Journal of the Optical Society of Korea, Vol. 1, No. 1, March 1997, pp. 44~47

MQW electroabsorption modulator integrated with a tapered waveguide vertical interconnect

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(Received; February 4, 1997)

The integration of a GaAs/AlGaAs multi-quantum well electroabsorption modulator and a tapered waveguide vertical direction optical interconnect has been performed without the complicated regrowth process. Zn impurity-induced layer disordering of MQW layer is used to achieve the energy transfer between SQW and MQW regions. Light coupled into a SQW region was transferred to an MQW region and an intensity modulation of 10 dB extinction ratio was demonstrated.

I. INTRODUCTION

The monolithic integration of several optical components is very important in establishing photonic functional circuitries for applications such as optical communications and optical computing. In particular, the integration of a semiconductor laser diode and an optical modulator[1-3] is essential for high speed optical transmission systems. On-chip integration of various optoelectronic devices requires both the variation of band gap of the components on the chip as well as their mode sizes by controlling local composition and refractive index. One of the useful integration schemes is an integration of a single quantum well (SQW) laser diode and an multi quantum well (MQW) modulator with minimal insertion loss. In order to minimize the coupling loss caused by the mode size difference between an SQW and an MQW waveguides, a waveguide type optical connect which can perform the energy transfer between two waveguide regions is required. Recently, tapered waveguide optical interconnects between an SQW and an MQW utilizing Zn and F impurity induced layer disordering (IILD) of GaAs/AlGaAs MQWs[4,5] were reported to achieve the proposed integration of an SQW laser diode and an MQW modulator without resorting to a complicated regrowth processes.

In this paper, we report on the monolithic integration of a tapered waveguide vertical interconnect and a GaAs/AlGaAs MQW electroabsorption intensity modulator without regrowth by exploiting IILD. Light butt-coupled to a SQW region was transfered to the MQW region by tapering the extent of disordering in the depth direction, with electroabsorption modulation performed in the MQW region. The schematic of the integrated structure is shown in Fig. 1. Energy transfer from a SQW region to an MQW region was confirmed experimentally. A modulation on/off ratio of ~10 dB with a -3 V bias at an energy 10 meV below the band edge of the MQW was obtained. The tapered structure was fabricated by Zn IILD of GaAs/AlGaAs quantum wells through a tapered SiOx layer followed by thermal annealing[4].

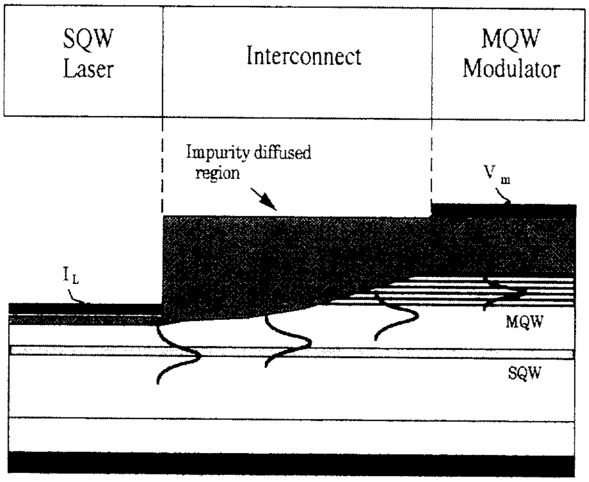


Fig. 1. Schematic of the integrated structure.

II. FABRICATION

The MQW waveguide consists of a guiding region of 15 pairs of 19 nm thick $Al_{0.40}Ga_{0.60}As$ barriers with 6.5 nm thick GaAs wells, surrounded by a cladding layer of $Al_{0.40}Ga_{0.75}As$, on both sides. The 10 nm thick GaAs SQW is seperated by 0.9 μm from the center of the MQW. Epitaxial growth of the MQW and SQW waveguide structures, in addition to the nesessary buffer and cap layers, was performed in a single growth sequence in an atmospheric pressure MOCVD system at a temperature of 725°C using TMG, TMA, and AsH3 as the precursors. The tapers were fabricated by gradually disordering a section of the MQW region in the

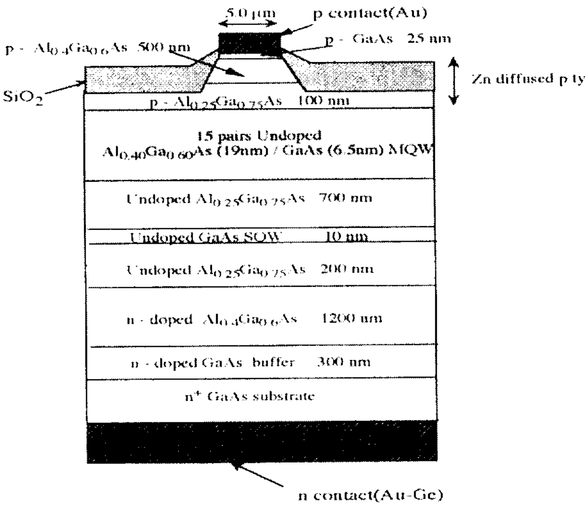


Fig. 2. Cross sectional view of an MQW modulator.

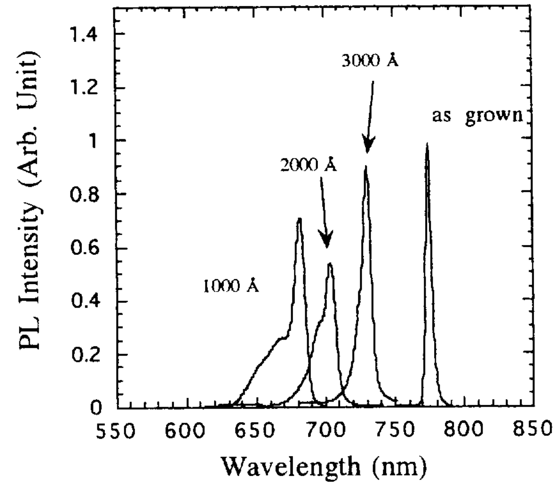


Fig. 3. PL spectrum variation with different oxide barrier thickness.

propagation direction permitting both the effective thickness of the MQW region as well as the refractive index, to be changed correspondingly. This results in the evolution of the normal mode of the waveguide structure from the SQW to the MQW region with propagation distance. For fabrication of tapers, an SiO_x layer with thickness varying linearly from 0 to 300 nm was deposited using a stepping-motor controlled knife edge shadow mask during the SiO_x evaporation process. 350 nm of SiO_x was deposited on the modulator section. After deposition of 300 nm Zn on top of the SiO_x barrier, the sample was capped with SiO_x and annealed at 675°C for 30 minutes. For modulation measurements, 5 μm wide and 0.3 μm deep ridges were fabricated to have lateral confinement of the optical beam. The p^+ contact layer on the modulator section was formed by shallow Zn diffusion through the thicker SiO_x layer and the passivation and metallization were performed sequentially. Fig. 2 shows cross-sectional view of the modulator section.

III. RESULTS AND DISCUSSION

To verify the degree of the quantum well intermixing due to IILD, low temperature (13K) photoluminescence (PL) measurements of MQW layer were performed along the tapered waveguide region as a function of SiO_x barrier thickness. The band edge blue shifts are clearly seen in Fig. 3. The extent of bandgap shifts becomes larger for thinner SiO_x thickness (more disordering). A detailed description of the disordering process and its effect on the optical properties of the MQW layer can be found in Ref. 6. Light from a Ti-sapphire tunable laser was butt-coupled into the most disordered end of the SQW section.

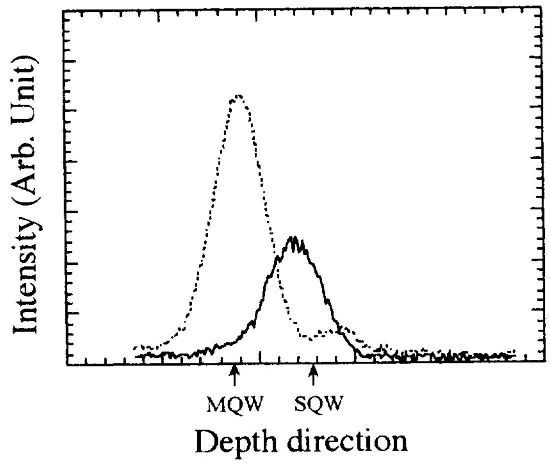
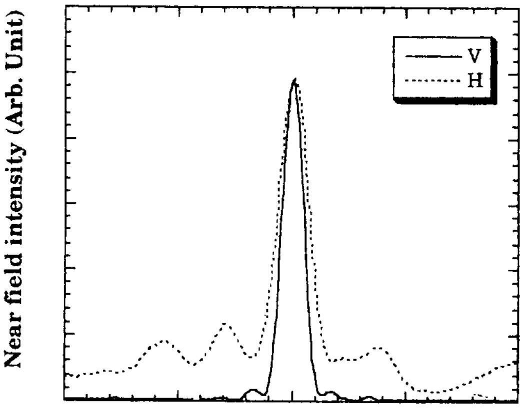


Fig. 4. Normal mode intensity profiles at light coupled region (solid) and modulator region (dotted).

Since the refractive index of MQW changes according to the extent of disordering[6] (index decreases as the disordering increases), the fundamental normal mode of the structure evolves from the SQW to the MQW region, transferring energy from the SQW to the MQW region. Fig. 4 shows the measured near-field intensity profiles (normal mode profiles) at both in and out light coupled ends. To ensure that the beam is in the MQW before it enters the modulator section, the passive absorption profile at the end of the modulation was measured. From the fact that the beam is almost absorbed at 835 nm, it appears that the beam is completely transferred to the MQW modulator section.

Before a modulation characteristics measurement, a discrete MQW modulator which has the same layers structure to the integrated one has been fabricated and tested. Fig. 5 shows the measured near field intensity profile for horizontal and vertical directions at the wavelength of 0.86 μm. The waveguide are single mode for both the directions, and ridge placed on top of the MQW region performs well within a strip-loaded waveguide structure. The absorption spectra measurements were performed in a waveguide structure by measuring the transmission as a function of the reverse bias voltage. The measured transmission spectra for TM polarization case are shown in Fig. 6. In the case of TE polarization, the absorption changes were relatively smaller than those of TM case. Electroabsorption measurements were performed in an integrated structure with a 900 μm long modulator section at three different wavelengths (840, 843 and 846 nm) near the band edge. Fig. 7 represents the intensity modulation as a function of reverse bias voltage. A maximum on/off ratio of 10dB was obtained with -3 V bias. Although the interaction length is long and the confinement factor $\Gamma \simeq 0.2$, the modulation efficiency is still not as high as that for the discrete MQW modulator. Our previous measurements on the discrete modulator of the same structure indicate a ~23 dB on/off ratio at -4.4 V with less Zn diffusion, and compare favorably with other results[7]. We attribute this low on/off ratio to difficulties encountered in isolating the guided energy from the scattered light in our near-field measurements, in addition to the possibility of Zn diffusing into the MQW region also exists. The PL measurements were done on the modulator section to see whether Zn had diffused into the MQW region or not. Fig. 8 shows the measured PL peak of the MQW in the modulator section where the peak was blue shifted slightly (6 nm) and had become asymmetric. Based on the PL measurements, the Zn was seen to have diffused into the MQW region and the modulation efficiency decreased by either a reduced optical confinement factor or by the possible reduction of the quantum confined stark effect in Zn diffused MQW



Figu. 5. Near-field intensity profiles of the modulator where the solid and dotted curves represent vertical and horizontal directions, respectively.

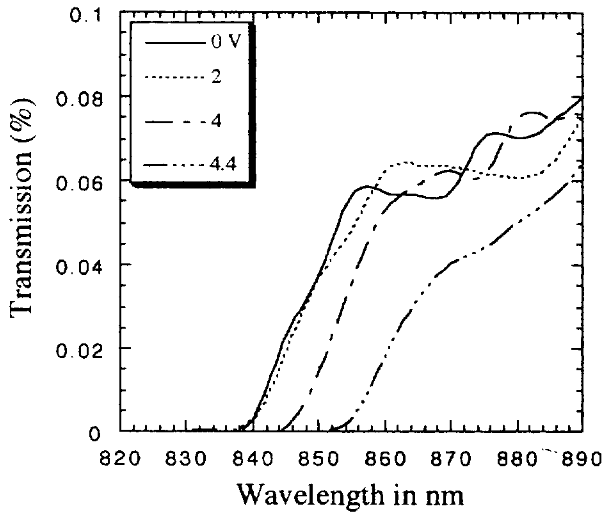


Fig. 6. Waveguide transmission spectrum with different reverse bias voltages.

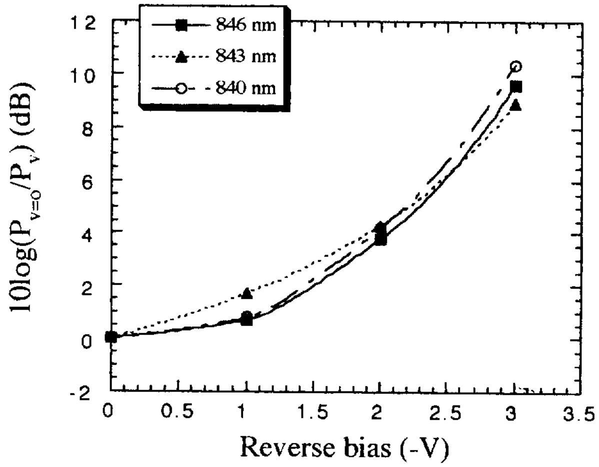


Fig. 7. Intensity modulation as a function of the reverse bias voltage.

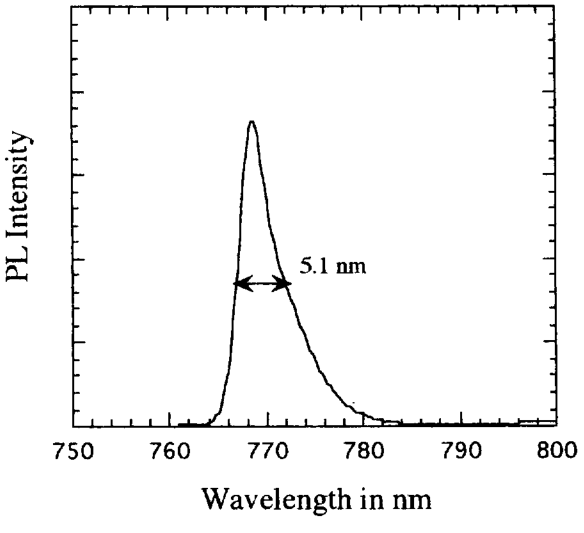


Fig. 8. PL spectrum of a Zn diffused MQW layer.

structure. Thus, to increase the modulation efficiency of the MQW modulator while maintaining the modal evolution in the tapered interconnect intact, the Zn diffusion process needs to be optimized. One of the possibilities is a precisely controlled two step process of two different Zn diffusions for the tapered waveguide and the modulator contact region.

IV. SUMMARY

In summary, the monolithic integration of an MOCVD grown tapered waveguide optical interconnect with a GaAs/AlGaAs MQW electroabsorption modulator has been presented. The IILD technique was used to transfer the energy from SQW to MQW region. Optical beam in a SQW region was transferred to an MQW region and the intensity modulation was performed in an MQW by applying reverse bias voltages. The performed integration would be very useful in achieving the ultimate on chip integration of a high gain SQW laser diode with a large on/off ratio MQW intensity modulator.

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