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Low-Temperature Boron-Doped $Si_{1-x}Ge_x$ Heteroepitaxy by LPCVD

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$Si_{1-X}Ge_X$ heteroepitaxy in a temperature range of 550-700°C is demonstrated by LPCVD using $Si_2H_6/GeH_4/B_2H_6/H_2$ gas system. B-doping characteristics of $Si_{1-X}Ge_X$, aimed at applying to npn $Si_{1-X}Ge_X$ base HBTs, are then investigated in detail. The B doping velocity controlled by the B_2H_6 partial pressure is independent of the $Si_{1-X}Ge_X$ growth conditions. The resistivity of $Si_{1-X}Ge_X$ doped higher than $1x10^{20}cm^{-3}$ is $1x10^{-3}$ Ω·cm. The dislocation density is below 10^8cm^{-2}, which is one order lower than that of the undoped $Si_{1-X}Ge_X$.

1. Introduction

$Si_{1-X}Ge_X/Si$ heterostructures are expected to be applied to silicon-based heterostructure devices, Si-HBTs for instance, utilizing their remarkable band-gap differences dependent on the Ge content and the strain.[1-5] $Si_{1-X}Ge_X/Si$ heterostructures have been fabricated using chemical vapor deposition (CVD), molecular beam epitaxy (MBE), and solid phase epitaxy (SPE) techniques. The CVD technique is superior to the MBE and the SPE techniques from a productivity and suitability point of view in conventional Si LSI processes. However, the CVD technique using SiH_4 and GeH_4 requires temperatures above 900°C.[6,7] Consequently, such problems arise as strained layer relaxation, interface reaction and impurity diffusion. Reduction in growth temperature has therefore been demanded. So far, rather incoventional CVD techniques such as UHV/CVD and limited reaction processing (LRP) using SiH_4 and SiH_2Cl_2 with GeH_4, respectively, have been reported to lower the growth temperature.[8,9)

The purpose of the present study is to realize low-temperature heteroepitaxy of $Si_{1-X}Ge_X/Si$ with a conventional low-pressure CVD (LPCVD) reactor. Heteroepitaxy of B-doped $Si_{1-X}Ge_X$ is investigated especially in detail, since it is essential to fabricating npn $Si_{1-X}Ge_X$ base HBTs. To lower the growth temperature, we adopted two means. One is using Si_2H_6 in replacement of SiH_4 as the source gas of Si. This is because the decomposition probability of Si_2H_6 is higher than that of SiH_4. The other is hydrogen-flow processing on the Si surface at a growth temperature performed prior to $Si_{1-X}Ge_X$ deposition. This processing promotes the removal of Si oxide on the surface through the reduction reaction with Si_2H_6 and GeH_4.[10] In the following, heteroepitaxy achieved in a temperature range of 550-700°C is demonstrated. B-doping characteristics up to $4x10^{20}cm^{-3}$ are described.

2. Experimental

A horizontal CVD reactor with an infrared lamp heater was used for the experiments. The substrate was a p-type (100) silicon wafer with a resistivity above 1k Ω·cm. The wafer was rinsed with NH_4OH/H_2O_2, HF, and HCl/H_2O_2 solutions and set on the susceptor in the reactor just after HF-dip. Purified-hydrogen was supplied on the wafer surface for 5 min at a growth temperature. A $Si_{1-X}Ge_X$ film was grown by introducing Si_2H_6 and GeH_4 with H_2 carrier gas. For B-doping, H_2-based B_2H_6 was added to the forming gas. The growth temperature range was 550-700°C. In the B-doping experiments, the growth temperature was fixed at 680°C, because the minimum temperature for Si crystal growth on Ge is 650°C in the present CVD reactor[11,12], and it is most convenient in Si-HBT fabrication to perform B-doped $Si_{1-X}Ge_X$ growth and following Si crystal growth at the same temperature. The total pressure during deposition was about 3 Torr.

3. Results and Discussion

The epitaxial growth of the $Si_{1-X}Ge_X$ films in a temperature range of 550-700°C at constant partial pressures of Si_2H_6 (5.3×10^{-2} Torr) and GeH_4 (1.5×10^{-2} Torr) is confirmed by reflection electron diffraction (RED). Germanium content X is almost constant, 0.2, irrespective of growth temperature. Crystallinity of the $Si_{1-X}Ge_X$ films grown at temperatures below 600°C is better than that above 630°C as revealed by streaky patterns with Kikuchi lines in the RED photographs. The cross-sectional TEM (XTEM) photographs of the samples formed at 650°C and 550°C are shown in Fig. 1. The 650°C-grown sample includes a great deal of dislocations that originate from the lattice misfit between $Si_{0.8}Ge_{0.2}$ and Si (~0.8%). The dislocation density is roughly evaluated to be $4\times10^8 cm^{-2}$. In contrast with this, the dislocation density of the 550°C-grown sample decreases to about $4\times10^7 cm^{-2}$. This result corresponds to that of the RED patterns.

Fig. 2 shows dependence of the $Si_{0.75}Ge_{0.25}$ growth rate on the growth temperature. The partial pressures of Si_2H_6 and GeH_4 are retained at 1.5×10^{-2} Torr. The activation energy of the growth rate is 1.8eV, which is even larger than an activation energy, 1.4eV, reported [12] for surface-reaction limited Si growth using a Si_2H_6/H_2 gas system. Therefore, the growth rate of $Si_{1-X}Ge_X$ is considered to be controlled by the Si_2H_6 and GeH_4 surface reaction.

The dependence of the B doping velocity on the B_2H_6 partial pressure (P_{B2H6}) under various $Si_{1-X}Ge_X$ growth conditions is shown in Fig. 3. The B doping velocity is defined

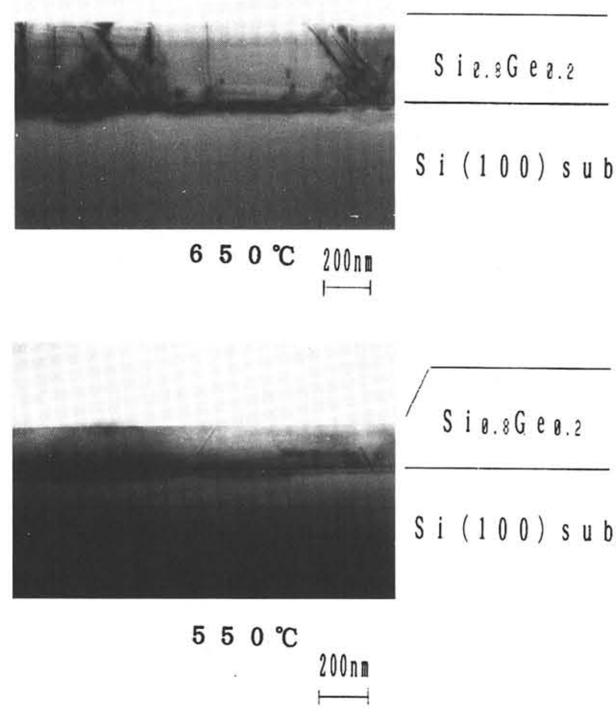

Fig. 1 XTEM Photographs of the $Si_{0.8}Ge_{0.2}$ /Si Heterostructures Formed at 650°C and 550°C

by the product $C_B \times R$ of the B concentration (C_B) and the $Si_{1-X}Ge_X$ growth rate (R). The doping velocity is nearly proportional to P_{B2H6}. Besides, no dependence of the doping velocity on the growth condition is observed. These facts suggest that B doping is independent of $Si_{1-X}Ge_X$ growth and the B doping velocity is controlled by B_2H_6 supply onto the surface.

Fig. 4 shows the dependence of the $Si_{1-X}Ge_X$ resistivity on C_B. The C_B is determined by the B_2H_6 partial pressure. Boron atoms can be doped into $Si_{1-X}Ge_X$ up to $C_B=4\times10^{20}cm^{-3}$. The minimum resistivity of 1×10^{-3} Ω·cm is obtained with epitaxial $Si_{1-X}Ge_X$ films doped with B above $1\times10^{20}cm^{-3}$. The polycrystalline $Si_{1-X}Ge_X$ films (dashed line) show a high resistivity, compared with that of crystalline films (solid line). Little resistivity change is observed for these samples after the heat-treatment at 800°C for 10 min in N_2.

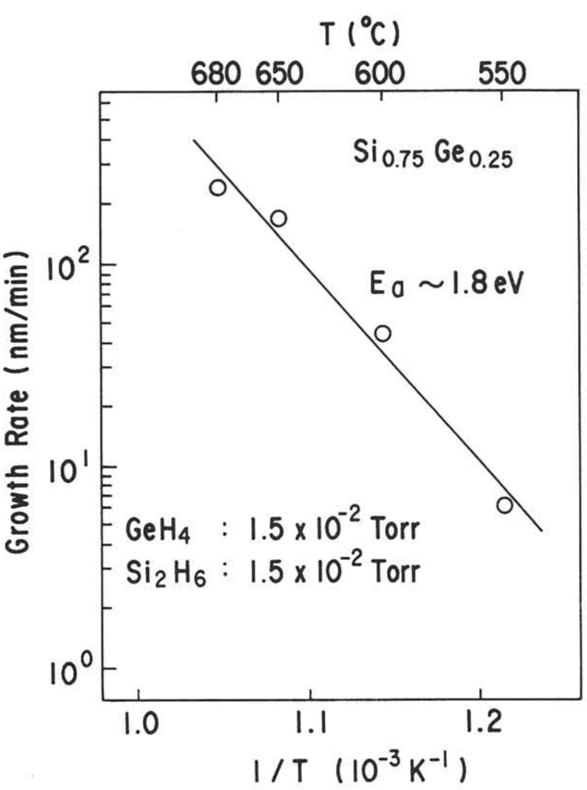

Fig. 2 Growth Temperature Dependence of the $Si_{0.75}Ge_{0.25}$ Growth Rate

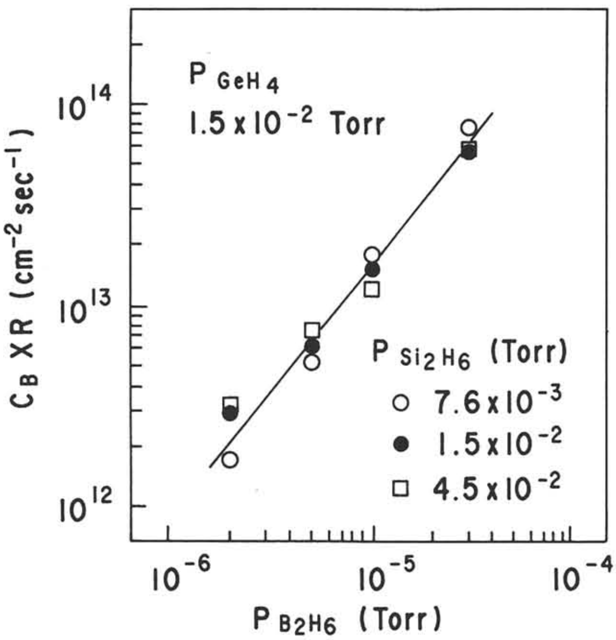

Fig. 3 P_{B2H6} Dependence of B Doping Velocity

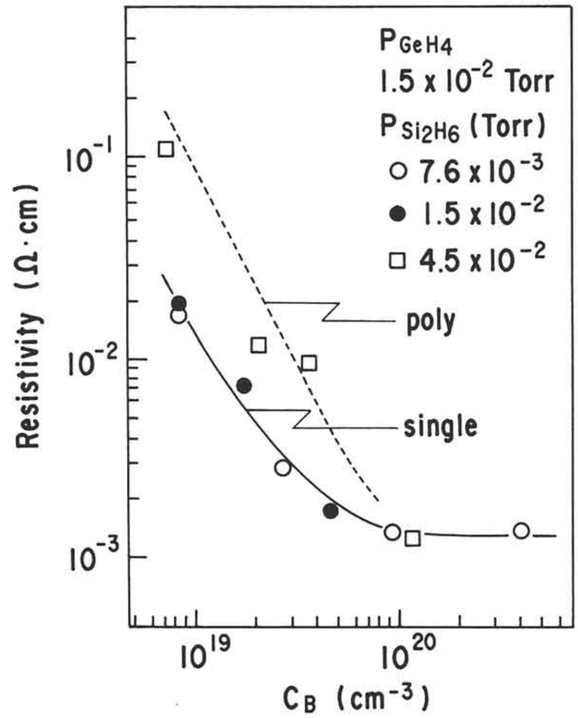

Fig. 4 B Concentration Dependence of Resistivity

Fig. 5 shows the XTEM photographs of undoped and highly B-doped ($\sim 1x10^{20}cm^{-3}$) $Si_{0.75}Ge_{0.25}$ films on Si(100) substrates. The film thicknesses are 180 nm and 150 nm. They are larger than the critical thickness reported in the literature[13,14]. A great deal of dislocations, originating from the lattice misfit ($\sim$ 1%), are observed in the undoped film, which is similar to the upper (650°C-grown) photograph in Fig. 1. It is seen, on the other hand, that the dislocations drastically decrease by high B doping. The dislocation density is roughly evaluated below 10^8cm^{-2}. The reason for the crystallinity improvement is considered to be that the doped B atoms reduce the strain of $Si_{1-X}Ge_X$ layer on Si. Detail investigation is necessary to verify this.

4. Conclusion

The heteroepitaxy is demonstrated in a temperature range of 550-700°C. The dislocation density of undoped 550°C-grown $Si_{0.8}Ge_{0.2}$ is $\sim 4x10^7cm^{-2}$. The growth rate is controlled by the Si_2H_6 and GeH_4 surface reaction. Its activation energy is $\sim$1.8eV. B-doping characteristics are investigated at a growth temperature of 680°C. The B doping is independent of the $Si_{1-X}Ge_X$ growth. The minimum resistivity of $1x10^{-3}\Omega\cdot cm$ is obtained in highly B-doped $Si_{1-X}Ge_X$ ($>1x10^{20}cm^{-3}$). The dislocation density of highly B-doped films decreases below 10^8cm^{-2}, although a great deal of dislocations, originating from the lattice misfit ($\sim$1%), are observed in the undoped films grown at 680°C.

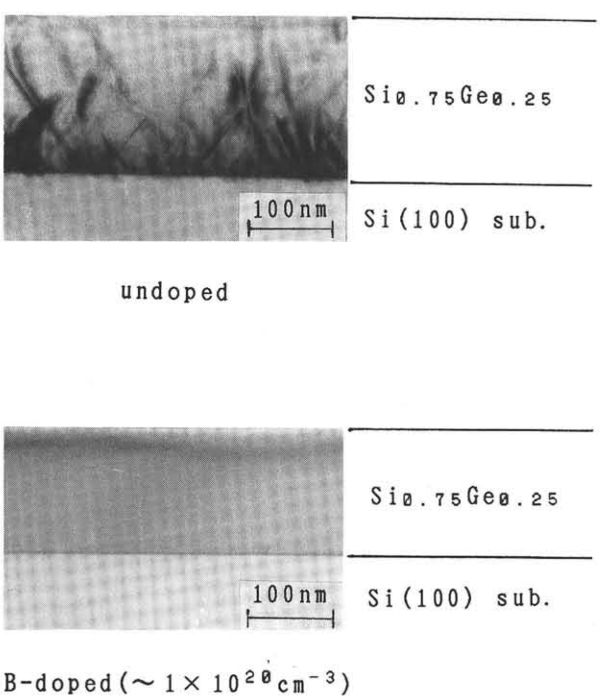

Fig. 5 XTEM Photographs of the Undoped and Highly B-doped($1x10^{20}cm^{-3}$) $Si_{0.75}Ge_{0.25}$/Si Heterostructures Formed at 680°C

References

1) T. P. Pearsall et al; IEEE Electron Device Lett. 7 (1986) 308.
2) H. Temkin et al; Appl. Phys. Lett. 48 (1986) 963.
3) G. L. Patton et al; IEEE Electron Device Lett. 9 (1988) 165.
4) C. A. King et al; IEEE Electron Device Lett. 10 (1989) 52.
5) K. Ohta et al; in Extended Abstracts of the 20th (1988 International) Conference on Solid State Devices and Materials, (Tokyo 1988) p.235.
6) H. M. Manasevit et al; Appl. Phys. Lett. 41 (1982) 464.
7) C. M. Gronet et al; J. Appl. Phys. 61 (1987) 2407.
8) B. S. Meyerson et al; Appl. Phys. lett. 53 (1988) 2555.
9) C. A. King et al; IEEE Electron Device Lett. 9 (1988) 229.
10) K. Fujinaga et al; Inst. Electron. & Commun. Jpn. Technical Report, SDM88-116 (1988) [in Japanese].
11) K. Fujinaga et al; J. Vac. Sci. Technol. B5 (1987) 1551.
12) K. Fujinaga et al; J. Vac. Sci. Technol. B7 (1989) 225.
13) R. People et al; Appl. Phys. Lett. 47 (1985) 322.
14) Y. Kohama et al; Appl. Phys. Lett. 52 (1988) 380.