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Evaluation of effective mass of inversion-layer holes in strained-Si pMOSFETs utilizing Shubnikov de-Haas (SdH) oscillation

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Abstract

The effective mass of inversion-layer holes in bi-axial tensile strain Si p-MOSFETs on $Si_{0.7}Ge_{0.3}$ and $Si_{0.9}Ge_{0.1}$ buffers is evaluated by SdH oscillation. The strain dependence of the effective hole mass is systematically examined in comparison with the previous results. We have found that the effective mass is reduced down to 0.4-0.5 m_0 for strained-Si on $Si_{0.7}Ge_{0.3}$ buffers, while it increases around 1.0-1.1 m_0 on $Si_{0.9}Ge_{0.1}$.

1. Introduction

Strained-Si technologies, which increase the current drive of Si MOSFETs through the mobility enhancement, have been widely used for boosting the device performance over several technology nodes [1]. Here, the theoretical predictions [1, 2] have attributed the mobility enhancement of inversion-layer holes in strained-Si pMOSFETs mainly to the reduction in the effective mass. However, experimental studies on direct evaluation of the hole effective mass in strained-Si pMOSFETs are very limited [3]. Only one report by Tezuka *et al.*, who evaluated the effective mass by using the Shubnikov de-Haas (SdH) oscillation [3-6], has revealed that the effective mass of inversion-layer holes in bi-axial tensile strain pMOSFETs on relaxed $Si_{0.82}Ge_{0.18}$ buffers is almost the same as that of unstrained Si pMOSFETs [3]. As a result, any clear and direct evidence of the effective mass reduction in strained-Si holes has not been reported yet.

In this study, we evaluate the effective mass of inversion-layer holes in bi-axial tensile strain Si on $Si_{0.7}Ge_{0.3}$ and $Si_{0.9}Ge_{0.1}$ buffers by the temperature dependence of SdH oscillation. The strain dependence of the hole effective mass is systematically examined in comparison with the previous data including the results of unstrained Si pMOSFETs [3-5].

2. MOSFETs used for Measurement and Measurement Method of Effective Mass

We employed (100) strained-Si p-MOSFETs with bi-axial tensile strain on $Si_{0.7}Ge_{0.3}$ and $Si_{0.9}Ge_{0.1}$ buffers, shown in Fig. 1 [7, 8], with channel length/width of 500µm/50µm. The uniform tensile strain induced by the SiGe buffers is indispensable in accurate effective mass extraction in such a large size MOSFETs by SdH. The gate stack is composed of a phosphorus-doped poly-Si gate/SiO_2 (9.2 nm). In addition, no strain bulk Si pMOSFETs were also measured as control samples. The conductance measurement was carried out at 2, 3 and 4 K under magnetic field strength (B) of 12-14 T. The drain voltage of 10 mV was used for minimizing the increase in the electron temperature [9]. The effective mass can be evaluated through the temperature dependence of the amplitude of the SdH oscillation (A) as a function of surface carrier concentration (N_s) by using the following equation [4-6].

$$A_1/A_2 = \frac{\theta_1/\sinh\theta_1}{\theta_2/\sinh\theta_2},\quad \theta_i = \frac{4\pi^2 k_B T_i m^*}{hqB} \qquad (1),$$

where k_B, h, q, T_i and B are the Boltzmann constant, the plank constant, the elementary charge, temperature and magnetic field, respectively.

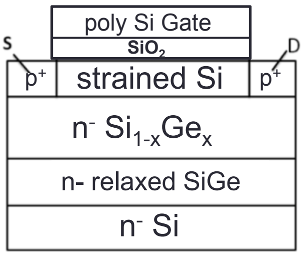

Fig. 1 Schematic cross sectional view of bi-axial tensile strain Si p-MOSFETs used for the present measurements.

3. Experimental Results

Fig. 2(a) shows the G_m-V_g characteristics of strained-Si p-MOSFETs on $Si_{0.7}Ge_{0.3}$ buffers at 2 K under magnetic field of 14 T. Clear periodic oscillations are clearly observed. The surface carrier concentration corresponding to one period oscillation (ΔN_s), extracted from the results of Fig. 2(a), is plotted as a parameter of B in Fig. 2(b). Under the SdH oscillation, ΔN_s is given by

$$\Delta N_s = qB/\pi\hbar \qquad (2),$$

also plotted in Fig. 2(b). Fairly good agreement with the experimental and theoretical ΔN_s indicates that the present G_m oscillation is attributed to SdH.

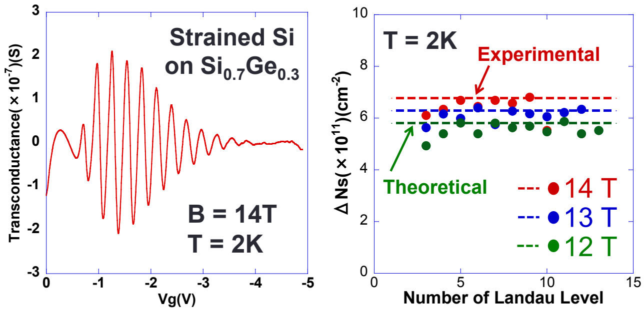

Fig. 2 (a) G_m-V_g characteristics of strained-Si p-MOSFETs on $Si_{0.7}Ge_{0.3}$ buffers at 2 K under magnetic field of 14 T (b) ΔN_s for each Landau level extracted from the SdH peaks and the theoretical values for 12, 13 and 14 T.

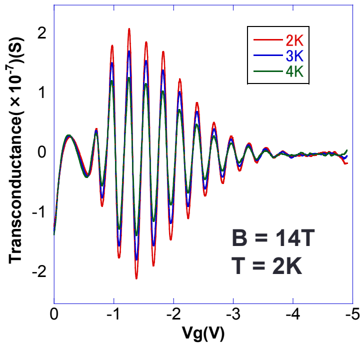

Fig. 3 Temperature dependence of the G_m-V_g characteristics of strained-Si p-MOSFETs on $Si_{0.7}Ge_{0.3}$ buffers at 2, 3 and 4 K under magnetic field of 14 T.

This SdH oscillation of strained-Si pMOSFETs on $Si_{0.7}Ge_{0.3}$ buffers was evaluated at different temperatures of 2, 3 and 4 K, as shown in Fig. 3. It is confirmed that the amplitude of the oscillation decreases with increasing temperature, as expected. The effective mass was evaluated through (1) by using A at 2/3K and 2/4 K. Fig. 4 shows the extracted effective mass normalized by that of an elemental charge (m_0) as a function of N_s. The effective mass extracted by A at 2 and 3K has almost no change in that extracted by A at 3 and 4 K, indicating the accuracy of the effective mass extraction in the present measurements.

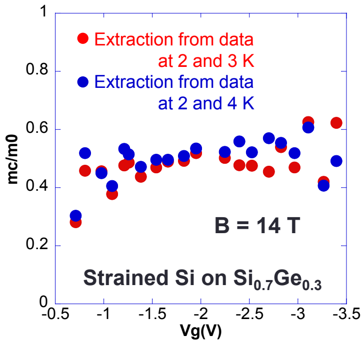

Fig. 4 Extracted effective mass normalized by that of an elemental charge (m_0) as a function of N_s. The values taken by the data at 2/3 K and at 2/4 K are shown for comparison.

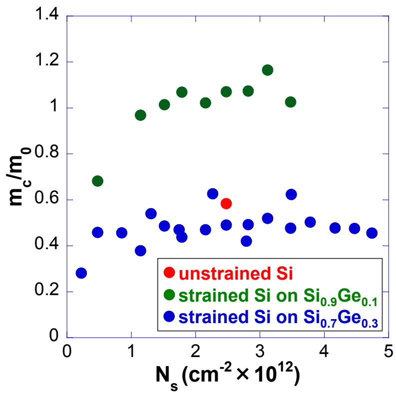

Fig. 5 Extracted effective mass normalized by m_0 for unstrained-Si, strained-Si-on-$Si_{0.9}Ge_{0.1}$ and strained-Si-on-$Si_{0.7}Ge_{0.3}$ pMOSFETs as a function of N_s.

The similar extraction of the effective mass was also performed for strained-Si pMOSFETs on $Si_{0.9}Ge_{0.1}$ buffers and unstrained-Si pMOSFETs. The extracted effective mass for all the samples are plotted as a function of N_s in Fig. 5. We have found that the effective mass is reduced down to around 0.4 -0.5 m_0 for strained Si on $Si_{0.7}Ge_{0.3}$, while the effective mass increases up to around 1.0-1.1 m_0 for strained Si on $Si_{0.9}Ge_{0.1}$. This result for pMOSFETs on $Si_{0.7}Ge_{0.3}$ buffers is the first clear evidence of the effective mass reduction of inversion-layer holes with bi-axial tensile strain.

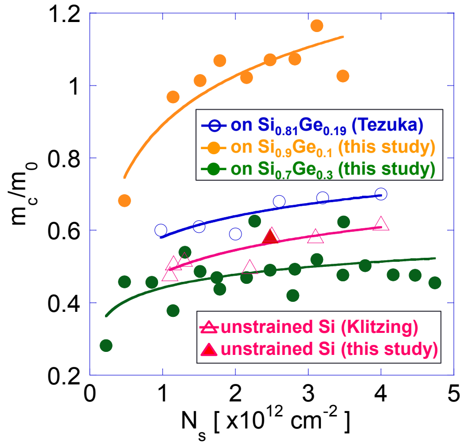

Fig. 6 Comparison of the extracted effective mass for the present strained- and unstrained-Si pMOSFETs with the reported data of unstrained Si pMOSFETs [5] and strained-Si pMOSFETs on relaxed $Si_{0.82}Ge_{0.18}$ buffers [3].

The extracted results are compared with the experimental data, reported previously for (100) unstrained-Si pMOSFETs [5] and (100) strained-Si pMOSFETs on relaxed $Si_{0.82}Ge_{0.18}$ buffers [3]. A good match in the effective mass of unstrained-Si pMOSFETs between the present data and the data by Klitzing confirms us the accuracy of the present measurements. The tendency of the increase in the effective mass with increasing N_s is attributable to the non-parabolicity of the valence band structure of Si. For the strain dependence, the results of Fig. 6 suggest that the effective mass would increase in a low strain region and would begin to decrease from some strain value. According to the previous data [3], the effective mass is still slightly heavier on $Si_{0.82}Ge_{0.18}$ than that without any strain. However, as the amount of strain further increases, the effective mass can keep decreasing and be reduced down to around 0.4-0.5 m_0 for the strain on $Si_{0.7}Ge_{0.3}$ buffers.

5. Conclusions The effective mass of inversion-layer holes in strained-Si pMOSFETs with bi-axial tensile strain has been successfully extracted by SdH oscillation. It has been found, for the first time, that the effective mass is reduced down to 0.4 m_0 for strained-Si on $Si_{0.7}Ge_{0.3}$ buffers.

References [1] Y. Sun et al., “Strain Effect in Semiconductors: Theory and Device Applications”, Springer (2009) [2] D. K. Nayak et al., Appl. Phys. Lett. **64**, 2914 (1994) [3] T. Tezuka *et al.*, Proc. 25th Conf. Phys. Semicond., 1753 (2000) [4] K. von Klitzing *et al.*, Solid State Commun. **14**, 387 (1974) [5] K. von Klitzing *et al.*, Solid State Commun. **19**, 1031 (1976) [6] T. Takahashi *et al.*, J. Appl. Phys. **109**, 034505 (2011) [7] T. Numata et al., Tech. Dig. IEDM, 177 (2004) [8] S. Takagi et al., Ext. Abs. SSDM, 38 (2005) [9] K. H. Park et al., Appl. Phys. Lett. **91**, 132118 (2007)