Development of Evaluation Method for Estimating Stress-Induced Change in Drain Current in Deep-sub-micron MOSFETs*

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Abstract
We developed a method to predict the change in the drain current in deep-sub-micron MOSFETs due to strain. The change in MOSFET drain current can be explained as a linear function of normal strains. The strain sensitivities of the MOSFETs drain current were clarified experimentally. The results indicated that drain current in N-MOSFETs increases with increases in in-plane tensile strains and normal compressive strain. Whereas, the results indicated the drain current of in P-MOSFETs increases with in-plane compressive strain parallel to the channel, and in-plane tensile strain perpendicular to the channel. The drain current also increases with normal tensile strain. The predicted values showed good agreement with the measured values. This method for predicting change in the drain current due to stress will help us to improve electronic performance of MOSFETs.

Key words: Electronics, Residual Stress, Strain, MOSFET, Current, Structural Analysis, Computational Mechanics

1. Introduction
Information technology requires the development of highly integrated semiconductor devices, such as dynamic random access memories and large-scale integration chips. With the trend towards developing these highly integrated devices, the mechanical stress in these devices has been increasing rapidly. Because these devices have high-intrinsic-stress films in their structures, they have become more complex than past device structures. As a result, the stress occurring in the device sometimes exceeds a hundred mega pascals.

The stress increase causes mechanical failure of the device, such as delamination of laminated thin films, cracking of wiring, and dislocation(1). In addition, the stress also causes degradation of the electrical characteristics, such as the leakage current of memory capacitors and the drain current in metal oxide semiconductor field effect semiconductors (MOSFETs).

The mobility of an electron and a hole in a MOSFET depend on strain because the strain affects the band-structure(2). Therefore, the drain current in MOSFETs is affected by the stress load to the MOSFETs(3), and the drain current is affected by internal stress. The
effect has become noticeable in current structures than past structures because of increasing internal stress. A relationship between the drain current and the stress in a device structure has been researched\(^{(4)}(5)\). However, no researchers can quantitatively predict the change in the drain current due to the internal stress in a device.

Controlling the mechanical stress in a deep-sub-micron MOSFET is important to improve mechanical reliability and electronic performance. In this work, we clarified the strain (stress) sensitivity of drain current in deep-sub-micron MOSFETs and developed a method to predict changes in the drain current in MOSFETs caused by thin-film processing.

2. Relationship between drain current and strain

2.1 Structure and electrical properties of MOSFETs

Figure 1 shows a schematic diagram of a MOSFET. The MOSFET is fabricated on a silicon substrate and consisted of a gate-dielectric-film made of silicon dioxide, a gate electrode made of poly-silicon and a source/drain. The wiring and interlayer above the MOSFET are fabricated.

The drain current is a current in a channel between the source and drain. The drain current flows when gate voltage \(V_{gs}\) and drain voltage \(V_{ds}\) are applied to each electrode. The drain current saturates when the drain voltage increases under applying constant gate voltage. In the following text, the saturation drain current is called the drain current, \(I_{ds}\).

There are two different kinds of MOSFETs: N-MOSFETs and P-MOSFETs. The carrier of drain current in N-MOSFETs is an electron, whereas the carrier of drain current in P-MOSFET is a hole. The characteristics of N-MOSFETs and P-MOSFETs are different. Therefore we investigated both kinds of MOSFETs.

2.2 Formulation of relationship between drain current and strain

We investigated the relationship between the drain current and the strain, when the carrier velocity of the current reached saturation velocity. The drain current has been reported to be a linear function of strain (stress) because of the piezoresistance effect\(^{(7)}\). However, the relationship is applicable to carrier velocity that does not reach saturation velocity. The carrier velocity of the MOSFETs we investigated nearly reached saturation velocity. So, the relationship may not apply to be true for our MOSFETs. Therefore, we investigated the relationship by the same way as that reported elsewhere\(^{(7)}\).

The drain current for a MOSFET at saturation carrier velocity is expressed by\(^{(8)}\)

\[
I_{ds} = WC_{ox}v_{sat}(V_{gs} - V_{th})
\]

where \(W\) is the gate width, \(C_{ox}\) is the capacitance of the gate electrode, \(v_{sat}\) is the carrier saturation velocity, \(V_{gs}\) is the gate voltage, and \(V_{th}\) is the threshold voltage.
The carrier saturation velocity, \( v_{\text{sat}} \), is expressed by

\[
E_c = \frac{2v_{\text{sat}}}{\mu_{\text{eff}}} \tag{2}
\]

where \( E_c \) is the critical lateral electric field (the electric field between source and drain) for the carrier saturation velocity and \( \mu_{\text{eff}} \) is the carrier mobility.

Equation (1) and (2) are rewritten as

\[
I_{ds} = \mu_{\text{eff}} E_c C_{ox} \frac{W}{2} \left( V_{gs} - V_{th} \right). \tag{3}
\]

Assuming small fractional changes under strain occur, the change in drain current \( \Delta I_{ds} \) is given by

\[
\frac{\Delta I_{ds}}{I_{ds}} = \frac{\Delta \mu_{\text{eff}}}{\mu_{\text{eff}}} + \frac{\Delta C_{ox}}{C_{ox}} + \frac{\Delta W}{W} - \frac{\Delta V_{th}}{V_{gs} - V_{th}}. \tag{4}
\]

The strain caused by stress is less than 1% so that the changes, such as \( \Delta C_{ox} \) and \( \Delta W \), due to dimensional changes can be ignored. Assuming a change in threshold voltage, \( \Delta V_{th} \) can also be ignored because of its small change, Eq. (4) is rewritten as

\[
\frac{\Delta I_{ds}}{I_{ds}} \approx \frac{\Delta \mu_{\text{eff}}}{\mu_{\text{eff}}}. \tag{5}
\]

The change in carrier mobility can be approximated to the change in resistance of the channel\( \text{7)(7)} \)

\[
\frac{\Delta I_{ds}}{I_{ds}} \approx \frac{\Delta \mu_{\text{eff}}}{\mu_{\text{eff}}} = -\frac{\Delta R}{R}. \tag{6}
\]

When the carrier velocity does not reach saturation velocity, the drain current is expressed by

\[
I_{ds} = \mu_{\text{eff}} C_{ox} \frac{W}{2L} \left( V_{gs} - V_{th} \right)^2 \tag{7}
\]

where \( L \) is the gate length. By similar discussion, Eq. (7) is rewritten by\( \text{7)} \)

\[
\frac{\Delta I_{ds}}{I_{ds}} \approx \frac{\Delta \mu_{\text{eff}}}{\mu_{\text{eff}}} = -\frac{\Delta R}{R}. \tag{8}
\]

Equation (8) is the same as Eq. (6). Therefore, we treated the relationship between the drain current and the strain at the carrier saturation velocity the same as the relationship between the drain current and the strain when the carrier velocity is not saturated.

Assuming a linear function between the strain and the resistance of channel in Eq. (6), the change in drain current can be expressed as a linear function of normal strain for x, y, and z-axis. In this work, we expressed the change in drain current in Eq. (6) by

\[
\frac{\Delta I_{ds}}{I_{ds}} = \sum_i A_i \Delta \varepsilon_i \tag{9}
\]

where \( \Delta \varepsilon_i \) \((i = x, y, \text{and } z)\) is the change in a three-dimensional strain component, and \( A_i \) \((i = x, y, \text{and } z)\) is the strain sensitivity.

Figure 2 shows a coordinate system and a crystallographic axis of a silicon wafer we defined. The test MOSFETs were fabricated on a Si (001) surface (x,y-plane), and the channels were fabricated parallel to the Si<110> axis (x-axis).

### 3. Experiment for estimating strain sensitivity

The strain sensitivity, \( A_i \) \((i = x, y, \text{and } z)\), in Eq. (9) was estimated experimentally. We applied a strain to the MOSFETs in three ways to determine the dependence of the drain current on the strain. The strain sensitivity coefficients were calculated by using the drain current dependence on the strain.

We applied a four-point-bending method to determine \( A_x \) and \( A_y \). And \( A_z \) was determined by changing the intrinsic stress in a thin film used for a gate structure in a MOSFET. The change in the strain in the MOSFET structure during the above loading tests
was analyzed by using a finite element method.

3.1 Method for in-plane strain loading

The dependence of the change in drain current on the change in in-plane strain was measured by a four-point-bending method, as shown in Fig. 3. The four-point-bending method can load an in-plane axial strain in the longitudinal direction of a sample. Therefore, we cut out a test sample from a wafer so that the channel direction of the MOSFET was parallel or perpendicular to the longitudinal direction of each sample, as shown in Fig. 4. The size of the stripe specimen was 15 × 70 mm. Spans of the four-point-bending method were 20 mm (inside) and 57 mm (outside).

The strain value in the MOSFETs loaded by the four-point-bending method was assumed to equal the maximum strain in a surface of beam structure caused by four-point-bending method because the MOSFETs were fabricated on the top surface of a 725-µm-thick-Si wafer.

The dependence of the change in drain current on the change in strain was measured for 0.14-µm-gate-length MOSFETs. The voltage bias was \( V_{gs} = V_{ds} = 1.5 \) V for N-MOSFETs or \( V_{gs} = V_{ds} = -1.5 \) V for P-MOSFETs.

3.2 Results of in-plane strain loading

Figure 5 summarizes the measured change in drain current due to a load parallel to the channel. The drain current in N-MOSFETs increases by about 0.29% with a 1×10^{-4} increase in tensile strain, \( \Delta \varepsilon_x \). Whereas, the drain current in P-MOSFETs decreases by about 0.41% with a 1×10^{-4} increase in tensile strain, \( \Delta \varepsilon_x \).

Figure 6 shows the change in drain current due to a load perpendicular to the channel. The drain current in the N-MOSFETs and P-MOSFETs increases with an increase in tensile strain. The drain current in the N-MOSFETs and the P-MOSFETs increases by about 0.15% and 0.20% with a 1×10^{-4} increase in tensile strain, \( \Delta \varepsilon_y \).

The four-point-bending method can load an in-plane axial strain in the longitudinal direction of a sample. However, not only the strain in the longitudinal direction of a sample but also the normal strain of a sample occurs in MOSFETs because of Poisson’s ratio of...
silicon. In this case, the strain in the transverse direction of a sample can be ignored because the strain is two or more digits smaller than the longitudinal strain. Therefore, the contribution of the three components enables the relationship between the drain current and the channel strain to be described as follows.

The change in drain current in the N-MOSFETs and the P-MOSFETs was about 0.29% and -0.41% per the change in channel strain ($\Delta \varepsilon_x$: $1.0 \times 10^{-4}$, $\Delta \varepsilon_y$: 0.0, and $\Delta \varepsilon_z$: $-1.3 \times 10^{-5}$). The change in drain current in the N-MOSFETs and the P-MOSFETs was about 0.15% and 0.20% per the change in channel strain ($\Delta \varepsilon_x$: 0.0, $\Delta \varepsilon_y$: $1.0 \times 10^{-4}$, and $\Delta \varepsilon_z$: $-1.3 \times 10^{-5}$).

### 3.3 Method for normal strain loading

The normal strain, $\varepsilon_z$, in the channel of the MOSFETs was varied by changing the intrinsic stress in an SiN film used as a contact etch-stop material for each MOSFET. The SiN film, about 100 nm thick, was deposited over a transistor structure. The intrinsic stress in an SiN film changes the strain field (especially $\varepsilon_z$) of the channel. The tensile strain in the channel increases with an increase in compressive stress in the film. The intrinsic stress in an SiN film can be varied by changing the deposition condition of the film. An SiN film is electrically inactive in the MOSFET, and its properties do not directly affect the device characteristics. An SiN film is, therefore, suitable for controlling channel stress because of its control of film stress. We varied the residual stress in the SiN film between -30 MPa and -1.4 GPa.

The strain field in the channel region of MOSFETs caused by the SiN-film stress was analyzed by using a finite-element-method stress simulation program, which takes the
intrinsic stress into account\(^9\). This program analyzes the stress in a thin-film structure, such as MOSFETs, when adding and removing thin films, that is, during the deposition and etching processes. We simulated the stress for three-dimensional MOSFET structures and evaluated the strain at room temperature.

The strain \(\Delta \varepsilon_x, \Delta \varepsilon_y,\) and \(\Delta \varepsilon_z\) is the average strain in silicon up to about 5 nm below the gate electrode. The drain current flows in the whole region of the channel. The SiN-film stress changes the strain of the whole channel region. Therefore, we considered that changes in the mobility of electron and hole causes changes in the whole channel region.

### 3.4 Results of normal strain loading

Figure 7 shows the dependence of the change in drain current on the SiN-film stress. The drain current represents the change in SiN residual stress at -30 MPa. The drain current in N-MOSFETs decreases by about 0.81% per 100 MPa increase in compressive stress. Whereas, the drain current in P-MOSFETs increases by about 1.5 % per 100 MPa increase in compressive stress.

Figure 8 shows the change in strain in response to change in applied SiN intrinsic stress from -30 MPa to -1.4 GPa. A large tensile strain is caused in the normal direction of the channel plane \((\Delta \varepsilon_z = 2\times10^{-3})\), and a large compressive strain is also caused parallel to the channel direction \((\Delta \varepsilon_x = -1.5\times10^{-3})\). Whereas, the strain perpendicular to the channel direction, \(\Delta \varepsilon_y\), hardly changes.

The normal strain in the channel was varied by changing the intrinsic stress in the SiN film because the expansion of SiN-film by compressive stress leads to tensile strain in the direction normal to the channel. The compressive stress of SiN film in the source/drain region also decreases channel strain in the direction parallel to the channel direction.
Figures 9 and 10 show the change in drain current due to channel strain ($\Delta \varepsilon_x$ and $\Delta \varepsilon_z$). The results shown in Fig. 9 indicate that the drain current in N-MOSFETs decreases by about 5.6% with a $1 \times 10^{-3}$ increase tensile strain, $\Delta \varepsilon_z$. Whereas, the drain current in P-MOSFETs increases by about 10% with a $1 \times 10^{-3}$ increase in tensile strain, $\Delta \varepsilon_z$. However, not only $\Delta \varepsilon_z$ but also $\Delta \varepsilon_x$ and $\Delta \varepsilon_y$ occur in channel field because of Poisson's ratio of silicon and the stress in the SiN film on the source/drain region. So, the contribution of the three components enables the relationship between the drain current and the channel strain to be described as follows.

The change in drain current in N-MOSFETs was about -5.6% per change in channel strain ($\Delta \varepsilon_x$: $-7.3 \times 10^{-4}$, $\Delta \varepsilon_y$: 0.0, and $\Delta \varepsilon_z$: $1.0 \times 10^{-3}$). Whereas the change in drain current in P-MOSFETs was about 10% per change in channel strain ($\Delta \varepsilon_x$: $-7.3 \times 10^{-4}$, $\Delta \varepsilon_y$: 0.0, and $\Delta \varepsilon_z$: $1.0 \times 10^{-3}$).

### 4. Strain sensitivity

By using the experimental results and Eq. (9), we can express the relationship between the change in drain current and change in strain for N-MOSFETs in Eq. (10) and for P-MOSFETs in Eq. (11).

\[
\begin{bmatrix}
0.29 \\
0.15 \\
-5.6 \\
-0.41 \\
0.20 \\
10
\end{bmatrix} =
\begin{bmatrix}
1.0 \times 10^{-4} & 0.0 & -1.3 \times 10^{-5} \\
0.0 & 1.0 \times 10^{-4} & -1.3 \times 10^{-5} \\
-7.3 \times 10^{-4} & 0.0 & 1.0 \times 10^{-3} \\
1.0 \times 10^{-4} & 0.0 & -1.3 \times 10^{-5} \\
0.0 & 1.0 \times 10^{-4} & -1.3 \times 10^{-5} \\
-7.3 \times 10^{-4} & 0.0 & 1.0 \times 10^{-3}
\end{bmatrix}
\begin{bmatrix}
A_x \\
A_y \\
A_z
\end{bmatrix}
\] (10)

\[
\begin{bmatrix}
0.29 \\
0.15 \\
-5.6 \\
-0.41 \\
0.20 \\
10
\end{bmatrix} =
\begin{bmatrix}
1.0 \times 10^{-4} & 0.0 & -1.3 \times 10^{-5} \\
0.0 & 1.0 \times 10^{-4} & -1.3 \times 10^{-5} \\
-7.3 \times 10^{-4} & 0.0 & 1.0 \times 10^{-3} \\
1.0 \times 10^{-4} & 0.0 & -1.3 \times 10^{-5} \\
0.0 & 1.0 \times 10^{-4} & -1.3 \times 10^{-5} \\
-7.3 \times 10^{-4} & 0.0 & 1.0 \times 10^{-3}
\end{bmatrix}
\begin{bmatrix}
A_x \\
A_y \\
A_z
\end{bmatrix}
\] (11)

From Eqs. (10) and (11), the strain sensitivity constants, $A_s$, for N-MOSFETs and P-MOSFETs are calculated. The equations for the strain-induced current in N-MOSFETs and P-MOSFETs that we determined is as follows. In these relationships, dimensions of the change in drain current $\Delta I_{ds}/I_{ds}$ is a percent, and the change in strain is non dimensional.

\[
\frac{\Delta I_{ds}}{I_{ds}} = 2.4 \times 10^{3} \Delta \varepsilon_x + 1.0 \times 10^{3} \Delta \varepsilon_y - 3.9 \times 10^{3} \Delta \varepsilon_z
\] (12)

\[
\frac{\Delta I_{ds}}{I_{ds}} = -3.0 \times 10^{3} \Delta \varepsilon_x + 3.1 \times 10^{3} \Delta \varepsilon_y + 8.1 \times 10^{3} \Delta \varepsilon_z
\] (13)

### 5. Verification of strain sensitivity

#### 5.1 Experimental method

We used Eqs. (12) and (13) to predict the drain current change in MOSFETs. The strain in the channel was changed by pattern layout.

A MOSFET is surrounded by shallow trench called shallow trench isolation (STI). The STI is filled with silicon dioxide. Annealing process in an oxidative atmosphere after STI manufacturing oxidized silicon on either side of the trench. The silicon-dioxide volume is 2.25 times that of silicon. As the result, the STI causes high compressive in-plane strain in the channel region\(^{1}\). The strain in the channel is a function of the length of the active region (active length). Thus, the effect of the active length on the drain current is discussed.

Figure 11 shows a schematic of an active-length-dependence MOSFET. The gate length of the MOSFET was 0.14 $\mu$m. The active length was 1, 3, or 20 $\mu$m (active length of the MOSFET shown in cheaper 4 is 20 $\mu$m). The MOSFET structure, except for the active length, was the same as the structure shown in chapter 3 and 4. The MOSFETs were patterned with enough separation from adjoining MOSFETs so as not to be influenced by the adjoining MOSFETs.
5.2 Strain analysis

Figure 12 shows the effect of active length on strain in a channel. In-plane strain $\Delta \varepsilon_x$ changes to a more compressive strain and changes about $1.5 \times 10^{-3}$ when the active length is reduced from 20 to 1 $\mu$m. Whereas, the normal strain $\Delta \varepsilon_z$ changes to a more tensile strain, and changes about $6 \times 10^{-4}$ when the active length is reduced from 20 to 1 $\mu$m. The change in normal strain, $\Delta \varepsilon_z$, corresponds to a strain due to Poisson's ratio caused by a large compressive strain $\Delta \varepsilon_x$.

5.3 Results and discussion

Figure 13 show a comparison of the predicted and measured changes in drain current in N-MOSFETs and P-MOSFETs. The drain current in the N-MOSFETs decreased rapidly with the decrease in active length when an active length was below 3 $\mu$m. Whereas, the drain current in the P-MOSFETs increased rapidly below the same length. The predicted values showed good agreement with the measured values. The prediction error was about 3% for the N-MOSFETs and about 4% for the P-MOSFETs. Current variation caused by manufacturing and measurement was about ±5%. Therefore, the predicted values are accurate enough to evaluate the drain current.

As mentioned above, this verification result shows the validity of this technique. Once the strain sensitivity in Eqs. (10) and (11) is determined for a MOSFET, the change in drain current due to change in structure (e.g. active length) in the same MOSFET process can be calculated. By using this method, we can determine the change in drain current due to strains, such as process-induced strain and packaging strain. Therefore, we can conclude that this method for predicting change in drain current will help us to improve the electronic performance of MOSFETs.

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**Fig. 11 Schematic of active-length-dependence MOSFETs**

**Fig. 12 Effect of active length on strain in channel**

**Fig. 13 Comparison of predicted and measured changes of drain current**
6. Conclusion

We investigated the strain sensitivity of the drain current in deep-sub-micron-MOSFETs and found that the drain current varies with the strain field in the channel region. Using the results of our investigation, we developed a method to quantitatively predict changes in the drain current.

(1) The strain sensitivity of the drain current in N-MOSFETs and P-MOSFETs was experimentally investigated by using stress analysis.

(2) The change in MOSFET drain current can be explained as a linear function of normal strains. The predicted values showed good agreement with the measured values.

(3) This method to predict change in the drain current due to stress will allow the better designed devices taking into consideration for the change in drain current due to stress.

References


