Diffusion behavior of delta-doped Si in InAlAs/InP heterostructures

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Diffusion behavior of delta-doped Si in InAlAs and InP was studied by using secondary ion mass spectroscopy. A significant broadening of the profile due to postgrowth annealing was observed in $In_{0.52}Al_{0.48}As$. In contrast, the depth profile of delta-doped Si in InP was scarcely changed by annealing. This indicates that the diffusion coefficient of delta-doped Si in InP is much smaller than that in $In_{0.52}Al_{0.48}As$. Suppression of Si diffusion by using a delta-doped InP layer as the carrier supply layer (CSL) improves the thermal stability of the InP-HEMT structures.

INTRODUCTION

Delta doping has shown its effectiveness in various device applications, such as the modulation-doped structure for InP-based high-electron-mobility transistors (HEMTs) (1). Control of the depth profile of delta-doped Si is a critical issue because the broadening of the depth profile due to thermal hysteresis during crystal growth degrades the characteristics of HEMTs, such as the electron mobility and the gate leakage current. The effect of the thermal hysteresis becomes more significant when other thick device layers, such as Shottky barrier diodes (SBDs) and/or resonant tunneling diodes (RTDs), are grown on the HEMT layers for the fabrication of the monolithic integrated devices (2). In order to achieve excellent performance of these devices, diffusion and migration of delta-doped Si during growth must be suppressed. However, to the best of our knowledge, there are few reports on the thermal diffusion behavior of delta-doped Si in $In_{0.52}Al_{0.48}As$ and InP.

In this paper, we discuss the diffusion behavior of delta-doped Si in $In_{0.52}Al_{0.48}As$ and InP during postgrowth annealing, which was investigated using secondary ion mass spectroscopy (SIMS). It is found that the diffusion coefficient of delta-doped Si in InP is much smaller than that in $In_{0.52}Al_{0.48}As$. Thermal stability of the InP-HEMT structures can be improved by using a delta-doped InP layer as the carrier supply layer (CSL).

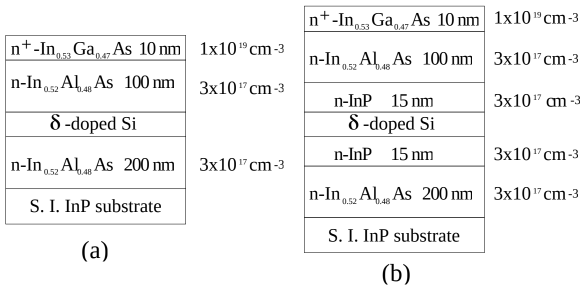

Figure 1. Layer structure of samples for SIMS measurements. Delta-doped Si (a) in InAlAs and (b) InP.

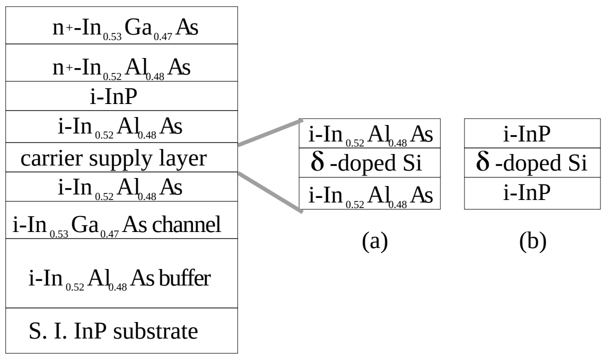

Figure 2. Layer structure of InP-based HEMTs. (a) InAlAs CSL. (b) InP CSL.

EXPERIMENTAL

Samples were grown by metal-organic vapor phase epitaxy on semi-insulating InP substrate at 620 ˚C. Figure 1 shows the layer structure of the samples. The sheet concentration of Si in the delta-doped layer was about 1×10^{13} cm^{-2} and controlled to be the same in all samples. In order to study the diffusion behavior of delta-doped Si, we performed postgrowth annealing in arsine atmosphere at temperatures ranging from 550 to 650 ˚C for 1 h. Thermal stability of the InP-HEMT structures were examined using the samples in Fig. 2 (3). They were grown at 620 ˚C and annealed in arsine atmosphere for 2 h. The van der Pauw-Hall effect was used at room temperature to measure the sheet carrier concentration (Ns) and mobility of electrons in the channel layer of those HEMT structures before and after annealing. For the Hall-effect measurements, the n^+-InGaAs/n^+-InAlAs contact layer was etched off in the evaluated area of the samples (4). SIMS measurements were carried out using Cs^+ primary ions at 1 keV to investigate the depth profiles of delta-doped Si.

RESULTS AND DISCUSSION

Diffusivities of delta-doped Si in InAlAs and InP

Figure 3 shows delta-doped Si profiles in $In_{0.52}Al_{0.48}As$ before and after postgrowth annealing at 550 to 625 ˚C. The profiles broadened symmetrically as the annealing temperature increased. Figure 4 shows delta-doped Si profiles in the InP layer before and after postgrowth annealing at 550 to 650 ˚C. The depth profiles in InP were scarcely changed by the postgrowth annealing. The full width half maximums (FWHMs) of the as-grown profiles in Figs. 3 and 4 are 9 and 5 nm, respectively. The small FWHM of the Si profile in InP reflects the suppression of diffusion during the

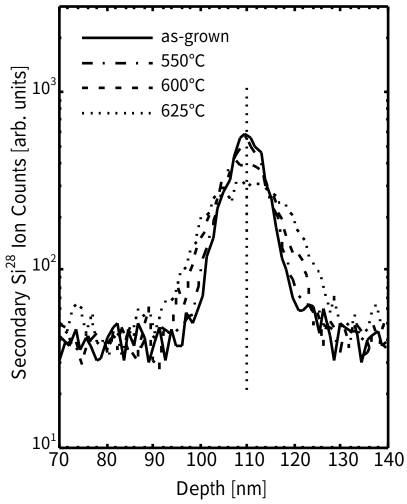

Figure 3. SIMS profile of delta-doped Si in InAlAs.

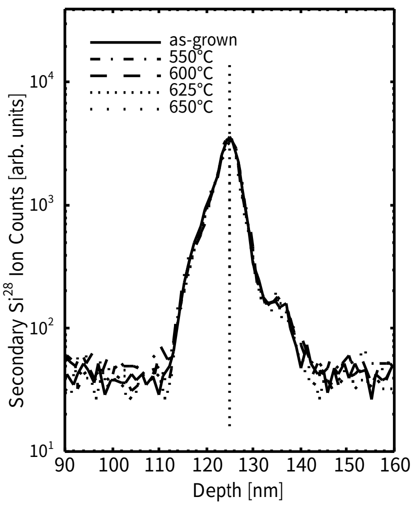

Figure 4. SIMS profile of delta-doped Si in InP.

growth. In estimating the diffusivity of delta-doped Si in $In_{0.52}Al_{0.48}As$ and InP, we assumed that the initial delta-doped Si profile located at $x=x_0$ results in a Gaussian distribution with

$$N_D(x) = \frac{N_D^{2D}}{\sigma\sqrt{2\pi}} \exp[-\frac{1}{2}(\frac{x-x_0}{\sigma})^2], \qquad (1)$$

where σ is a standard deviation of the Gaussian function (5). The broadening of the SIMS

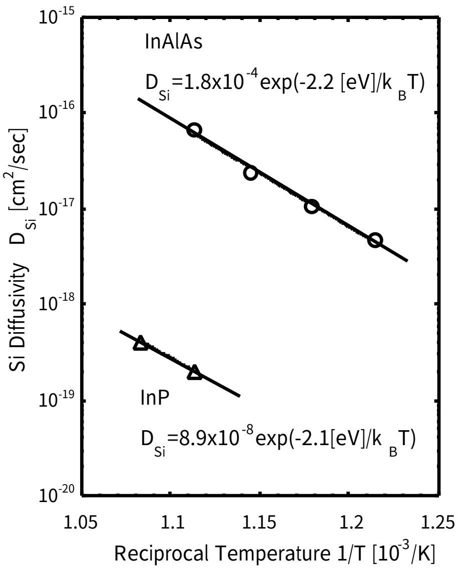

Figure 5. D_{Si} vs. reciprocal temperature.

profiles is

$$\sigma^2 = \sigma_{diff}^2 + \sigma_0^2, \quad (2)$$

where σ_{diff} is a diffusion induced term and σ_0 is a standard deviation of the as-grown sample (6). By fitting the SIMS profiles with eq. (1), we can obtain the diffusivities of Si D_{Si} using the relation

$$\sigma_{diff} = \sqrt{2D_{Si}t}, \quad (3)$$

where t is the annealing time.

Figure 5 shows the obtained diffusivities. The D_{Si} in the InP is about two orders of magnitude smaller than that in the $In_{0.52}Al_{0.48}As$. The activation energy of the diffusion process has a similar value in the two cases. However, the difference of ordinate intercept D_0 is quite large. The cause of the difference in D_0 has not been clarified yet. However, it might be related to a difference of the concentration of sites, such as Group-III vacancies (7), into which Si atoms can jump. Further study is expected.

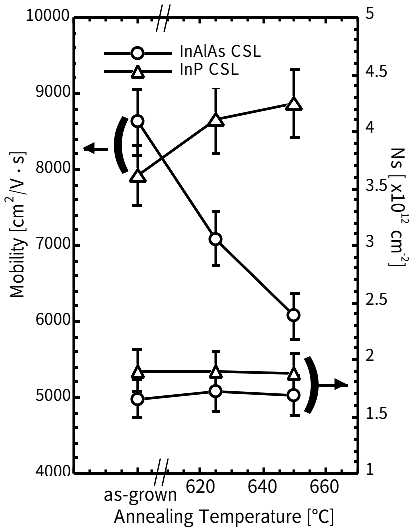

Figure 6. Thermal stability of the mobility and the Ns of InP-based HEMT structures.

Thermal stability of InP-based HEMT structures

The suppression of the Si diffusion in InP can be applied to improve the thermal stability of the InP-HEMT structure. Figure 6 shows the Ns and the mobility of electrons in the channel layer of InP-based HEMT structures with $In_{0.52}Al_{0.48}As$ or InP CSL before and after postgrowth annealing in arsine atmosphere. The Ns was quite stable after the annealing in both samples. However, when $In_{0.52}Al_{0.48}As$ is used as CSL, the mobility decreases significantly as annealing temperature increases. Such reduction of the mobility is prevented in the samples with InP CSL.

Figures 7 and 8 show the SIMS profiles around delta-doped Si CSL in the HEMT samples before and after annealing. The reduction of the Si peak intensity and the broadening of the profile toward the channel layer were observed in the sample with $In_{0.52}Al_{0.48}As$ CSL. Thus, the reduction of the mobility is explained by diffusion of the delta-doped Si in the $In_{0.52}Al_{0.48}As$ CSL toward the channel layer. In contrast, the diffusion of the

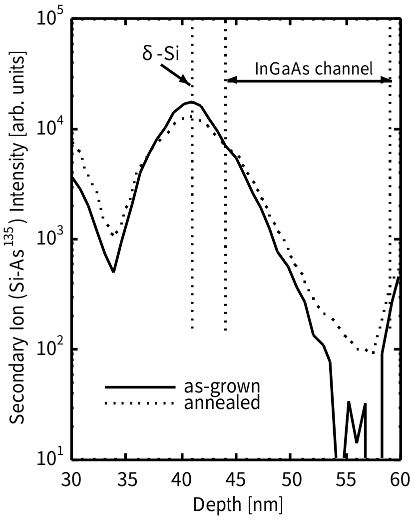

Figure 7. SIMS profile of InAlAs CSL.

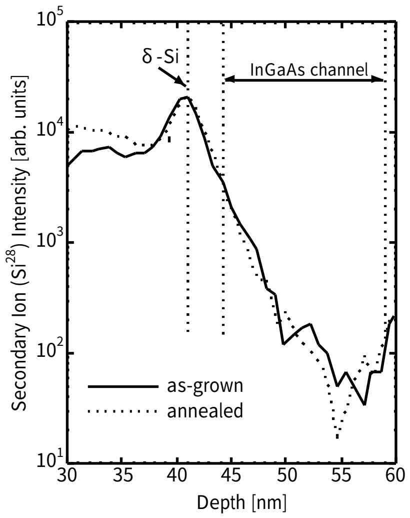

Figure 8. SIMS profile of InP CSL.

delta-doped Si toward the channel was not observed in the sample with InP CSL. This is consistent with the stability of the mobility of the HEMT with InP CSL.

SUMMARY

In summary, from SIMS measurements of the diffusion behavior of delta-doped Si in $In_{0.52}Al_{0.48}As$ and InP, we found that the diffusive coefficient of delta-doped Si in InP is much smaller in InP than $In_{0.52}Al_{0.48}As$. The thermal stability of InP-based HEMT structures was improved by using an InP CSL to suppress the Si diffusion.

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