IEICE TRANS. ELECTRON., VOL. E80-C, NO. 5 MAY 1997

PAPER *Special Issue on Photonic Integrated Circuits*

Characterization of Butt-Joint InGaAsP Waveguides and Their Application to 1310 nm DBR-Type MQW Gain-Clamped Semiconductor Optical Amplifiers

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SUMMARY Butt-joint waveguide couplings are fabricated for use in InP-based photonic integration, and characterized by scanning electron microscopy and optical transmission measurements. Several parameters have been optimized in the characterization study: size and shape of the mask protecting the first waveguide layer during butt-joint regrowth, and the crystallographic direction of the butt-joint interface. The studies show that high-quality butt-joints having negligible optical loss can be made with good fabrication tolerance. Using the optimized butt-joint, DBR-type, gain-clamped SOAs have been fabricated which are free of internal —excess— reflections. A constant optical gain of 21 dB is obtained up to a signal output power of 25 mW. The devices show CATV grade linearity in a 77 channel CATV linearity test at a distortion level of −55 dB below carrier.

key words: *photonic integration, InP, butt-joint, gain-clamped semiconductor optical amplifier*

1. Introduction

In the fabrication of InP-based Photonic Integrated Circuits (PICs), a variety of optical coupling techniques is employed to integrate active and passive sections, or active sections of different composition. Among these techniques are butt-joint coupling, evanescent coupling, selective area epitaxy of multiple quantum well (MQW) structures and quantum well intermixing [1]–[3]. Butt-joint coupling offers maximum freedom in optimizing the design (composition, thickness, conductivity type) of the different sections of the PIC. A butt-joint is fabricated by first growing one waveguide composition (e.g. a laser active layer), locally removing it by etching in the regions where the other composition is required (e.g. an electroabsorption or passive waveguide layer) and then selectively growing the second composition. If necessary, this process can be repeated to fabricate additional sections with different waveguide compositions.

However, the butt-joint coupling technique may have the disadvantage that unevennesses (overgrowths or openings) arise at the growth interface [4], [5]. Such unevenesses can result in reduced optical transmission due to reflection or scattering of light. For instance, in an integrated semiconductor optical amplifier (SOA) these effects would lead to a reduced optical gain, deterioration of the noise figure, increased gain ripple, and the introduction of multiple path interferences.

An improved butt-joint fabrication procedure yielding high optical transmission was developed during our work on wavelength tunable Distributed-Bragg-Reflector (DBR) lasers [6], [7]. The absence of optical reflections was demonstrated by measurements of the DBR laser performance, which, in general, is very sensitive to residual reflections. In this paper, the morphology of the growth interface is studied by scanning electron microscopy (SEM). This was done both as a function of the width of the mask used in the selective growth step and as a function of the angle between front (back) and side plane of the masked mesa block containing the first waveguide composition. In addition, we determined the optical transmission of various test waveguides containing many (> 10) butt-joints as a function of the mesa block angle for waveguides parallel to the [110] and [−110] crystallographic directions. The fabrication and characterization of the test waveguides containing butt-joints are treated in Sect. 2.

In Sect. 3, the application of the optimized butt-joint coupling procedure to the fabrication of 1310 nm DBR-type, gain-clamped (GC) SOAs and the performance of the obtained devices are described. Gain-clamped SOAs have many advantages over conventional SOAs in analog as well as in digital optical transmission systems [8]–[10]. In our DBR-type, GC-SOAs, the gain is clamped by the wavelength selective feedback offered by DBR gratings which are located at both ends of the amplifier cavity [11]. The optical gain of such devices is independent of signal power, a necessary requirement for analog cable-television (CATV) systems. The gain clamping concept is also useful in digital optical transmission in order to prevent extinction ratio degradation by cascaded SOAs as well as in wavelength division multiplexing (WDM) systems, where the linearized gain can

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Manuscript received October 25, 1996.
Manuscript revised December 24, 1996.

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result in reduced inter-channel crosstalk, signal distortion and eye closure.

2. Fabrication and Characterization of Butt-Joint Test Waveguides

2.1 Fabrication

The fabrication procedure for the test waveguides containing butt-joints starts with the growth of the first waveguide layer by Low-Pressure Organometallic Vapour Phase Epitaxy (LP-OMVPE) at a pressure of 0.1 bar and 625°C. In the present case, this first waveguide layer consists of a $\lambda=1300$ nm MQW layer with four compressively strained InGaAsP quantum wells similar to the active layer employed in the GC-SOA [11]. The total layer thickness of the MQW structure including confinement layers is 0.17 μm. The MQW structure is clad by a 0.1 μm thick InP layer.

In the next step, mesa blocks are defined around which the epitaxial structure is locally removed by lithography and etching. The test mask contains mesa blocks with a length of 500 μm spaced by 500 μm and having various widths in the range 10 to 45 μm. In addition, as shown schematically in Fig. 1, 20 μm wide mesa blocks with different angles of the front and back planes with respect to the side planes were included. The angles vary from 90° to 10° in steps of 10°. In principle, an angled butt-joint interface should result in reduced optical reflection, because the transition between the two waveguide sections having different effective refractive indices is distributed over a larger region. As can be seen in Fig. 1, uninterrupted 20 μm wide mesa blocks and "empty" regions are present on the mask as well. These are used to fabricate reference waveguides not interrupted by butt-joints for the optical characterization. The locations of the ridge waveguides fabricated in a later stage of the processing are also shown in Fig. 1. To study the influence of the crystallographic orientation of the butt-joints, the mesa side planes are aligned parallel to both the [110] and the [−110] crystallographic directions. Silicon dioxide is used as a mask for the selective, wet-chemical etching of the mesa blocks and for the subsequent selective area LP-OMVPE growth step (conditions identical to first epitaxy, see above). The block height is equal to the sum of the MQW and the InP cladding layer thicknesses (0.27 μm). The mask undercut is typically 0.05 μm (maximum 0.1 μm). The etching could be carried out by Reactive Ion Etching (RIE) as well, but exact control of the etch depth is more difficult in that case because of the lack of material selective RIE etchants in the InP/InGaAs(P) system.

In the next step, a waveguide layer consisting of $\lambda=1100$ nm InGaAsP material (thickness 0.15 μm) is selectively grown by LP-OMVPE forming the butt-joints at the front and back planes of the mesa blocks. The InGaAsP layer is clad by a 0.1 μm thick InP layer. Note that the butt-joint is fabricated against rather shallow mesa blocks, which limits the unevenesses at the interface to a minimum. Then, after removing the silicon dioxide mask, the entire wafer is overgrown with a 1.0 μm thick InP layer. Ridge waveguides (height 1.0 μm, width 2.5 μm) placed at the centre of the mesa blocks are subsequently fabricated by RIE etching.

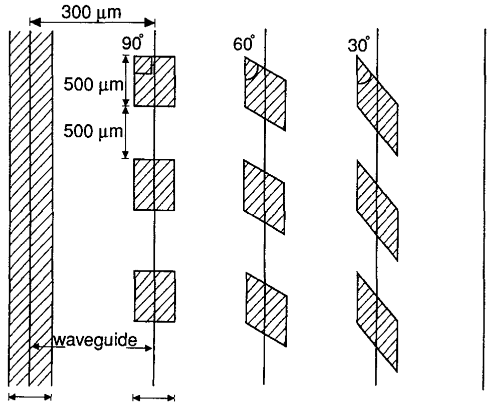

Fig. 1 Schematic mask layout for test waveguides with various types of butt-joints as well as continuous waveguides. The locations of the ridge waveguides fabricated in a later stage of the processing are indicated by the solid lines.

2.2 Characterization of Butt-Joints

Figure 2 shows a series of SEM micrographs of cleaved cross-sections (stain-etched in $K_3Fe(CN)_6/KOH$) of butt-joints fabricated from mesa blocks having widths of 10, 20 and 45 μm. The cleavage plane is parallel to the side planes of the mesa blocks (thus parallel to the eventual waveguide direction). A discontinuity is observed in the immediate vicinity of the butt-joint

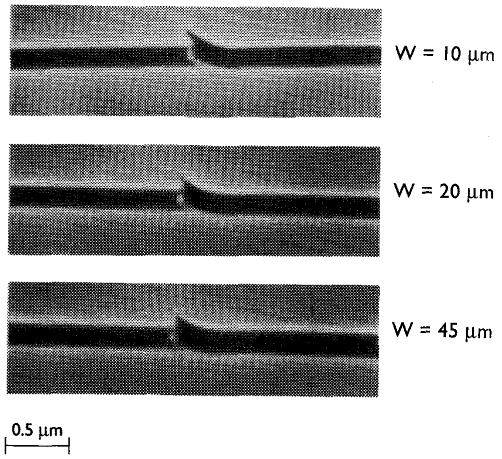

Fig. 2 SEM micrographs of cleaved cross-sections (stain-etched) of butt-joints fabricated from mesa blocks having widths (from top to bottom) $w=10$, 20 and 45 μm. The mesa blocks are etched by selective, wet-chemical etching and the epitaxial regrowth is accomplished by LP-OMVPE at 625°C.

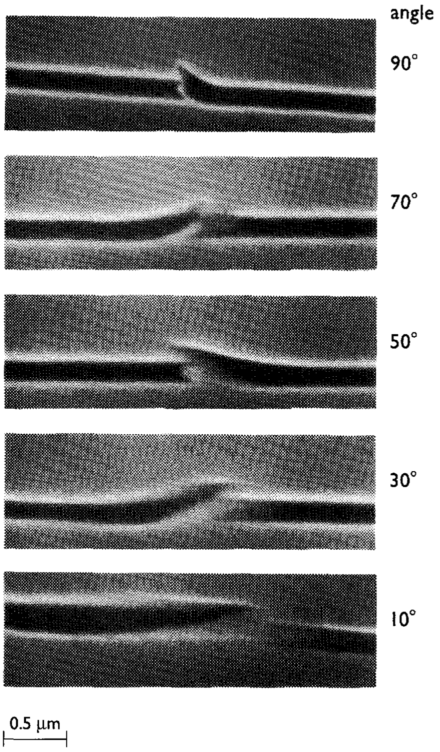

Fig. 3 SEM micrographs of cleaved cross-sections (stain-etched) of butt-joints fabricated from mesa blocks with various angles between front (back) and side planes.

interface due to mass transport and enhanced growth near the edge of the mask. The influence of the mesa block width on the morphology of the butt-joint is negligible within the given range of widths. In all cases the $\lambda=1100$ nm InGaAsP waveguide layer attains its constant, designed thickness within a distance of 0.25 μm from the butt-joint interface. At the interface, a small mass transported region (<0.10 μm, typically 0.05 μm) is formed consisting of InP or InGaAsP with low Ga and As content. The location and size of this region corresponds with the mask undercut. The absence of any width dependence of the butt-joint morphology demonstrates the fabrication tolerance and robustness of the fabrication procedure.

In contrast to the width, the angle between front (back) plane and side planes of the mesa blocks has some influence on the butt-joint morphology, as can be seen in Fig. 3. The length of the transition region increases to about 0.75 μm if the angle is decreased from the standard 90° to 10°. In all cases a mass-transported region containing InP is present at the interface (note that for angles deviating from 90° the butt-joint interface is not normal to the plane of the photograph, making the mass-transported region to appear larger in volume as it is). The optical transmission of waveguides containing many butt-joints as well as of reference waveguides containing continuous MQW or $\lambda=1100$ nm InGaAsP layers was determined by means of the Fabry-Perot method [12]. The measurements have been performed with TE polarized light at 1550 nm. The number of butt-joints is 12 for the waveguides // [110] (waveguide length 6 mm) and 26 for those //[−110] (waveguide length 13 mm). The results are summarized in Fig. 4, from which the following conclusions can be drawn:

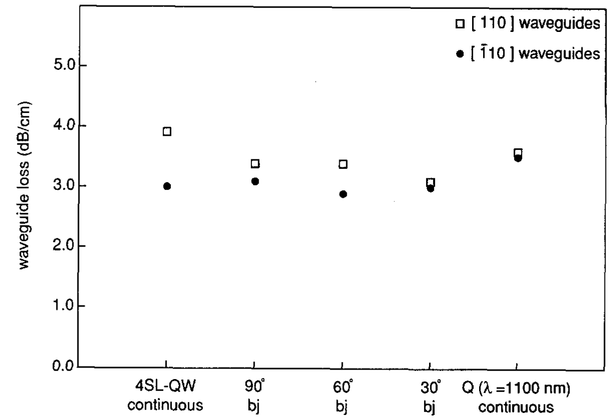

Fig. 4 Waveguide loss in dB/cm for waveguides containing continuous strained-layer, four QW (4SL-QW) or $\lambda=1100$ nm InGaAsP material and for waveguides containing both materials simultaneously butt-joint (bj) to each other. The various mesa block angles used are indicated.

1. The same optical loss is measured for continuous waveguides and for waveguides containing 12 or 26 butt-joints. So, the introduction of butt-joints does not lead to any excess waveguide loss; this holds for all three angles investigated (30, 60 and 90°).
2. The crystallographic direction of the waveguide (and thus of the butt-joint interface) does not affect the waveguide loss.

The optical measurements thus indicate that the fabrication procedure is also tolerant to the shape of the mask and the crystallographic orientation. The difference of about 1 dB in waveguide loss for the continuous MQW waveguides in the two crystallographic directions is not understood so far. The accuracy of the data is better than 0.5 dB. It can be concluded that although the butt-joint morphology is somewhat worse for angles $<90°$, this is not reflected in the optical transmission. The reason may be that an increase in reflection due to the morphology and a decrease due to the angle cancel out, thus maintaining the very small (undetectable) reflectivity at the butt-joint. The absence of any excess loss due to the butt-joints here is in contrast to previous reports [4], [5]. The excess losses per butt-joint reported in those papers are 0.9 dB [4] and 0.5 dB [5], respectively. This may be caused by the severe growth inhomogeneities due to the rather large heights of the mesa blocks (1 and 2 μm, respectively) used by these authors. The shallow mesa blocks employed in the present procedure on the other hand eliminate the excess loss entirely.

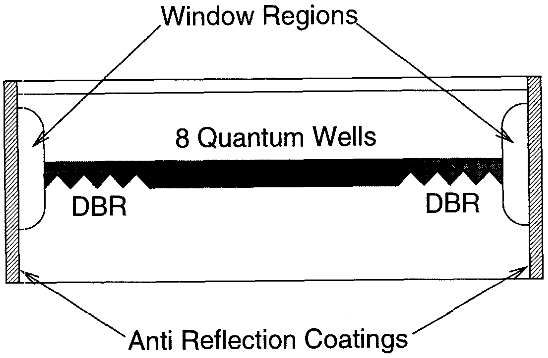

Fig. 5 Schematic, longitudinal cross section of DBR type, GC-SOA chip showing the active, DBR and window sections.

3. Fabrication and Performance of GC-SOAs

3.1 Fabrication

A schematic longitudinal cross-section of the DBR-type GC-SOA chips indicating the active, DBR, and window sections is shown in Fig. 5. The chip fabrication consists of the following steps: First the amplifier active layer is grown by LP-OMVPE on a 2-inch diameter, n-type InP substrate. The active layer consists of eight compressively strained InGaAsP quantum well layers embedded within $\lambda=1080$ nm InGaAsP barrier and separate confinement layers, and has a total thickness of 0.2 μm. The structure is clad by a 0.1 μm thick p-type InP layer. Then mesa blocks (length 500 μm, width 20 μm) are fabricated according to the procedure described in the previous section. In order to facilitate the formation of angled active stripes [13], [14] for reduction of the facet reflectivity, the side planes of the mesa blocks are angled 10° with respect to the [110] direction; the 20 μm wide back and front planes are perpendicular to the [110] direction. The butt-joint-grown passive waveguide layer consists of $\lambda=1100$ nm InGaAsP material and contains a DBR grating corresponding to a wavelength of 1284 nm. The length of each DBR section is 100 μm. In the next step, 10° angled, 2 μm wide mesas are etched for fabricating semi-insulating planar buried heterostructure devices [15]. With the SiO_2 etching mask still on the mesa, the Fe-doped semi-insulating InP and n-type InP current blocking layers are grown. During this step, 20 μm long free-propagating InP window regions are simultaneously introduced at both ends of the DBR sections to reduce the facet reflectivity. The combination of an angled stripe, window regions and anti-reflective facet coating leads to effective reflectivities as low as 6×10^{-6} [14]. After removing the mask, p-type InP and InGaAs layers are grown on the entire wafer. The final processing consists of thinning, metallization, facet coating of bars of amplifier chips and mounting (p-side up) of the chips on copper carriers.

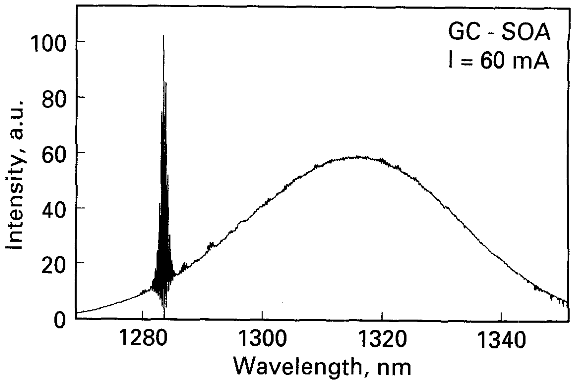

Fig. 6 Amplified spontaneous emission spectrum of a DBR-type, gain-clamped MQW SOA measured at $I=60$ mA, i.e. below lasing threshold. The chip temperature was 20°C.

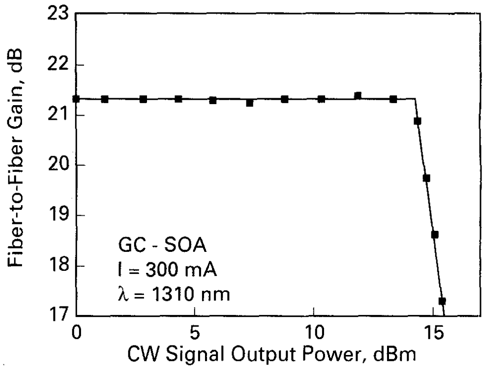

Fig. 7 Optical gain at 1310 nm versus signal output power for a DBR-type, gain clamped MQW SOA at 300 mA drive current ($T=20$°C).

3.2 Device Performance

Figure 6 shows the amplified spontaneous emission spectrum of a GC-SOA measured below the lasing threshold at a drive current of 60 mA. The lasing threshold of the device is 80 mA. At the Bragg wavelength of 1284 nm, a series of Fabry-Perot fringes is observed. In addition, a number of "supermode" fringes is observed entirely due to the presence of the Bragg reflectors. Thus, no optical reflections at the butt-joint interface are found, which is in line with the results of the butt-joint characterization presented in the previous section.

A first indication of the gain linearity of the GC-SOA can be obtained from Fig. 7, where the optical gain is plotted as a function of signal output power at a drive current of 300 mA, i.e. well above lasing threshold. The input signal is in the TE polarized state. (It should be noted that the exclusive use of compressively strained quantum wells leads to pure TE gain). Two regimes may be distinguished: (1) for output powers below 14 dBm (25 mW), the gain is constant within the accuracy of the measurement (0.1 dB), and (2) for output powers above 14 dBm the gain drops steeply. Here the carrier concentration in the device is depleted to such an extent due to the amplified signal light, that laser oscillation can no longer be sustained. The gain ripple as a function of wavelength is 0.2 dB.

The performance under analog optical transmission of the GC-SOAs has also been studied using a realistic 77 channel CATV linearity test [16]. Distortion products such as the composite second order (CSO) distortion were found to be in the vicinity of −55 dB below carrier. Such a performance is very encouraging for analog transmission systems.

4. Conclusions

In this paper, an optimized butt-joint coupling procedure for InP based photonic integration is characterized, and applied to the fabrication of gain-clamped 1310 nm DBR-type MQW semiconductor optical amplifiers. The butt-joint is optimized by reducing the step height of the regrown interface to a minimum. The following parameters have been varied in the characterization study: size and shape of the mask protecting the first waveguide layer during butt-joint regrowth, and the crystallographic direction of the butt-joint interface. The interface morphology is independent of the mask width up to the maximum value studied of 45 μm, but it depends on the angle between front (back) and side planes of the mesa blocks. Minimum disturbance of the morphology is obtained at an angle of 90°. Optical transmission measurements show no excess loss due to the butt-joint for the angles investigated (90, 60 and 30°) in both the [110] and [−110] direction. The characterization by SEM and optical measurements thus clearly demonstrates that high quality butt-joints can be made with good fabrication tolerance to a number of design parameters (mask size and shape, crystallographic direction).

Using the optimized butt-joint, DBR-type, gain-clamped SOAs have been fabricated which are free of internal — excess — reflections (except for the built-in reflection from the DBR gratings). A constant optical gain of 21 dB is obtained up to a signal output power of 25 mW. The devices show CATV grade linearity in a 77 channel CATV linearity test at a distortion level of −55 dB below carrier. Their linear gain performance makes the GC-SOAs promising devices for both analog and digital (TDM and WDM) transmission systems.

Acknowledgements

The authors gratefully acknowledge the technical assistance of A. van Leerdam, J. Donkers and M. Vermeulen-Hartjes. We thank V. G. Mutalik of Philips Broadband Networks, Manlius, NJ, USA for discussions and assistance in the CATV linearity tests.

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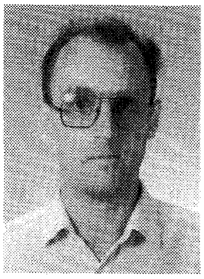

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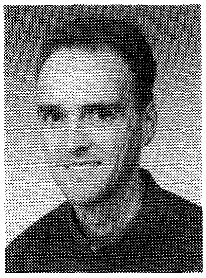

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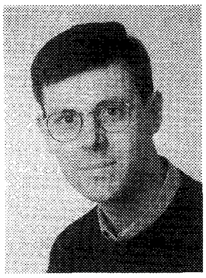

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