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Examination of the Universality of Hole Mobility in Strained-Si p-MOSFETs

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1. Introduction

Strained-Si channels have recently been recognized as an indispensable technology booster for the mobility enhancement in advanced CMOS. In particular, bi-axially-strained-Si MOSFETs fabricated on relaxed SiGe layers have extensively been studied [1, 2], because of the large and uniform strain in the Si channels.

Although the bi-axial strain dependence of inversion-layer mobility has so far been characterized [2], the understanding of hole mobility in strained-Si p-MOSFETs is still poor. Also, it has been reported [3] that the electron mobility in bi- axial strained-Si n-MOSFETs still obeys to the universal relationship against the effective field, E_{eff}, which is well known for conventional unstrained n- and p-MOSFETs [4]. The universality and the E_{eff} dependence are informative in understanding scattering mechanisms of carriers in inversion layers. However, it has not been examined yet whether the hole mobility in strained-Si pMOSFETs has the universality or not.

In this study, the mobility in strained-Si p-MOSFETs on relaxed SiGe bulk substrates is evaluated in terms of the universality with systematically changing substrate impurity concentration, N_{sub}, and substrate bias, V_{sub}.

2. Samples and Measurement Method

The structure of bi-axially-strained-Si p-MOSFETs used in the present measurement is schematically shown in Fig. 1. The bulk strained-Si substrates, whose Ge content in relaxed SiGe substrates is varied from 0 % to 50 %, are commercial ones. The amount of strain is varied by this Ge content. The wafers are divided into two sets, which were manufactured in different terms.

The mobility is determined by the split C-V method.

$$\mu(V_g) = \frac{W}{L} \cdot \frac{I_d}{V_d} \cdot \frac{1}{Q_s(V_g)}, \quad E_{eff} = \frac{1}{\varepsilon_{Si}}(Q_{depl} + \eta \cdot Q_s),$$

$$Q_s = \int_{V_g}^{\infty} C_{gc}(V_g')dV_g', \quad Q_{depl} = \int_{V_g}^{V_{FB}} C_{gb}(V_g')dV_g'$$

where C_{gc} and C_{gb} are gate-channel and gate-bulk capacitance, respectively (Fig. 2). A parameter, η, included in E_{eff}, is determined so as to yield the universal relationship. Here, the flat band voltage, V_{FB}, should be accurately evaluated to determine E_{eff}. It is found that V_{FB} in strained-Si MOSFETs changes with the Ge content even under constant N_{sub}, because of space charges near strained-Si/SiGe hetero-interface associated with the band offset (Fig. 3). Thus, C_{OX}, N_{sub} and V_{FB} are determined by fitting simulated C-V curves of MOS capacitors with experimental ones, assuming a band offset physical model [5].

3. Results and Discussions

Fig. 4 shows hole mobility as a parameter of the Ge content. Here, the value of η is taken to be 1/3, as used in hole mobility in unstrained-Si p-MOSFETs [4]. It is confirmed that mobility increases with an increase in strain [6, 7]. Fig. 5 shows the mobility-E_{eff} curves in strained-Si with Ge content of 10 % and the universal curve in unstrained Si for comparison. N_{sub} and V_{sub} are varied to change N_{depl} and resulting E_{eff}. Here, η is taken to be 1/3. It is found that hole mobility in strained Si has the universal relationship against E_{eff} with η of 1/3 for mobility with different N_{sub} and V_{sub}, although the E_{eff} dependence is different from the mobility in unstrained Si. This universality with η of 1/3 is also found in the mobility with Ge content of 15 % (Fig. 6) and 20 % (Fig. 7), where the change in the E_{eff} dependence from that in unstrained Si is much clearer. This is the first experimental evidence that the hole mobility in bi-axially-strained-Si p-MOSFETs does hold the universality against E_{eff} with η of 1/3. According to theoretical calculations, the increase in hole mobility and the change in the E_{eff} dependence due to bi-axial strain have been attributed to the suppression of inter-band scattering caused by the band splitting [8, 9] and the change in the effective mass [10]. However, the results of Figs. 5-7 strongly suggest that the essence of device physics to yield the universality with η of 1/3 could not be affected by the modulation of the subband structures and the subband occupation into heavy and light hole bands.

On the other hand, the mobility with Ge content of 30 % exhibits more complicated behaviors. Fig. 8 show the mobility-E_{eff} curves with Ge content of 30 % on strained-Si wafers manufactured at the same time. The universality with η of 1/3 is clearly confirmed. Fig. 9 also shows the mobility with Ge content of 30 % taken from a different set of strained-Si wafers. Slight deviation from the universal curve is observed particularly in lower E_{eff} region. Important points are that application of V_{sub} leads to higher mobility and that the mobility with higher N_{sub} and V_{sub} tends to converge into the universal one. Since it is known that holes at relaxed SiGe/strained Si buried interface can contribute to the current more with increasing Ge content [11], the deviation from the universal curve in Fig. 9 might be attributable to possible lower mobility of holes at the SiGe buried channel.

4. Summary

It was found, for the first time, that hole mobility in strained-Si pMOSFETs has the universality against E_{eff} with η of 1/3, at least up to the Ge content of 20 % and in most cases to 30 %. It was, thus, concluded that the essence of device physics to yield the universality is not affected by the modulation of the subband structures and the subband

occupation of inversion-layer holes due to strain.

Acknowledgements

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References [1] C. K. Maiti et al., *"Strained silicon heterostructures: materials and devices"*, The institute of Electrical Engineers, 2001 [2] M.J. Lee et al., *JAP* **97**(2005) 011101 [3] H. M. Nayfeh et al., *EDL* **24** (2003) 248 [4] S. Takagi, et al., TED **41** (1994) 2357 [5] L. Yang et al., *Semicond. Sci. Techno.* **19**(2004) 1174 [6] C. W. Leitz et al., *JAP* **92**(2002) 3745 [7] T. Numata et al., *IEDM* (2004) 177 [8] T. Mizuno et al., *TED* **51**(2004) 1114 [9] S. Thompson et al., *IEDM* (2004) 221 [10] H. Nakatsuji et al., *IEDM* (2002) 727 [11] N. Sugii et al., *Semicond. Sci. Technol.* **16**(2001) 15

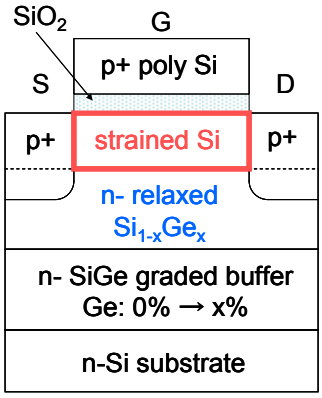

Fig. 1 Cross section of device structure of strained- Si p-MOSFETs used in this study

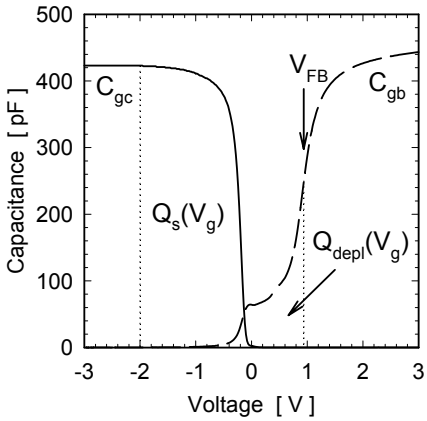

Fig. 2 Typical C_{gc} and C_{gb} curves and illustration of ways of determining Q_s and Q_{depl}

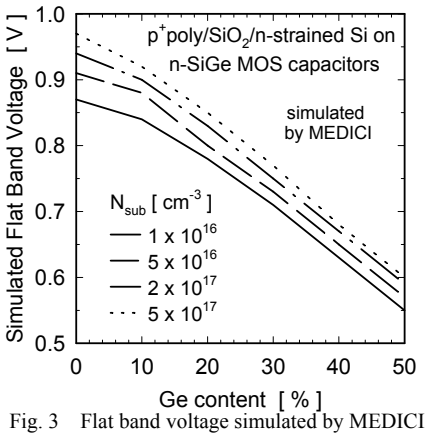

Fig. 3 Flat band voltage simulated by MEDICI vs. Ge content in SiGe substrates as a parameter of substrate impurity concentration

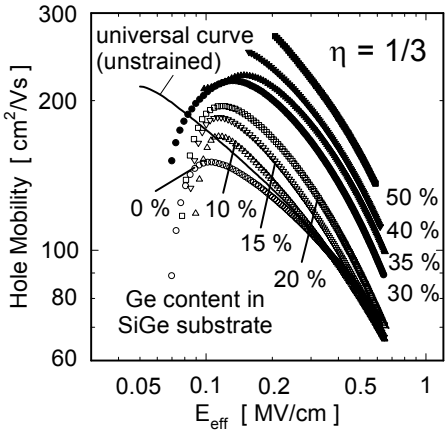

Fig. 4 Hole mobility versus E_{eff} with η of 1/3 as a parameter of the Ge content in SiGe substrates (strain)

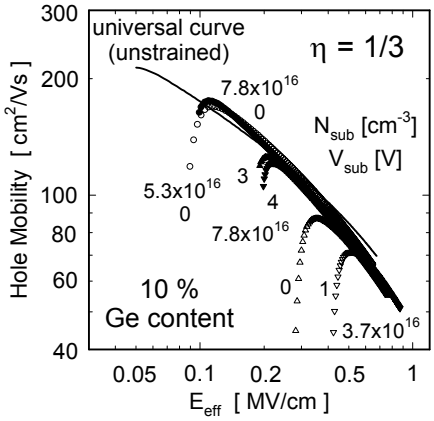

Fig. 5 Hole mobility with Ge content of 10 % versus E_{eff} with η of 1/3 with different substrate impurity concentration and substrate bias

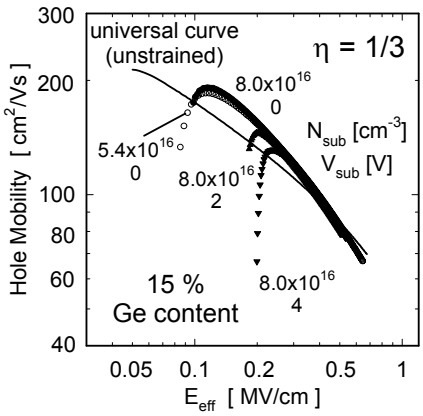

Fig. 6 Hole mobility with Ge content of 15 % versus E_{eff} with η of 1/3 with different substrate impurity concentration and substrate bias

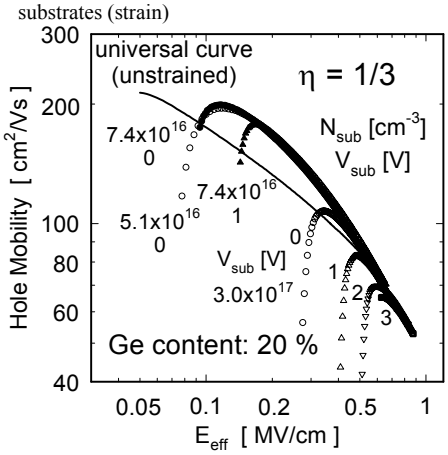

Fig. 7 Hole mobility with Ge content of 20 % versus E_{eff} with η of 1/3 with different substrate impurity concentration and substrate bias

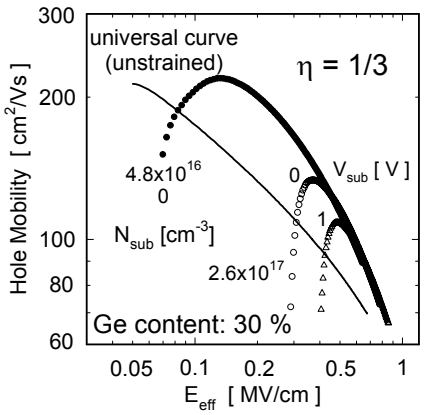

Fig. 8 Hole mobility with Ge content of 30 % versus E_{eff} with η of 1/3 with different substrate impurity concentration and substrate bias. Used strained- Si wafers were manufactured at the same time.

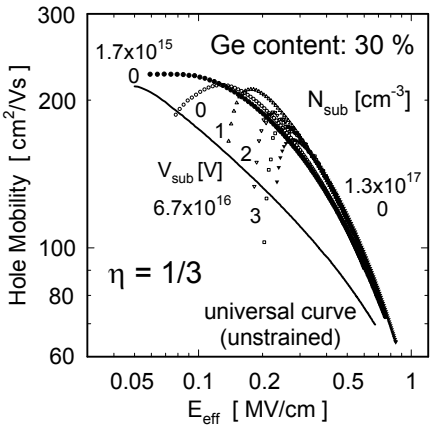

Fig. 9 Hole mobility with Ge content of 20 % versus E_{eff} with η of 1/3 with different substrate impurity concentration and substrate bias. Strained-Si wafers shown here were manufactured in a different term from those shown in Fig. 8.