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Evaluation of change in drain current due to strain in 0.13-μm-node MOSFETs

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1. Introduction

With the trend towards high integration of LSIs, the mechanical stress in a device has been increasing rapidly because of the high intrinsic stress in thin films. The stress developed in recent MOSFETs sometimes exceeds a few hundred mega pascals, which is high enough to cause a change in the transistor characteristics. That is, the mechanical stress can change the drain current of an 100-nm MOSFET more than 10% [1, 2]. The change occurs as a result of the piezoresistance effect caused by residual stress in a silicon substrate [3]. It is thus very important to control the mechanical stress in 100-nm MOSFET devices in order to improve mechanical reliability and electronic performance.

In this work, we clarified the strain (stress) sensitivity of drain current of a 0.13-μm-node MOSFET, and developed a method for predicting the change in MOSFET drain current caused by thin-film processing.

2. Strain sensitivity of drain current

It has been reported that the electronic performance of a MOSFET changes almost linearly with applied or residual stress [3-5]. We thus assumed that the change in saturation drain current (Ids) can be explained as a linear function of normal strains,

$$\Delta Ids = \sum A_i \Delta\varepsilon_i \quad \text{(i=x, y, z)} \qquad (1)$$

where ΔIds is the change of Ids, $\Delta\varepsilon_i$ is the change of the three-dimensional strain component, and A_i is strain sensitivity. We applied a four-point-bending method to determine A_x and A_y, and A_z was determined by changing an intrinsic stress in a thin film used for a gate structure of a MOSFET. The test MOSFETs were fabricated on a Si (001) surface (xy-plane), and the channels were fabricated parallel to the Si<110> axis (x-axis).

The change in the strain in the MOSFET structure during the above loading tests was analyzed by using a finite element method. The strain was then related to the measured Ids change in order to determine A_i of the n-MOSFET and A_i of the p-MOSFET.

Four-point-bending test, in-plain (x, y) axis loading

A four-point-bending test, which is depicted in Fig. 1, can load an in-plane axial strain along to the longitudinal direction of a sample. Therefore, we cut out a test sample from a wafer so that the channel direction of a MOSFET was parallel or perpendicular to the longitudinal direction of each sample. The length and width of MOSFETs were both 15 μm.

Figure 1 summarizes the measured change in drain current due to the load parallel to the channel. The drain current of an n-MOSFET increases with increase in tensile strain by about 7.2%/1000 micro strain. While the drain current of a p-MOSFET decreases with increase in tensile strain by about 10.0%/1000 micro strain.

Figure 2 shows the change in drain current due to the load perpendicular to the channel. The drain current of both the n-MOSFET and p-MOSFET increases with increase in tensile strain. The change in drain current of the n-MOSFET and the p-MOSFET are about 4.0%/1000 micro strain and 7.0%/1000 micro strain, respectively.

Z-axis loading

The normal strain (ε_z) in the channel of the MOSFETs was varied by changing the intrinsic stress in the SiN film that was used as a contact etch-stop material of the MOSFET. The SiN film, about 50 nm to 100 nm thick, was deposited over the transistor structure. The intrinsic stress in the SiN film changes the strain field (especially ε_z) of the channel. The compressive strain in the channel increases with increase in compressive stress in the film and decrease in gate length. The intrinsic stress in the SiN film can be varied by changing the deposition condition of the film. The strain field of the channel region of the MOSFET was analyzed using a stress simulation program, which can take the intrinsic stress into account [5]. In the case of a MOSFET with a gate length of 0.14 μm, this analysis, for example, showed that the change in SiN film stress of +1.3 GPa causes the change in ε_z of -1.1×10^{-3}, ε_x of 3.8×10^{-4}, and ε_y of 3.0×10^{-5}. From these experiments and analyses, we determined the change rate of drain current due to the strain change in the channel region.

Figure 3 summarizes the change in the drain current due to normal strain (ε_z). The drain current of the n-MOSFET decreases with increase in tensile strain by about 13.8%/1000 micro strain. On the other hand, the drain current of the p-MOSFET increases with increase in tensile strain by about 11.2%/1000 micro strain.

Strain sensitivity of drain current

By using these experimental results, we determined the strain sensitivity constants (A_is) for an n-MOSFET and a p-MOSFET as follows.

$$\Delta Ids_N = 5.2\times10^3\Delta\varepsilon_x + 2.2\times10^3\Delta\varepsilon_y - 9.7\times10^3\Delta\varepsilon_z \ (\%) \quad (2)$$

$$\Delta Ids_P = -7.4\times10^3\Delta\varepsilon_x + 8.3\times10^3\Delta\varepsilon_y + 8.2\times10^3\Delta\varepsilon_z \ (\%) \quad (3)$$

The drain current of an n-MOSFET increases with increase in in-plane tensile strains and decrease in normal strain. On the other hand, the drain current of a p-MOSFET increases with increase in in-plane compressive strain parallel to the channel, and in-plane tensile strain perpendicular to the channel. It also increases with increase in normal tensile strain. Therefore, a bi-axial in-plain tensile strain field can improve performance of an n-MOSFET, while an anisotropic in-plain strain field is necessary for improving performance of a p-MOSFET.

3. Verification

We applied eqs. (2) and (3) to predict the drain current change in MOSFETs. Shallow trench isolation (STI) causes high compressive in-plain strains in the channel region. The developed strain is a function of length of the active region as shown in Fig. 4. Thus, the effect of the active length on the drain current was discussed.

Figures 5(a) and (b) compare the predicted change in the drain current of the MOSFETs with the measured results. The drain current of the n-MOSFET decreased rapidly at an active length of 0.96 μm, while that of the p-MOSFET increased rapidly at that point. The predicted values agree well with the measured ones. The errors of the prediction are about 3% for the n-MOSFET and about 10% for the p-MOSFET. It can, therefore, be concluded that this method for predicting change in the drain current will help us to improve electronic performance of MOSFETs.

4. Conclusions

We investigated the strain sensitivity of the drain current of MOSFETs and found that the drain current varies with the strain field in the channel region. Using the results of this investigation, we developed a method for predicting the change in the drain current quantitatively.

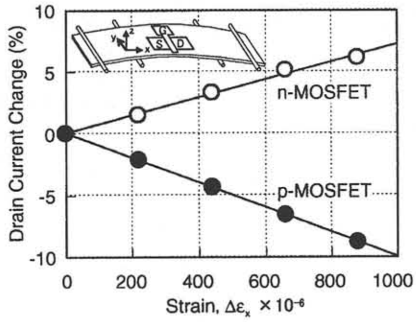


Fig. 1 Change in drain current due $\Delta\varepsilon_x$.

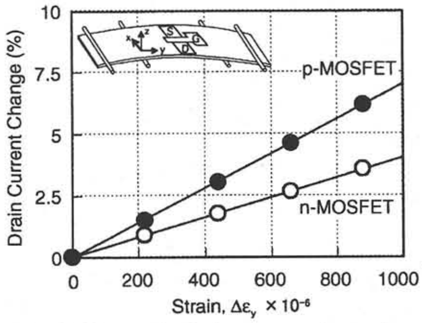


Fig. 2 Change in drain current due to $\Delta\varepsilon_y$.

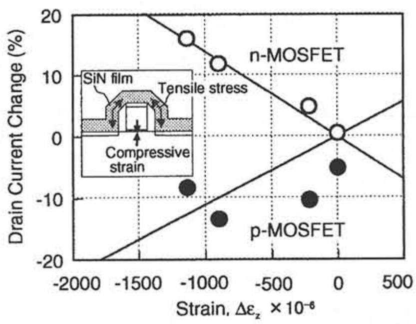


Fig. 3 Change in drain current due to $\Delta\varepsilon_z$.

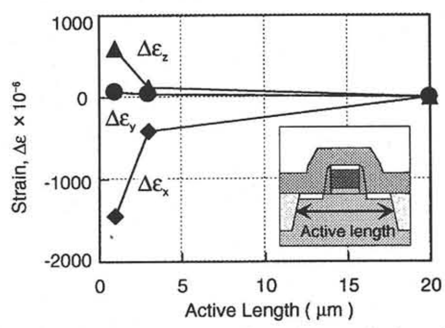
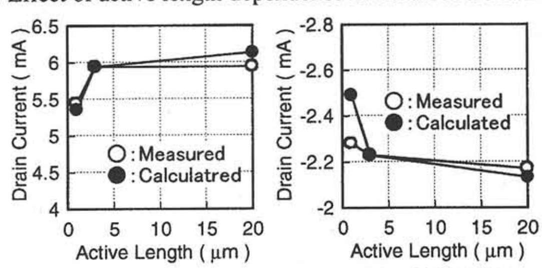


Fig. 4 Effect of active length dependence on strain in a channel.



(a) n-MOSFET (b) p-MOSFET

Fig. 5 Comparison of predicted change of drain current of MOSFETs with the measured change.

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