Fabrication of Silicon-on-Reflector for Si-Based Resonant-Cavity-Enhanced Photodetectors

Cheng Li, Qinqing Yang, Haiyan Ou, Qiming Wang

State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors,
Chinese Academy of Sciences, P. O. Box 912, Beijing 100083, P. R. China
Email: chli@red.semi.ac.cn , Tel:+86-10-62339511, Fax +86-10-62322388

Abstract

A novel silicon-on-reflector substrate for Si-based resonant-cavity-enhanced photodetectors has been fabricated by using Si-based sol-gel and smart-cut techniques. The Si/SiO_2 Bragg reflector is controlled in situ by electron beam evaporation and the thickness can be adjusted to get high reflectivity. The reflectance spectra of the silicon-on-reflector substrate with five pairs of Si/SiO_2 reflector have been measured and simulated by transfer matrix model. The reflectivity at operating wavelength is close to 100%. Based on the silicon-on-reflector substrate, SiGe/Si multiple quantum wells resonant-cavity-enhanced photodetectors for 1.3μm wavelength have been designed and simulated. Ten-fold enhancement of the quantum efficiency of resonant-cavity-enhanced photodetectors compared with conventional photodetectors is predicted.

I. Introduction

Resonant-Cavity-Enhanced (RCE) photodetectors have become more and more attractive components for optical communication for its high quantum efficiency, high speed and wavelength selectivity. The fabrication of low cost, high reflectivity silicon-on-reflector (SOR) substrate is one of the key points for Si-based RCE photodetectors. Epitaxially deposited SiGe/Si Bragg reflector has been experimentally demonstrated. However, The reflectivity of SiGe/Si Bragg reflector has been proved to be very low due to both the limitations of SiGe critical thickness and the small refractive difference between SiGe alloy and Si [1][2]. Ishikawa et.al [3] have reported 4- and 5- pairs of Si/SiO_2 reflectors fabricated by Si epitaxy and multiple separation-by-implanted-oxygen techniques. However, there was practical limitation on the choice of the thickness of SiO_2 and Si and the quality of top Si layer was not guaranteed by multiple epitaxy and implantation. In addition, the cost of multiple epitaxy and implantation is too expensive and the process is time consuming. Recently, Si direct bonding and smart-cut process was reported for fabricating silicon-on-insulator (SOI) substrate [4][5]. This process requires that the roughness of Si surface should be less than 1nm. Otherwise, the roughness of the surface of Si/SiO_2 reflector evaporated by electron-beam evaporation is larger than 1nm, which makes bonding to silicon directly impossible.

In this paper, we report on a novel method for fabricating a low cost, high reflectivity silicon-on-reflector substrate. The thickness of top Si crystal layer is about 1.2μm (determined by the energy of implanted hydrogen) and the reflectivity of the SOR substrate at 1.3μm was close to 100%. The advantages of SOR substrate make it attractive to Si-based resonant-cavity-enhanced photodetectors with low cost, high reflectivity and easily controlled for different operating wavelength.

2. Fabrication process

The gluing by silica gels and smart-cut process for achieving SOR substrate is as following: One Si wafer A is implanted by hydrogen ions with an implantation energy of 140keV and a dose of $6\times10^{16}cm^{-2}$ and five pairs of SiO_2 (15nm) and Si(130nm) Bragg structure is evaporated on another Si wafer B with in-situ controlling. Both wafer A and wafer B are coated with silica gels prepared by catalyzed method described in Ref.[6]. Then, wafer A is glued onto wafer B at room temperature. Wafer B is taken as a handle wafer in the process. After that, two-step heat treatments of the two glued wafers are carried out. During the first step, wafer A splits into two parts at 450°C for 30 minutes giving rise to a thin silicon layer transferred to wafer B. Once the splitting occurred, high-temperature annealing is proceeded at 1100°C for 1 hour to strengthen the bonding.

3. Experimental results

The cross-sectional scanning electron micrograph (SEM) image of the SOR substrate with 5 pairs of Si/SiO_2 Bragg reflector structure is shown in Fig.1. The thickness of top silicon layer is about 1.2μm, directly related to the hydrogen ion implanted energy. The glued and evaporated interface of SiO_2 and Si is smooth, sharp and flat. The average thickness of Si/SiO_2 in Bragg reflector is about 130nm/150nm, which is designed for high reflectivity at 1.3μm wavelength and evaporated by electron-beam evaporation with in-situ monitoring. The thickness of Si/SiO_2 can be easily changed for different operating wavelength.

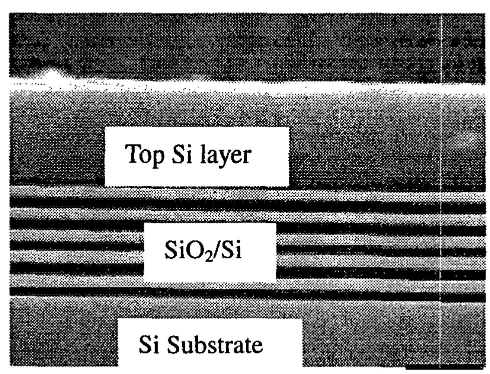

Fig.1 TEM images of Silicon-on-reflector substrate

The smart-cut surface of top monocrystalline Si is characterized by atomic force micrograph. The surface roughness (characterized by root mean square (RMS)) is

15.2nm, which makes polishing of the split surface necessary for epitaxy of SiGe/Si multiple-quantum wells for resonant-cavity-enhanced photodetectors. The value of RMS is consistent with the data reported for the smart-cut surface obtained by high-temperature Si direct bonding [7].

The reflectivity of the SOR substrate under near-normal incidence is measured and simulated by transfer matrix method (shown in Fig.2). The simulated reflectance spectra are similar to the measured ones, but there are still some discrepancies between them in details. We consider that the discrepancies may be due to non-uniform of interfaces of SiO_2 and Si layers. The maximum reflectivity at wavelength 1.3μm in which we are currently interested is near 99.5%. The high reflectivity of the Bragg reflector used as a bottom mirror is benefit to the resonant-cavity-enhanced photodetectors.

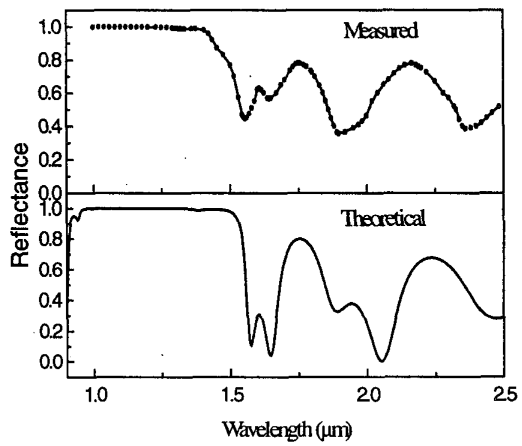

Fig.2 Measured and simulated Reflectance of SOR substrate

4. Design and simulation of Si-based RCE photodetectors

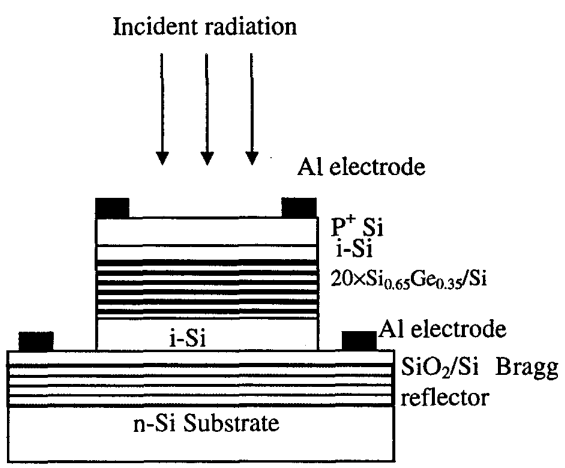

Fig.3 Schematic of RCE photodetectors

Based on the SOR substrate mentioned above, a SiGe/Si multiple quantum well resonant-cavity-enhanced photodetector operating at 1.3μm is designed. The schematic of device structure is shown in fig.3. A p-i-n structure including 20 periods (6nm)$Si_{0.5}Ge_{0.5}$/(25nm)Si multiple quantum-well as absorption region is grown on the SOR substrate by molecular beam epitaxy. The buried SiO_2/Si Bragg reflector is used as a bottom mirror to form resonant cavity with the interface of air and silicon as a top mirror. The device would be fabricated using standard photolithography and dry etching technology. Mesas are etched down to the intrinsic silicon buffer layer by SF_6+O_2. Aluminum is then evaporated to form the contacts. Input light can pass through a window in the center of the photodiodes.

The RCE photodetectors are simulated with transfer matrix method. To calculate the propagation and absorption of incident light in the multiple layer structure inside the cavity, a transfer matrix model for light propagation is used. Each layer is characterized by its complex refractive index $N_i=n_i-jk_i$ and thickness d_i. At 1.3μm, the refractive index of silicon and silicon dioxide can be considered 3.5 and 1.46, respectively with the absorption to the light being neglected. For SiGe alloy, the complex refractive index can be written as $N_{SiGe}=n_{SiGe}-jk_{SiGe}$, the real part n_{SiGe} can be obtained by linear interpolation, while the imaginary is $k_{SiGe}=\frac{\alpha\lambda}{4\pi}$. The relationship between the amplitudes of the propagating waves in air and substrate is given by

$$\begin{bmatrix} E_{0D} \\ E_{0U} \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} E_{sD} \\ E_{sU} \end{bmatrix} \quad (1)$$

where $\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$ is the total propagation matrix, E_{0D}, E_{0U} represent the down travelling wave and up travelling wave in the air respectively. E_{sD}, E_{sU} represent the down travelling wave and up travelling wave in the substrate. The reflectivity R, the transmission T and the absorption A of the photodetector can be obtained by

$$R=\left|\frac{M_{21}}{M_{11}}\right|^2 \quad (2)$$

$$T=\frac{n_s}{n_0}\left|\frac{1}{M_{11}}\right|^2 \quad (3)$$

$$A=1-R-T \quad (4)$$

where, n_0, n_s are the refractive indices of air and substrate, respectively. Quantum efficiency is approximately as the difference between the reflection coefficients for a lossless cavity and a cavity with a finite absorption coefficient in the active layer.

The quantum efficiency of the device versus wavelength is shown in Fig.4. Large oscillations are observed with the RCE photodetectors. Compared with conventional pin photodetectors with the same structure, the quantum efficiency of RCE photodetectors is enhanced by 10 folds at 1.3μm.

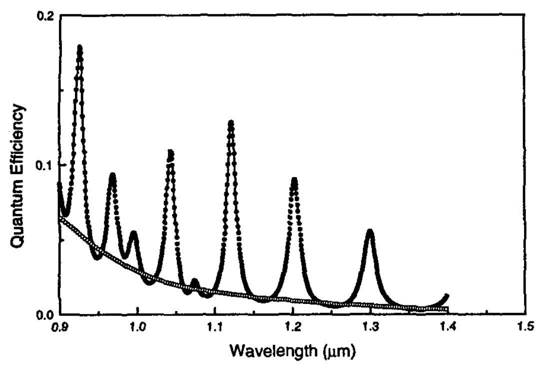

Fig.4 Comparison of the simulated quantum efficiency between RCE and conventional photodetectors

5. Conclusion

In conclusion, the silicon-on-reflector substrate with high reflectivity Bragg structure and thin monocrystalline Si layer is designed and fabricated by sol-gel and smart-cut techniques. The interface between SiO_2 and Si in the Bragg reflector is sharp, smooth and flat. The maximum reflectivity at designed wavelength 1.3μm is close to 100%. Based on the substrate, the resonant-cavity-enhanced photodetectors are designed and simulated. The quantum efficiency at 1.3μm is enhanced by 10 folds compared with that of conventional pin photodetectors with the same structure.

Acknowledgments:
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