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Design and Analysis of an In-Plane Resonant Nano-Electro-Mechanical Sensor for Sub-Attogram-Level Molecular Mass-Detection

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1. Introduction

Silicon-based Nano-Electro-Mechanical (NEM) sensors are getting increasing interest because of their compatibility with "In-IC" integration as well as high sensitivity to a change in mass [1], [2]. The NEM sensors enable to detect a small amount of biological or chemical molecules thanking to their nanoscale dimensions and sensitive frequency response. This paper presents design and analysis of a newly-proposed In-Plane Resonant NEM (IP R-NEM) sensor based on a mass-detection principle and discusses its extremely high mass sensitivity in comparison with present-day mass-detection-based biosensors [3], [4]. In contrast with previous reports, our resonator architecture has amplified output signal [5] due to the integrated lateral FET and can be realized by a top-down process on SOI substrates, which is expected to enable monolithic integration of the NEM sensors with CMOS ICs.

2. 3D FEM Analysis of Impacts of Surface Modification on Resonant Frequency of IP R-NEM structure

A basic structure of the IP R-NEM sensor used for present design simulation is shown in Fig. 1. It consists of a suspended Si beam with its both ends fixed and two side electrodes. Highly-doped Si was assumed for the beam and electrodes. The structure was simulated using CoventorWare [6] based on SOI technology. The 3D modal analysis was first conducted by using Analyzer [6] to verify that the suspended beam has an in-plane movement in the y-direction as a dominant mode: the first resonant mode frequency is 432 MHz. The lateral beam displacement is shown in Fig. 2 as a function of side gate voltage. The beam was designed to operate in the hatched voltage region which is separated well from the pull-in voltage of 56.95 V.

Self-assembled linker molecules and adsorbed target molecules on the Si beam surface were modeled simply by adding an extra surface coating layer. Two different coating configurations were introduced in this study: Top-and-Bottom (TB) and All-Around (AA) coating (Fig. 3). The TB coating assumes only the top and bottom surfaces of the beam are coated with linker molecules. The AA coating assumes all the beam surfaces are coated uniformly. Realistic situations may lie in-between, depending of the dimensions of the beam and lateral air gap as well as the linker molecule length. The resonance frequency, f_r, versus the surface layer thickness for both configurations is shown in Fig. 3. We found for the TB that f_r decreases by increasing the surface layer thickness while the trend is reverse for the AA. This is because both mass and stiffness changes influence on the resonant frequency, and the stiffness change appears to be dominant in the case of the AA.

As mentioned above, the realistic coating configurations may well lie between the TB and AA. We therefore employed an intermediate configuration in which the thickness of the side adsorbed layer is less than that of the top and bottom layers, t_{top}= t_{bottom}= 2 nm and t_{side}= 1 nm. We then varied density (i.e., mass) of the functionalization layer in order to evaluate the mass sensitivity. The resonance frequency versus mass of the coating layer is shown in Fig. 4. It shows that 10 ag changes in the mass results in 0.16 MHz changes in the resonance frequency.

3. Hybrid Circuit Analysis of IP R-NEM Sensor

The IP R-NEM structure is integrated with an in-plane readout MOSFET for electrical detection: the schematic of the IP R-NEM sensor is shown in Fig. 5. Resonant spectra analysis was then conducted for the IP R-NEM sensor using a hybrid circuit model in Fig. 6 prepared for Architect [6]. In this structure the suspended beam will play the role of an in-plane gate for the MOSFET, therefore the structure is called In-Plane Resonant Suspended Gate MOSFET (IP RSG-MOSFET). The small signal AC analysis was performed. Fig. 7 compares the resonant spectra obtained for two beam structures with their mass of 11.655 fg (a solid line) and 11.655 fg+0.88 ag (a broken line). The resulting resonance frequencies were found 394.57 MHZ and 394.65 MHz, respectively. A change in the beam mass, Δm= 0.88 ag, causes the variation of the resonance frequency, Δf_r, equal to 0.08 MHz. Transient response analysis was also conducted by setting the frequency of the AC voltage to f_r obtained from the small signal AC analysis (Fig. 8). The output voltage versus frequency is also shown in Fig. 8.

It is worth comparing the above results with the performance of recent mass-detection-based biosensors. For example, a quartz crystal microbalance (QCM) biosensor [7] features a detection area of 0.049 cm^2 and a mass detection limit of 100 pg with a sensitivity of 30 pg/Hz. Our IP R-NEM sensor has an extremely-small sensing area of the order of nano cm^2, about seven orders of magnitude smaller than that for the QCM sensor. This potentially enables to achieve a mass-detection limit of 1 ag or even smaller and a sensitivity less than 1 zg/Hz.

4. Conclusions

We have conducted design and analysis of a newly-proposed IP R-NEM sensor based on a mass-detection scheme by using both 3D FEM and hybrid circuit simulation. The simulation results showed that the IP R-NEM sensor enables a mass-sensitivity of more than eight orders of magnitude smaller than present-day QCM-based sensors.

Acknowledgements

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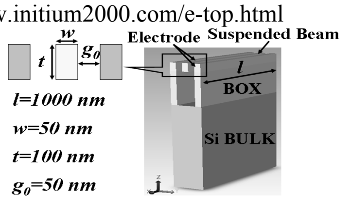

Fig. 1 A basic IP R-NEM structure used for 3D analysis.

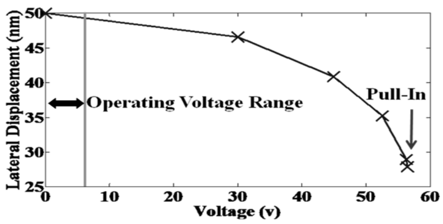

Fig. 2 Voltage dependence of lateral beam displacement.

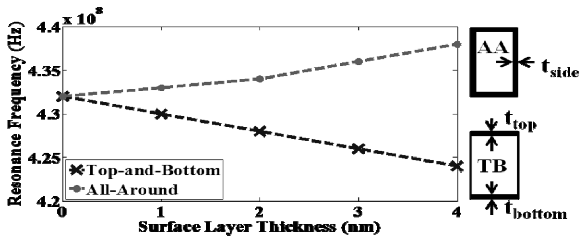

Fig. 3 Resonance frequency vs. surface coating thickness obtained for two different coating configurations, TB and AA.

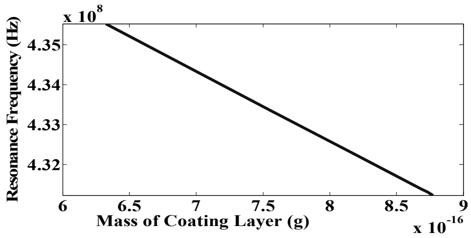

Fig. 4 Resonance frequency vs. coating layer mass.

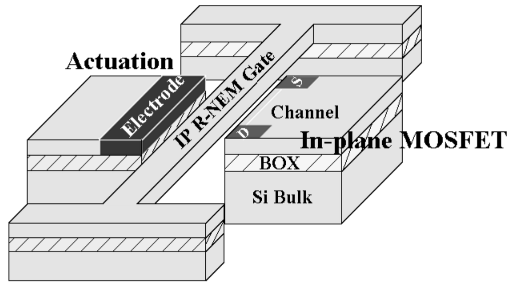

Fig. 5 An IP R-NEM with MOSFET readout.

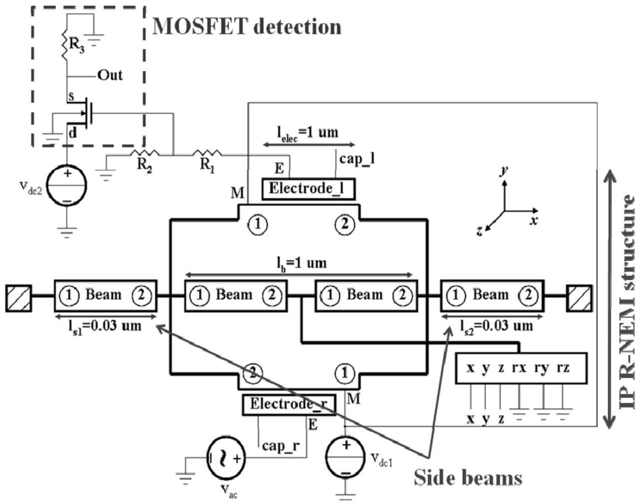

Fig. 6 A hybrid circuit model of the IP R-NEM with MOSFET.

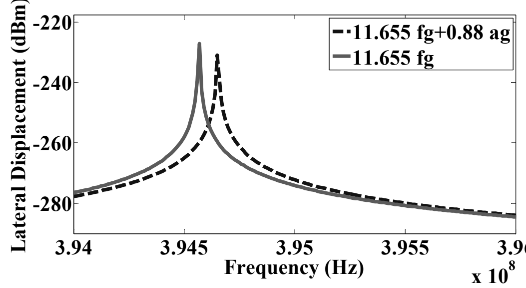

Fig. 7 Resonant spectra obtained for two different values of beam mass.

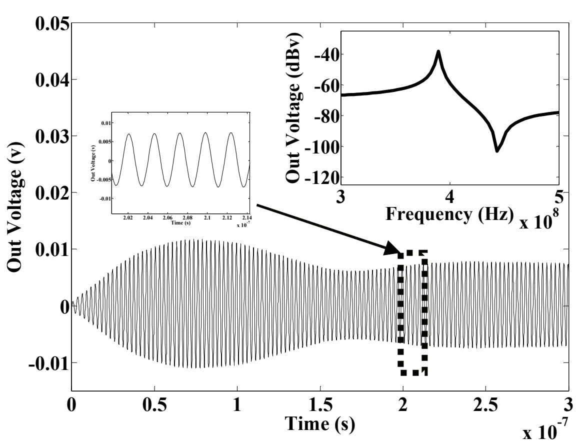

Fig. 8 AC output signal obtained for the IP R-NEM sensor.