Electro-Mechanical simulation of programming/readout characteristics for NEMS memory

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Introduction

Recent progress of silicon nanofabrication techniques has enabled to explore a new field of silicon Nano Electro-Mechanical Systems (NEMS) research. Since the characteristic frequency of electromechanical systems, in principle, increases in inverse proportion to their sizes, the NEMS have a possibility of extremely high-speed operation [1]. We proposed a new non-volatile memory device concept based on mechanically-bistable operation of the floating gate (FG) in the cavity, combined with nanocrystalline Si (nc-Si) dots (Fig. 1) [2] and analyzed the mechanical properties of the floating gate by using the 3-D finite element simulation [3]. In this paper we analyze the gate voltage-displacement of the floating gate characteristic using the 3-D finite element mechanical simulation combined with electrostatic simulation. We also analyze the electric properties of the NEMS memory using semi-analytical method.

Structural dependence of Z-V_g characteristics

The structure used for the present simulation is shown in Fig. 2. It consists of a suspended SiO_2 beam, double SiO_2 side walls and a top metal gate electrode. In the mechanical simulation we assumed that the top and side outer surfaces and the two bottom surfaces of the side walls were physically fixed. For realistic modeling of the floating gate we introduced the internal compressive stress into the suspended beam. In the electrostatic simulation the side-wall bottom surfaces were grounded, and the potential of the gate electrode was given by the gate voltage V_g. We assumed that the positive surface charge is introduced into the suspended beam. The Si substrate surface electron density was calculated via the surface potential.

Under these conditions, we calculated the beam displacement with changing V_g. We first studied how the FG position in the cavity affects the NEMS memory properties. We varied the vertical position where the FG was clamped in the cavity with maintaining the total cavity height. The Z-V_g curves showed large hysteresis loops, and they shifted horizontally towards higher V_g as the beam clamp position was moved up in the cavity. The shift of the Z-V_g curve apparently causes the difference in the gate voltages needed to flip the beam between the two buckled states. Assuming that the surface potential and gate voltage are zero, the electrostatic potential of the beam is approximately given by the parabolic curve with its maximum at the center of the cavity. The potential of the beam differs for the upward and downward bent beams when the beam is not clamped at the mid height of the cavity. In addition, the electrostatic potential is higher near the substrate as the surface potential is not zero due to the charge retained in the beam. These lead to the Z-V_g curve shift.

Next we analyzed the effects of the FG mechanical boundary conditions on the NEMS memory characteristics. As the beam is clamped on the side walls, the whole cavity structure is expected to influence on the memory characteristics. So we calculated the Z-V_g curves for various mechanical boundary conditions. In Fig. 4, "fg side" represents the ideal boundary condition that the positions of the beam both ends are physically fixed. In this case, the beam is mechanically free from the surrounding cavity structures. The switching voltages are obviously highest for "fg side" as any beam stress cannot be absorbed by the cavity. A slight asymmetry in the Z-V_g curve is caused only by the electrostatic phenomenon discussed earlier. "wall side" represents that both the bottom and the outer side surfaces are physically fixed, and "gate top" that the top surface of the gate electrode is also fixed physically in addition to "wall side". In other words the surrounding cavity becomes more flexible for the beam by varying the condition in the order of "fg side", "gate top", "wall side", "wall bottom". Figure 4 shows that the switching voltage is reduced when the cavity becomes more flexible. However, the softer cavity causes a larger shift of the Z-V_g curve, and the beam does not show any bistability at $Vg = 0$ for the softest cavity with "wall bottom". It should also be noted that equilibrium beam displacements (Z at $Vg=0$) also becomes smaller when the cavity becomes softer. These results indicate that optimization of the overall beam-in-cavity structure is crucial.

Electrical readout characteristics

We finally studied the electrical readout characteristics of the NEMS memory. By using the above results, we calculated the surface potential for upward and downward bent states. As shown in Fig. 5 about a half area of the substrate surface is in the strong inversion for the downward bent state, and in the depletion for the upward bent state. A remarkable change in the surface potential is converted into the conduction current change by designing the sense MOSFET underneath properly.

We then evalulated the C-V_g and I_{ds}-V_{ds} characteristics by using the semi-analytical method (Fig. 6). The C-V_g curve shows clear bistability at V_g = 0V. The I_{ds}-V_{ds} characteristic was calculated using Pao-Sah's double integral. As shown in Fig. 7 I_{ds} at V_g=0V was about 10^{-6}A and 10^{-15}A at ON and OFF states, respectively. We got very high ON/OFF ratio. These results indicate that the NEMS memory states can indeed be read out at V_g=0V.

Summary

We analyzed the Z-V_g relationship with changing the structural and mechanical conditions. We found that the floating gate could switch its state by the electrostatic force, and the position in which the floating gate was installed and the surrounding mechanical conditions cause the Z-V_g curve shift. We also analyzed electric properties of the NEMS memory by using semi-analytical method. We found that this memory may be possible to read out the current state at V_g=0V, and to be high ON/OFF ratio.

References

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[3] T.Nagami *et al.*, Abstr.of Si Nanoelectronics Workshop, p.94,2005

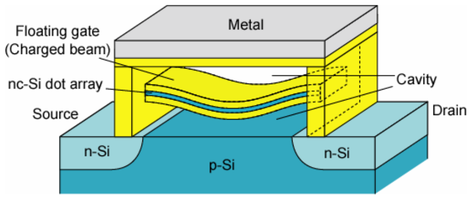

Fig.1: Schematic illustration of a NEMS memory device

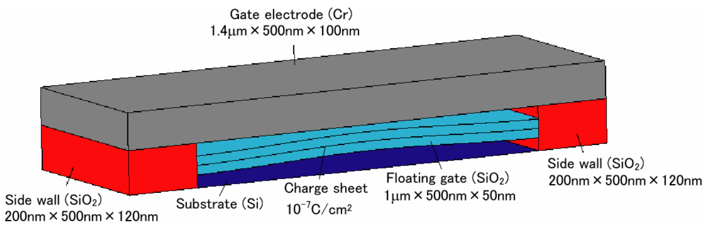

Fig.2: Simulation model

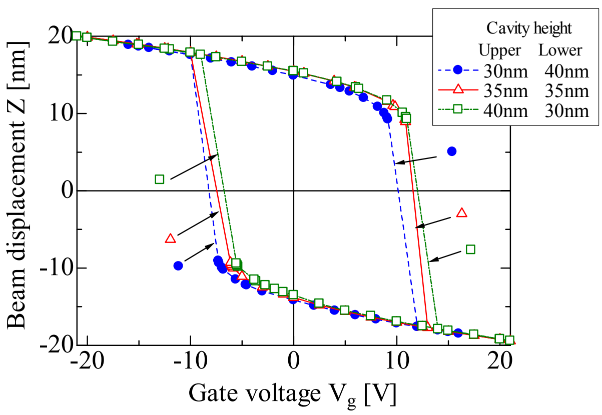

Fig.3: Displacement-voltage characteristic with changing the position of the beam

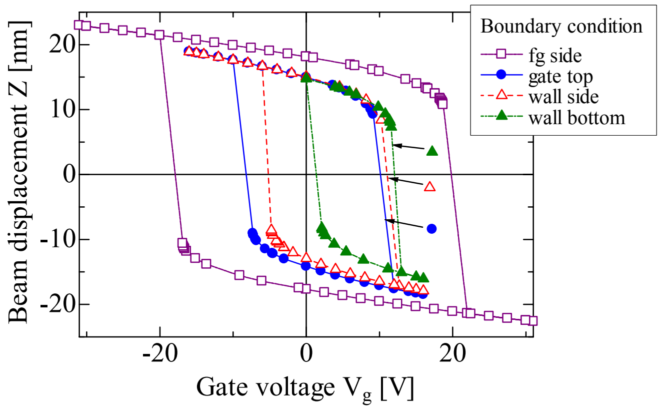

Fig.4: Displacement-voltage characteristic with changing mechanical condition. Upper and lower cavities are 30nm and 40nm, respectively.

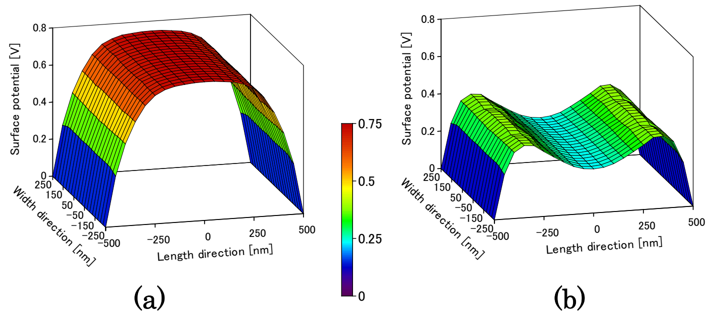

Fig.5: Surface potential distribution for 30nm upper cavity and 40nm lower cavity. Strong inversion voltage ψ_{inv} is 0.683V. (a) downward bent (ON state), (b) upward bent (OFF state)

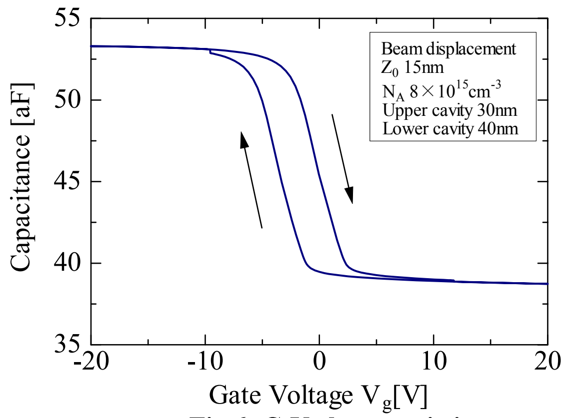

Fig.6: C-V characteristic

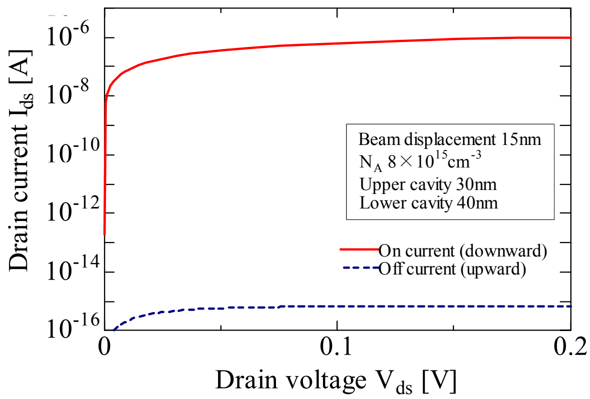

Fig.7: I_{ds}-V_{ds} characteristic at V_g=0V