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Fabrication of 1.55μm Si-Based Resonant Cavity Enhanced Photodetectors *

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Abstract: A novel bonding method using silicate gel as bonding medium is developed. High reflective SiO_2/Si mirrors deposited on silicon substrates by e-beam deposition are bonded to the active layers at a low temperature of 350 ℃ without any special treatment on bonding surfaces. The reflectivities of the mirrors can be as high as 99.9%. A Si-based narrow band response InGaAs photodetector is successfully fabricated, with a quantum efficiency of 22.6% at the peak wavelength of 1.54μm, and a full width at half maximum of about 27nm. This method has a great potential for industry processes.

Key words: RCE photodetector; high quantum efficiency; direct bonding; bonding medium; InGaAs

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1 Introduction

The increasing demand for bandwidth of telecommunication has greatly promoted the development of optical fiber communications. One of the promising technologies is wavelength-division multiplexing (WDM). In the early sixties, single channel communication was not able to meet the explodingly increasing demand of information, while resonant cavity enhanced (RCE) photodectors with the ability of wavelength selectivity, have become a promising candidate, and have attracted much attention in the past few years due to their potential of circumventing the trade-off between quantum efficiency and high speed[1~3]. In addition, compared with wave-guide photodectors, they are easier to couple with fibers[4].

A lot of work about the design and optimization of RCE photodetectors have been conducted[5~8]. However, how to fabricate long wavelength RCE photodetectors with high-reflectivity distribute bragg reflectors (DBR) and high absorption layers is still a problem, and how to fabricate Si-based high-efficiency long-wavelength RCE photodectors at 1.55μm for fibre-optic communication is even more difficult[9]. Traditionally, one-stop epitaxy technology is used for fabrication of high quantum efficiency narrow band response RCE photodetectors, and for such technology

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the difficulties can be summed up into following: the difficulty for growing high-reflectivity DBR mirrors by molecular beam epitaxy (MBE) or chemical vapor deposition (CVD) systems, due to their small refractiveness difference[10], and the one for growing a high-quality active layer with the peak absorbing wavelength at about 1.55μm[11,12]. Direct wafer bonding technology has been developed to alleviate the difficulty[13]. However, for a high bonding quality, special treatments such as chemical-mechanical polishing and wet etching are required to ensure flat and clean surfaces of the wafers to be bonded together. Bonding media such as Au, AuGeNiCr are also used for alleviating the bonding requirement[14,15]. However, it is difficult to deposit a flat metal layer on the epitaxy layer. Moreover, metal used as bonding medium would absorb most of long-wavelength incident light, which makes it impossible to integrate with optic-components vertically. Other technologies such as air-gap[16] are reported, but the fabrication processes are complicated. In this work a novel bonding method using silicate gel as bonding medium was developed to fabricate InGaAs narrow band-response RCE photodetectors on a silicon substrate. The mirrors were deposited on silicon substrates by plasma enhanced chemical vapour deposition (PECVD) and the bonding was performed at a low temperature of 350 ℃ without any special treatment on bonding surfaces. Thus, the cost is decreased. The reflectivity of the mirrors can be as high as 99.9 % without significantly increasing cost. Silicate gel is prepared by the acid catalyzed hydrolysis of tetraethylorthosilicate[17], and converted into silicon oxide after annealing, which is transparent for long wavelength light. It makes practicable to integrate photodetectors with other optic-components verti-cally.

2 Experiment and results

A schematic diagram of the device is shown in Fig. 1. A 1.4μm thick InGaAsP active layer of photodetector was grown on a (100) InP substrate by metal organic chemical vapour deposition (MOCVD) with the $In_{0.53}Ga_{0.47}As$ absorbing layer of 200nm thick. The as-grown wafer was cut into a typical size of 0.8cm ×1cm, and was then coated with a 300nm thick PECVD SiO_2 layer at 340 ℃. A 3.5 periods SiO_2/Si bottom DBR was deposited on a silicon substrate by e-beam evaporation. Prebonding surface cleaning, including solvent cleaning, DI water rinsing, and standard RCA1, was performed on both wafers. The wafers were then blow-dried in N_2, and coated with silicate gel, after which the wafers were immediately brought together. The bonded InP/Si pair was annealed at 350 ℃ for 4h in a low vacuum under uniaxial pressure to increase the bonding strength. After annealing, the silicate gel was converted into glass, which was proved to have little absorption at the operation wavelengths by other experiments. After bonding, the InP substrate was removed by HCl : H_3PO_4 = 1 :1 chemical etching solution with the epitaxy layer fully transfered onto the silicon substrate. The bonding strength was strong enough to endure the following processes, including ultrasonic cleaning. Standard photolithography and chemical etching were used to define the photodetector mesa. A 400nm thick SiO_2, deposited by PECVD at 340 ℃, was used for passivating layer. Finally a 2.5 periods SiO_2/Si top DBR was deposited on the top device by PECVD to complete the RCE photodector structure.

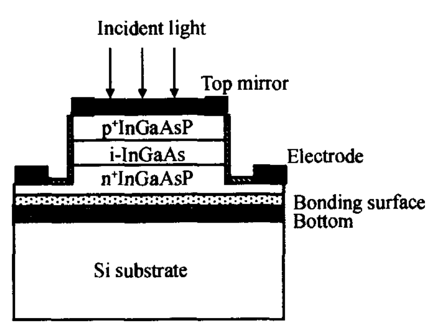

Fig. 1 Schematic diagram of the InGaAs RCE photodetector

The dark current of the RCE photodetector was measured by HP 4140B amperemeter. The dark current density is 16.7μA/cm^2 at 5V reverse bias.

Figure 2 shows the experimental photocurrent spectral response of the Si-based InGaAs RCE photodetector. A monochrometer with 1nm resolution was used to select the excitation wavelength from a chopped tungsten light source. The signal was measured by a lock-in amplifier. The spectral response was measured under zero reverse bias. The resonant peak value is about 1.54μm, with the quantum efficiency of 22.6%. From the figure, a 3 fold improvement on the quantum efficiency of the RCE photodetector due to the resonant cavity enhancement is observed.

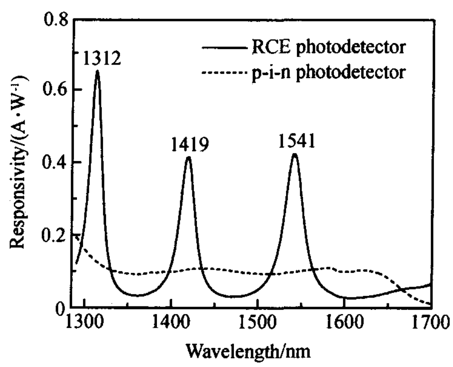

Fig. 2　Measured photocurrent response of the sample under zero reverse bias

However, compared with the simulation result of about 20nm, a larger FWHM of about 27nm may be caused by mirror undulation and unflat bonding surfaces[18]. Also, the small refractive index of 2.7 of silicon grown by low temperature PECVD is contributed to the wider FWHM. Assuming an internal quantum efficiency of 100%, the external quantum efficiency for the RCE photodetectors can be expressed as[5]

$$\eta = \frac{P_l}{P_i} = \left(\frac{1 + R_2 e^{\alpha d}}{1 - 2\sqrt{R_1 R_2} e^{-\alpha d} \cos(2\beta L + \psi_1 + \psi_2) + R_1 R_2 e^{-2\alpha d}}\right) \times (1 - R_1)(1 - e^{-\alpha d}) \quad (1)$$

where R_1, R_2 are the power reflectivity of the top and bottom mirrors respectively, d is the total thickness of the absorption layer, L is the total length of the cavity, ψ_1, ψ_2 are the phase shifts at the mirrors. Since the propagation constant $\beta = \frac{2 n_{eff} \pi}{\lambda}$ (where λ is the vacuum wavelength and n_{eff} is the effective refractive index) is wavelength dependent, η is a periodic function of the inverse of wavelength. When the cosine term in the denominator reaches maximum, the peak quantum efficiency can be express as[5]

$$\eta = \frac{P_l}{P_i} = \left(\frac{1 + R_2 e^{-\alpha d}}{(1 - \sqrt{R_1 R_2} e^{-\alpha d})^2}\right)(1 - R_1)(1 - e^{-\alpha d}) \quad (2)$$

When the reflectivities of top and bottom mirrors match the relation

$$R_1 = R_2 e^{-2\alpha d} \quad (3)$$

the quantum efficiency reaches maximum.

Due to their Fabry-Parot cavity configurations, RCE photodectors have intrinsic wavelength selectivity, which may be useful in some wavelength division multiplexing applications. The relation of the FWHM ($\Delta\lambda_{1/2}$) of the spectral response with the selectivity of photodetectors can be expressed as[5]

$$\text{FWHM} = \frac{\lambda_0^2}{2\pi n_{eff} L_{eff}} \times \frac{1 - \sqrt{R_1 R_2} e^{-\alpha d}}{4\sqrt{R_1 R_2} e^{-\alpha d/2}} \quad (4)$$

where L_{eff} is the effective optical cavity length.

In order to decrease the FWHM of photodetectors, the thickness of absorption layer should be reduced and the reflectivities of the mirrors must be increased. Figure 3 shows the simulated quantum efficiency of the optimized RCE photodetector by the transfer matrix method, in which the thickness of absorption layer is decreased to 45nm. The improved structure of the RCE p-i-n photodetector is as following: an active layer is sandwiched by two mirrors, a top mirror of 2.5 periods of SiO_2/Si and a bottom mirror of 5 periods of SiO_2/Si, and the active layer including a 45nm thick $In_{0.53}Ga_{0.47}As$, a 930nm thick upper spacer layer, and an 1085nm thick lower spacer layer. A narrower FWHM of about 4.5nm can be obtained. In theoretical calculation, an even narrower FWHM of about 0.8nm can be obtained, if the thickness of the InGaAs absorption layer is decreased to about 12nm, and a 3.5 periods top DBR is used. Of course, the difficulty of fabrication also increases.

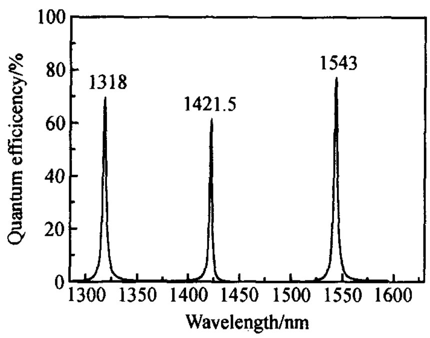

Fig.3 Simulated quantum efficiency of an optimized Si-based RCE InGaAs photodetector

3 Conclusion

In conclusion, a novel method has been developed to fabricate high quantum-efficiency InGaAs RCE photodetectors on silicon substrates, employing bonding technology at the low temperature of 350 ℃ without any special treatment on bonding surfaces, and a Si-based narrow band response InGaAs photodetector was first successfully fabricated, with a quantum efficiency of 22.6 % at the peak wavelength of 1.54μm, and a FWHM of about 27nm. In theoretical calculation, with the thickness of absorption layers decreased to 45nm, a narrower FWHM of about 4.5nm can be obtained. The fabrication process of Si-based InGaAs narrow band-response RCE photodetectors can be performed more simply and easily to thereby contribute to the improved quality, cost-effective fabrication and increased yields of the semiconductor devices.

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硅基 1.55μm 共振腔增强型探测器 *

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摘要: 报道了一种利用硅乳胶作为键合介质的新型键合技术. 高反射率的 SiO_2/Si 反射镜预先用 PECVD 系统生长在硅片上,然后键合到 InGaAs 有源区上,键合温度为 350 ℃,无需特殊表面处理,反射镜的反射率可以高达 99.9 % 以上,制作工艺简单,价格便宜. 并获得硅基峰值响应波长为 1.54μm,量子效率达 22.6 %的窄带响应,峰值半高宽为 27nm. 本方法有望用于工业生产.

关键词: RCE 探测器; 高量子效率; 直接键合; 键合介质; InGaAs

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