

Contribution of Carbon to Activation and Diffusion of Boron in Silicon

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Introduction

Complementary metal-oxide-semiconductor field-effect transistor (CMOSFET) has been aggressively scaled down to nanometer region. One of the principal technologies for scaling down the CMOSFET is ultra-shallow junction (USJ), which requires formation of very shallow, abrupt dopant profiles with high activation. Recently, it was found that co-implantation of carbon (C) in a range comparable with boron (B) concentrations could suppress B diffusion, resulting in a box-like B profile shape^[1-4]. On the other hand, the reducing of B activation in the presence of C has been reported^[2,4]. Those phenomena were attributable to the formation of C-interstitial clusters^[5]. In contrast, the improvement of B activation by using C co-implantation has also been presented^[3]. The influence of C on activation properties in wide C and B concentration range has not been sufficiently investigated.

In this work, we investigated the diffusion and the activation characteristics of B in the C-doped Si (Si_{1-y}C_y) epitaxial film in wide C and B concentration ranges by electrical and chemical analyses.

Experimental Procedure

Blanket Si_{1-y}C_y (y : 0 - 0.01) with a thickness of 100 nm was grown epitaxially on p-type Si (100) substrate with resistivity of 1-2 ohm-cm using a residual pressure chemical vapor deposition below 600 °C. To study the diffusion and the activation of B in the Si_{1-y}C_y film, B ions at energy of 2.5keV were implanted with dose ranging from 5 x 10¹⁴ cm⁻² to 3 x 10¹⁵ cm⁻² into Si_{1-y}C_y layer. Then, conventional spike annealing was performed at 1050 °C for 1.5 s residence time with preheated temperature in N₂ below 650 °C.

The B profiles in Si_{1-y}C_y were measured by secondary-ion mass spectroscopy (SIMS) with a primary ion of Cs⁺. Electrical properties in B-implanted Si_{1-y}C_y were evaluated by a liner four-point probe method and Hall measurement with the van der Pauw method.

Results and Discussion

Depth profiles of B in Si_{1-y}C_y layer after spike annealing at 1050 °C are shown in Fig. 1. The reduction of the B diffusion by C showed strong C concentration dependence. The B diffusion was reduced with increasing C concentration in Si. This reduction in B diffusion is mainly caused by a chemical species effect whereby C interacts with Si interstitials. Moreover, in the case of 5 x 10¹⁴ cm⁻² and 1 x 10¹⁵ cm⁻² B implant, B peak concentration increased with increasing C concentration, as indicated in the insets in Figs. 1(a) and (b). It was supposed that an intrinsic B diffusion was suppressed by C resulting in the increase of B peak concentration. In contrast, in the case of 3 x 10¹⁵ cm⁻² B implant, the increase of B peak concentration was not confirmed owing to the incorporation of C, as shown in the inset in Fig. 1(c). In the case of heavy B implant dose such as 3 x 10¹⁵ cm⁻², the stable B-containing clusters and precipitates are easily created at high B concentration region after high-temperature spike annealing at 1050 °C. Thus, it is thought that the reduction of intrinsic B diffusion and the increase of B peak concentration are not caused by C incorporation into Si.

The change of B profile caused by C has a great effect on the electrical conduction characteristic of B activation layer in Si_{1-y}C_y. Figure 2 shows the sheet carrier concentration (Ns) of B activation layer in Si_{1-y}C_y as a function of C concentration. The dependence of C concentration and B dose on Ns of B activation layer in Si_{1-y}C_y showed a characteristic tendency. Once Ns had decreased with increasing C concentration, it then increased with increasing C concentration. In the case of light B implant dose such as 5 x 10¹⁴ cm⁻² and 1 x 10¹⁵ cm⁻², Ns of B activation layer in Si_{1-y}C_y decreased by about 0.2 at.% C incorporation. The suppression of B diffusion in Si_{1-y}C_y, as indicated in Figs. 1(a) and (b), was thought to be the main cause of decreasing Ns by about 0.2 at.% C incorporation. It was considered that the increase of Ns above about 0.2 at.% C incorporation greatly affected the increase of B peak concentration by C incorporation, as indicated in the insets in Figs. 1(a) and (b).

Whereas, in the case of heavy B implant dose such as 3 x 10¹⁵ cm⁻², Ns of B activation layer in Si_{1-y}C_y was decreased by about 0.6 at.% C incorporation. Approximately 24 % of Ns decreasing was observed compared with B activation layer in Si. Since B peak concentration was not increased by C incorporation as shown in the inset in Fig. 1(c), the suppression of B diffusion in Si_{1-y}C_y, as indicated in Fig. 1(c), was thought to be the main cause of decreasing Ns.

The solubility limit and the activation ratio at 1050 °C spike annealing were estimated from the results of SIMS and Hall measurement, as illustrated in Fig. 3. Figures 4 and 5 show the estimated solid solubility and the ratio of activation ratio of B activation layer in Si_{1-y}C_y to that in Si at 1050 °C spike annealing as a function of C concentration. In the case of light B implant dose such as 5 x 10¹⁴ cm⁻² and 1 x 10¹⁵ cm⁻², it was found that the solubility limit and the activation ratio were increased dramatically by C incorporation. This might be attributable to interaction with Si interstitials and suppression of the boron Si-interstitials clustering by C incorporation. In contrast, in the case of heavy B implant dose such as 3 x 10¹⁵ cm⁻², the solubility limit and the activation ratio were decreased slightly by C incorporation. When the stable B-containing clusters and precipitates were created at high B concentration region after high-temperature spike annealing at 1050 °C, the effect of C incorporation on activation ratio was considered to be small.

Figure 6 shows the mobility of B activation layer in Si_{1-y}C_y as a function of C concentration. With the increase of C concentration, the mobility decreased, as shown in Fig. 6. The main factor in decrease of mobility was thought to be lattice strain attributable to the taking of C in lattice substitution of Si crystal. At the same time, when B implant dose was heavy, the decrease of the mobility with increasing C concentration was small compared with light B implant dose. This was thought to be because the effect of the impurity scattering on mobility was dominant, and the effects of C were difficult to discern.

Finally, the dependence of C concentration and B implant dose on the sheet resistance of B activation layer in Si_{1-y}C_y showed a characteristic tendency based on the above-mentioned results, as indicated in Fig. 7. In the case of heavy B implant dose such as 3 x 10¹⁵ cm⁻², the sheet resistance increased proportionally with increasing C concentration by 0.6 at.%. More than 0.6 at.% C had a tendency to saturate the sheet resistance. On the other hand, once the sheet resistance had increased with increasing C concentration, it then decreased with increasing C concentration in the case of light B implant dose such as 5 x 10¹⁴ cm⁻² and 1 x 10¹⁵ cm⁻².

Conclusions

In the experiment on wide C and B concentration range, it was clarified for the first time that B activation ratio in Si was increased or decreased depending on C incorporation concentration. The activation ratio of B activation layer was increased dramatically by C incorporation in the case of light B implant such as the range of 8 x 10¹⁹ to 3 x 10²⁰ cm⁻³ concentration. This might be attributable to interaction with Si interstitials and suppression of the boron Si-interstitials clustering by C incorporation. In contrast, in the case of heavy B implant such as 1 x 10²¹ cm⁻³ concentration, the activation ratio was decreased slightly by C incorporation. When the stable B-containing clusters and precipitates were created at high B concentration region, the effect of C incorporation on activation ratio was considered to be small.

References

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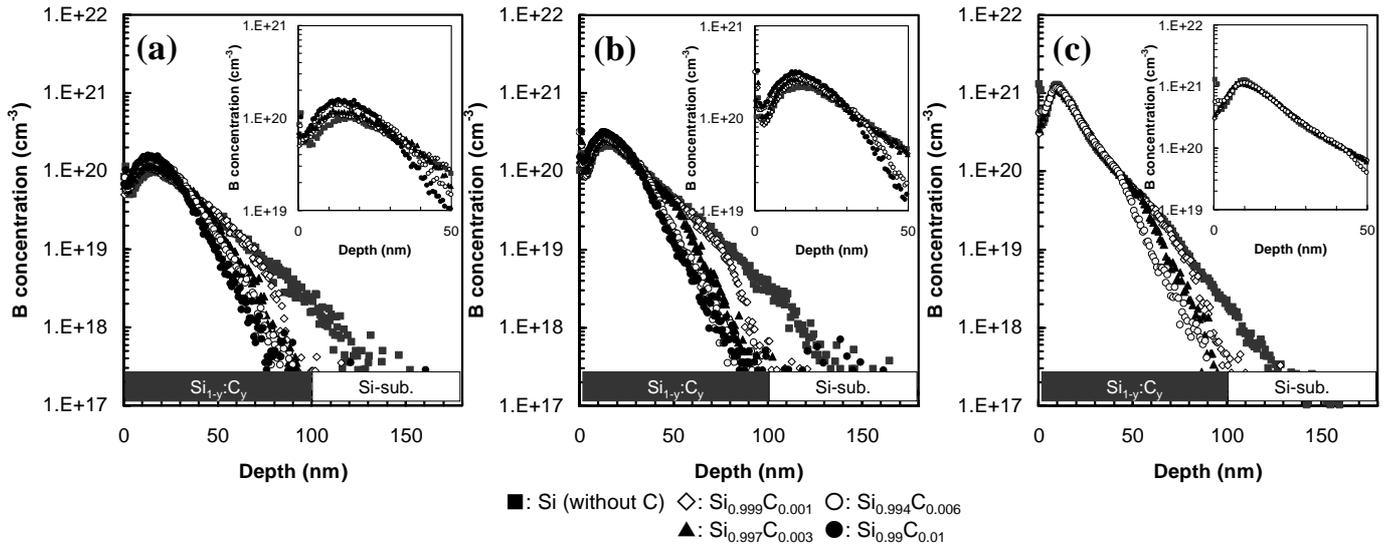


Fig.1 B diffusion dependence on C concentration in $\text{Si}_{1-y}\text{C}_y$ films. (a) $5 \times 10^{14} \text{ cm}^{-2} \text{ B}^+$ implant, (b) $1 \times 10^{15} \text{ cm}^{-2} \text{ B}^+$ implant, (c) $3 \times 10^{15} \text{ cm}^{-2} \text{ B}^+$ implant.

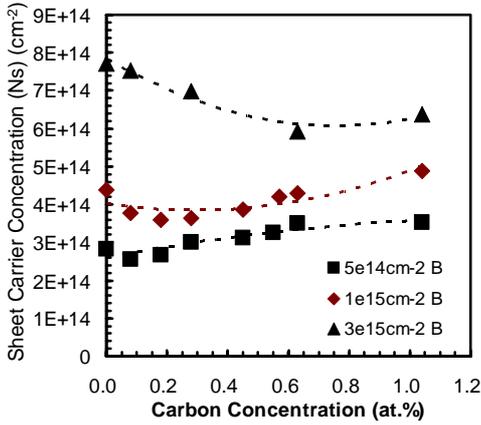


Fig.2 Sheet carrier concentration (Ns) of B activation layer in $\text{Si}_{1-y}\text{C}_y$ as a function of C concentration by the Hall measurement.

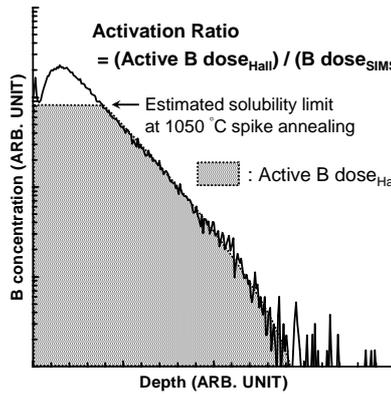


Fig.3 Schematic of the estimation for solubility limit and activation ratio from SIMS and Hall measurement.

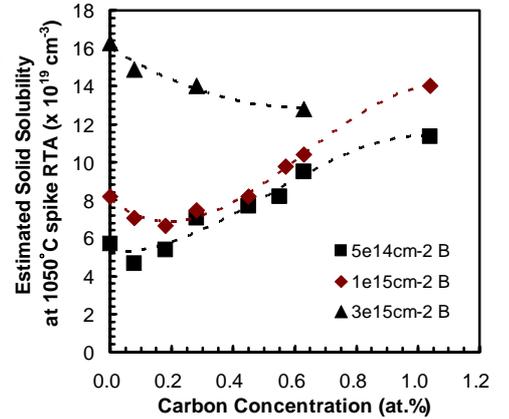


Fig.4 Estimated solid solubility at $1050 \text{ }^\circ\text{C}$ spike annealing of B activation layer in $\text{Si}_{1-y}\text{C}_y$ as a function of C concentration from SIMS and Hall measurement.

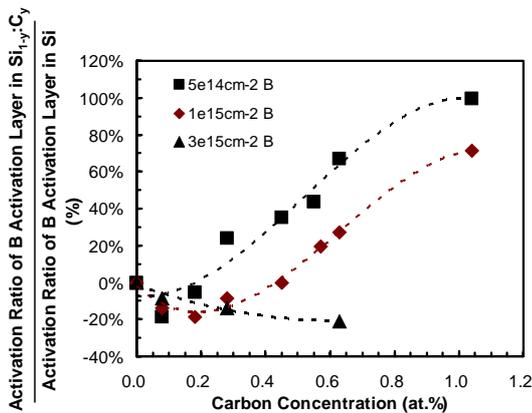


Fig.5 Estimated ratio of activation ratio of B activation layer in $\text{Si}_{1-y}\text{C}_y$ to that in Si at $1050 \text{ }^\circ\text{C}$ spike annealing as a function of C concentration from SIMS and Hall measurement.

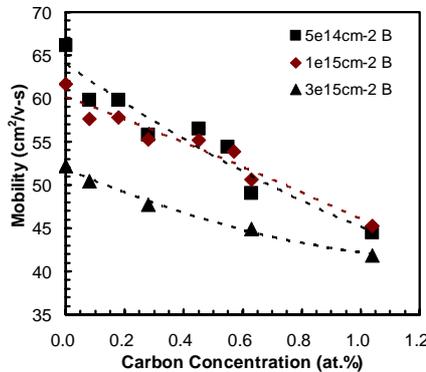


Fig.6 Mobility of B activation layer in $\text{Si}_{1-y}\text{C}_y$ as a function of C concentration by the Hall measurement.

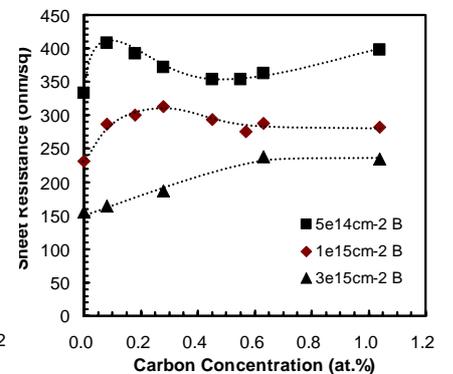


Fig.7 Sheet resistance of B activation layer in $\text{Si}_{1-y}\text{C}_y$ as a function of C concentration.