Integrated VCSOA and PIN with high sensitivity

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Abstract. An integrated vertical cavity semiconductor optical amplifier (VCSOA) and PIN photodetector was proposed in attempting to raise the sensitivity in high speed fiber-optic communication systems. Two slightly different structures have been studied under this configuration. For the cascade and the resonance structure, our simulation results showed that their sensitivity could reach -33dBm and -36dBm at a bit rate of 10Gb/s, respectively. We also managed to fabricate the cascade structure and demonstrated a 7dBm improvement on sensitivity as compared to the conventional PIN photodetector.

1. Introduction

Optical communication systems are rapidly growing towards higher transmission rate and channel capacity, where the need for high speed, high sensitivity detectors is increasing. Conventional optical receivers typically use PIN or APD as the front-end photodetector. However, either device has its own limitation. The role of PIN is to convert photons to electrons. Although its bandwidth is sufficient, it usually suffers a low sensitivity due to the lacking of gain [1]. On the contrary, APD has the required gain for high sensitivity. Its bandwidth, however, is very much limited as the signal amplification is carried out in electronic domain [2].

An attractive solution to this problem is the integration of a PIN and a semiconductor optical amplifier (SOA) [3]. In this scheme, the signal is amplified in optical domain before it is converted into electronic domain. Its bandwidth is therefore much broader, as the optical amplification established on the wave’s passing through the gain medium in SOA is much faster than the electronic amplification created by the avalanche process in APD. However, the combination of a surface incident PIN and an edge-emitting SOA needs hybrid integration or co-package, which consequently brings in reliability concerns and cost-ineffective issues.

Vertical cavity SOA grown on top of a surface incident PIN solves the integration problem. To obtain sufficient gain within a limited region in such a stacked layer structure, we will have to force the optical signal to go back-and-forth by passing through the gain region again and again, i.e., we will have to sandwich the gain region into a pair of distributed Bragg (grating) reflectors (DBRs). Namely, we will form a VCSOA in a similar way to the vertical cavity surface emitting laser (VCSEL) consisted of a top DBR, an active region, and a bottom DBR [4].

Apparentely, there are two ways to integrate the VCSOA and PIN: the PIN is placed after the VCSOA (cascade structure) or inside the cavity of the VCSOA (resonance structure). In either case, the entire integrated structure forms a single layer stack hence can be grown by one epitaxial step. This work aims at studying both structures to find their common and different characteristics.
The paper is organized as follows, the structure and numerical simulation of the devices are presented in section 2, then the fabrication details and the experimental results are presented in section 3, finally in section 4 we summarize our results.

2. Structure optimization and simulation

We have designed two types of structures. The cascade structure and the resonance structure are shown in fig.1. The two pictures on the left of fig.1 are the cross-sectional views of the partition design and the three-dimensional design of the cascade structure, and the two pictures on the right are ones of the resonance structure. The difference of two structures is whether PIN is part of the VCSOA resonator.

The devices are all designed to be an NPN-type mesa structure, considering that the N-type substrate process is more mature. Therefore the three-layer electrode is designed to be N-type top electrode, P-type bottom electrode and N-type back electrode, respectively.

For the cascade structure, the mesa etching stops at the top of the lower Bragg grating to reduce the series resistance of the VCSOA part, and to avoid the leakage of the VCSOA injection current as well. For the resonance structure, the mesa etching stops at the contact layer between PIN and the active region of VCSOA.

The travelling wave equation model [5] is called to simulate the VCSOA part and the time domain split step method [6] is used to solve the equations. As for the PIN part, we called the carrier transport model to simulate [7].

The cascade structure is the simple combination of VCSOA and PIN, so we can refer to the existing structure design for each part. The gain of VCSOA benefits from the increase of the reflectivity of the DBR. However, higher reflectivity of the DBR will lead to a sacrifice of the optical bandwidth. The optimized reflectivity of the DBR for the device is calculated to be 0.96.

The simulation results of the cascade structure are shown in fig.2, where the red line in the first diagram represents the incident signal of a 100-bit pseudo random binary sequence (PRBS), and the blue line is the time-varying output power of VCSOA. Further calculation shows that the average gain of the device is 13.16dB when the incident current of VCSOA is 50mA, the responsivity is 19.85A/W, and the sensitivity is -33.41dBm at a bit rate of 10Gb/s.

As for the resonance structure, it is necessary to do some optimization to get the best structural design. Apparently the reflectivity of the bottom grating should be as large as possible. The parameters that need to be optimized include the pairs of the top grating and the relationship between gain coefficient, gain active layer thickness, absorption coefficient, and absorption intrinsic layer thickness.
In order to do such optimization, we defined a normalized gain absorption combination value as \( GA = g L_g - \alpha L_\alpha \), where \( g \) and \( \alpha \) is gain and absorption coefficient respectively, \( L_g \) and \( L_\alpha \) is the thickness of the gain active layer and the absorption intrinsic layer respectively. We then defined the absorption efficiency as \( \eta = |E_{abs}|/|E_{in}| \), where \( E_{in} \) and \( E_{abs} \) is the intensity of the incident light and the light in the absorption region respectively. The relationship between the absorption efficiency and the pairs of the top grating under different normalized gain absorption combination values is shown in fig. 3.

**Fig. 3 Parameter optimization for the resonance structure**

The results indicate that when the normalized gain absorption combination value is positive, the absorption efficiency generally increases first and then decreases as the pairs of the top grating rise. The reason why there is an optimal value for the pairs of the top grating is that the gain of the resonant cavity benefits from the larger reflectivity, i.e., larger pairs of grating, while too much reflectivity of the top grating will lead to less incident signal power into the cavity.

In addition, according to the characteristics of the DBR, the field of the light in the cavity will be concentrated in the absorption region to the greatest extent under certain condition, which is the total phase shift between upper and lower DBRs satisfies the formula \( \phi = 2m\pi + 0.5\pi \), where \( m \) is a positive integer.

In conclusion, the optimized parameters of the resonance structure are chosen as, the thickness of the gain active layer is 1\( \mu \)m where the gain coefficient is 3500\( \text{cm}^{-1} \), the thickness of the absorption intrinsic layer is 0.286\( \mu \)m where the absorption coefficient is 7000\( \text{cm}^{-1} \), the total length of the phase shift area is 1.146\( \mu \)m, the top DBR consists of 12 pairs of grating, and the bottom DBR consists of as many pairs of grating as possible, depending on the level of the epitaxial process.

The performance of the resonance structure is shown in fig. 4, where the red line of the first diagram represents the incident signal of a 100-bit PRBS, and the blue line is the time-varying power of light in the absorption region of the device. From fig 4 we can learn that the average gain of the device is 19.76dB when the incident current of VCSOA is 50mA, the responsivity is 43.84A/W, and the sensitivity is -36.17dBm at a bit rate of 10Gb/s. Further calculation shows that the device has a bandwidth of 190GHz under this condition.

**Fig. 4 The simulation results of the resonance structure**
3. Fabrication and experimental results

We customized the epitaxial wafer according to the structure design. The mesa etching and the electrodes fabrication were performed by the design mentioned before. Finally we got the detector chips of each structure. Unfortunately, the resonance structural chips’ dark currents are tested to be quite large, leading to an enormous background noise, so that the chips cannot work normally. We have done some verifications to determine how it happened. The secondary ion mass spectrometry (SIMS) analysis confirmed that the concentration of Zn in the P-InP region of PIN is too high, and Zn penetrates into the intrinsic region, making the intrinsic layer to be a high concentration P-type doping. Such a high background impurity concentration will accumulate a large number of minority carriers in PIN, which will unavoidably form a considerable reverse saturation current, i.e. dark current.

So we did the follow-up tests only on the cascade structural chips. Due to the process limitations, the actual structure of the cascade structural chips are as follows. The PIN part is grown on a 350μm N-type InP substrate, consisting of a 500nm N-type InP layer, a 3000nm absorption intrinsic layer, and a 100nm P-type InP layer. The VCSOA part is grown above the PIN part, the gain active layer of which consists of strained InAlGaAs quantum well surrounded by strained InAlGaAs barriers, with a total thickness of 138nm. The gain active region is sandwiched by 12 pairs of N-type InP/InGaAsP top grating and 18 pairs of P-type InP/InGaAsP bottom grating. The aperture of the chip is 25nm in radius and the etching depth is about 3250nm.

First of all, in order to check the basic condition of the chips, we tested the PN junction characteristics of the PIN and VCSOA part, respectively. Fig.5 (a) shows the reverse bias I-V curve of the PIN and the forward bias V-I curve of the VCSOA. The minimum dark current of the PIN is 0.19μA, which is larger than the conventional PIN, presumably because of the inaccurate control of the doping concentrations, and the series resistance of the VCSOA is about 38Ω, which is quite normal.

In order to get the best operating wavelength of the device, we then plotted the responsivity curves at different wavelengths, as shown in fig.5 (b), which illustrates that the maximum responsivity is 1.24A/W, appeared at 1590nm.

![Fig.5 (a) The PN junction characteristics (b) The responsivities under different wavelengths](image_url)

Then we tested the dynamic characteristics of the chips. The eye diagrams under different injection currents is shown in fig.6, from which we can see that with the increase of the injection current, the eye diagrams are getting wider, indicating the gain of the VCSOA part is becoming more and more significant.

![Fig.6 The eye diagrams under different injection currents](image_url)
With further calculation, we got the qualitative relationship between the gain and the injection current at the peak wavelength of 1590nm, as shown in fig. 7 (a). The maximum gain of the device can approximately reach 25dB when the injection current is 30mA.

Fig. 7 (b) shows the curve of the bit error rate (BER) versus injection optical power under different injection currents. Although the absolute value of sensitivity deduced from the curve is lower than normal photodetector, due to the large dark current of the PIN, the relative value of sensitivity under different injection currents can still characterize the role of the VCSOA part. From fig.7 (b) we can see that the sensitivity of the device when the injection current of VCSOA is 40mA, is 4-7dBm greater than those when VCSOA does not work (the injection current of VCSOA is 0).

![Graph of gain vs. injection current](image)

![Graph of BER vs. injection optical power](image)

Fig. 7 (a) The gain under different injection currents (b) BER versus injection optical power

To solve the quality problem of the epitaxial wafer mentioned before, following works can be continued as follows: 1. Grow low doped PIN in common ways; 2. Cut the PIN samples for testing; 3. Select the PIN wafers that meet the quality requirements and use them as new substrates; 4. Grow the high doped VCSOA part above the PIN wafer.

4. Conclusion
We have designed two structural types of photodetector chips, which are the cascade structure and the resonance structure. The simulation shows that the cascade structure device and the resonance structure device has a sensitivity of about -33dBm and -36dBm at a bit rate of 10Gb/s, respectively. The experiments show that the cascade structure devices have the gain of nearly 25dB and the sensitivity of which can provide up to 7dBm improvement than the normal PIN detector.

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