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A 1.3-um Operation Si-Based Planar P-I-N Photodiode with Ge Absorption Layer Using Strain-Relaxing Selective Epitaxial Growth Technology

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1. Introduction

Recently, P-i-N SiGe/Si photodiodes for long-wavelength operation (λ = 0.96 - 1.3 µm) have been reported [1]-[6]. In our previous work [4][6], a 0.98-µm-operation P-i-N SiGe/Si planar photodiode using selective epitaxial growth technology was successfully integrated in electronic circuits. However, it is very difficult to obtain sufficient quantum efficiency at 1.3-µm operation when using a SiGe/Si optical absorption layer. This is because an increase in Ge concentration in the strained SiGe layers causes an increase in dislocation density, which decreases quantum efficiency.

This paper reports the first trial of a 1.3-µm-operation planar P-i-N photodiode with a selective epitaxial growth Ge optical absorption layer on silicon-on-insulator (SOI) substrate for Si-based opto-electronic integrated circuits (OEICs). To form a thick (-2.0 µm) pure Ge absorption layer on Si, we have developed a unique Ge epitaxial growth method that achieves complete strain relaxation of the Ge layer on Si by cold-wall ultra-high-vacuum chemical-vapor-deposition (UHV/CVD).

2. Photodiode structure

In addition to the previously mentioned structure [4] with 68-µm-deep / 128-µm-wide trench for the optical fiber guide, the developed P-i-N planar photodiode has the following features:

(1) For easy fabrication of the Si-based OEIC with a 1.3-µm-operation photodiode, the photodiode has a planar structure with a pure Ge optical absorption layer, which is filled selectively in a trench on the SOI substrate.

(2) A 0.5 to 2.0-µm-thick pure Ge layer, which was completely strain-relaxed and had flat surface, has been grown selectively on the Si surface without forming an intermediate buffer layer such as a graded SiGe layer.

Fig. 1 shows a schematic view of the integrated SiGe/Si planar photodiode with the trench for the optical fiber guide. The optical fiber is easily attached to the trench and coupling of the optical fiber core to the photodiode is alignment-free.

A schematic cross section of the photodiode is shown in Fig. 2. Selective epitaxial growth Ge and P^+-Si layers are formed in the SOI substrate. Use of an SOI substrate can increase the external quantum efficiency of the photodiode. This is because direct incident light as well as light reflected by the buried SiO_2 (0.5 µm) from the core (10 µm ϕ) of an optical fiber is absorbed by the Ge layer.

3. Ge selective epitaxial growth

To realize the thick Ge layer growth, unique epitaxial growth method [7] for complete strain relaxation of Ge layer has been developed, as shown in Fig. 3. The key steps in the process are as follows: (A) A 20-nm-thick strain Ge layer was grown on Si substrate. (B) A thin (< 1-nm) capping SiGe layer was formed on a 20-nm Ge layer, and annealing was carried out at 680℃ for strain relaxation of a 20-nm-thick Ge layer. (C) An undoped 0.5 to 2.0-µm-thick Ge absorption layer (boron concentration N_B : less than $1x10^{15}cm^{-3}$) of the photodiode was grown selectively on the strain-relaxed 20-nm-thick Ge layer. (D) A thin (< 1-nm) capping SiGe layer was formed on the thick Ge layer, and 790℃ annealing was carried out. (E) A 0.8-µm-thick P^+-Si contact layer (N_B:$1x10^{20}cm^{-3}$) was made selectively. The P^+-Si contact layer prevents germanium contamination in the silicon process after selective epitaxial growth.

Complete strain relaxation of the 20-nm-thick Ge layer after annealing at 680 ℃ was observed by X-ray diffraction measurement (Fig. 4). The peak for the 680℃-annealed sample coincided with the ideal position for bulk Ge (400). Hence, it is possible to grow a selectively thick (-2.0 µm) epitaxial Ge layer. Fig. 5 shows a cross-sectional TEM micrograph of the selective epitaxial growth layer of the photodiode after the Ge and P^+-Si contact layer growth. No defects are observed in the epitaxial growth layer.

4. Results

Fig. 6 shows the dependence of external quantum efficiency (η_{ext}) on photodiode size for λ = 1.3 µm at 0.3 V. The dark current density is about 3 nA/µm^2 at 0.3 V. A maximum η_{ext} of 14% was obtained. The η_{ext} increased as the photodiode width was extended, because the incident light radiated from the ball-point optical fiber. Fig. 7 shows the bias dependence of the η_{ext}. Higher quantum efficiency can be achieved by using a thicker Ge thickness, as shown in Fig. 7, because of the increased optical coupling efficiency from optical fiber to the photodiode.

5. Conclusion

By using a unique Ge epitaxial growth method, 1.3-µm-operation Si-based planar P-i-N photodiode with external quantum efficiency of 14% has been achieved. This result proves realization of low-cost and high-performance long-wavelength operation (-1.3 µm), Si-based OEIC receivers incorporating the planar photodiode.

References

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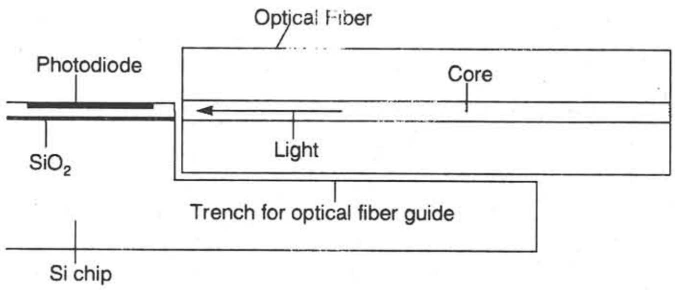

Fig.1 Schematic cross section of the integrated planar photodiode with the trench for optical fiber guide. The optical fiber is attached to the trench and the core of optical fiber is coupled to photodiode with alignment-free.

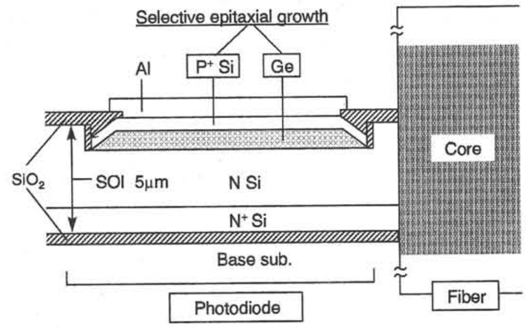

Fig.2 Schematic cross section of the photodiode on bonded SOI showing layer doping and composition. An undoped Ge absorption layer, P^{+}-Si contact layer are formed selectively in a trench on SOI.

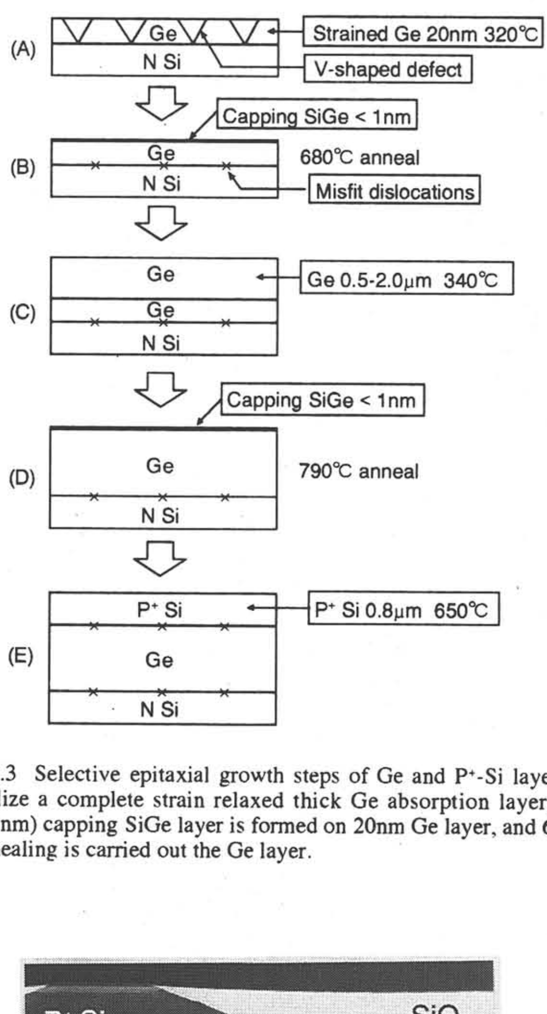

Fig.3 Selective epitaxial growth steps of Ge and P^{+}-Si layer. To realize a complete strain relaxed thick Ge absorption layer, thin (<1nm) capping SiGe layer is formed on 20nm Ge layer, and 680℃ annealing is carried out the Ge layer.

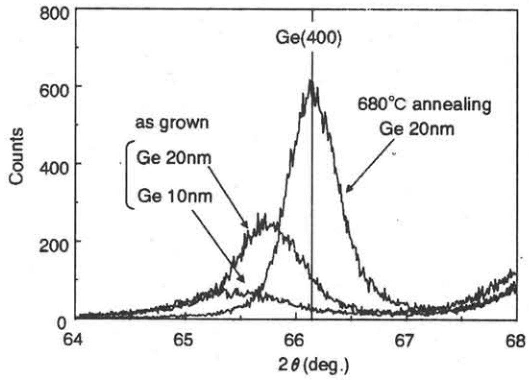

Fig.4 Rocking curve of selective epitaxial Ge layer. After 680℃ annealing, complete strain relaxation of the Ge layer was confirmed in 20nm Ge.

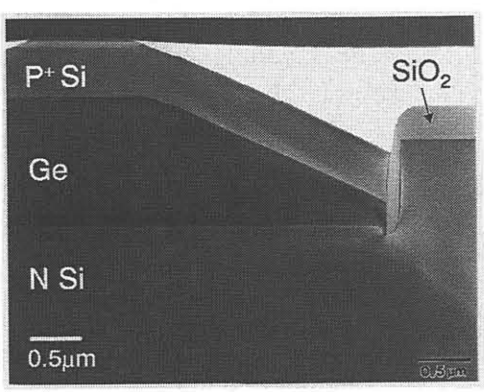

Fig.5 A cross-sectional TEM micrograph of selective epitaxial growth layer of the photodiode.

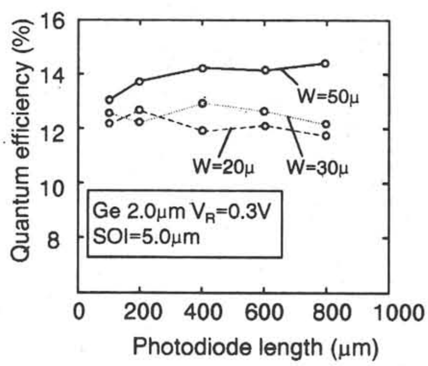

Fig.6 External quantum efficiency dependence of photodiode width (W=20-50μm) as a function of photodiode length at 0.3V reverse bias on SOI.

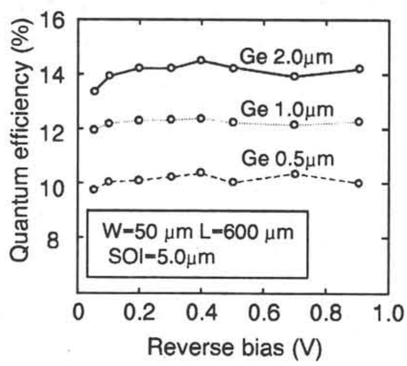

Fig.7 External quantum efficiency dependence of Ge thickness as a function of reverse bias voltage at photodiode area of 50 x 600 μm^2 on SOI.