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Monolithically integrated tunable dual-wavelength photodetector with flat-top response

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ABSTRACT

This paper elaborates the design and analysis of a novel monolithically integrated tunable dual-wavelength photodetector which can be formed by heteroepitaxial growth of an InP-based p-i-n absorption structure on a GaAs-based Fabry–Pérot filter. The photodetector presents two response peaks resulting from the introduction of 4-step Fabry–Pérot cavity. The wavelength spacing between the two peaks, as well as the peak shapes, can be accurately and easily tailored by adjusting the corresponding step height. This photodetector can be tuned via thermal-optic effect. With optimum design by using Transfer Matrix Method, the detectable wavelength range of the photodetector will be twice as that of its counterpart being with a uniform filter cavity; what is more, flat-top responses of the two peaks can also be obtained, simultaneously. We discuss the epitaxial growth and fabrication of the photodetector at the end, indicating the mature technique available for the device.

1. Introduction

Narrow spectral linewidth, widely tunable photodetectors with flat-top response are essential for wavelength demultiplex receiving applications in optical-fiber communications. Up to now, with the heteroepitaxial growth of an InP-based p-i-n absorption structure on a GaAs-based GaAs/AlGaAs Fabry–Pérot (FP) filter, a series of promising receiving devices such as taper-cavity-based wavelength-selective photodetectors [1,2], long-wavelength tunable photodetectors [3,4], taper-substrate-based tunable dual-wavelength photodetector [5], monolithically integrated photodetector array [6], as well as reconfigurable optical drop module [7], have been realized. Although these receiving devices present narrow spectral linewidth (<0.8 nm), the tuning range of no more than 10.5 nm and response lineshape with a steepletop cannot satisfactorily meet the requirement of wavelength-division multiplexing (WDM) applications.

In an effort to expand the detectable wavelength range, widely tunable phodetectors are favorable. What is more, tunable dual-wavelength photodetector may be another alternative. Lv et al. [5] have exhibited their successful implementation of a tunable dual-wavelength photodetector based on a tapered GaAs substrate. However, the complicated manufacture process of the tapered substrate and the tremendous difference between the amplitudes of the two detectable wavelength peaks, as well as the polarization dependence feature, make this design rather futureless.

Besides the detectable wavelength range, the response lineshape of the photodetector is another consideration. In the optical network, the quick and accurate alignment with wavelength is an important issue during the channel detection. A photodetector having flat-top response is quite desirable in WDM system preferred for signal fidelity and tolerance of signal wavelength drift, because a slight fluctuation in the source wavelength would cause dramatic performance degradation in the detection efficiency. Several methods have been reported to get the flat-top spectral response [8–10]. The traditional way is to cascade two or three FP cavities together, but the cavity is so long and precision is so difficult to control [8]. By using an anomalous-dispersion mirror, a flat-top Resonant-Cavity-Enhanced (RCE) photodetector has been shown in [9]; however, 3-dB linewidth of around 40 nm in the experimental results strictly limits its application in WDM system. Using cascaded subwavelength resonant grating filters to get the flat-top response is too complicated in fabrication technique [10].

With the help of multistep FP cavity structure, a Si-based flat-top FP filter [11] and a photodetector array for multiple wavelengths receiving applications have been demonstrated [6], respectively, indicating the potential applications of this stepped structure in various optoelectronic devices. In this paper, with the employment of a 4-step FP cavity structure, we present the design and analysis of a monolithically integrated tunable dual-wavelength photodetector. Comparing with its counterpart being with a uniform FP cavity, the detectable wavelength range of this photodetector has been doubled due to the two tunable response peaks; furthermore, flat-top responses of the two peaks can also be achieved, simultaneously.

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2. Design and theoretical analysis

The cross-sectional schematic structure of this photodetector is depicted in Fig. 1. It consists of two parts: the lower GaAs-based FP filter and the upper InP-based p-i-n absorption structure. The two parts can be monolithically integrated through high quality heteroepitaxy by employing a thin low temperature buffer (LTB) layer of InP material [4–6]. The lower filter comprises two identical distributed bragg reflectors (DBRs) of k (a positive integer) pairs of GaAs/AlGaAs quarter-wave-stacks, between which a 4-step cavity filled with GaAs material is sandwiched. Both DBRs are designed for high reflectivity at central wavelength of 1550 nm. What needs to be stated clearly here is that all layers above the stepped cavity, including top DBR and p-i-n absorption structure, are stepped type, too, though planar ones are presented in Fig. 1, as well as in subsequent Fig. 2. Owing to the back-illumination of the device, FP effect of the substrate with thickness of around 350 μm, should be considered [12]. To our best knowledge, two schemes exist to suppress or eliminate this effect: one is the suitable control of substrate thickness [12]; the other is to deposit a favorable antireflection (AR) coating on backside of the substrate [1,2,11]. Considering the tuning property, AR coating resides in our design, as shown in Fig. 1. According to simulations, FP effect of the substrate around 1550 nm can be completely suppressed while AR coating is with a refractive index of 1.878, and a thickness of $(2k-1)\times1550/(4\times1.878)$ nm. Yttrium oxide (Y_2O_3) may be a best choice due to its refractive index of 1.87 and excellent transparency at long wavelength range.

The spectral response of this photodetector is determined partly by the performance of the filter, and partly by the thickness of absorption layer. The optical signals pass through the filter and then come into the p-i-n absorption structure. Generally, step height Δh is much larger than step heights Δh_A and Δh_B. With a favorable Δh_A, the light waves transmitted through parts A1 and A2, respectively, will be superimposed, eventually leading the photodetector to a flat-top response peak P_A corresponding to part A. Similarly, the other flat-top response peak P_B corresponding to part B can be achieved by the suitable control of Δh_B between parts B1 and B2. The wavelength spacing between P_A and P_B can be easily tailored by varying Δh. Applying tuning power on the tuning electrode patterned in the filter cavity can obtain the thermal-optic effect induced tuning property of the device [4,5].

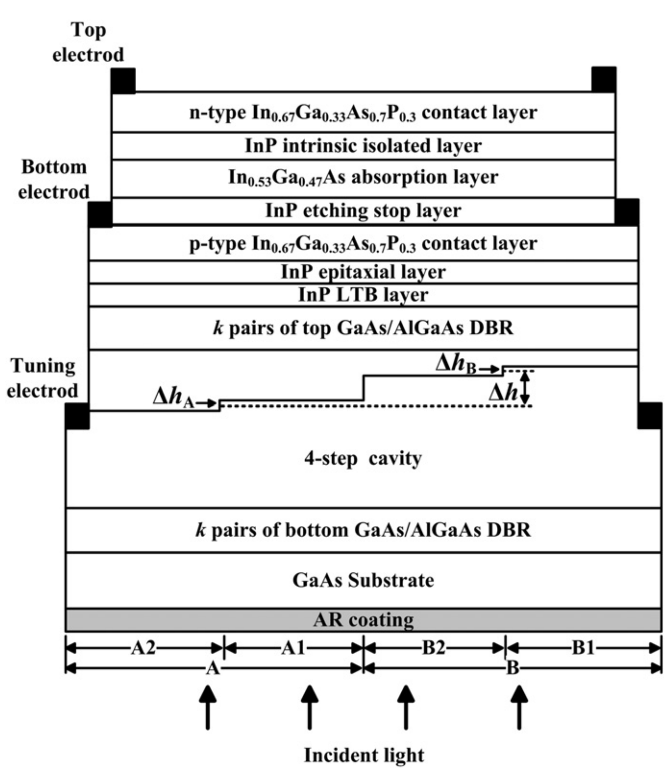

Fig. 1. Cross-sectional schematic structure of the tunable dual-wavelength photodetector.

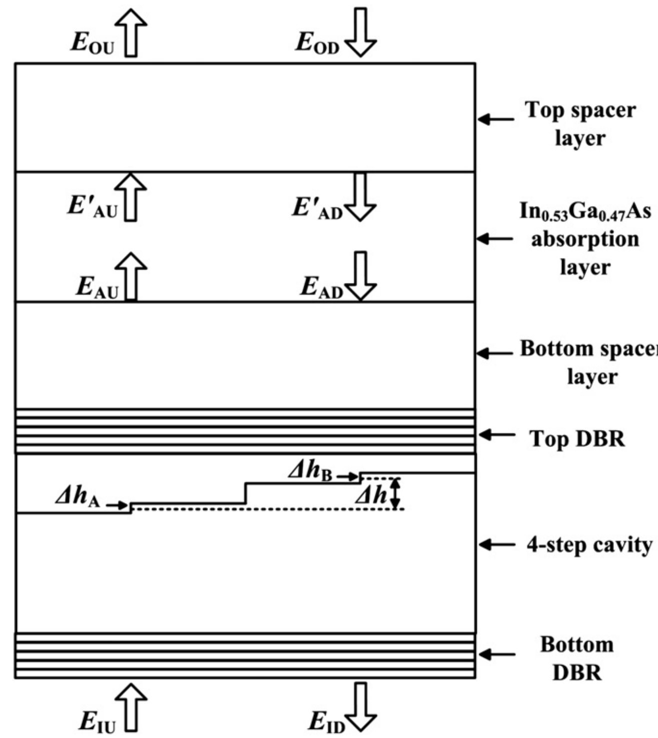

Fig. 2. Theoretical analysis model of the tunable dual-wavelength photodetector.

Fig. 2 illustrates the theoretical analysis model of the device. Comparing with Fig. 1, some simplifications are made for analysis convenience. The bottom spacer layer in Fig. 2 includes InP LTB layer, InP epitaxial layer, p-type $In_{0.67}Ga_{0.33}As_{0.7}P_{0.3}$ contact layer and InP etching stop layer in Fig. 1, while the top spacer layer representing Inp intrinsic isolated layer and n-type $In_{0.67}Ga_{0.33}As_{0.7}P_{0.3}$ contact layer. We choose Transfer Matrix Method (TMM) to calculate the spectral response of the device due to its powerful strength when facing to multilayer structures [12–15]. One advantage of TMM over other calculation methods is that TMM can inherently include the standing-wave-enhancement effect and multiple reflections of light wave in the filter cavity. (E_{IU}, E_{ID}) and (E_{OU}, E_{OD}) denote the electric components of upward- and downward-traveling light waves in the incident and emergent sides, respectively. (E_{AU}, E_{AD}) describes the electric component at the interface between the $In_{0.53}Ga_{0.47}As$ absorption layer and the bottom spacer layer, while (E'_{AU}, E'_{AD}) is that at the interface between the absorption layer and the top spacer layer.

We firstly consider a uniform FP cavity without any step by assigning $\Delta h_A=\Delta h_B=\Delta h=0$. Each layer of the device in Fig. 2 is numbered consecutively from bottom to top. Assuming that the layer numbers of the n-type $In_{0.67}Ga_{0.33}As_{0.7}P_{0.3}$ contact layer and the $In_{0.53}Ga_{0.47}As$ absorption layer are n and m, respectively, the relationship between (E_{IU}, E_{ID}) and (E_{OU}, E_{OD}) can be determined by

$$\begin{pmatrix} E_{IU} \\ E_{ID} \end{pmatrix} = T_1T_2T_3\cdots T_m\cdots T_n\begin{pmatrix} E_{OU} \\ E_{OD} \end{pmatrix}, \quad (1)$$

where T_i $(i=1, 2, 3\cdots m\cdots n)$ is a 2×2 layer matrix corresponding to layer i, and it can be expressed as

$$T_i = U_iM_{i,i+1}, \quad (2)$$