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Channel Strain Analysis in High Performance Damascene-gate pMOSFETs by High Spatial Resolution Raman Spectroscopy

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1. Introduction

Strained-Si is one of the most promising technologies to realize high performance MOSFET. Raman spectroscopy can non-destructively evaluate the strain sensitively with high spatial resolution. Moreover, the extremely surface sensitive analysis can be achieved by using ultra-violet (UV) excitation. The evaluation of the channel strain by Raman spectroscopy has been difficult, because the gate is not transparent in the conventional MOSFET. However, the damascene gate technology which needs the dummy gate removal process allowed us to analyze the channel strain in MOSFETs from the surface [1, 2]. As results the channel strains measured by Raman measurements could be reproduced by stress simulations, and explain the device performance very well. However, the spatial resolution for the Raman measurement was limited to 0.2 μm even with specially designed quasi-line shape excitation source. Thus, the improvement of the spatial resolution has been strongly desired for the detail analysis of the state-of-the-art fine structure devices.

In the present study, we verified the Raman measurement and extended the strain measurement in MOSFET with gate length less than 0.2 μm

2. Experiments

A. Damascene gate samples

The schematic of damascene gate pMOSFETs after the dummy gate removal was shown in Fig. 1. The detailed fabrication process is described in Ref. [1]. This was fabricated on (001) silicon wafer. The 80 nm eSiGe epitaxial growth was carried out after Si recess for some samples. The 40 nm compressive stress liner with the inner stress of - 2.0 GPa was deposited after Ni silicidation. Only the c-SL above the dummy gate was cut by CMP, and the dummy gate was removed. We measured the channel strain of this stage. Three opening gates were existed side-by-side in the measurement area.

B. Micro-Raman spectroscopy

The strain measurements were performed by Raman spectroscopy equipped with the argon ion laser (λ = 363.8 nm), whose penetration depth into Si is approximately 5 nm and a quasi-line excitation source [3]. The Raman measurements were performed at room temperature in back-scattering geometry from the (001) silicon wafer surface. The incident light was polarized along a <110> direction. The beam length was elongated to 100 μm by the galvano-mirror. Owing to the horizontal beam length of 100 μm divide by the 512 of pixels, the spatial resolution attained approximately 0.2 μm. Rayleigh scatterings were used for the wave-number calibration. A quasi-line excitation source makes it possible to obtain strain profile in three opening gates at a time. Optical components of monochromator were installed on the Super Invar metal which has extremely small thermal coefficient, so it realized the stable analysis of the energy dispersion in the scattered light.

3. Results and Discussion

The exposure time for the Raman measurement was 10 minutes for the MOSFET with Lgate more than 0.2 μm [1, 2]. Typical Raman spectra obtained with these conditions are shown in Fig. 2. The Raman spectra obtained in Lgate more than 0.2 μm had single peak (Fig. 2(a) and (b)). Therefore, after the single peak fitting, the strain profiles across the channels were obtained as shown in Fig. 3(a) for Lgate = 10 μm and Fig. 3(b) for Lgate = 0.21 μm, respectively. For the Lgate more than 1.0 μm, clear U-sharp strain profiles in the channel, huge strain enhancement at the channel edge and relative small strain at the channel center, are observed. For the Lgate between 1.0 μm to 0.2 μm, U-shape strain profile disappeared probably due to the limitation in the spatial resolution. Thus we defined channel strain by the maximum value obtained around channels.

On the other hand, for the samples with Lgate less than 0.2 μm, the strain profile disappeared completely due to the limitation in the spatial resolution. Thus, we tried to extract strain components from the Raman spectra. To achieve it, we increased the laser exposure time to 40 minutes, which can be achieved thanks to the extremely stable optical set-up in our Raman apparatus. The Raman spectra obtained from Lgate = 40 nm samples with and without eSiGe were shown in Fig. 4. As shown in Fig. 4(a), there were three peaks appeared clearly in the Raman spectra. After the triple peak fitting for the spectra, we considered that the right, center, and left peaks were from the strained channel, the Si substrate, and the eSiGe, respectively. The Raman spectrum from sample without eSiGe is shown in Fig. 4(b), in which it is apparent that there were two peaks without left one. Therefore, we confirmed that the left peak can be attributed to eSiGe. Because the central peaks exhibited no or very small strain at least, we defined the channel strain from the right peak. Finally we have established channel strain extraction conditions for Lgate more than 1.0 μm, between 1.0 μm to 0.2 μm and less than 0.2 μm.

Thus, we obtained Fig. 5, which shows Raman peak shifts corresponding channel strain depending on the Lgate. The calculated stresses are also displayed on the right axis under the uni-axial stress estimation. Here, the channel stress was calculated by

$$\sigma = \frac{\Delta\omega}{-2.0} \quad [GPa]$$

where, σ is the stress in the direction of the channel, $\Delta\omega$ is the difference between the measured frequency of the silicon Raman peak and the stress free value [4]. The extraordinarily large compressive strain was especially observed in 30-nm-Lgate with eSiGe. The Raman shift and the channel stress was approximately 5.0 cm^{-1} and -2.5 GPa, respectively. This should be the first time to measure such large strain in the channel region induced by the local strain

technology. The strain was comparable to that observed in the global strain substrates such as strained-Si-On-Insulator (sSOI) [5, 6]. It is also apparent from Fig. 5, the eSiGe was effective for the samples with Lgate less than 1.0 μm, and became more effective as Lgate decreased. The eSiGe induced the compressive strain more than 1.7 times than that without eSiGe in Lgate = 30 nm. Device performance evaluated by the electrical characteristics, both Lgate dependence and eSiGe effect, can be explained by the carrier mobility enhancement thanks to the compressive strain [7].

4. Conclusions

The channel strain in the fine region for damascene pMOSFET with eSiGe was evaluated by Raman spectroscopy with a quasi-line excitation source. For Lgate > 1.0 μm, the strain profiles in the channel can be obtained. For 1.0 μm > Lgate > 0.2 μm, the channel strain could be recognized although the strain profiles in the channel disappeared. For Lgate < 0.2 μm, the channel strain could be extracted by the multi peak fitting from the spectra obtained with long exposure time. Finally, we have succeeded in measuring the extremely large stress of - 2.5 GPa in the channel of Lgate = 30 nm pMOSFET. The device performance can be clearly explained by the compressive stress calculated from the Raman measurements both in Lgate dependence and eSiGe effect.

Acknowledgements

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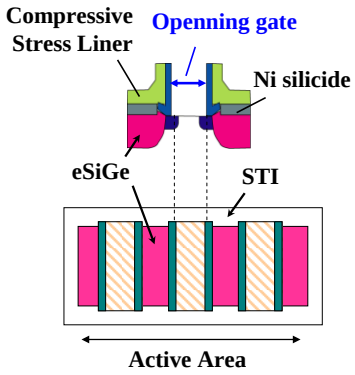

Fig. 1 Schematic diagram of damascene gate pFETs after dummy gate removal.

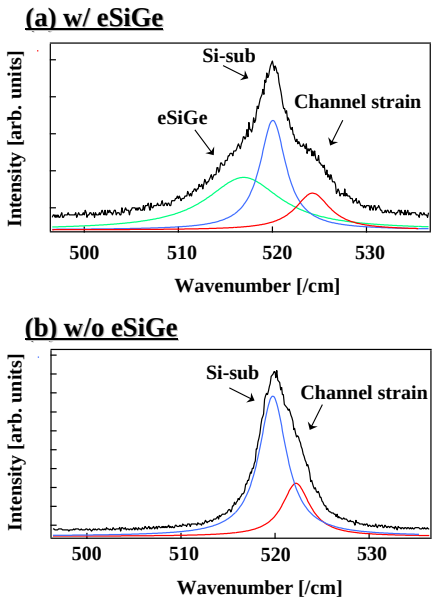

Fig. 4 Raman spectra obtained with 40-minutes laser exposure from damascene-gate pFETs (a) with and (b) without eSiGe. Red, Blue, and Green lines signified the fitting line for each Peak.

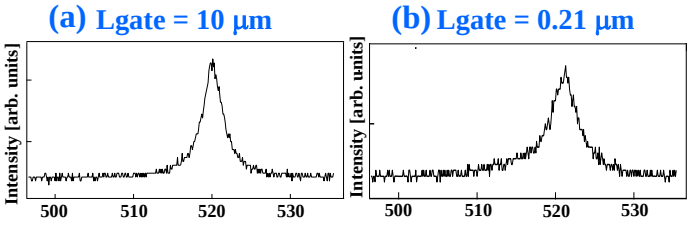

Fig. 2 Raman spectrum in the channel center obtained from (a) Lgate = 10 μm and (b) 0.21 μm, respectively.

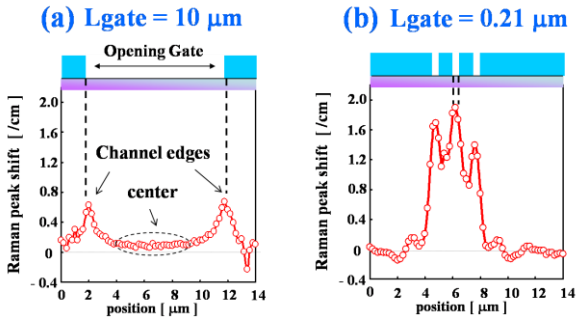

Fig. 3 Channel strain distribution obtained from (a) Lgate = 10 μm and (b) 0.21 μm, respectively.

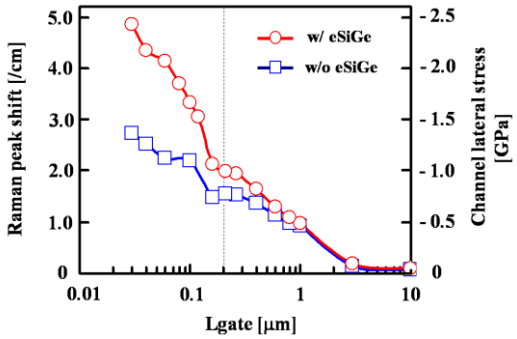

Fig. 5 Raman peak shift (left axis) and channel lateral stress (right axis) dependence on Lgate for pMOSFET with and without eSiGe.