Modeling of VB-FET Taking into Account Electro-Mechanical Interaction Between Gate and Channel

●Shinji Ueki , Yuki Nishimori , Hiroshi Imamoto and Gen Hashiguchi

Abstract

Keywords: MOSFET, Oscillator, Equivalent circuit

In this study, we evaluated properties of Vibrating-Body Field Effect Transistor (VB-FET), which integrated MOSFET into MEMS oscillator, taking into account electro-mechanical interaction between gate and channel. Our modeling was started to express VB-FET as an equivalent circuit and then derived Lagrange's function and dissipation function of VB-FET from the equivalent circuit. From the modeling we calculated a transconductance and an output resistance of Coupled VB-FET and found that the value of the transconductance peak is increased up to 6 times and the output resistance of VB-FET is reduced by half at the resonance frequency . As described here, VB-FET has unique properties which offer new class of functions in MEMS.

Introduction

Vibrating-Body Field Effect Transistor (VB-FET) was proposed in 2007 by D.Grogg et al. The device is integrated FETs into the side wall of MEMS oscillators such as ring oscillator, disk oscillator and parallel plate oscillator. The proposed modeling was divided the VB-FET with electro static actuators composed of gate-source electrodes or gate-drain electrodes and FET modulated by the displacement between the gate and channel. In this study, we consider gate-channel interaction as an energy exchange media between electric and mechanical system and simulate characteristics of the VB-FET supposed that both of gate and channel are movable.

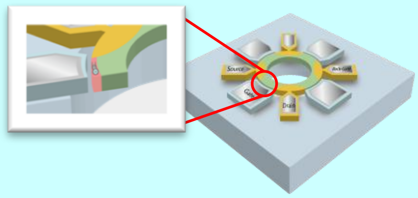

Fig. 1. A schematic view of VB-FET

Methods

■We calculated Lagrange 's function and dissipation function from the equivalent circuit.

●Lagrange's function

$$L = \frac{1}{2}m_g v_g^2 + \frac{1}{2}m_c v_c^2 + \sum_{i=1}^{n}\frac{C_i}{2}(V_{GS} + e_G - V_T - V_i - e_i)^2 + \frac{C_{GS}}{2}(V_{GS} + e_G - V_T)^2 + \frac{C_{GD}}{2}(V_{GS} + e_G - V_T - V_{DS} - e_D)^2 - \frac{1}{2}k_{sg}(d_g + y_g)^2 - \frac{1}{2}k_{sc}(d_c + y_c)^2$$

● Dissipation function

$$F = \frac{1}{2}r_g v_g^2 + \frac{1}{2}r_c v_c^2 + \sum_{i=1}^{n}\frac{1}{2R_i}(V_i + e_i - V_{i-1} - e_{i-1})^2$$

■Using Lagrange 's function and dissipation function, we make linear equations in terms of mechanical velocity v and voltage e and calculated motion equations .

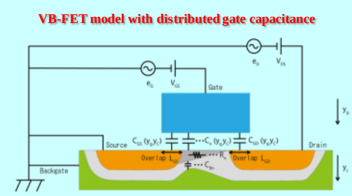

Fig. 2. Schematic diagram of VB-FET

●Motion equations of VB-FET

$$f_g = \left(Z_{mg} - \frac{\frac{C_0}{(d_0-d_g-d_C)^2}\sum_{i=1}^{n}(-V_i+V_p)^2 + \frac{W\epsilon\left(L_{GD}(-V_{DS}+V_p)^2 + L_{GS}(V_p)^2\right)}{(d_0-d_g-d_C)^3}}{j\omega}\right)v_g + \left(\frac{\frac{C_0}{(d_0-d_g-d_C)^2}\sum_{i=1}^{n}(-V_i+V_p)^2 + \frac{W\epsilon\left(L_{GD}(-V_{DS}+V_p)^2 + L_{GS}(V_p)^2\right)}{(d_0-d_g-d_C)^3}}{j\omega}\right)v_c - \frac{C_0}{(d_0-d_g-d_C)}\sum_{i=1}^{n}(V_i-V_p)e_i + \frac{W\epsilon(L_{GD}+\Delta x)(V_{DS}-V_p)}{(d_0-d_g-d_C)^2}e_D + \left(\frac{C_0}{(d_0-d_g-d_C)}\left(\sum_{i=1}^{n}V_i - V_p\right) - \frac{W\epsilon\left(L_{GD}(V_{DS}-V_p) - L_{GS}V_p\right)}{(d_0-d_g-d_C)^2}\right)e_G$$

$$f_c = \left(\frac{\frac{C_0}{(d_0-d_g-d_C)^2}\sum_{i=1}^{n}(-V_i+V_p)^2 + \frac{W\epsilon\left(L_{GD}(-V_{DS}+V_p)^2 + L_{GS}(V_p)^2\right)}{(d_0-d_g-d_C)^3}}{j\omega}\right)v_g + \left(Z_{mc} - \frac{\frac{C_0}{(d_0-d_g-d_C)^2}\sum_{i=1}^{n}(-V_i+V_p)^2 + \frac{W\epsilon\left(L_{GD}(-V_{DS}+V_p)^2 + L_{GS}(V_p)^2\right)}{(d_0-d_g-d_C)^3}}{j\omega}\right)v_c - \frac{C_0}{(d_0-d_g-d_C)}\sum_{i=1}^{n}(V_i-V_p)e_i + \frac{W\epsilon(L_{GD}+\Delta x)(V_{DS}-V_p)}{(d_0-d_g-d_C)^2}e_D + \left(\frac{C_0}{(d_0-d_g-d_C)}\left(\sum_{i=1}^{n}V_i - V_p\right) - \frac{W\epsilon\left(L_{GD}(V_{DS}-V_p) - L_{GS}V_p\right)}{(d_0-d_g-d_C)^2}\right)e_G$$

$$i_k = \left(\frac{C_0(V_i-V_p)}{(d_0-d_g-d_C)} + \frac{A_i}{j\omega}\right)v_g + \left(\frac{C_0(V_i-V_p)}{(d_0-d_g-d_C)} + \frac{A_i}{j\omega}\right)v_c + C_{i-1}e_{i-1} + (j\omega C_0 + B_i)e_i + C_i e_{i+1} - (j\omega C_0 - D_i)e_G$$

$$i_D = \left(\frac{C_0(V_i-V_p)}{(d_0-d_g-d_C)} + \frac{L_{GD}(V_{DS}-V_p)W\in}{(d_0-d_g-d_C)^2} + \frac{E_i}{j\omega}\right)v_g + \left(\frac{C_0(V_i-V_p)}{(d_0-d_g-d_C)} + \frac{L_{GD}(V_{DS}-V_p)W\in}{(d_0-d_g-d_C)^2} + \frac{E_i}{j\omega}\right)v_c + C_{i-1}e_{i-1} + \left(j\omega\left(C_0 + \frac{L_{GD}W\in}{(d_0-d_g-d_C)}\right) + F_i\right)e_i - \left(j\omega\left(C_0 + \frac{L_{GD}W\in}{(d_0-d_g-d_C)}\right) - G_i\right)e_G$$

$$i_G = \left(-\frac{C_0}{(d_0-d_g-d_C)}\left(\sum_{i=1}^{n}V_i - iV_p\right) + \frac{L_{GD}(V_{DS}-V_p)W\in}{(d_0-d_g-d_C)^2} + \frac{L_{GS}V_pW\in}{(d_0-d_g-d_C)^2} + \frac{H_i}{j\omega}\right)v_g + \left(-\frac{C_0}{(d_0-d_g-d_C)}\left(\sum_{i=1}^{n}V_i - iV_p\right) + \frac{L_{GD}(V_{DS}-V_p)W\in}{(d_0-d_g-d_C)^2} + \frac{L_{GS}V_pW\in}{(d_0-d_g-d_C)^2} + \frac{H_i}{j\omega}\right)v_C - \sum_{i=1}^{n}(j\omega C_0 - D_{i-1})e_{i-1} - \left(j\omega\left(C_0 + \frac{L_{GD}W\in}{(d_0-d_g-d_C)}\right) + F_i\right)e_i + j\omega\left(iC_0 + \frac{(L_{GD}+L_{GS})W\in}{(d_0-d_g-d_C)}\right)e_G$$

※$A_i, B_i, C_i, D_i, E_i, F_i, G_i,$ and H_i are the coefficients.

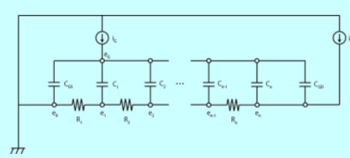

Fig. 3. Equivalent circuit of VB-FET

Results

■We evaluated properties of VB-FET by motion equations .

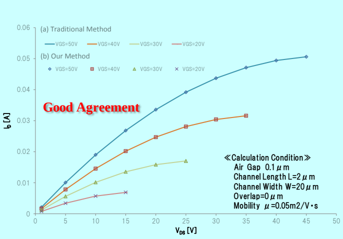

Fig. 4. Comparison of IV-curves between (a) traditional method and (b) our method

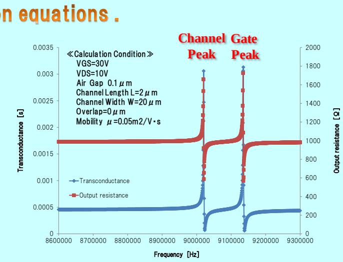

Fig. 5. Calculated a transconductance and a output resistance of Coupled VB-FET

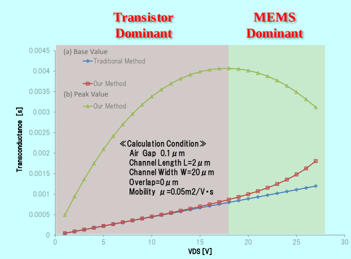

Fig. 6. Comparison of transconductance (a) base and (b) peak value

Summary

■We derive motion equations of VB-FET taking into account electro-mechanical interaction.
■The transconductance of VB-FET shows peaks at the resonance frequency of mechanical vibration.
■There is an optimal condition to maximize the transconductance.