Journal of Korean Vacuum Science & Technology; JKVST
Vol. 4, No. 1, March 2000, pp. 11~17

Low temperature electron mobility property in Si/$Si_{1-x}Ge_x$ modulation doped quantum well structure with thermally grown oxide

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(Received January 15, 2000)

The low temperature electron mobilities were investigated in Si/$Si_{1-x}Ge_x$ modulation Doped (MOD) quantum well structure with thermally grown oxide. N-type Si/$Si_{1-x}Ge_x$ structures were fabricated by a gas source MBE. Thermal oxidation was carried out in a dry O_2 atmosphere at 700°C for 7 hours. Electron mobilities were measured by a Hall effect and a magnetoresistant effect at low temperatures down to 0.4 K. Pronounced Shubnikov-de Haas (SdH) oscillations were observed at a low temperature showing two dimensional electron gases (2 DEG) in a tensile strained Si quantum well. The electron sheet density (n_s) of 1.5×10^{12} [cm^{-2}] and corresponding electron mobility of 14200 [$cm^2V^{-1}s^{-1}$] were obtained at low temperature of 0.4 K from Si/$Si_{1-x}Ge_x$ MOD quantum well structure with thermally grown oxide.

I. Introduction

Si/$Si_{1-x}Ge_x$ heteroepitaxy devices have lately been investigated with particular interest for future high-speed device applications [1-4]. In addition to the general advantages of heteroepitaxy technology which offers precisely controlled layers of a high crystalline quality, the special advantage of Si/$Si_{1-x}Ge_x$ devices is the use of Si-based technology which is widely available, more reliable and economical than GaAs-based technology [2-6].

The strain due to lattice mismatch in Si/$Si_{1-x}Ge_x$ structures results in the band discontinuities. Such band discontinuities are used to separate conducting electrons (holes) from parent donor (acceptor) atoms, so called modulation doped (MOD) structures, which results in enhanced mobility at low temperature because of the reduced ionized impurity scattering [3,7]. Fig. 1 shows both type I and type II band discontinuity in Si/$Si_{1-x}Ge_x$ structures. A type II band discontinuity is expected in a tensile strained Si/$Si_{1-x}Ge_x$ structure, while a type I band discontinuity is expected in unstrained Si/$Si_{1-x}Ge_x$ structure. In a type II band discontinuity, electrons can be confined in the Si quantum well by the shifts of energy bands and accordingly the band gap [7]. The tensile strain in the Si channel reduces the degeneracy of the Si conduction band edge from six-fold to two-fold, resulting in reduced intervalley scattering [2,3]. The two-fold degeneracy in a tensile strained Si channel shows a high electron effective mass perpendicular to the heterointerface ($m_\perp^* = 0.98\ m_0$) and a low in-plane effective mass ($m_\parallel^* = 0.19\ m_0$) [7]. Thus the enhanced electron mobility in the MOD Si/$Si_{1-x}Ge_x$ quantum wells results from reduced ionized impurity scattering, reduced interface roughness scattering, and reduced intervalley scattering, etc [1,2,6,7].

In Si/$Si_{1-x}Ge_x$ MOD structures, electron mobilities of about 3000 [$cm^2V^{-1}s^{-1}$] at room temperature, which is twice as high as those for pure Si bulk of 1450 [$cm^2V^{-1}s^{-1}$], and those of about 100000 [$cm^2V^{-1}s^{-1}$] at low temperatures (~2 K) have already been reported [2,3,9-14]. Low temperature electron mobilities in modulation doped layers have been observed to be up to 50 times higher than those in standard Si-based metal-oxide-semiconductor field-effect transistors (MOSFETs) [4].

Molecular beam epitaxy (MBE) has been widely used for the growth of heteroepitaxy structures because of its ultra-high vacuum ambient and high controllability of layer structure [2,15]. Low pressure chemical vapour deposition (LPCVD) and organometallic vapor phase epitaxy (OMVPE) have also been used for the growth of high quality heteroepitaxy structures [7,16]. Gas source molecular beam epitaxy (GSMBE) has been known to reduce heavy

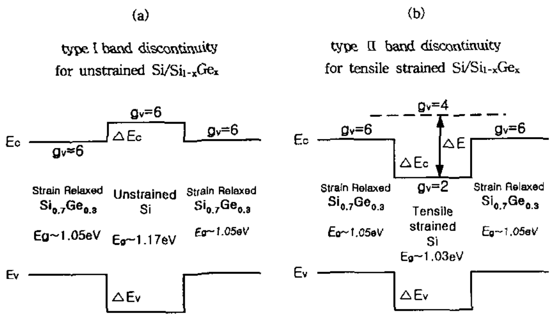

Fig. 1. Energy band discontinuity in Si/Si$_{1-x}$Ge$_x$ MOD structure. (a) type I band discontinuity for unstrained Si/Si$_{1-x}$Ge$_x$ MOD structure, (b) type II band discontiuity for *tensile strained* Si/Si$_{1-x}$Ge$_x$ MOD structure.

metal incorporation encountered in solid source MBE systems, where the Si is evaporated at high temperature [2]. Low substrate temperature and high growth selectivity in GSMBE are previously reported to be attractive features for heteroepitaxy devices [7].

The superior electron mobilities in Si/Si$_{1-x}$Ge$_x$ MOD structures will be of special interest for future high-speed device applications if they can be readily processed via conventional MOS fabrication techniques. One of the important topics in this regard would be the best way to form the oxide [8]. Oxide growth at temperatures T>750°C has been used to make both n- and p- channel devices [17,18]. However, the electron mobilities of Si/Si$_{1-x}$Ge$_x$ MOD structures with thermally grown oxides have not been so successful as those of Si/Si$_{1-x}$Ge$_x$ MOD structures without oxides because of thermal degradation effects such as interdiffusion, strain relaxation, etc [1,8]. Si/Si$_{1-x}$Ge$_x$ structures involve a lattice mismatch that produces strain in the epitaxial layer. The lattice mismatch between Si and Ge is approximately 4.2%. The lattice constant of relaxed Si$_{1-x}$Ge$_x$ layers have an intermediate value between Si and Ge varying with the Ge content(x). The strain introduced by the lattice mismatch will always find a way to be thermally activated and relieved by the formation of numerous dislocations and nonplanar surface morphology [4,5,19-25]. Planar surfaces are highly desired for the applications of high-speed heteroepitaxy devices [18]. These strain relaxation mechanisms are known to be largely dependent on various fabrication conditions such as temperature, surfactants, thickness, or compositional grading, etc [1,4,5,19,21]. It is thus necessary to study the electron mobility property in Si/Si$_{1-x}$Ge$_x$ MOD quantum well structures with thermally grown oxides along with low temperature oxide growth techniques such as anodic oxidation or plasma oxidation, etc.

The purpose of this study was to investigate the low temperature electron mobility of Si/Si$_{1-x}$Ge$_x$ MOD quantum well structure with thermally grown oxide. N-type Si/Si$_{1-x}$Ge$_x$ MOD quantum wells were fabricated. Thermal oxidation was carried out in a dry O_2 atmosphere at 700°C for 7 hours. Electron mobilities were measured by a Hall effect and a magnetoresistant effect at low temperatures down to 0.4 K. Shubnikov-de Haas (SdH) oscillations at a low temperature showed well behaved 2 DEGs in a tensile strained Si quantum well.

II. Experiment

N-type Si/Si$_{1-x}$Ge$_x$ MOD quantum well structures were fabricated by GSMBE as described the details elsewhere [3,7]. Fig. 2 shows a schematic diagram of the n-type Si/Si$_{1-x}$Ge$_x$ MOD quantum well structures used in this study. The modulation doped quantum well structures consist of a relaxed SiGe virtual substrate grown on a p-type silicon substrate. The virtual substrate is linearly graded SiGe buffer with a germanium concentration up to 30% over a distance of 2 μm. The SiGe buffer layer is used for strain

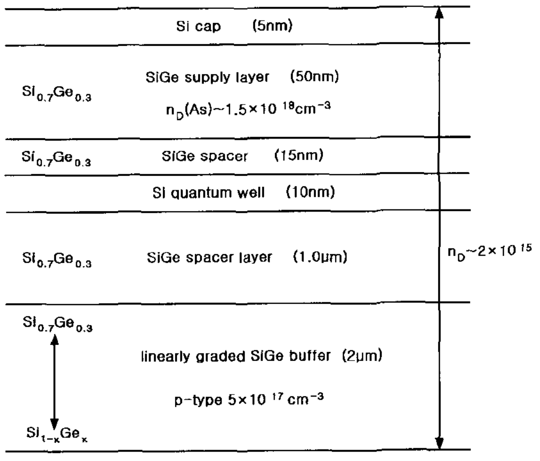

Fig. 2. A schematic diagram of the n-type Si/Si$_{1-x}$Ge$_x$ MOD quantum well structure.

relaxation in the alloy and dislocation confinement near the substrate-epilayer interface [7]. The use of the SiGe buffer layer is an important feature of $Si/Si_{1-x}Ge_x$ structures. Not only does its use minimize the formation of dislocation densities, but by varying the Ge content of the layer, the strain experienced could be changed continuously [25]. The virtual substrate is followed by a 1.0 μm spacer layer of $Si_{0.7}Ge_{0.3}$. The silicon quantum well is subsequently grown with a 10 nm thickness, which is separated from a 50 nm thick heavily arsenic doped SiGe supply layer with a doping concentration of $\sim 10^{18}$ cm^{-3} by an undoped SiGe spacer layer of 15 nm. The SiGe supply layer is capped by 5 nm of silicon.

The quantum wells were processed into Hall bars for a low temperature electron mobility measurement using standard techniques as depicted in Fig. 3. The Hall bar etch was performed by using 1% O_2 and 50% CHF_3 reactive ion etcher (RIE) for 4 min. The etching rate was approximately 500 Å/min. After dipping into buffered HF for 20 sec. to remove

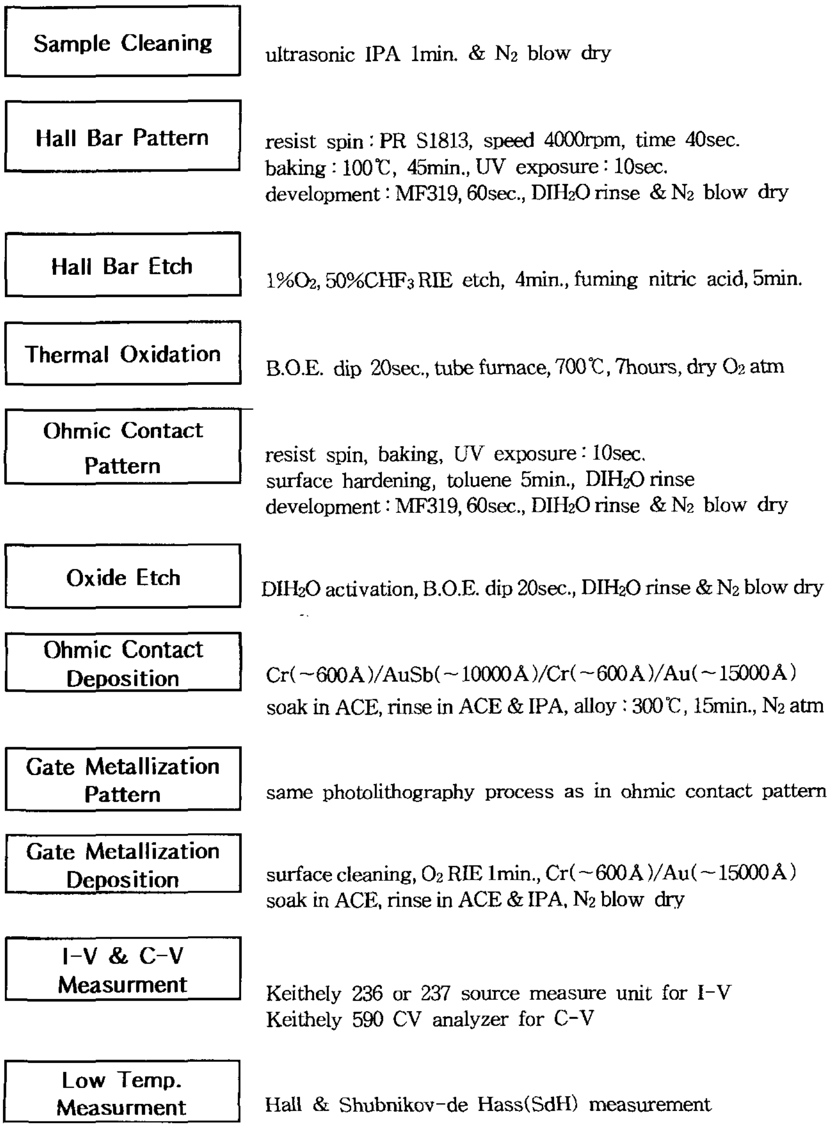

Fig. 3. The fabrication process of a Hall bar pattern for a low temperature electron mobility measurement.

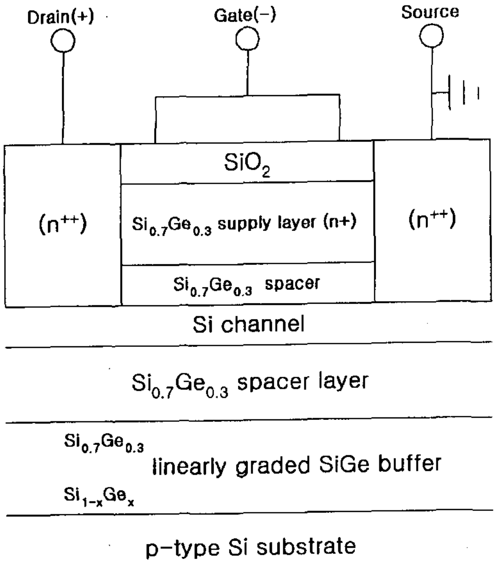

Fig. 4. A cross sectional view of the gated n-type Si/Si$_{1-x}$Ge$_x$ MOD quantum well structure.

any native oxide, the sample was thermally oxidized in an electric tube furnace maintained in a dry O$_2$ atmosphere at 700°C for 7 hours. The thickness of the oxide was estimated to be ~200 Å by elipsometry and CV measurements. The ohmic contact was made by subsequent thermal evaporations of Cr(~600 Å)/AuSb(~10000 Å)/Cr(~600 Å)/Au(~15000 Å) followed by alloying in a N$_2$ atmosphere at 300°C for 15 min. The gate metallization was also formed by thermal evaporation of Cr(~600 Å)/Au(~15000 Å). Fig. 4 shows a cross sectional view of the gated n-type Si/Si$_{1-x}$Ge$_x$ MOD quantum well structure. The gated Hall bars were connected for the measurements and then cooled down to 0.4 K in a He^3 cryostat. During the cooling process, the connections were sometimes found to be damaged. Thus two different points of Hall bar patterns, one 840 μm and the other 420 μm length, were prepared for the measurements. The two different points of Hall bar patterns did not show considerable effects on the electron mobilities. Low temperature electron mobilities were measured by the Hall effect and Shubnikov-de Haas magnetoresistant effect under magnetic field up to 4 T at low temperatures down to 0.4 K. The typical Hall bar pattern used in this study is shown in Fig. 5. The total length and width of Hall bar was 840 and 60 μm, respectively.

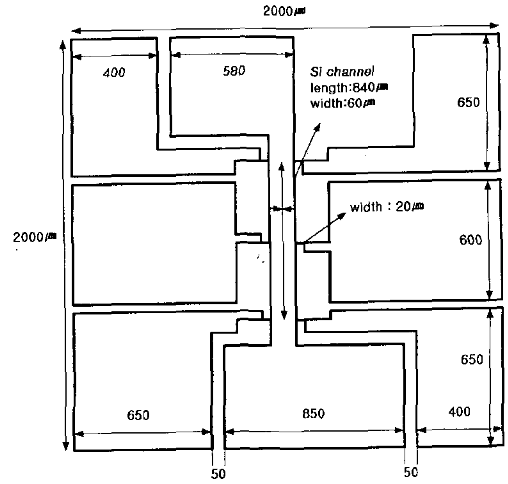

Fig. 5. Schematic diagram of the Hall bar pattern.

III. Results and discussion

Two dimensional electron gases are characterized by Shubnikov-de Haas (SdH) oscillations under a high magnetic field at low temperatures. This is illustrated in Fig. 6, which shows the magnetic field (B) dependence of longitudinal (R$_{\text{longitudinal}}$) and Hall (R$_{\text{Hall}}$) resistance at a temperature of 0.4 K in Si/Si$_{1-x}$Ge$_x$ MOD quantum well structures with thermally grown oxides. Pronounced Shubnikov-de Haas oscillations can be observed in the longitudinal resistance with plateaus in the Hall resistance, both of which result from a high quality 2 DEG in the Si quantum well. The Shubnikov-de Haas (SdH) oscillations arise because of the step-like density of states associ-

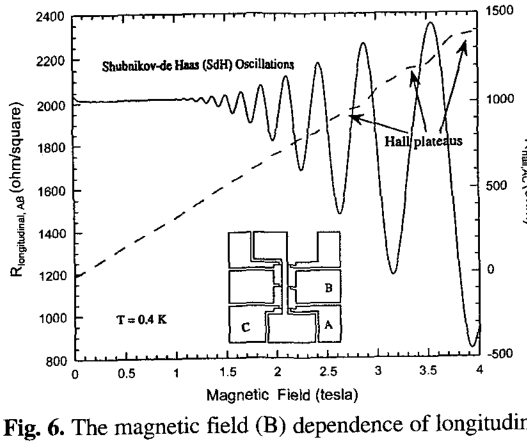

Fig. 6. The magnetic field (B) dependence of longitudinal (R$_{\text{longitudinal}}$) and Hall (R$_{\text{Hall}}$) resistance at a temperature of 0.4 K.

ated with a 2 DEG at high magnetic fields [26].

Fig. 7 depicts Landau level index at longitudinal resistance minima as a function of reciprocal magnetic field, 1/B, taken from the magnetic field dependence of longitudinal resistance in Fig. 6. The number of occupied Landau levels changes with increasing the magnetic field (B). The longitudinal resistance goes through one cycle of oscillation as the Fermi energy moves from one Landau level to the next Landau level. The magnetic field values between two successive peaks are related by $n_s/4eB_1/h - n_s/4eB_2/h = 1$ so that the electron sheet density $n_s = 4e/h\ 1/(1/B_1 - 1/B_2)$ for the two-fold degeneracy in a tensile strained 2 DEG Si quantum well [26]. Thus the electron sheet density (n_s) can be calculated from the slope of the straight line as shown in Fig. 7. The electron mobility is then calculated by $\mu_{el} = L/n_s ReW$ where L and W is the length and width of Si quantum well, respectively [26]. From the magnetoresistant SdH oscillation effect, the electron sheet density (n_s) of 1.5×10^{12} [cm^{-2}] and corresponding low temperature electron mobility of 14200 [cm^{2}V^{-1}s^{-1}] were measured at a temperature of 0.4 K from Si/Si$_{1-x}$Ge$_x$ MOD quantum well structure with thermally grown oxide. The electron sheet density (n_s) observed by the Hall effect was 1.9×10^{12} [cm^{-2}].

Fig. 8 shows the magnetic field (B) dependence of longitudinal ($R_{longitudinal}$) and Hall (R_{Hall}) resistance at low temperatures of 5, 2 and 0.4 K. As expected, Shubnikov-de Haas (SdH) oscillations, which resulted from a well behaved 2 DEG in the Si quantum well, are observed at low temperatures. More pronounced SdH oscillations appeared at lower temperatures. SdH oscillation characteristics of 2 DEG are generally known to be evident at cryogenic temperatures below 4 K [26]. The straight lines of Landau level index as a function of reciprocal magnetic field, 1/B, were taken from the longitudinal resistance minima at both 2 and 5 K. The the electron sheet density (n_s) of ~1.5×10^{12} [cm^{-2}] and 1.6×10^{12} [cm^{-2}] were measured at low temperatures of 2 and 5 K, respectively. The corresponding electron mobility of 14000 [cm^{2}V^{-1}s^{-1}] and 13900 [cm^{2}V^{-1}s^{-1}] were observed at low temperatures of 2 and 5 K from Si/Si$_{1-x}$Ge$_x$ MOD quantum well structure with thermally grown oxide, respectively.

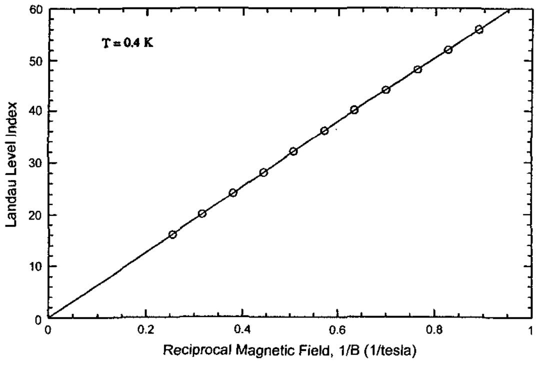

Fig. 7. Landau level index at longitudinal resistance minima as a function of reciprocal magnetic field, 1/B.

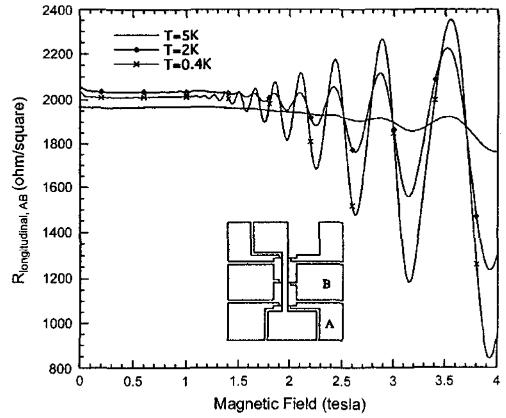

Fig. 8. The magnetic field (B) dependence of longitudinal ($R_{longitudinal}$) and Hall (R_{Hall}) resistance at low temperatures of 5, 2, and 0.4 K.

Fig. 9 shows the magnetic field dependence of longitudinal and Hall resistance in Si/Si$_{1-x}$Ge$_x$ MOD structures without oxide at 5 K. the electron sheet density (n_s) of 1.4×10^{12} [cm^{-2}] and corresponding low temperature electron mobility of 20000 [cm^{2}V^{-1}s^{-1}] were measured from the magnetoresistant SdH oscillation effect in Si/Si$_{1-x}$Ge$_x$ MOD structure without oxide. The electron sheet density (n_s) observed by the Hall effect was 1.6×10^{12} [cm^{-2}]. Compared with Si/Si$_{1-x}$Ge$_x$ without oxide, the lower electron mobility in Si/Si$_{1-x}$Ge$_x$ MOD structure with thermally grown oxide is believed to be caused by thermal degradation effect such as interdiffusion, strain relaxation, etc. However, low temperature electron mobility in this study was much improved in comparison with previous electron mobility measured in similar Si/Si$_{1-x}$Ge$_x$ MOD structures with thermally grown oxides [7].

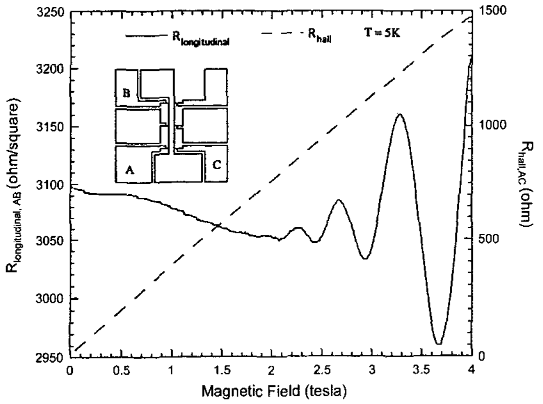

Fig. 9. The magnetic field (B) dependence of longitudinal ($R_{longitudinal}$) and Hall (R_{Hall}) resistance in $Si/Si_{1-x}Ge_x$ MOD structure without oxide at 5 K.

Thermal stability is very important for the process of the MOS fabrication. The thermal stability is known to be largely affected during the fabrication at various conditions [1,4,5,19,21]. Thus further improvement of electron mobility in $Si/Si_{1-x}Ge_x$ MOD structures with thermally grown oxide can be expected with further optimization of the various fabrication conditions such as temperature, material structure, or compositional grading, etc. Low temperature electron mobility properties of the $Si/Si_{1-x}Ge_x$ MOD structures including electron sheet density from the magnetoresistant SdH oscillation effect and the Hall effect, electron mobility from SdH oscillation effect are summarized in Table 1. The electron sheet densities in a 2 DEG typically ranges from 2×10^{11} [cm^{-2}] to 2×10^{12} [cm^{-2}] for the use in a field effect transistor [26]. In $Si/Si_{1-x}Ge_x$ structures used, the electron sheet densities of ~1.5×10^{12} [cm^{-2}], and electron mobility of 20000 [$cm^2V^{-1}s^{-1}$] for $Si/Si_{1-x}Ge_x$ without oxide and that of 13900 [$cm^2V^{-1}s^{-1}$] for $Si/Si_{1-x}Ge_x$ with thermally grown oxide are shown. The difference between the electron sheet densities of $n_{s,Hall}$ and those of $n_{s,SdH}$ in $Si/Si_{1-x}Ge_x$ with thermally grown oxide could be probably caused by parallel conduction. The electron sheet density changes with various gate voltages would be another work to study next.

Table 1. Results of Hall and Shubnikov-de Haas measurements at low temperatures

Samples	T (K)	n_{Hall} ($10^{12}cm^{-2}$)	n_{SdH} ($10^{12}cm^{-2}$)	μ_e ($cm^2V^{-1}s^{-1}$)
$Si/Si_{1-x}Ge_x$	5	2.0	1.6	13900
(with thermal	2	1.9	1.5	14000
oxides)	0.4	1.9	1.5	14200
$Si/Si_{1-x}Ge_x$ (without oxides)	5	1.6	1.4	20000

IV. Conclusion

Two dimensional electron gases in a tensile strained Si quantum well were obtained in $Si/Si_{1-x}Ge_x$ MOD structure with thermally grown oxide. The electron sheet density (n_s) of 1.5×10^{12} [cm^{-2}] and corresponding electron mobility of 14200 [$cm^2V^{-1}s^{-1}$] were obtained at a low temperature of 0.4 K from the magnetoresistant SdH oscillation effect. The electron mobility of 20000 [$cm^2V^{-1}s^{-1}$] were measured at 5 K in $Si/Si_{1-x}Ge_x$ MOD structure without oxide. Further optimization of the various fabrication conditions is believed to improve the low temperature electron mobility property in $Si/Si_{1-x}Ge_x$ MOD structures with thermally grown oxide.

Acknowledgements

The present research has been conducted by the Research Grant of Kwangwoon University in 1999. The author would like to thank Dr. T. Thornton, Dr. P. Green, Dr. M. Ahmad, Dr. S. Kaya, Dr. M. Zai, and Mr. J. Yeoh for their help, technical support, and valuable discussion, etc.

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