Extended Abstracts of the 2006 International Conference on Solid State Devices and Materials, Yokohama, 2006, pp. 164-165

H-1-3

Effect of Tensile Strain on Gate and Substrate Currents of strained-Si n-MOSFETs

T. Hoshii, S. Sugahara and S. Takagi

Graduate School of Frontier Science, The Univ. of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
Phone & Fax: +81-3- 5841-7467, e-mail: aaktuy@mosfet.k.u-tokyo.ac.jp

1. Introduction

Application of strain is currently becoming indispensable in the performance improvement of advanced CMOS devices. Thus, physical and quantitative understanding of the effects of strain on the electrical characteristics of MOSFETs is quite important. It has been reported that the gate current of MOSFETs decreases by applying tensile strain [1]. However, the physical origin and the quantitative model to explain this phenomenon have not been clarified yet. Also, the effect of strain on the substrate hole current associated with electron injection into gates, which is known to be a good indicator of the oxide reliability, has not been studied yet.

In this study, we systematically investigate the effects of bi-axial tensile strain on gate current, I_g, and substrate hole current, I_{sub}, of Si n-MOSFETs by measuring global strained-Si MOSFETs on SiGe substrates with Ge contents ranging from 0 to 30%. Using the FN (Fowler-Nordheim) plot of I_g, the dependence of the barrier height on the strain is evaluated. Also, the physical origin of I_{sub} is examined from the effects of strain on the quantum yield.

2. Experiments

The devices used in this study were poly-silicon gate n-channel MOSFETs having four different amounts of global tensile strain, fabricated on relaxed-SiGe virtual substrates with the Ge content of 0, 10, 20 and 30 %(Fig.1). The Ge content of 30 % corresponds to the strain of 1.23 %. The accurate determination of the electric field across the gate oxide, E_{ox}, is quite important in obtaining an accurate F-N plot. In this study, E_{ox} is accurately evaluated from integrating C (= $C_{gc}+C_{gb}$) -V curves from the flat band voltage, V_{FB} (Fig. 2) [2]. Also, the gate oxide (pure SiO_2) thickness, T_{ox}, and V_{FB} are determined by fitting experimental C-V curves of MOS capacitors with simulated ones. Here, it has been found that T_{ox}, ranging from 8.0 to 9.2 nm, decreases with an increase in strain, suggesting that the oxidation rate is dependent on the strain. The $I_g(I_{sub})$-V_g characteristics are measured in the setup of Fig. 3.

When I_g is dominated by FN tunneling current, the current density, J_{FN}, is represented as the FN plot by

$$\ln\left(J_{FN}/E_{ox}^2\right) = -B/E_{ox} + \ln(A)$$

where A and B are constants determined by the barrier height against SiO_2, ϕ_b, and the tunneling mass, m^*. As a result, ϕ_b is determined from the value of B by

$$\phi_b = \left\{ \left(3\eta / 4\sqrt{2m^* q}\right) \cdot B \right\}^{2/3}$$

3. Result and Discussion

Fig. 4 shows the plot of I_g versus E_{ox}. Since the leakage current component, which might be attributed to any traps, is observed in low E_{ox} region for MOSFETs with higher Ge content, the analyses have been carried out mainly in E_{ox} higher than 8 MV/cm. Fig. 5 shows the plot of I_g versus T_{ox} for five devices with each strain at E_{ox} of 9.0 MV/cm, where I_g is dominated by FN tunneling. It is found that I_g decreases monotonically with an increase in the strain. The tensile strain of 1.23 % (Ge content of 30 %) is observed to lead to the decrease I_g in by one order of the magnitude. The FN plots can discriminate the contributions of A and B on this I_g decrease. As a result, the variation in the pre-factor 'A' between 0 and 30 % is less than 2 and, thus, the change in I_g is attributed mainly to the exponential factor 'B', determined by ϕ_b.

Fig.6 shows the plot of ϕ_b versus T_{ox} as a parameter of strain. It is clearly seen that ϕ_b increases with an increase in the strain. The increase in ϕ_b is estimated to be 50-60 meV by every 10% strain. Since it is known that the energy of the conduction band edge, E_c, lowers with an increase in tensile strain [3], this is simply expected to lead to the increase in ϕ_b, as shown in Fig.7. It should be noted here that the lowest subband energy with and without tensile strain must be quite similar, because the lowest subband is composed of the 2-fold valleys. Fig. 8 shows the comparison the change in ϕ_b evaluated in this study with the values of ΔE_c reported previously [3, 4]. It is found that $\Delta\phi_b$ and ΔE_c are in good agreement. This result means that the decrease in I_g due to tensile strain is quantitatively explained by the change of the energy of the Si conduction band and the resulting increase in ϕ_b.

As for the substrate hole current in nMOSFETs, on the other hand, two physical origins are known, as shown in Fig. 8. One is tunnel-back holes from gate electrodes and the other is the absorption of photons generated by electron injections into gate electrodes, though the tunnel-back hole current is regarded as a dominant component. The amounts of tunnel-back holes and generated photons are determined by the energy of electrons injected into the gate, E_{at}, which can be evaluated, under the assumption of no energy loss inside SiO_2, by

$$E_{at} = E_{ox} \cdot T_{ox} - \left(\phi_b - \phi_{b0}\right)$$

where ϕ_{b0} is the barrier height of Si MOSFETs with no strain. Fig. 9 shows the plot of the quantum efficiency, I_{sub}/I_g versus E_{at}. It is found that the quantum efficiency is slightly dependent on strain, even if compared at the same T_{ox}. This fact suggests that the photon-induced current component could be included in the measured I_{sub}. This is because the decrease in the band gap due to strain can lead to the increase in the absorption and resulting I_{sub} even under constant amount of photons, while I_{sub} due to tunnel-back holes must be the same under the constant values of E_{at} and T_{ox}.

4. Conclusion

It is observed that tensile strain leads to the decrease in gate current due to FN tunneling in Si n-MOSFETs. The strain of 1.23 % can reduce the gate current by one order of the magnitude. It has been found, for the first time, that this decrease in the gate current is quantitatively explained by the increase of the barrier height against SiO_2, due to the strain-induced lowering of the conduction band edge. Also, the quantum efficiency of the substrate hole current in Si n-MOSFETs is found to slightly increase with an increase in strain, suggesting that the component of photo-induced current could be included into the substrate hole current.

Acknowledgements

This work was partly supported by NEDO/MIRAI project and by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology.

References [1] S. Takagi et al., Tech. Dig. IEDM (2003) 57 [2] S. Takagi et al., Tech. Dig. IEDM (1999) 461 [3] J. Welser, Ph.D dissertation (1994) 146 [4] L. Yang et al., Semicond. Sci. Technol., 19 (2004) 11

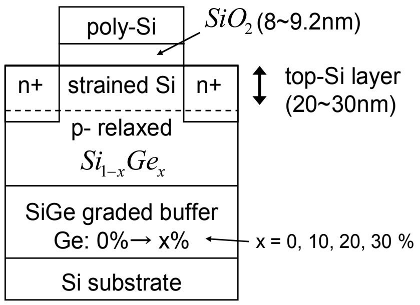

Fig. 1 Cross section of device structure of strained- Si n-MOSFETs used in this study.

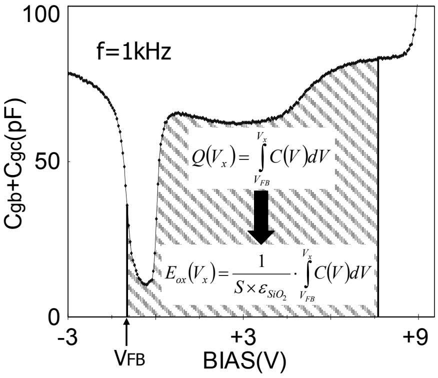

Fig. 2 Typical C-V curve and the calculation method of the electric field across the gate oxide. The measurement frequency is 1 kHz.

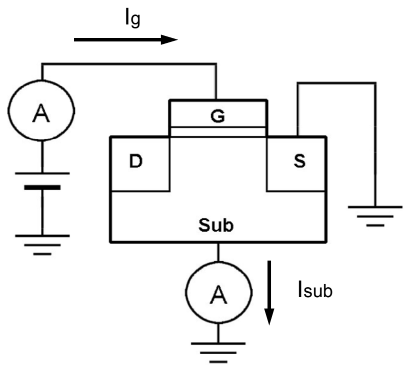

Fig. 3 Set-up for measurement of gate current and substrate current in an n-MOSFET.

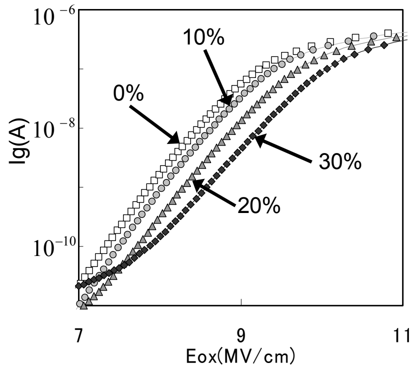

Fig. 4 Measured gate current versus electric field in each strain. The FN plots of these curves provide the sufficient linearity to estimate values of B.

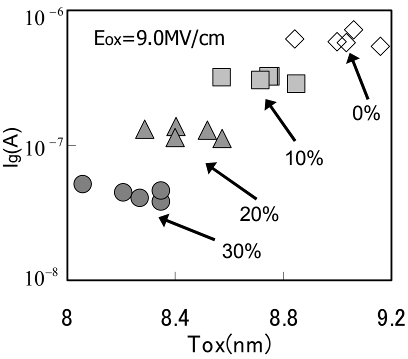

Fig. 5 Gate current versus oxide thickness at Eox=9.0MV/cm. The gate current decreases monotonically with an increase in strain.

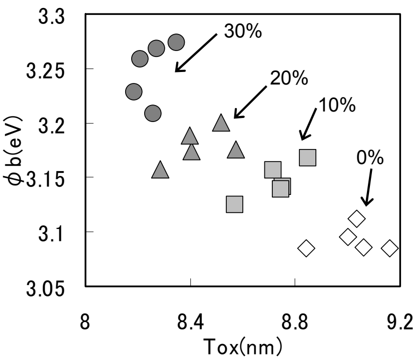

Fig. 6 Barrier height versus oxide thickness. The barrier height increases with an increase in strain.

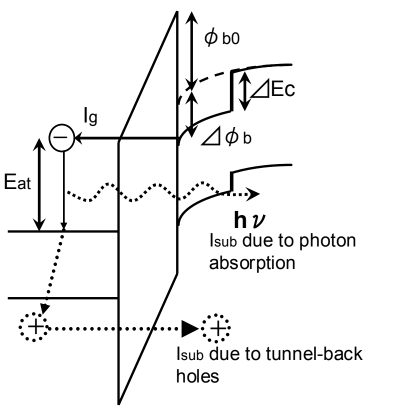

Fig. 7 Energy band diagram of the strained-Si MOS structure, illustrating possible physical mechanisms of Ig and Isub.

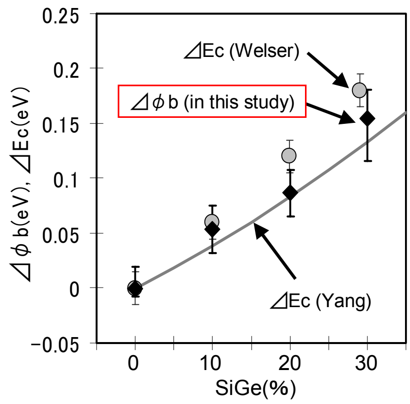

Fig. 8 Comparison between the increase in the barrier height evaluated in this study and the reported values of the change in the energy of the conduction band edge due to strain [3, 4].

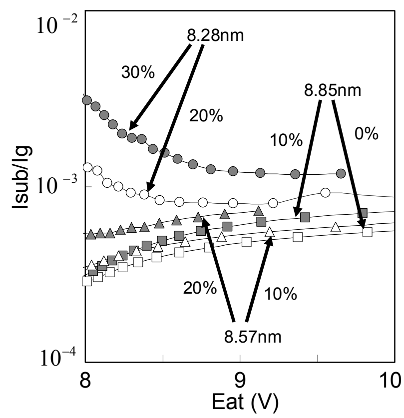

Fig. 9 Ratio Isub/Ig (quantum efficiency) as a function of energy of electrons injected into the gate.