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Channel Strain in Advanced CMOSFETs Measured Using Nano-Beam Electron Diffraction

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1. Introduction

In advanced CMOSFETs, mobility enhancement using channel strain is a post scaling technology [1,2]. Since the channel strain is affected by the mechanical stress of device components as shown in Fig. 1, it is necessary to consider the influences of channel strain in device/circuit design.

Nano-Beam electron diffraction (NBD) is the local lattice strain measurement method which uses a transmission electron microscope [3]. In conventional NBD, small reciprocal lattice vectors, such as (044), are used, where the measurement error is thought to be about $\pm 1\times 10^{-3}$. However, larger reciprocal lattice vectors have a smaller measurement error, which enables systematic and detailed channel strain measurements.

We improved the accuracy of NBD using large reciprocal lattice vectors, adapting it for systematic channel strain measurements. We measured the channel strain which depends on the distance between the gate-electrode and shallow trench isolation (STI). We showed that the channel strain was inversely proportionally dependent on this distance and that it changed compressively by 2×10^{-3} due to STI stress with a decrease in that distance. This compressive strain results in about a 5% variation in the drive current in n-/p-MOSFETs. Therefore, we concluded that STI stress reduction is effective for controlling drive current variation, depending on the circuit's layout.

2.High-accuracy nano-beam electron diffraction (NBD)

Using the Bragg's equation, the Bragg angle change ($\Delta\theta_B$) due to strain ($\Delta d/d$) is expressed as $\Delta\theta_B = -g\times(\Delta d/d)/(2K)$, where g and K is the absolute value of the reciprocal lattice vector and the incident electron waveumber, respectively. A larger g gives a larger $\Delta\theta_B$ for constant strain, resulting in high strain sensitivity. Therefore, it is possible to improve the accuracy by measuring a larger reciprocal lattice vector in NBD. Figure 2 plots the standard deviations in our NBD strain measurements against the absolute value of reciprocal lattice vectors used in the measurements. To observe larger reciprocal lattice vector results in the smaller standard deviations. We used the reciprocal lattice vector (660) for the normal strain in the channel length direction in the following results.

NBD was observed using a TOPCON 002B transmission electron microscope with a 3 nm diameter electron probe.

3. Channel strain depending on distance from gate-electrode to shallow trench isolation

The distance between the gate-electrode and STI in the channel direction is defined as LSD and is shown in Fig. 3(a). We measured the channel strain in the channel length direction (ε_{xx}) of [110] channel MOSFETs at positions indicated by numbers in Fig. 3(b). In Fig. 3(c), averaged ε_{xx} over measurement positions from 1 to 5 are plotted against LSD (closed circle) and 1/LSD (open circle). We found that the averaged ε_{xx} changes compressively with a decrease in LSD. In particular, it changes drastically at LSD<1um. Furthermore, we found that averaged ε_{xx} has 1/LSD dependence on LSD. This 1/LSD dependence of the channel strain was interpreted as follows: assuming that the mechanical stress of STI is represented by the stress caused by the force **F** acting locally at the STI edge, as shown in Fig. 4(a), the mechanical stress at the center of channel σ_{xx} is calculated approximately as $-4F/(\pi \mathrm{LSD})$ [3]. Therefore, averaged ε_{xx} has inversely proportional dependence on LSD. Although the 1/LSD dependence of σ_{xx} was predicted by Bianchi et al., [4] using finite element simulation, we proved it experimentally for the first time.

In Fig. 5, the drive current (Ion) is plotted against the averaged ε_{xx} for n-/p-MOSFET. The Ion changes linearly against averaged ε_{xx} in each type of MOSFET. The sings of the slopes are different. This difference is due to the fact that electron/hole mobility decreases/increases with compressive strain in the channel length direction in a [110] channel MOSFET [2]. Furthermore, a compressive strain of 2.0×10^{-3} results in about a 5% drive current variation for both types of MOSFETs. This result and the drastic change of averaged ε_{xx} in LSD<1um (Fig. 3(c)) indicate that one should pay attention to the channel strain, and in particular to the channel strain in the case of LSD<1um in device/circuit design.

4. Conclusions

Based on our measurements taken using high-accuracy NBD, the dependence of the channel strain on the gate-electrode to STI distance was clarified. The absolute value of channel strain is inversely proportionally dependent on the gate-electrode to STI distance. The drive current of n-/p-MOSFET changes about 5% with 2×10^{-3} channel strain variation. This result suggests that reduction of STI stress is effective for controlling drive current variation depending on circuit layout, and that clarifying circuit layout dependence and/or device dimension dependence of the channel strain can provide effective data for device and circuit design.

Acknowledgements

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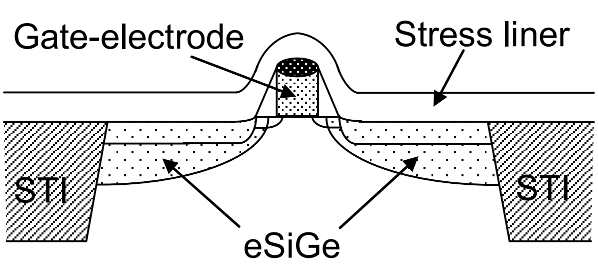


Fig. 1 Mechanical stress sources in an advanced CMOSFET.

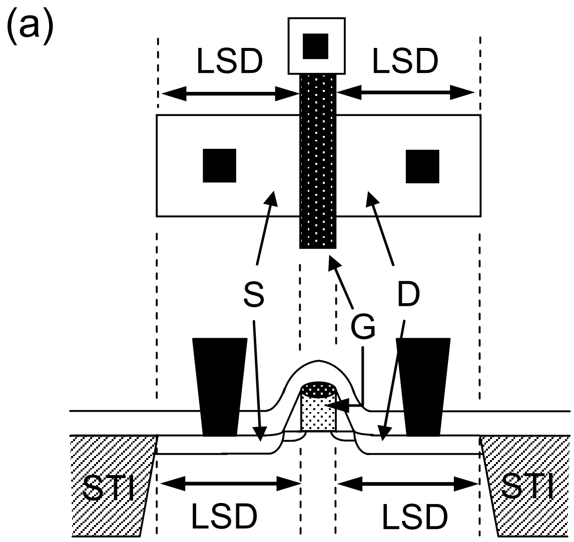
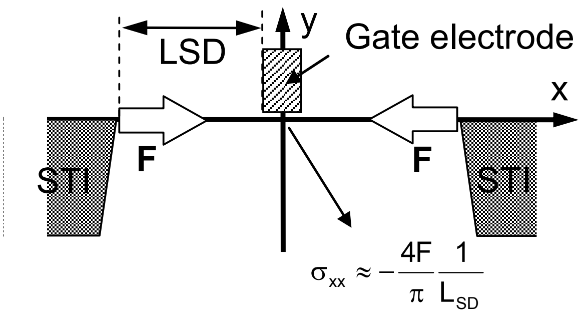


Fig. 3 (a) Schematics defining LSD. (b) Cross-sectional TEM image indicating strain measurement positions. (c) Dependence of averaged ε_{xx} on LSD(closed) and 1/LSD (open).



$$\sigma_{xx} \approx -\frac{4F}{\pi}\frac{1}{L_{SD}}$$

Fig. 4 A model of channel stress caused by STI.

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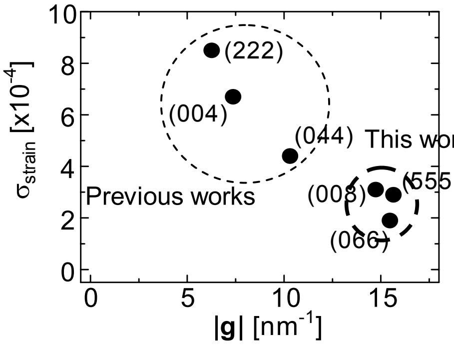
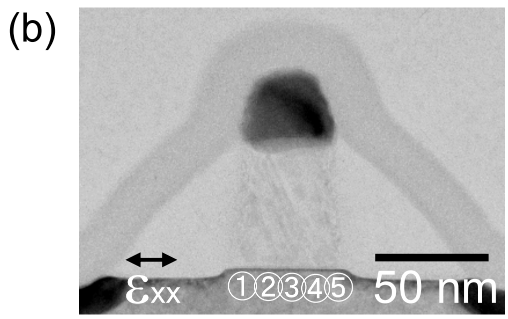
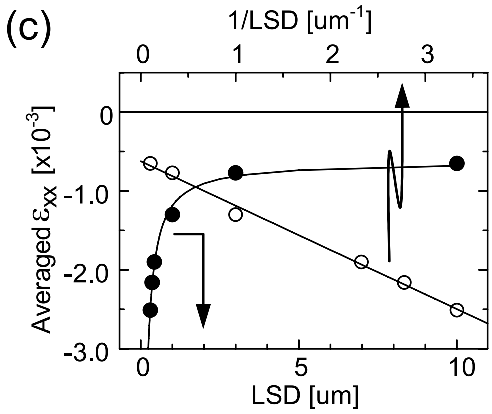


Fig. 2 Standard deviation of measured strain against absolute value of reciprocal lattice vectors used in measurements.





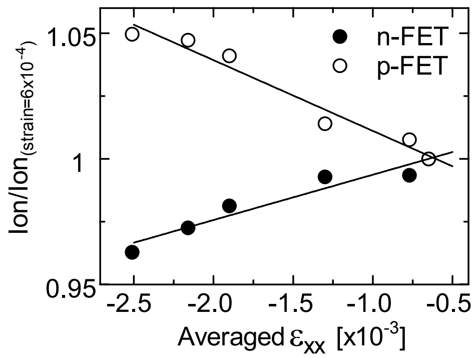


Fig. 5 Dependence of Ion on channel strain in n-/p-MOSFET.