bond at the Si-SiO\(_2\) interface and resultant hydrogen diffuses away from the interface. (a) In ON-state of the NEMFET (stress phase), hydrogen diffuses in the oxide/poly region, whereas (b) in the OFF-state of the NEMFET (relaxation phase), the poly region gets disconnected and only the hydrogen within the oxide repassivates the broken bonds or \(N_{IT}\). (c) Hydrogen profile during stress phase in NEMFET is similar to the one for classical FET. However, (d) in the relaxation phase (contrary to classical FET), only the hydrogen within the oxide repassivates \(N_{IT}\).}\]
These electrostatic quantities will vary along the length of the NEMFET, because of the non-uniform displacement of the membrane (Fig. 2c). For example, Fig. 2d shows the \( \psi_S \) along the channel at a particular gate voltage of \( V_{gb}=-1.2\text{V} \). Now, since surface potential varies along the channel, the oxide electric field will also vary. Therefore, the region with maximum oxide electric field (i.e., the middle of the channel) will be more susceptible to NBTI degradation.

B. NBTI of NEMFET and Comparison with Classical CMOS

During stress phase or ON state (Fig. 3a,c), NEMFET behaves like a classical MOSFET, because the gate is in the down state (Fig. 1e) and both the FETs show similar amount of degradation for similar electric fields. However, when NBTI stress is removed (OFF state), gate moves up for NEMFET (Fig. 1d) and takes away all the hydrogen with it (Fig. 3b,d) and thus only the hydrogen within the oxide takes part in \( N_{IT} \) re-passivation. Therefore, we observe that NBTI relaxation in NEMFET is much smaller than the same for classical CMOSFET (Fig. 4a). Hence, after multiple cycles of AC NBTI stress, NEMFET shows higher degradation than classical FET (Fig. 4b). Since hydrogen within gate does not take part in \( N_{IT} \) re-passivation, AC NBTI for NEMFET is worse compared to that for CMOS FET. Hence, NBTI-induced \( N_{IT} \) generation is expected to be an important reliability phenomenon for NEMFET as well. Such \( N_{IT} \) generation will reduce the pull out voltage of NEMFET and thus cause permanent failure for the device.

ACKNOWLEDGEMENT

We gratefully thank Prediction of Reliability, Integrity and Survivability of Microsystems (PRISM) for the funding support and Network for Computational Nanotechnology (NCN) for the computational resources.

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