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Design of a Vertically Movable Gate Field Effect Transistor (VMGFET) Sensor for Low Frequency Applications

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Abstract **–** In this research, the design, analysis, fabrication, and measurement of a vertically movable gate field effect transistor (VMGFET) sensor has been carried out to see if low-frequency applications are practically possible. For the structure of a movable gate, vibration analyses and measurements are described, such as natural frequencies, the vibration modes corresponding to the natural frequencies, and dynamic responses to some seismic impacts; in addition, electro-magnetic analyses and measurements are performed to identify basic sensor characteristics such as the threshold voltage and drain current of the VMGFET as a function of the effective charge density and the gap between the gate and the substrate body. It turns out that the first natural frequency of 1.6 kHz is measured, which is three-fold higher than the target frequency of 500 Hz, and that a threshold voltage of 2.32 V is obtained from the fabricated sensor, which is electro-magnetically characterized as an enhancement mode.

Keywords**:** VMGFET, accelerometer, vibration characteristics, threshold voltage, enhancement mode.

1. Introduction

Recent remarkable advancements of semiconductor fabrication technology have enabled Micro-Electro-Mechanical Systems (MEMS) technology to make more precise micro-scale mechanical structures, even three-dimensional (3D) micro structures on silicon wafers. The technology may be applied to form a suspended gate structure of a Metal Oxide Semiconductor Field Effect Transistor (MOSFET), in which the electrical current between the source and drain fluctuates by a varying gate position, as shown by (Nathanson et al., 1967). The suspended gate is free to move over the channel. The electric field, resulting from the gate motion with respect to the substrate, modulates the channel charge density, and hence the channel conductivity underneath the gate.

Utilization of a movable gate Field Effect Transistor (FET) has been investigated as a sensing element in the lateral and vertical directions, as shown by (Edmans et al., 2000) and (Schranagl et al., 1999). Fig. 1 shows a 3D movable gate FET, or suspended gate FET.

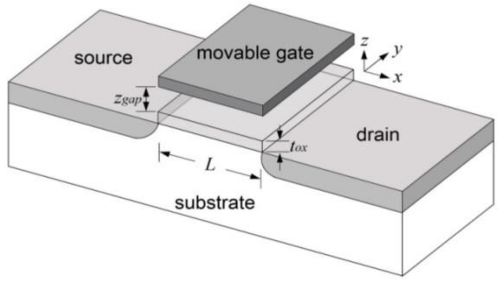

Fig. 1. 3D movable gate field effect transistor.

The device moving in the vertical direction is called a vertically movable gate field effect transistor (VMGFET) [5-7]. Fig. 2 shows a cross-sectional view of the VMGFET design schematic. An external force, such as an electrostatic force or acceleration, applied perpendicularly to the gate surface modulates field-induced charges in the FET channel due to the change in distance between the movable gate and substrate, or the air gap distance z_{gap}; field-induced charges can be identified as the drain current.

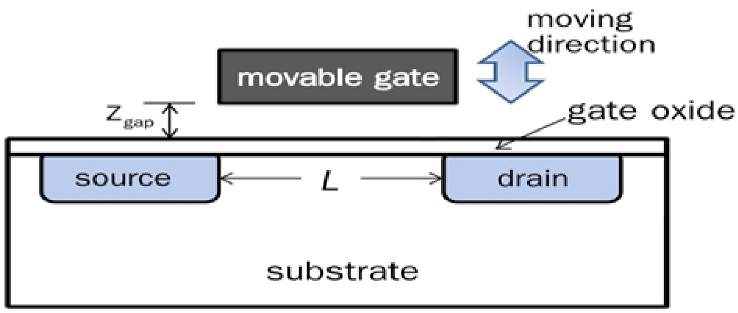

Fig. 2. Cross-sectional view of the vertically movable gate field effect transistor (Williams, et al., 2013).

VMGFETs have been proposed for various sensing applications, such as accelerometers, pressure sensors, and gas sensors. In this study, a particular application is intended for low-frequency range (~500 Hz) with high-sensitivity. The suspended gate structure should be designed to avoid resonance to the proposed range of frequency; a frequency three-times higher than 500 Hz may be accepted. To ensure the gate having suitable resonant frequencies, a finite element (FE) modal analysis has been performed by ABAQUS. Considering the application of the proposed sensor to seismic environment, the structural integrity of the sensor itself has been analysed using typical seismic loads, which are utilized for the design of a nuclear power plant.

In addition, a VMGFET sensor was fabricated to measure the mechanical and electro-magnetic characteristics as a sensing element. As the gap changes between the gate and oxide by vibration inputs, the conductance of the channel of the VMGFET between the source and drain is modulated resulting in a change in the threshold voltage. The threshold voltage is presented as a function of vertical gate position for various effective charge densities. The measurement reveals that the VMGFET sensor has an enhancement mode with a threshold voltage of 2.32 V.

2. VMGFET Design and Modal Analysis

The VMGFET gate consists of two anchors, a proof mass, and serpentine leg structures, as shown in Fig. 3.

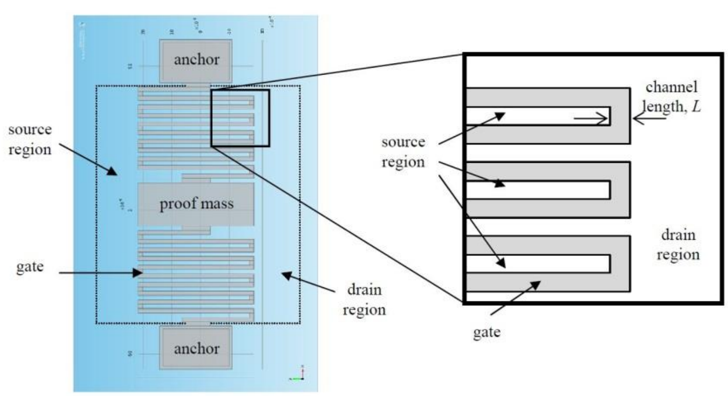

Fig. 3. Top view of the serpentine gate structure with two fixed silicon dioxide anchors (Williams, et al., 2013).

Fig. 3 illustrates the serpentine gate structure design and indicates the location of the fixed silicon dioxide anchors of the gate structure. A large current between drain and source (I_{DS}) was designed by altering the dimensions of the VMGFET while maintaining the structure integrity of the serpentine structure. As the width W may increase, the drain current amplitude increases. The same concept is true for the length of the channel: as L increases, the drain current amplitude decreases. Regarding the thickness of the serpentine gate structure, an increase in thickness would correspond to not only an increase in mass but also an increase in the stiffness constant, and thus each of these parameters needed to be optimized based on the scope of the application for the VMGFET. A high I_{DS} was balanced with a proper input frequency range, a simpler fabrication process, and a structurally stable serpentine gate.

For this modal analysis, the density of the gate material is 2.329 g/cm^3. The Young's modulus and Poisson's ratio were chosen as 150 GPa and 0.17, respectively. In the early stage of development, Williams et al. (2013) reported that natural frequencies of the serpentine gate varied insignificantly as the beam width varied from 10 μm to 15 μm. Thanks to their study, a beam width of 15 μm was chosen. For verification of the design, ABAQUS CAE 6.10-1 was used for the finite element model of the serpentine gate and modal analysis. The FE model and analysis results are shown in Fig. 4.

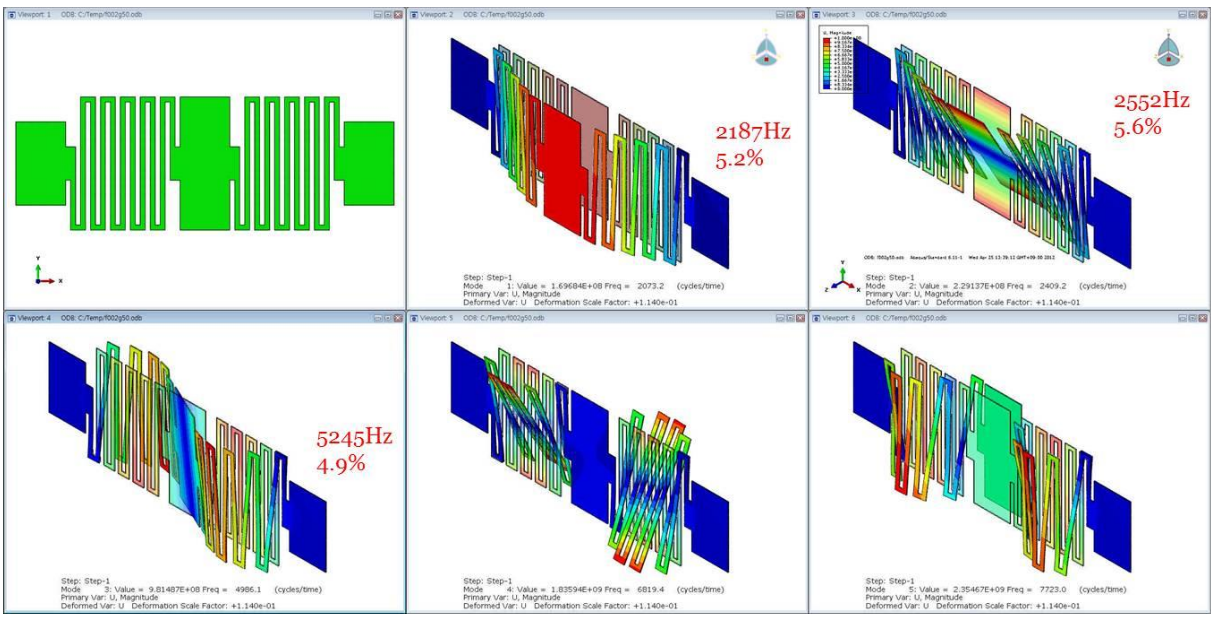

Fig. 4. FE model and analysis results for the designed movable gate.

As we expected, a typical bending mode is obtained at 2.19 kHz. The first twisting mode at 2.55 kHz, and the second bending mode at 5.25 kHz is followed in sequence. The first natural frequency is four-fold higher than the frequency that MEMS sensor will be used for; which means that the signal from the object to be measured would hardly be affected from the vibration of the sensor itself.

Twofold of gravity (2 g) was set for the target acceleration of the sensor. To investigate the structural integrity of the sensor itself while vibrating with the target acceleration, 0.1 g to 3 g acceleration was selected with a typical seismic spectrum; most the energy narrowly spread out within 30 Hz. Fig. 5 shows the seismic spectrum, the displacement response of the sensor corresponding to the spectrum, and the stress field over the sensor. The peak stress on the sensor is predicted to be 0.23 MPa at most, even at three-fold the force of gravity, which is 1.5-times higher than the highest operating acceleration. The calculation stress is a negligible level considering the yield stress of the material.

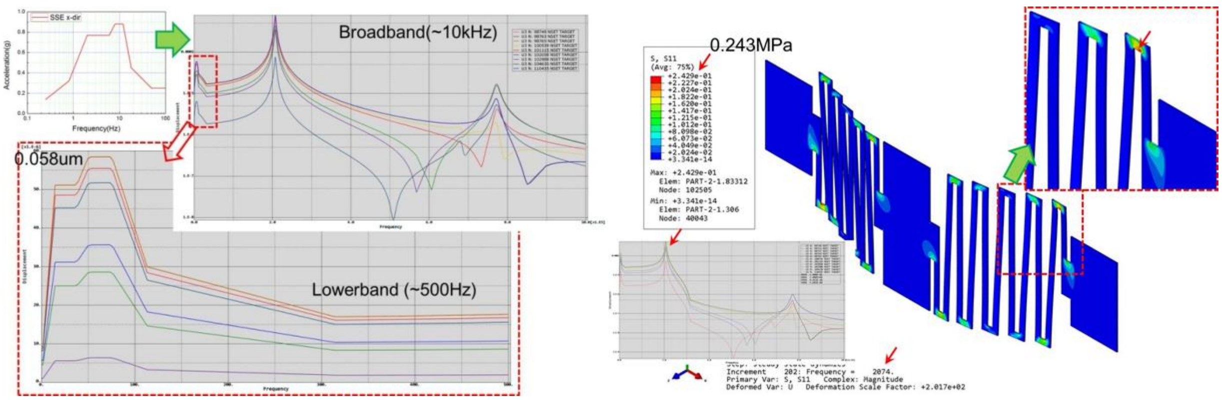

Fig. 5. Seismic spectrum, response displacement spectrums, and the stress field over the serpentine gate.

2. Electro-magnetic Analysis and Measurement of VMGFET

2. 1. Electro-magnetic Analysis (Williams et al., 2012)

The sensing scheme of the VMGFET is used to detect the air gap change between the gate and substrate. The threshold voltage of a MOSFET, V_{Th}, is the minimum voltage required to induce a channel between the source and drain in a MOSFET. The V_{Th} is given by

$$V_{Th} \cong \varphi_{MS} + 2\varphi_F \pm \frac{mkT}{q} - \frac{\left(Q'_{eff} + Q'_B\right)}{C'_{eff}} \tag{1}$$

where the parameters are as follows: φ_{MS} is the metal-semiconductor work function potential difference; φ_F is given by $\varphi_F = -(kT/q)ln(N_A/n_i)$ for a p-type substrate and $\varphi_F = -(kT/q)ln(N_D/n_i)$ for an n-type substrate; N_A is the net ionized acceptor density, and N_D is the donor impurity density in silicon; k is the Boltzmann constant, $k = 1.38 \times 10^{-23}$ J/K; T is the temperature; q is the magnitude of the electron charge, q = 1.602×10^{19} C; n_i is the intrinsic doping concentration of silicon, $n_i = 1.45 \times 10^{10}$ cm^{-3}; Q'_{eff} is the effective gate capacitance per unit area between the gate and silicon substrate; Q'_{eff} is the effective charge density at the oxide-silicon interface; and Q'_B is the depletion region charge density in the semiconductor at the onset of the moderate inversion given by $Q'_B = -(4\varepsilon_s qN_A\ \varphi_F)^{1/2}$ for p-type and $Q'_B = -(4\varepsilon_s qN_D\ |\varphi_F|)^{1/2}$for an n-type silicon substrate, where 1s is the permittivity of silicon and $\varepsilon_s = 1.04 \times 10^{-12}$ F/cm. The parametric value of m is extracted from the experiment values for a specific device technology. The sign associated with the term (mkT/q) is positive for a p-type substrate and negative for an n-type substrate.

C'_{eff} of the VMGFET is an effective value of the series combination of two capacitances; oxide capacitance per unit area, $C'_{ox} = (\varepsilon_0\varepsilon_{rox})/(t_{ox})$ and gap capacitance per unit area, $C'_{gap} = (\varepsilon_0\varepsilon_{rgap})/(Z_{gap})$. In these expressions, the following parameters are used: ε_0 is the permittivity of free space, $\varepsilon_0 = 8.854 \times 10^{-14}$ F/cm; 1rox is the relative dielectric permittivity of silicon dioxide, $\varepsilon_{rox} = 3.9$; t_{ox} is the oxide layer thickness; and z_{gap} is the gap between the bottom of the moving gate and top of the silicon dioxide layer over the channel. Since the relative permittivity of the air gap, ε_{rgap}, is 1, C'_{eff} is given by

$$C'_{eff} = \frac{C'_{ox}C'_{gap}}{C'_{ox} + C'_{gap}} = \frac{\varepsilon_0\varepsilon_{rox}}{Z_{gap}\varepsilon_{rox} + t_{ox}} \tag{2}$$

The threshold voltage, V_{Th}, may be given in terms of the effective charge density, Q'_{eff}, and the gap distance utilizing Eq. (1) and (2), as shown in Fig. 6.

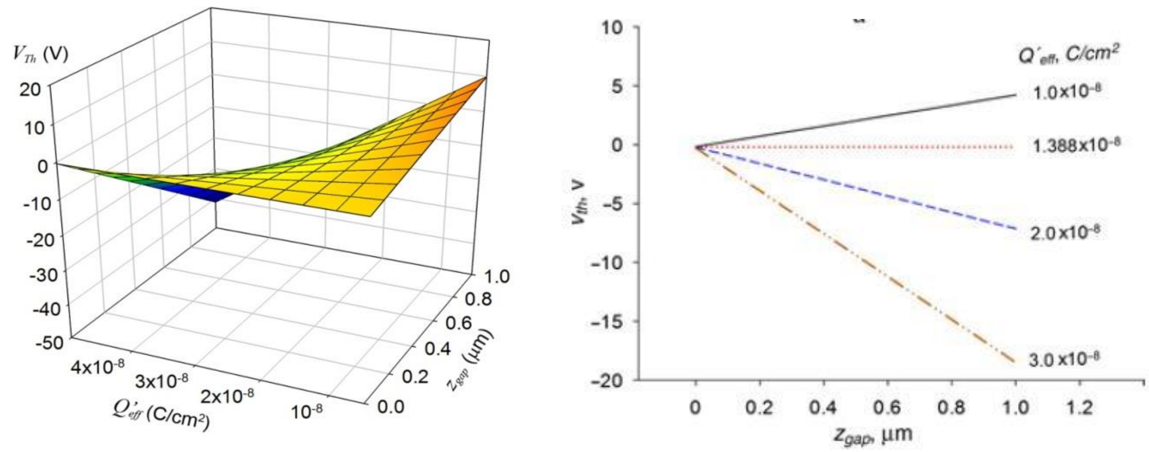

Fig. 6. Threshold voltage as functions of effective charge density and the gap distance (Williams, et al., 2012).

As shown in Fig. 6, V_{Th} is manipulated by Q'_{eff} while varying the air gap distance. When $Q'_{eff} + Q'_B > 0$, V_{Th} becomes a larger positive number as the air gap increases. In contrast, for $Q'_{eff} + Q'_B < 0$, V_{Th} becomes more negative as the air gap increases. When $Q'_{eff} + Q'_B = 0$, V_{Th} is independent of the air gap. The reader may refer to the research results by Williams et al. (2012).

2. 2. Electro-magnetic Measurement of VMGFET Sensor

The measurement from the specimen as shown in Fig. 7 gave 2.32 V as the threshold voltage, as shown in Fig. 8.

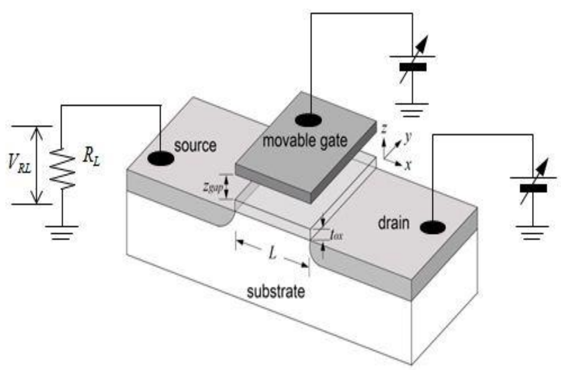

Fig. 7. Measurement setup to measure the threshold voltage of the sensor specimen.

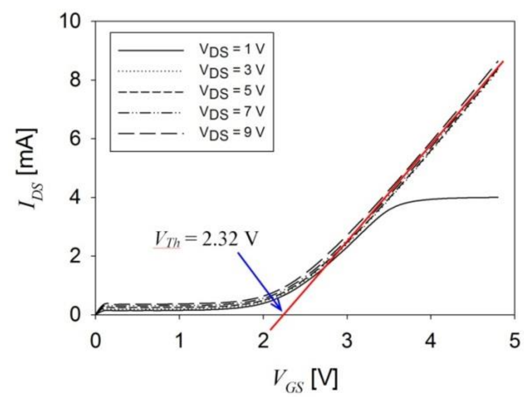

Fig. 8. Threshold voltage as functions of the source-drain voltage.

Since the threshold voltage is less than 3 V, the sensor specimen can be operable using two mercury cells. Fig. 9 shows the MEMS sensor on a PCB board containing a simple circuit operating with two mercury cells. The original signal from the sensor is a little weak. Thus, a signal amplification module was constructed on the circuit board shown in Fig. 9. The reason why the sensitivity of the signal is blunt is believed to be the gold plating on the serpentine gate, which is for the wirings to connect with batteries and measure the voltage and current, as shown in Fig. 7.

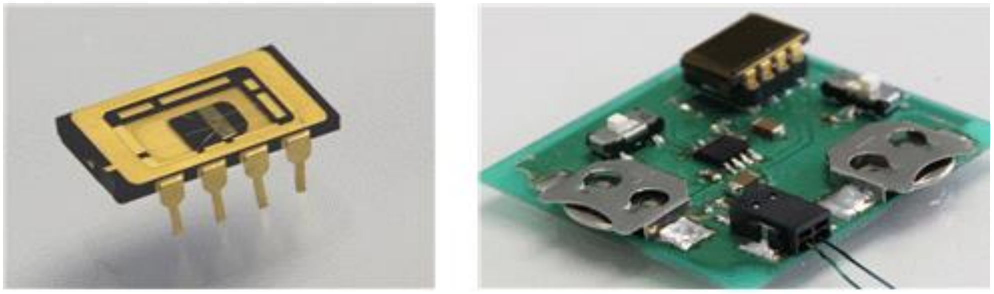

Fig. 9. Sensor specimen on a PCB circuit board.

4. Vibration Measurement of the Sensor

The vibration measurement was simply made to see how flat the measuring frequencies are over the operation range, and to verify how far the first natural frequency is from the highest operating frequency. Fig. 10 shows the flatness over the operating range and the first natural frequency measured from the specimen. The first natural frequency was measured as approximately 1.6 kHz at the bending mode of the serpentine movable gate. As shown in Fig. 10, the flatness seems to be good over the entire operation range, although the flatness goes down a little after 300 Hz.

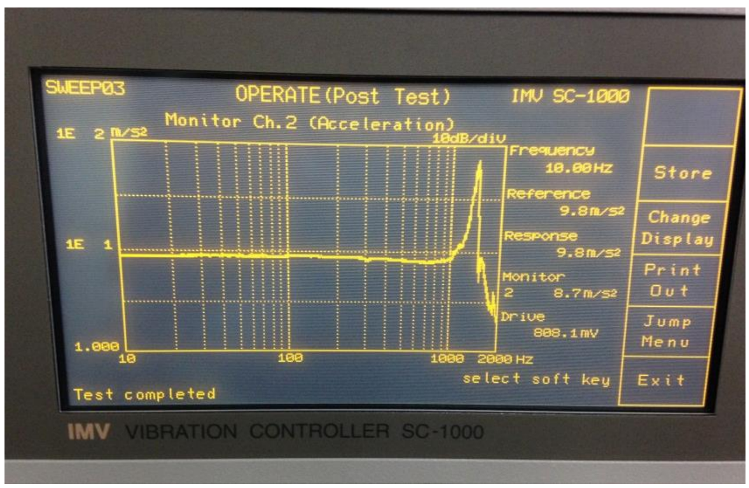

Fig. 10. Vibration response captured from an oscilloscope.

4. Conclusion

A vertically movable gate field effect transistor (VMGFET) has been designed, fabricated, and measured to demonstrate that the field effect transistor can be utilized as an accelerometer for a low-frequency range of up to 500 Hz.

For the mechanical design, the natural frequencies and modes of the serpentine-shaped movable gate have been calculated to verify that the operating frequency is far below the first natural frequency of the gate, and the structural integrity was checked using a typical seismic spectrum with 1.5-times larger acceleration than the operating one.

With the measurement of the electro-magnetic characteristics of the movable gate, the fabricated sensor was characterized as an enhancement mode and n-channel type having a positive threshold voltage.

On the other hand, for the mechanical characteristics, the vibration response was measured to verify whether the flatness of the sensor is acceptable, and if the natural frequency of the sensor exists far beyond the operating frequency range.

In conclusion, through the development process we underwent, it was judged that VMGFET can be utilized as an accelerometer for a low-frequency range.

Acknowledgements

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