Extended Abstracts of the 1996 International Conference on Solid State Devices and Materials, Yokohama, 1996, pp. 773-775

Mobility Limiting Factors of n-Channel Si/SiGe Modulation-Doped Systems with Varied Channel Thickness

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We studied the channel thickness dependence of electron mobility in modulation-doped strained-Si/relaxed $Si_{0.8}Ge_{0.2}$ in order to investigate the effect of the interface roughness. When the channel thickness, W, was wider than 50Å, the Fermi velocity of electrons determined the mobility. When W was thinner than 50Å, interface roughness was found to have a large influence on the conduction. In particular, when W was about 40Å, the interface roughness scattering was the most important process which decided the mobility. Moreover, when W was less than 30Å, the two-dimensional variable range hopping governed the conduction.

1 Introduction

Strained Silicon/relaxed Silicon-Germanium (Si/SiGe) heterostructures have controllable band discontinuities in which the conduction band bottom of Si is lower than that of SiGe. Therefore, this system is attracting a great interest as Si-based novel materials used for high-speed n-channel modulation-doped (MOD) field-effect transistors (FETs). The mobilities up to 3000cm^2/Vs at room temperature[1] and 500000cm^2/Vs at 0.4K[2] have been reported.

To improve the mobility, it is necessary to precisely know what mechanism dominates the mobility. At the very beginning, it was said that the mobility was limited by the scattering by dislocations threading from the relaxed SiGe buffer to the strained Si channel. In order to reduce the scattering, the "graded buffer" technique was developed, resulting in a drastic decrease of threading dislocation density[3]. However, the measured mobilities were still much lower than expected[4], indicating that other scattering processes came to be important. Gold[5] and Monroe *et al.*[4] calculated mobilities determined by several scattering mechanisms such as remote and background impurity scattering. Ismail *et al.* reported that the scattering by the strain field near the misfit dislocations in the Si channel governs the mobility under a certain condition[2]. However, experimental details of the scattering have not been fully understood yet.

In the present paper we report the influence of the interface roughness on the mobility. Since the matrix element of the interface roughness scattering strongly depends on the channel thickness[6], we fabricated samples with various thickness of quantum wells ranging from large value of 200Å to extremely small value of 13Å, and investigated the transport properties.

2 Experimental

Schematic structure of the samples for the present study is shown in Fig. 1.

The heterostructures were grown by a combination of gas-source MBE (GSMBE) and solid-source MBE

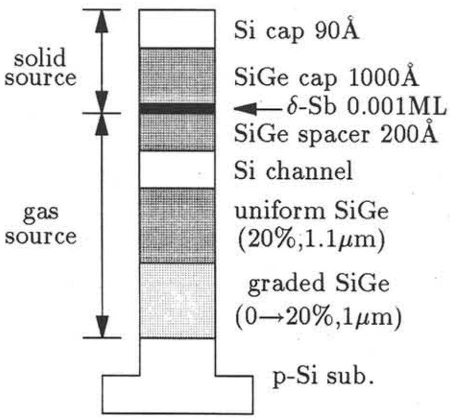

Fig. 1: Sample structure grown for the present study.

(SSMBE). It is known that GSMBE-grown samples have better crystal quality than SSMBE-grown samples, and are free from Ge segregation. On the other hand, SSMBE has better doping controllability. Accordingly, it is expected that samples with higher quality can be grown by the combination of these two MBEs.

Si substrates used were p-type, (100)-oriented 5–10Ωcm wafers. After cleaning in H_2SO_4–H_2O_2 solution and oxide removal in HF, graded buffer, uniform buffer, channel and spacer layers were grown by gas-source MBE. As mentioned, channel thickness, W, was varied systematically from 200Å to 13Å. The wafers were then transferred to the solid-source MBE through the air within 5 minutes. δ-Sb supply and cap layers were successively grown.

The transfer through the air introduces contamination on the grown surface. Just after loading to the SSMBE, the reflection high energy electron diffraction (RHEED) pattern of the surface was 1×1, indicating contaminated (100) surfaces. However, thermal treatment at 700°C for 2minutes in UHV changed the pattern to 2×1 which is known as the pattern of reconstructed clean (100) surface, and did not change during the following growth.

The Hall measurements were performed on van der Pauw or Hall bridge geometries. Electrodes were formed by AuSb evaporation and successive annealing at 300°C

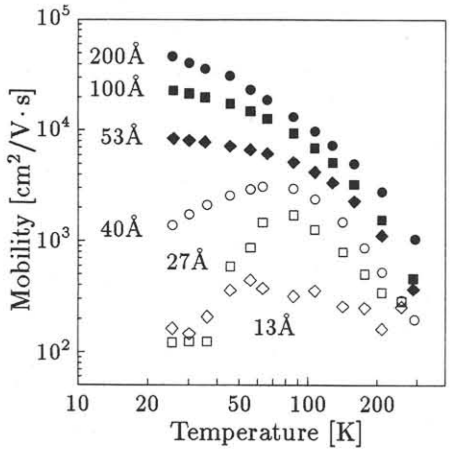

Fig. 2: Temperature dependence of the Hall mobility.

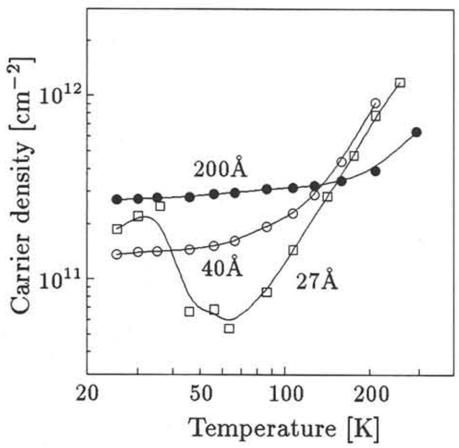

Fig. 3: Temperature dependence of the sheet carrier density.

for 1 minute.

3 Results and Discussion

The temperature dependence of the mobility is shown in Fig. 2. It is seen that the thinner the well width is, the lower the mobility is in all temperature range. When W is thicker than 53Å, the mobility monotonically increases with decreasing temperature. On the other hand, when W is thinner than 40Å, the mobility shows a peak and then decreases with decreasing temperature.

In Fig. 3, the temperature dependence of the carrier density is shown. For simplicity, results of 200Å, 40Å and 27Å samples are shown, since the characteristics of 100Å, 53Å and 13Å samples are similar to 200Å, 40Å and 27Å samples, respectively. When W is wider than 40Å, the carrier densities are almost constant at low temperatures. On the other hand, when W is 27Å or 13Å, the Hall voltage drastically dropped and became unstable at low temperatures, resulting in a steep increase in calculated carrier density.

From these results, it is seen that the low temperature characteristics have three regimes with respect to

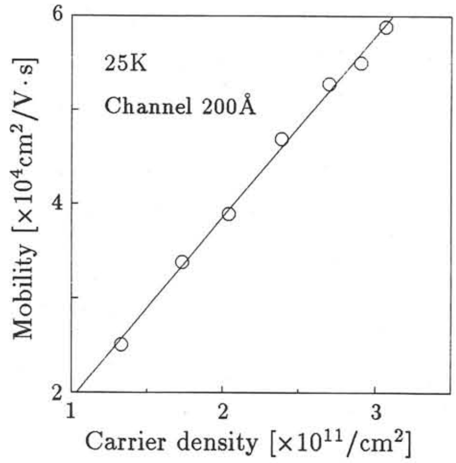

Fig. 4: Relationship between carrier density and mobility of a 200Å sample.

the channel width W: (1)W=200Å, 100Å and 53Å, (2)W=40Å and (3)W=27Å and 13Å. For each cases more detailed properties at low temperatures are discussed separately.

3.1 200Å, 100Å and 53Å samples

At low temperatures their mobilities increase with decreasing temperature, while carrier densities keep almost constant. This feature is typical of MOD systems.

Since the mobility does not strongly depend on the channel thickness, interface roughness scattering is thought not to be dominant. In order to know the scattering processes, samples with back-gate electrodes were fabricated and the relationship between mobility and carrier density was measured. A result of a 200Å sample at 25K is shown in Fig. 4. It is seen that the mobility increases with increasing carrier density, showing that the mobility is limited by the Fermi velocity of the electrons. Screened remote impurity scattering or background impurity scattering may dominate the mobility.

3.2 40Å sample

In this sample, both mobility and carrier density decrease with decreasing temperature in the low temperature range. Around this W the mobility strongly depends on the channel thickness, indicating that the interface roughness scattering is important. From this point of view, temperature dependence of the mobility limited by this interface roughness scattering was estimated. Matrix element deduced by Sakaki *et al.* [6] and screening factors derived by Stern[7, 8] and Maldague[9] were employed for the calculation. The results are shown in Fig. 5. The calculation well reproduces the measured data at low temperatures. As the fitting parameters for several samples, vertical mean roughness, Δ, and lateral correlation length, Λ, were found to be 6.5–8.0Å and 120–130Å, respectively. These parameters are different from Feenstra *et al.*'s recent results by atomic force microscope (AFM) [10], which may be due to the different

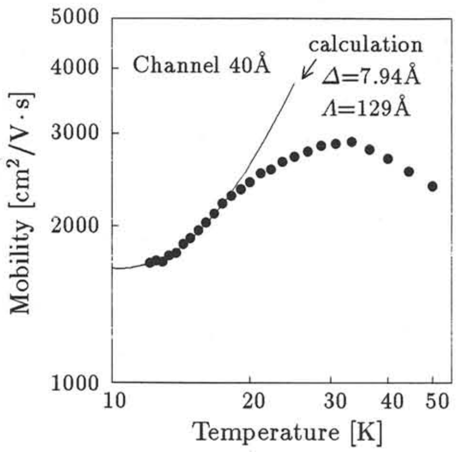

Fig. 5: Measured mobility and calculated interface-roughness-limited mobility of a 40Å sample.

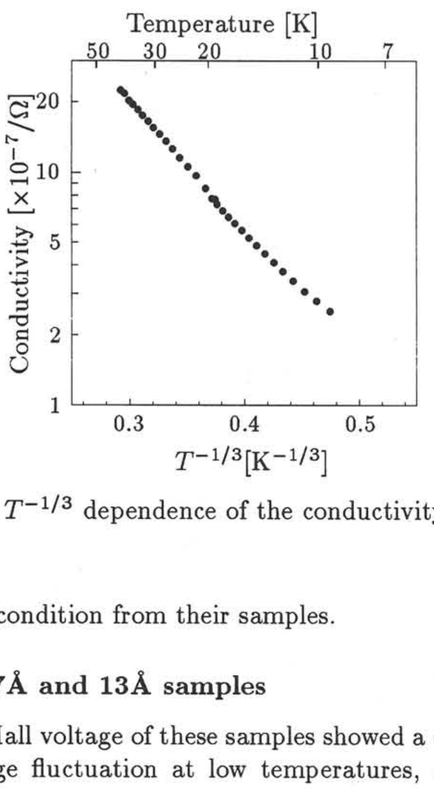

Fig. 6: $T^{-1/3}$ dependence of the conductivity of a 13Å sample.

growth condition from their samples.

3.3 27Å and 13Å samples

The Hall voltage of these samples showed a quick drop and large fluctuation at low temperatures, suggesting that the electrons are localized in this temperature range. Accordingly, temperature dependence of the conductivity was studied instead of mobility and carrier density. It should be noted that the conductivity was stable in contrast with the Hall voltage.

The $T^{-1/3}$ dependence of the conductivity of a 13Å sample is shown in Fig. 6. This plot gives better linearity than that of the conductivity vs $1/T$, showing that two-dimensional variable range hopping conduction, rather than thermally activated conduction, occurs[8, 11]. This is the first observation of the hopping in the present system.

In these samples with extremely thin channels, the quantum energy level of the channel is influenced largely by a small fluctuation of the channel thickness. Therefore, it is thought that the interface roughness induces the hopping conduction.

4 Conclusion

Mobility limiting factors in n-channel modulation-doped Si/SiGe heterostructures were investigated by varying the channel thickness from 200Å to 13Å. When the channel was thicker than 50Å, the Fermi velocity of electrons determined the mobility. In cases W was thinner than 50Å, the interface roughness had a large influence on the conduction. When the thickness was about 40Å, interface roughness scattering was found to limit the mobility. When the channel was thinner than 30Å, electrons were localized under the influence of the interface roughness, and two-dimensional variable range hopping conduction was observed.

Acknowledgments

The authors would like to thank Dr. K. Nakagawa for fruitful discussions. A part of this work was supported by a Grant-in-Aid for Scientific Research on Priority Area, "Ultimate Integration of Intelligence on Silicon Electronic Systems", from the Ministry of Education, Science and Culture.

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