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High Gain, High Efficiency Vertical-Cavity Semiconductor Optical Amplifiers

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Abstract

Highly efficient long wavelength vertical-cavity semiconductor optical amplifiers (VCSOAs) are presented. A carrier confining structure was introduced by etching mesas in the active region. The carrier confinement resulted in increased efficiency and amplifier gain. The efficiency was increased by a factor of 3 as compared to previous devices made from the same active region material. 17 dB fiber-to-fiber was measured and the internal gain was estimated to be 24 dB. This is the highest reported amplifier gain for a long wavelength VCSOA to date.

Introduction

Vertical-cavity semiconductor optical amplifiers (VCSOAs) are interesting devices for applications such as wavelength selective preamplifiers [1], optical interconnects [2], and switching/modulation [3]. VCSOAs show a number of advantages over edge emitting devices stemming from their different device geometry. Advantages include high coupling efficiency to optical fiber (yielding a low noise figure), small form factor, and the potential of fabricating high-density 2D arrays on wafer. Furthermore, the vertical-cavity design is compatible with low-cost manufacturing and testing techniques.

VCSOAs operating at all important telecommunication wavelengths have been demonstrated. The highest continuous wave (CW) gain reported for a long wavelength VCSOA is 18 dB, measured at 217K and 1.55-μm wavelength [4]. We have previously demonstrated optically pumped devices operating in reflection mode at 1.3-μm wavelength [5]. The planar structure of these devices consisted of a stacked multiple quantum well (QW) InP-based active region wafer bonded to two Al(Ga)As distributed Bragg reflector (DBR) mirrors. No confining or guiding structures were formed on the sample; the lateral dimensions of the active region were defined by the spot size of the pump beam. These devices showed low quantum efficiency as carriers could diffuse freely laterally in the quantum wells. It has been shown that too high mirror reflectivity results in lasing at low values of material gain, thereby limiting the achievable amplifier gain. Low mirror reflectivity is desired for high gain, high saturation power and low noise figure [5]. With low mirror reflectivity however, strong pumping is required to reach high signal gain.

The objective of the work presented here was to increase the efficiency of our devices by incorporating a carrier confining structure. This would enable higher amplifier gain and better noise figure for a decreased mirror reflectivity without the need for higher pump powers.

Device design

In order to create carrier confinement the volume of the active region has to be constrained. A simple way to achieve this is to etch mesas in the active layers of the vertical cavity structure. The effectiveness of the carrier confinement is greatly affected by the dimensions of the mesas as well as the properties of the sidewall surfaces. Mesas that are too large will leave room for diffusion of carriers out of the active area. Mesas that are too small, on the other hand, will lead to increased optical losses through scattering off the sidewalls. The optimum mesa size depends on the spot size of the pump beam as well as the size of the optical mode of the signal. The sidewall recombination velocity is smaller in InP/InGaAsP materials than in Al(Ga)As [6]. Still, it is necessary to have as smooth sidewalls as possible. The sidewall roughness is determined by the dry-etching. Ideally, it is desired to cover the sidewalls with some passivating material to prevent carrier recombination, or a wide-bandgap material, which would create a buried heterostructure.

In our VCSOA design two GaAs/$Al_{0.9}Ga_{0.1}As$ DBRs were wafer bonded to an InGaAsP/InP active region. The bottom and top mirror had 25 and 10.5 periods, respectively. The calculated reflectivities are R_b=0.999 and R_t=0.918. The active region had three sets of 7 compressively strained $InAs_{0.5}P_{0.5}$ QWs surrounded by strain compensating $In_{0.8}Ga_{0.2}P$ barriers. InP spacing layers were used to position the three QW sets at the three central standing wave peaks in the 5/2λ cavity. The processing of the devices began with bonding the InGaAsP/InP active region to the bottom GaAs/$Al_{0.9}Ga_{0.1}As$ DBR. After bonding, the InP substrate was removed. Prior to the second bonding, mesas were defined in the active region using reactive ion etching (RIE) in a $CH_4/Ar/H_2$ chemistry. The etch was stopped after the third set of QWs leaving the bottom InP cladding intact. In addition to etching vertical mesas, the QWs were under-etched using a 3:1:5 solution of $H_2SO_4:H_2O_2:H_2O$ at 75ºC. This resulted in a step-like sidewall profile as shown in the schematic of the final VCSOA structure in Figure 1. Finally, the top GaAs/$Al_{0.9}Ga_{0.1}As$ DBR was bonded to the active region. The second bond took place at 575ºC for 30 minutes in a N_2 atmosphere. Details about wafer bonding can be found in Ref. [7].

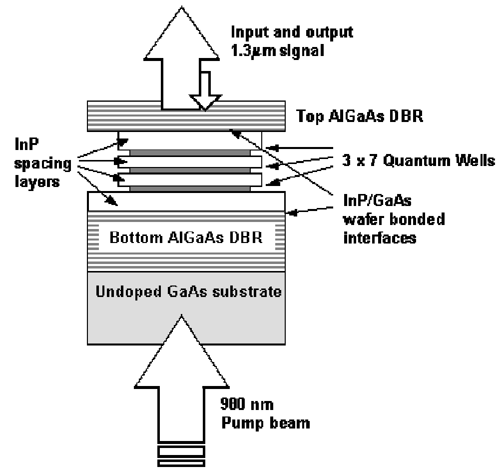

Fig. 1. Structure of laterally carrier confined VCSOA, showing direction of pump beam and 1.3-μm signal.

The active region material and the bottom DBR were from the same wafers that were used in our previous devices to enable a quantitative comparison of the devices. Figure 2 shows a SEM of the cross section of the selectively underetched active region bonded between the two DBRs.

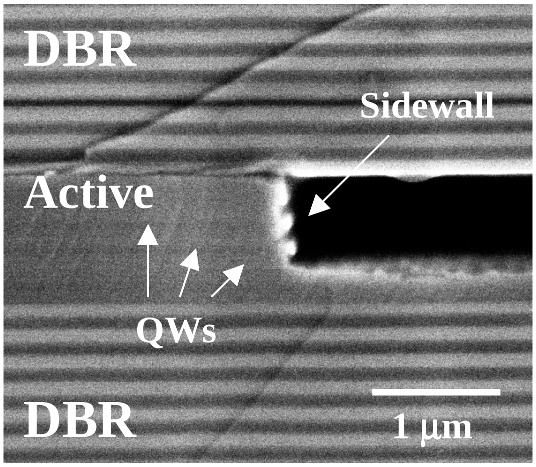

Fig. 2. SEM of cross section of carrier confined VCSOA.

Amplifier results

The devices were optically pumped through the bottom DBR and GaAs substrate using a 980-nm Nortel laser diode. A 1.3-μm tunable laser was used as a signal source. The input signal was injected, and the output signal collected, through the top DBR using a fiber and lens. A circulator was used to separate the input and output signals. The output was monitored using an optical spectrum analyzer. The spot size of the pump beam and signal were about 8 μm and 6 μm, respectively. The total coupling loss in the system, including loss through the circulator, was estimated to be 7 dB.

Figure 3 shows fiber-to-fiber gain versus pump power for a device with a 9 μm diameter active region (triangles). The input signal power is –30 dBm. 10 dB of fiber-to-fiber gain was measured for a pump power of 33 mW. The maximum fiber-to-fiber gain was 17 dB, which means that the intrinsic gain was about 24 dB. This is the highest gain reported to date for a long wavelength VCSOA. For our previous devices that had the same active region but no carrier confinement, the pump power needed to achieve 10 dB of fiber-to-fiber gain was 70 mW for R_t=0.98 and 100 mW for R_t=0.973 [4]. Since R_t is lower for the present devices (R_t=0.918) higher single pass gain is required to reach 10 dB of gain. The efficiency is thus improved by *more* than a factor of 3 in the carrier confined devices. The efficiency as indicated by the dashed line is 0.34 dB/mW. Also shown in Figure 3 is noise figure versus pump power (circles). The best noise figure of 6.1 dB is, as expected, measured for the highest gain. The gain spectrum for an input signal power of –30 dBm and a peak fiber-to-fiber gain of 15 dB is shown in Figure 4. The triangles are measurements and the line is a curve-fit based on Fabry-Perot equations as described in [5]. The gain bandwidth is measured to be 32 GHz.

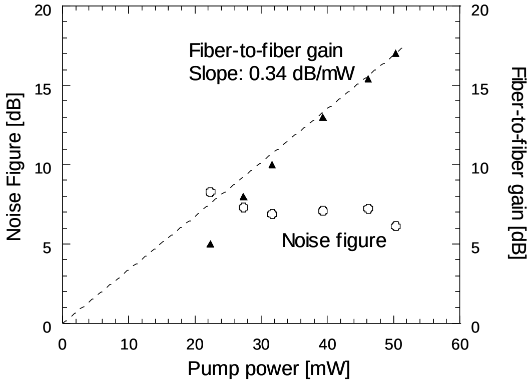

Fig. 3. Gain and noise figure versus pump power. Input signal power is –30 dBm.

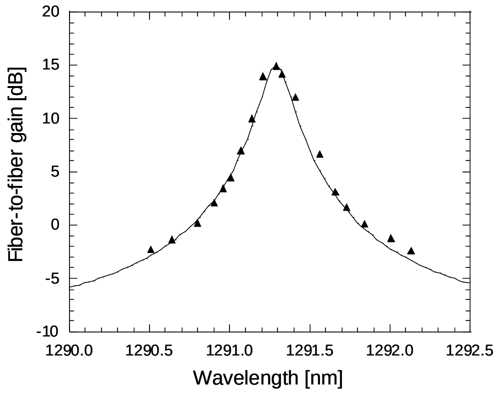

Fig. 4. Gain spectrum at 15 dB peak gain. Input signal power is –30 dBm.

Discussion

The amplifier gain was increased and the efficiency of the VCSOAs was greatly improved by using a carrier confined active region. Carrier recombination will inevitably occur at the sidewalls of the laterally confined active region. However, the loss of carriers by sidewall recombination in the confined active region is far less than the loss of carriers to lateral carrier diffusion in a non-confined active region.

The active region was selectively under-etched before the second bonding, leaving a step-like sidewall profile (Fig.1). The second bonding was performed at 575ºC, which is higher than the growth temperature for the QWs. At this temperature, it is likely that InP from the cladding and spacer layers migrates and fills the steps in the sidewalls. Evidence of this effect can be seen in Fig. 2, where the initially step-like profile of the sidewall is smoothened. However, further investigations are required to establish the exact composition and crystalline structure of the material covering the QWs edges. We believe that the surface recombination at the sidewalls of the active region was suppressed by the selective underetching of the active region and the subsequent mass transport of InP filling in these steps. This suppressed surface recombination further improved the gain and efficiency in the carrier confined VCSOA.

A small polarization dependence in the gain was observed for the smallest devices. 4 dB polarization dependence was measured for 9 μm devices; devices of 15 μm diameter and larger were polarization independent. The polarization dependence can be attributed to either non-circular mesas or non-isotropic strain in the QWs [8] resulting from the high temperature and high pressure during the wafer bonding. This can be avoided by optimizing the mesa formation process and the bonding conditions.

Summary

We have incorporated carrier confinement into an optically pumped vertical-cavity semiconductor optical amplifier structure. The carrier confinement improved the efficiency by at least a factor of 3. The signal gain of the new structure was 17 dB, fiber-to-fiber; the internal gain was estimated to be 24 dB, which is the highest gain reported to date for a long wavelength VCSOA.

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